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SURVEY

Key Market Mechanisms for Cross-Regional Tradings in the Electricity Market: Insights From Theory and Real-World Implementations

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ABSTRACT Cross-regional electricity trading is critical to optimizing energy resource allocation and enhancing societal benefits. Reviewing theoretical research on key mechanisms of cross-regional electricity markets and drawing lessons from typical markets are of great significance for developing such markets. Firstly, key mechanisms of cross-regional electricity markets are outlined, including market basic structure, trading modes, market coordination mechanisms, and transmission pricing mechanisms. Secondly, the key mechanisms of typical cross-regional trading markets, including those in Europe, the United States, and China, are analyzed and compared. In addition, a summary analysis is conducted on the problems existing in further developing typical regional electricity markets towards cross-regional trading markets, along with corresponding solutions. Moreover, the key issues needing focus in different mechanism designs of cross-regional trading markets are summarized to provide theoretical foundations for other countries or regions.

INDEX TERMS Cross-regional trading, electricity market, market mechanisms.

I. INTRODUCTION

A. BACKGROUND

There are two main drawbacks to resource allocation within a single subregion. On the one hand, many countries or regions exhibit characteristics of mismatched supply and demand in their electricity resources. In terms of energy structure, many countries or regions have a single-source electricity structure within a subregion, lacking the ability to achieve complementary advantages within the region [1], [2]. For example, the distribution of power resources in European countries is extremely uneven. Hydropower is concentrated in the Nordic region, while wind power is very abundant in the Iberian Peninsula and the United Kingdom. Continental European countries like France and Germany primarily rely on traditional thermal and nuclear power [3]. In terms of supply and demand, the distribution of power sources and load distribution is inconsistent with the characteristics. For example, China's power generation resources are mainly concentrated in the western region, while the large load area is in the eastern region [4]. On the other hand, maximizing social welfare cannot be achieved solely by resource allocation within a single subregion. According to economic theory, allocating resources over a broader range can further optimize resource allocation capabilities and enhance social welfare [5].

Expanding the scope of resource allocation is a key solution to the above problems. Broadening the scope of resource allocation can enhance market competition, improve the efficiency of resource allocation, facilitate effective resource complementarity among subregions, safeguard power supply security, and better accommodate the demand for large-scale integration of clean energy [6]. Fully leveraging the market's ability to optimize the allocation of electricity resources

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on a larger scale has become a common direction for the development of the world electricity market.

B. MOTIVATION

1) CURRENT STATUS OF RESEARCH ON THE THEORY OF CROSS-REGIONAL ELECTRICITY TRADING

Regional electricity markets have conducted extensive research, focusing on trading modes, coordination mechanisms between different markets, clearing mechanisms, and transmission pricing mechanisms. The following will review research in these four areas.

a: TRADING MODES

In terms of trading modes, considerable discussion and analysis have been conducted by scholars. References [7] and [8] defined the concept of ''unified market'' and ''common market'', and compared the market efficiency of the two. Reference [9] analyzed the characteristics of the regional common market, and proposed a variety of regional electricity market transaction models. The author in [10] believed that the regional common market trading model should be implemented first, and then gradually transitioned to the regional unified market model after the market operates stably. Reference [11] proposed a ''interconnected market'' model based on the ''common market'' model and compared the social welfare of the connected market and the unified market. The results of the study show that the interconnected market and the unified market have the same market benefits, and the interconnected market is a Pareto improvement. Reference [12] discussed the applicability of the ''unified balancing'' and ''zonal balancing'' models in the regional electricity market in southern China. Most of the above studies focused on the period before 2010, and in recent years, there have been relatively few studies on the regional market model, and there are unclear boundaries and overlapping definitions of the regional electricity market.

b: MARKET COORDINATION MECHANISMS

The coordination mechanisms between different markets are the key to guaranteeing the harmonious and stable operation of the region's sub-power market and regional power market. Some researchers have already studied the coordination mechanisms of regional markets. Reference [13] considered the economic efficiency and grid security of the power system, constructing a coupled dispatch model for coordinating inter-provincial and intra-provincial markets across different periods, and verifies the effectiveness and feasibility of the model through simulation. Reference [14] interprets key theories related to electricity market reforms, such as unified markets, electricity price reforms, and information disclosure, proposing that coordinated models at various levels of electricity markets should be a key focus for future market development. Reference [15] analyzed the key influencing factors of inter-provincial and intra-provincial market coordination, and studied the transitional issues during different stages of market development. It proposed relevant policy suggestions focusing on promoting market entities' participation in inter-provincial transactions, unified planning of power sources and grids, and related aspects. While there have been many studies on coordination mechanisms, different market mechanism designs can lead to variations in the design of market coordination mechanisms, with many studies overlooking the practicalities of market operations.

c: MARKET CLEARING FOR REGIONAL POWER MARKET

In terms of regional power market clearing, [16] drew lessons from the Nordic power market practices while considering the differences in provincial resource endowments, proposing a spot market clearing model based on flexible block trading. Reference [13], based on a regional market framework, presented a regional market clearing model adaptable to different stages, considering intra-regional and inter-regional coordination. Reference [17] proposed a multi-area power system clearing solution based on an optimal condition decomposition method. This method utilized a distributed framework without the need for central coordinators. Reference [18], considering the compatibility of each sub-region, presented a spot market clearing model incorporating constraints on sub-regional power exchange. Overall, research on regional market-clearing models has mostly focused on their effectiveness, but has not adequately integrated the characteristics of local power systems, nor fully considered the applicability of these models in the market.

d: TRANSMISSION PRICING MECHANISMS

As a crucial component of regional power market design, transmission pricing mechanisms have been the focus of research by numerous scholars, primarily concentrating on price forms and pricing mechanisms. The forms of electricity transmission pricing include single energy pricing, single capacity pricing, and a combination of both known as ''two-part tariff''. Based on analyzing whether the three forms of tariffs are in line with the basic principle of ''price reflects cost'', [19] suggested that capacity tariff should be adopted for the trans-regional transmission price. Reference [20] recommended the adoption of a single capacity tariff for the transmission price in the regional electricity market, taking into account the pricing objectives of China's inter-provincial and inter-regional transactions, and based on the experience of other typical regional electricity markets. Reference [21] established a two-part tariff mechanism for tiered delivery curves of guaranteed power curves, negotiated transmission curves and over-delivery curves. Reference [22] analyzed the impact of the two-part tariff on cost recovery of transmission companies under different capacity tariff shares. In terms of the pricing mechanism, [23] proposed a two-part tariff model based on sunk costs and added costs, where sunk costs are collected through the capacity tariff, while added costs and revenues are collected through the capacity tariff.

Reference [24] proposed that China's transmission pricing mechanism should be reasonably designed with zoning, and the pricing method should reflect the user's level of use of power grid trends. Overall, existing research has mostly focused on issues such as allowable transmission revenue and cost allocation, with limited empirical analysis of typical regional electricity markets.

2) CURRENT RESEARCH STATUS ON TYPICAL CROSS-REGIONAL ELECTRICITY MARKETS

Many scholars have also conducted research on typical regional markets internationally. Reference [25] summarized the idea of market establishment through legislation-led reform in combination with the history of transnational market reform in Europe. Reference [3] from a macro perspective, introduces the challenges encountered during the process of European market unification and their solutions. It also proposed standardized and market-oriented top-level design principles based on the political background, technical conditions, market driving forces, organizational structures, and grid architectures of China's unified electricity market. References [26] and [25] introduced the structural framework of the European transnational market as of the end of 2019, focusing mainly on introducing market operating institutions and functions, market distribution, and trading models. Reference [27] analyzes the treatment of the European electricity market in terms of offer and clearing and analyzes the superiority of the Price Coupling of Regions (PCR). References [28] and [29] provided a comparative analysis of the market in terms of its formation drivers, history, organizational structure, transaction types, and trading rules. References [6] and [30] analyzed the impact of the integration of the European electricity market. Reference [31] analyzes the lessons learned from the integration of regional markets in three developing countries, including the Southern African Power pool (SAPP), West African Power pool (WAPP) and the Central American Power Market (MER). Overall, existing research primarily focuses on monitoring the progress and operational outcomes of market development, which includes surface-level information. There is relatively less emphasis on summarizing key mechanisms crucial for promoting regional market development, such as trading modes, coordination mechanisms between different markets, clearing mechanisms, and electricity pricing mechanisms.

3) RESEARCH GAPS

Based on the above analysis, existing research has the following research gaps:

- In terms of theoretical research, there has not yet been a comprehensive study analyzing the key mechanisms of regional power markets. Existing research mainly focuses on certain aspects of the key mechanisms of regional power markets, resulting in an unclear understanding of the key mechanisms of regional power markets. This makes it difficult for researchers to fully grasp the current state of research on regional power markets.
- Existing research mainly focuses on surface-level information such as the progress of market establishment and operational outcomes. It lacks a summary of the key mechanisms of typical regional markets, such as market structure, trading models, market coordination mechanisms, and transmission pricing mechanisms. This makes it difficult for other countries that need to develop regional power markets to draw on the experiences of typical regional markets.
- At both theoretical and practical application levels, the future research directions and solutions to existing issues in the implementation of regional electricity markets remain unclear, which hinders the development of regional electricity markets.

C. PAPER CONTRIBUTIONS AND ORGANIZATION

Based on the previous analysis, it is necessary to conduct a comprehensive review from both the theoretical research level and the practical application level. The contributions of this study are summarized as follows:

- Theoretical Analysis: Comprehensively analyze the different feasible solutions for the key mechanisms of regional power markets from a theoretical perspective. This provides researchers with a theoretical basis to understand the current state of research on regional power markets and offers alternative solutions for other countries.
- Practical Analysis: Analyze the current status and the selection of key mechanisms in typical regional power markets from a practical perspective. This provides readers with a reference to understand the status of regional power markets and offers experiential insights for other countries or regions around the world.
- Issues and Recommendations: Summarizes the issues faced by typical regional power markets in the further development of cross-regional trading markets and provides corresponding solutions. Identifies key issues to focus on in the design of mechanisms for cross-regional trading markets to offer a reference for other countries or regions.

The rest of this study is structured as follows: section II analyzes feasible options for key mechanisms of regional electricity markets in terms of basic architecture, trading model, market coordination mechanism and transmission pricing mechanism; section III presents the establishment experience of typical regional electricity markets in Europe, the United States, and China, to provide meaningful experiences for other countries to learn from; section IV summarizes problems in theoretical research and actual establishment, and analyzes the direction of future theoretical research and ideas for improvement of actual implementation; and section V is the conclusions are drawn in Section V.

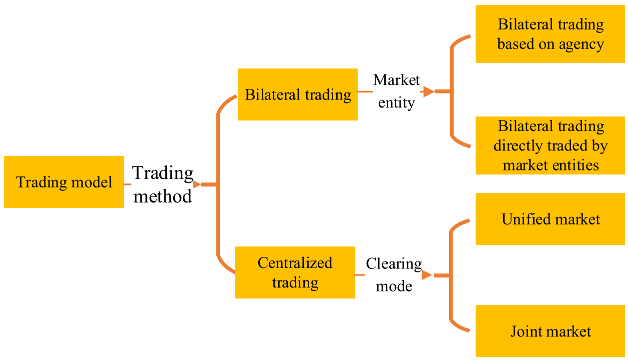

FIGURE 1. The classification of interregional electricity trading modes.

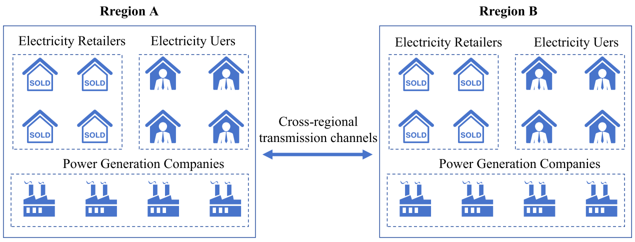

FIGURE 2. The diagram illustrating bilateral trading based on agency.

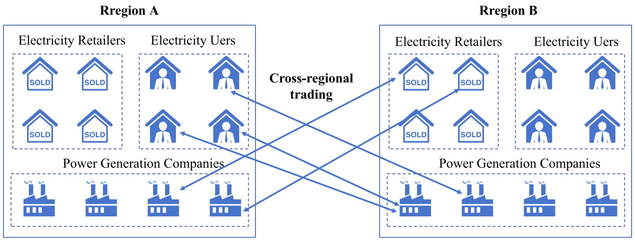

FIGURE 3. The diagram illustrating bilateral trading directly traded by market entities.

II. FEASIBLE OPTIONS FOR KEY MECHANISMS FOR CROSS-REGIONAL ELECTRICITY MARKETS

This section aims to provide readers with a comprehensive understanding of feasible solutions involving different mechanisms, while also deepening readers' understanding of the practical design content that follows. It begins by introducing the classification of cross-regional electricity trading patterns under different frameworks and comparing the applicability, advantages, and disadvantages of various models. Then, it delves into the coordination mechanisms of different markets from the perspectives of clearing mechanisms and organizational processes. Finally, the transmission pricing mechanism for cross-regional electricity trading is analyzed.

A. TRADING MODE

The classification of interregional electricity trading modes is illustrated in Fig. 1. In the literature [32], based on different trading methods, cross-regional electricity trading mainly includes two mechanisms: bilateral trading and centralized trading. Bilateral trading refers to a mechanism where market participants from two regions engage in power transactions through negotiation and consultation, primarily focusing on medium to long-term transactions. Centralized trading involves power generation companies, electricity users, and power retailers conducting transactions collectively through trading institutions, mainly focusing on short-term transactions [4].

1) OVERVIEW OF THE CATEGORIZATION OF THE DIFFERENT MODES

In bilateral trading, market entities from two regions reach cross-border electricity purchase agreements through bilateral negotiations. From the perspective of market entities, bilateral trading can be divided into two types:

- Agency Negotiation: This type of trading occurs when the level of electricity market liberalization is low in the two regions. Typically, grid companies or vertically integrated power companies act as agents for market entities to conduct purchase negotiations, known as "bilateral trading based on the agency". The diagram illustrating bilateral trading based on the agency is shown in Fig. 3.
- Direct Market Negotiation: This type involves direct negotiations between market entities such as power generation companies, electricity users, and power retailers from two regions. After reaching an agreement, the market entities are required to submit the agreement to the local power dispatch and trading institutions within the specified timeframe. The diagram illustrating bilateral trading directly traded by market entities is shown in Fig. 2.

In centralized trading, regional electricity markets are categorized into two types based on the market clearing mechanism: unified markets and coordinated markets [33], [34]. A unified market refers to establishing a single electricity market operating organization within a region, with traded power and prices formed within a market operator and a market platform [35]. A joint market refers to establishing a regional market operating organization along with several market operation branches within a region, with the clearing of electricity and prices in a hierarchical manner within the market operation agency. In multi-regional electricity markets, different regional operating entities conduct transactions via interconnection lines to achieve broader resource optimization and allocation.

Bilateral trading is already well-established internationally, so this section primarily analyzes cross-regional electricity trading modes under centralized trading modes.

2) CROSS-REGIONAL ELECTRICITY TRADING MODES UNDER CENTRALIZED TRADING MODES

As mentioned earlier, centralized trading markets can be divided into unified markets and joint markets. From the perspective of communication and dispatch methods, unified

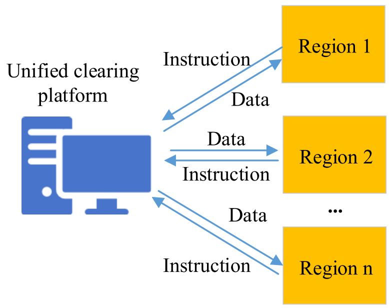

FIGURE 4. Centralized architecture for multi-regional systems.

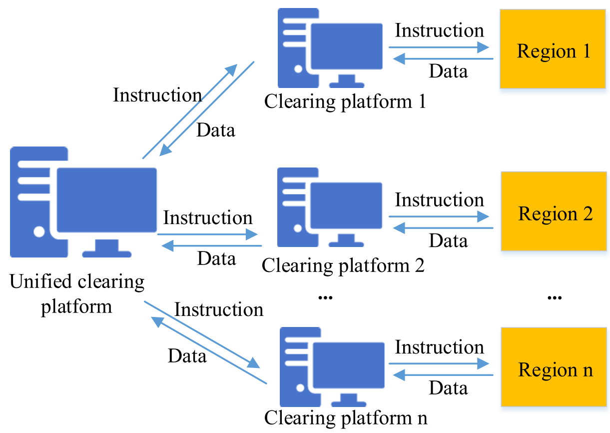

FIGURE 5. Distributed architecture for multi-regional systems.

markets adopt a centralized architecture, as shown in Fig. 4. System information is collected and computed by a central controller, which then sends instructions to various regional dispatch centers for execution. This architecture is more suitable for small-scale power systems. However, as the system scales up and the number of regions increases, the communication pressure on the system keeps rising. Additionally, different market participants' demands for information protection make this architecture increasingly challenging to apply [36]. The joint market adopts a distributed architecture, as shown in Fig. 5. Based on the hierarchical and partitioned characteristics of grid dispatch and control, control centers in each region collect and process information within their respective areas. Then important information is sent to higher-level dispatch centers [37]. The central controller consolidates this information, performs calculations, and sends coordinated information back to each region. Each region then performs its calculations. Different decomposition and coordination calculation models show significant differences in computational effectiveness and communication requirements. Frequent information communication and exchange, while improving the accuracy of computational results, also create communication pressure.

Based on the two architectures of a unified market and joint market, the market trading mode can be subdivided into four modes, namely, "unified market, unified clearing", "Two-tier clearing", "participation of surplus capacity" model, and "incremental trading across regions", of which, except for the first mode, all the other three modes belong to the common market mode, which adopts a distributed architecture.

a: MODE 1: UNIFIED MARKET, UNIFIED CLEARING

"Unified market, unified clearing" is defined as a market model where both the supply side (areas with surplus electricity resources) and the demand side (areas with scarce electricity resources) bid on the same platform, with centralized and unified clearing. Markets applying this mode exhibit centralized characteristics, typically featuring strong electrical network connections between the covered regions [38].

Assuming there are two markets, A and B, where market A has a shortage of electricity resources and market B has a surplus. Compared to independent market operations, under the "unified market, unified clearing" model, prices in market A will decrease, and prices in market B will increase. This means that the cost of electricity in Market B will be higher than in an independent market, while the cost in Market A will be lower than in an independent market [39]. Essentially, under the "unified market, unified clearing" model, the total social welfare of the regional markets will significantly increase compared to independent markets, accompanied by a transfer of benefits between the regions.

b: MODE 2: TWO-TIER CLEARING

"Two-tier clearing", was first proposed in 2018 [40], was defined as prioritizing the clearing of cross-regional trading to form cross-regional trading volumes and tariffs, with the clearing results of cross-regional trading serving as the boundary conditions for intra-regional clearing [41], [42]. When carrying out inter-regional trading clearing, it is necessary to take into account the total generation curve and total power purchase curve of each sub-region, the simplified equivalence model of each sub-region, as well as the balance of power generation and consumption of the whole network and the transmission capacity of the tie line, to obtain the clearing volume of power and the trading tariffs of power energy of the tie line between the sub-regions. After forming the inter-regional trading clearing results, the tie line schedule will be input to the sub-regional market, and the sub-regional market will use the tie line schedule as the market boundary to carry out the formal clearing of the intra-regional electricity market [43].

Under the mode of "two-tier clearing", inter-regional transactions are focused on implementing the national energy strategy, to promote the consumption of clean energy and the optimal allocation of resources on a wide scale. Intra-regional transactions aim to optimize resource allocation in the region, to ensure the balance of supply and demand for electricity and stable operation of the power grid security [44]. Compared to the "unified market, unified clearing" model, the "two-tier clearing" mode also leads to the convergence of clearing prices between surplus regions (areas with excess electricity resources) and deficit regions (areas with electricity shortages), and similarly results in inter-regional transfer of benefits.

c: MODE 3: PARTICIPATION OF SURPLUS CAPACITY

''Participation of surplus capacity'' is defined as prioritizing the clearing of electricity markets in sub-regions with surplus power. Once the clearing is completed in this region, the remaining power generation resources from the surplus sub-region participate in the market of sub-regions facing electricity shortages, bidding alongside other generating resources in those deficient sub-regions [45]. One of the features of this model is that, as the clearing process is prioritized within the sub-region with surplus electricity generation resources, the customer-side price in the sub-region can be stabilized for the time being, and there will be no short-term problems, such as benefit shocks, caused by inter-regional trading [46].

Under the ''participation of surplus capacity'' mode, the electricity prices at the supply end (Region B) can temporarily remain unchanged in the short term. However, under this model, the equilibrium point of market transactions will not remain constant. The reason for this is that the price of electricity sold from Region B to Region A is higher than the market price within Region B itself, indicating a price difference between intra-regional and inter-regional markets. Consequently, generators within Region B will deviate from marginal costs when bidding, raising their prices to offer more generating capacity in cross-regional transactions and achieve greater profits. This ultimately leads to a gradual increase in electricity prices within Region B, aligning them with the prices in the inter-regional market.

d: MODE 4: INCREMENTAL TRADING ACROSS REGIONS

In the ''Incremental trading across regions'' mode, each sub-region's system operator first conducts a pre-clearing process, and market participants in each region decide based on the pre-clearing results whether to participate in cross-regional trading between areas. Next, the operators of the cross-regional market conduct a clearing process based on declarations from market participants of each sub-region and physical boundary conditions, resulting in a clearing of electricity volumes and taffies in the cross-regional market. Finally, the system operators in each sub-region use the results of cross-regional transactions as constraints for the local electricity market clearing process within their respective regions [47].

In the ''incremental trading across regions'' mode, similarly to other models, some of the generators in market B may also deviate from marginal costs when bidding, resulting in higher bid prices, ultimately causing prices within market B (the region with abundant power generation resources) to gradually increase and align with regional market prices. It is important to note that compared to other modes, the ''incremental trading across regions'' mode significantly reduces the volume of cross-regional transactions. This means that the overall utility brought to users in market A (the region with a shortage of generating resources) through inter-provincial and inter-regional transactions sharply declines, and the high-priced demand from recipient regions may not necessarily be met.

e: COMPARISON OF FOUR TRADING MODES

A comparison of the four trading models is shown in the table1. In terms of market prices, a comprehensive comparison of the four typical market modes reveals that neither the ''surplus capacity stacking participation'' nor the ''incremental trading between regions'' clearing modes can ultimately guarantee the maintenance of stable electricity prices within a sub-region. That is to say, under the premise of not restricting the participation of market players in inter-regional transactions. When different price caps are used for inter-regional and intra-regional transactions to maintain price stability within the supplying region, it will lead to market participants engaging in cross-regional trading having prices generally higher than the generating units within the region. Ultimately, this will result in an overall increase in the prices offered by the generators in the sending end (the region with the surplus of power resources), which will gradually converge with the prices in the means region (the region with the shortage of power resources).

In terms of social welfare, mode 1 has the largest social welfare; mode 2 has the same social welfare as mode 1 when there is no blockage in the region; mode 3 has a smaller social welfare than mode 2; and mode 4 has the smallest social welfare. The essential reason for this result is the small volumes of inter-regional traded electricity in models 3 and mode 4 compared to mode 1 and mode 2, which prevents users in the region with the shortage of power resources from maximizing the use of cheaper electricity [45].

It should be noted that in the initial stages of market operation, there may inevitably be ''information barriers'' between inter-provincial and intra-provincial markets, which prevent price information from being transmitted promptly to all market participants. Additionally, the trading activities and outcomes of each participant may not be fully and promptly conveyed through the price system. However, as the market operation normalizes, with increased frequency of market transactions and greater disclosure of trading information, market participants are likely to become widely aware of clearing prices, traded volumes, and other basic information. They can quickly grasp the market situation and proactively optimize bidding to fully integrate into inter-regional and intra-regional market transactions.

3) THE COORDINATION MECHANISMS FOR CLEARING BETWEEN REGIONS

The clearance of cross-regional electricity markets refers to the process of minimizing the objective function value (usually total generation cost) while considering constraints

TABLE 1. Comparison of four trading modes.

Trading Mode	Connotation of the trading mode	Price changes (compared to subregional markets operating independently)	Comparison of social welfare among four modes
Unified market, unified clearing (Mode 1)	Market participants within each sub-region bid and clear on the same platform	Region abundant with generating resources: up; Region with scarce generating resources: down	Maximally
Two-tier clearing (Mode 2)	Cross-regional market and intra-regional markets clear sequentially	Region abundant with generating resources: up; Region with scarce generating resources: down	Same as mode 1 when there is no blockage in the region
Participation of surplus capacity (Mode 3)	Remaining generators participate in the market clearing of the region with the shortage of resources, bidding on the same platform as other generators in that subregion	Region with abundant generating resources: unchanged; Region with scarce generating resources: down	Smaller than Mode 2
Incremental trading across regions (Mode 4)	Subsequent cross-regional trading with residual electricity generation resources after each sub-regional market's pre-clearing	Region with abundant generating resources: unchanged; Region with scarce generating resources: down	Minimal

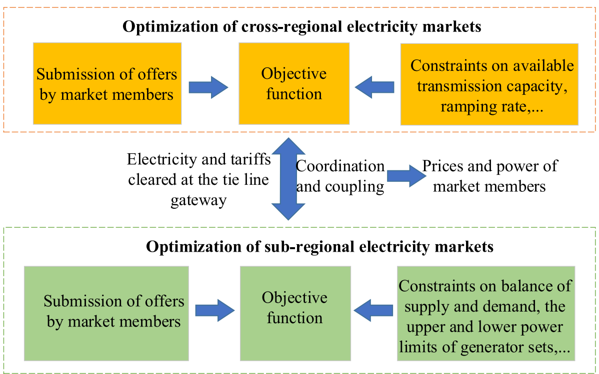

FIGURE 6. The schematic of the optimization model considering inter- and intra-regional coupling.

such as market participant bids and physical boundary conditions, to determine the traded electricity quantity and market clearance price. A schematic diagram illustrating models of inter-regional and intra-regional coupling is shown in Fig. 6.

From the perspective of the level of connectivity between sub-regions, the cross-regional electricity market clearing mechanism is mainly a sequential clearing model, loosely coupled layered coordinated clearing model and strictly coupled unified clearing model [48].

a: SEQUENTIAL CLEARING MODEL

Sequential clearing model means that the generators and users in each sub-region participate in the inter-area trading through the proxy of the system operator in each sub-region without a direct iterative process. The result of inter-regional trading is input and locked as the boundary conditions for market clearing in each sub-region, and market clearing in each sub-region is carried out. The market clearing within the region is optimized and calculated based on various boundary conditions and constraints to minimize the power purchase cost or maximize social welfare. The clearing process is shown in Fig. 7.

b: LOOSELY COUPLED LAYERED COORDINATED CLEARING MODEL

The loosely coupled clearing model refers to first coordinating the overall generation and consumption curves of each sub-region, along with simplified equivalent models for each sub-region, considering overall network generation and consumption balance, the transmission capacity of interconnection line, and conducting cross-border transaction clearance to obtain the cleared volumes and trading prices of electricity between sub-regions.

Then, the results of the centralized optimization of cross-border transactions (the traded volumes and prices across regions) are used as boundary input conditions for market clearing within each sub-region. Under this coordinated mechanism, there is an iterative process between intra-regional and inter-regional market clearance results.

When the upper-layer inter-provincial clearing results break some of the constraints of the lower-layer intra-provincial optimization models, the lower-layer provincial market operators will request adjustments to the transmitted power of tie-lines and recalculate under the new boundary conditions. The calculation procedure is shown in Fig. 7(b).

c: STRICTLY COUPLED UNIFIED CLEARING MODEL

The Strictly coupled unified clearing model refers to the transaction volumes and prices of market participants such as power generators, retailers, and electricity users in each sub-region being determined through global optimization on a single trading platform [49], [50]. The upper-layer cross-regional transactions and lower-layer intra-regional transactions are transformed into a single-layer optimization

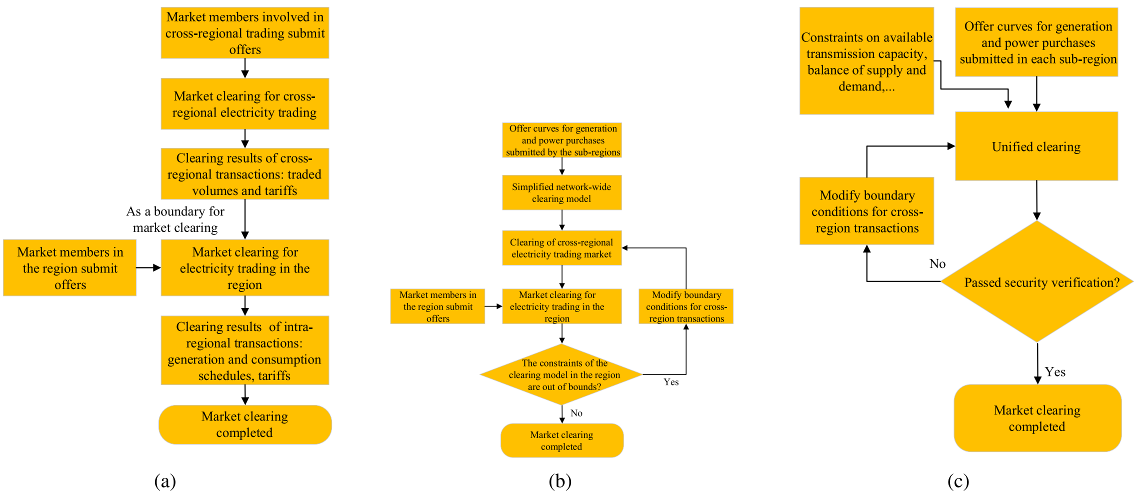

FIGURE 7. **Schematic diagram of three coordinated clearing models for cross-regional transactions: (a) Clearing process of Sequential clearing model). (b) Clearing process of loosely coupled layered coordinated clearing model. (c) Clearing process of strictly coupled unified clearing model.**

model, and clearing calculations are conducted through joint optimization, as illustrated in Fig. 7(c).

4) TEMPORAL COORDINATION

In addition to designing a coordinated clearing mechanism, cross-regional market transactions should also design mutually coordinated timing. The coordination of transaction timing is of great significance to ensuring the healthy and stable operation of the market. Firstly, timing coordination helps to enhance market liquidity. When market participants collaborate better, buyers and sellers in the market are more likely to find matching trading partners, thereby reducing transaction costs and improving market liquidity. Secondly, the synergy of transaction timing helps to allocate resources more effectively. When there is a synergistic relationship between different markets, investors can more flexibly allocate assets in each market, and quickly adjust their investment portfolio to adapt to the opportunities and risks of different markets. Finally, the synergy of trading timing helps to improve market efficiency. Through reasonable coordination in trading timing, market participants can better grasp the operating rules of the market, accurately judge market trends and fluctuations, and make wiser investment and trading decisions. Market synergy also facilitates the faster transmission of information in the market, helping the market to respond more quickly to new information and changes. The collaborative mechanism of market trading timing needs to be designed in conjunction with other market mechanisms and cannot be discussed separately [51].

B. TRANSMISSION PRICING MECHANISMS

The pricing mechanism for transmission services mainly consists of the following three steps [52]:

Step 1: Assessment and authorization of permitted revenue: Based on the costs of transmission network construction, operation, and maintenance, considering revenue-related factors, the annual permitted revenue of the transmission company is approved to determine the annual transmission service revenue that can be charged to users.

Step 2: Determination of the pricing structure for transmission services: Depending on the grid capacity occupied by market members or the expected amount of electricity to be delivered, it is determined whether the permitted revenue will be collected through fixed fees or based on a unit electricity price.

Step 3: Transmission Price Setting: Firstly, using a specific method, the utilization level of the transmission network by each market member is assessed. Then, based on the proportion of utilization levels, the total costs of the transmission company are allocated among each market member. Finally, the transmission cost to be borne by each market member is calculated to establish the transmission price.

1) ASSESSMENT AND AUTHORIZATION OF PERMITTED REVENUE

Permitted revenue for power transmission services refers to the total revenue allowed to be earned by a transmission enterprise within a regulatory year, as approved by the electricity regulatory authority based on certain standards. This permitted revenue serves as a fundamental indicator for the formation of transmission prices and directly reflects the overall level of transmission electricity prices [53]. The international mainstream theories of transmission price regulation mainly include two categories: cost recovery-based regulation and incentive regulation [54].

In cost recovery-based regulation theories, the method of determining permitted revenue mainly involves cost-plus pricing. Cost-plus pricing refers to using the total cost of transmission services as the basis for setting prices, adding a certain percentage of profit to determine the product price [55]. In cost-plus pricing, the determination of permitted revenue primarily considers three components: permitted costs, permitted returns, and taxes payable by the enterprise. Permitted costs for transmission and distribution include depreciation expenses and operation and maintenance costs. Permitted returns refer to the return level approved by the electricity regulatory authority for a specific regulatory year and are an important component of permitted revenue for transmission services.

Based on the regulatory authority's approach to incentivizing transmission enterprises, incentive regulation models can be categorized into two types: revenue (price) cap regulation and performance-based regulation [56]. Revenue (Price) Cap Regulation involves setting a maximum permitted revenue level or transmission service price level for transmission companies. Within this revenue or price cap, transmission enterprises can freely adjust prices based on the supply and demand conditions of the grid. Performance-based regulation introduces a dynamic adjustment mechanism for permitted revenue. It involves setting a baseline revenue level and several performance indicators for transmission companies. When a transmission company achieves the performance indicators satisfactorily, the permitted revenue level can be appropriately increased. Conversely, if the transmission company fails to meet the performance indicators, there may be deductions or adjustments to the permitted revenue level.

2) DETERMINATION OF THE PRICING STRUCTURE FOR TRANSMISSION SERVICES

The method of charging transmission fees mainly depends on the pricing structure adopted by the transmission company. Currently, in the electric power industry, the general pricing structures can be categorized into single-part tariff and two-part tariff, where the single-part tariff includes single-part capacity pricing and single-part energy pricing [57]. Single-part capacity pricing involves distributing the permitted revenue for electricity transmission services based on the total transmission capacity of users, thus forming the transmission price, which represents the amount of transmission service cost per kilowatt of capacity. Single-part energy pricing is calculated based on the estimated transmission volume. The permitted revenue for transmission services is divided by the expected transmission volume to determine the transmission price, representing the amount of transmission service cost to be allocated per unit of transmitted energy. The parties using transmission services calculate their transmission service fees based on their actual transmitted volumes multiplied by the unit energy transmission price applicable to them.

3) TRANSMISSION PRICE SETTING

According to research theories by scholars from various countries, existing cost allocation mechanisms can generally be classified into two main categories: comprehensive cost methods based on cost accounting theory and marginal cost methods based on microeconomic theory [58]. The key to the comprehensive cost method based on cost accounting theory lies in determining the proportion of grid utilization by users. Multiplying this utilization proportion by the total grid costs yields the transmission costs to be allocated to each user or type of transmission service. Depending on the differences in calculation methods for utilization proportions, comprehensive cost method include postage stamp pricing, the megawatt-kilometer method, the contract path method, the line-by-line method, the tidal current method, and the tidal current tracking method [59]. Postage stamp pricing is the most commonly used transmission pricing method in the power market. It involves first considering the costs of specific transmission equipment and grid operation and maintenance expenses to form the total transmission cost, and then calculating the transmission fees based on transmitted power.

The marginal cost method is based on the principles of microeconomics, including the long-term marginal cost method and the short-term marginal cost method. It calculates transmission prices based on the costs incurred when supplying the last unit of electricity or transmission capacity to electricity users. The marginal cost method helps businesses achieve maximum economic efficiency by accurately reflecting the incremental cost of providing a unit of electricity transmission service. As a result, it serves as an economic signal guiding electricity users to make informed decisions about production and operations.

Both the comprehensive cost method and the marginal cost method have their advantages and disadvantages. The comprehensive cost method, based on cost accounting theory, is straightforward to calculate and results in stable prices, achieving financial balance. However, it reflects historical cost situations and does not account for the future value of costs. On the other hand, the marginal cost method, based on microeconomic theory, can release economic signals through cost allocation. It provides insights into the incremental cost of providing services. However, its calculation method can be complex and is significantly affected by various uncertainties.

III. REAL-WORLD IMPLEMENTATIONS: EUROPE, USA, AND CHINA

The establishment of regional electricity markets has been ongoing internationally for many years. Among them, the Pennsylvania-New Jersey-Maryland (PJM) regional electricity market in the United States and the European electricity market have developed relatively maturely. Although China's regional electricity markets have been established for a short time, they have also experienced rapid development.

This section will analyze the design of typical market regional integration based on the analysis in the previous chapter, aiming to provide valuable insights and experiences for other countries around the world that are interested in developing cross-regional electricity markets.

A. THE EVOLUTION OF TYPICAL CROSS-REGIONAL TRADING MARKETS

1) EUROPE

Europe proposed the goal of establishing a unified electricity market reform in 1993, and since then has gone through three stages of market development: national electricity markets, regional electricity markets, and cross-border electricity markets.

a: STAGE OF DEVELOPMENT OF THE NATIONAL ELECTRICITY MARKET

In 1996, Europe issued the first directive (Directive 96/92/EC) to liberalize the electricity market. This directive required vertically integrated power generation companies to separate their generation, transmission, distribution, and supply businesses financially. Cross-border electricity transactions among transmission users in different countries were transitioned from the existing monopolistic approach to a system requiring at least negotiated third-party access (TPA). Concurrently, countries were actively establishing their national electricity markets, marking the official beginning of the reform towards a unified European electricity market.

b: STAGE OF DEVELOPMENT OF REGIONAL ELECTRICITY MARKET

In 2003, the EU issued the second energy directive (Directive 03/54/EC), which called for the legal unbundling of generation, transmission, and distribution into independent subsidiaries. This unbundling aimed to prevent monopolistic behavior, cross-subsidization, and unfair competition by integrated power companies. Transmission and distribution prices were to be regulated by government pricing authorities or regulatory bodies. Subsequently, the EU proposed the idea of establishing regional electricity markets within Europe. This initiative led to the gradual integration of national electricity markets into regional markets, primarily including the Nordic electricity market, the UK and Ireland electricity market, the Iberian electricity market, and the Southeast European electricity market.

c: STAGE OF DEVELOPMENT OF TRANSNATIONAL ELECTRICITY MARKET

In 2007, the EU timely proposed the "2020 Climate and Energy Package," which specified that by 2020, the EU's greenhouse gas emissions should be reduced by 20% compared to 1990 levels, the share of renewable energy in total final energy consumption should increase to 20%, and energy efficiency should improve by 20% [60]. Considering the different resource endowments and the uneven distribution of renewable energy resources across European countries, it became necessary to optimize energy resource allocation on a larger scale. This led to a significant increase in the demand for cross-border electricity transactions among countries, gradually steering Europe from regional electricity markets towards the development of cross-border electricity markets.

Currently, Europe has gradually established a unified electricity market characterized primarily by day-ahead and intraday market coupling, covering 23 countries. This extensive integration has significantly promoted the optimization of electricity resource allocation.

2) USA

The regional electricity markets in the United States has undergone three developmental stages: the regional electricity market model with competition on the generation side, the regional electricity market model organized by Independent System Operators (ISOs), and the regional electricity market model organized by Regional Transmission Operators (RTOs) [61], [62]. Unlike Europe, the integration of the U.S. market has always closely aligned with its long-standing system operation model of joint dispatch by local power companies. To establish four major regional electricity markets, the U.S. achieved the transition from regional electricity markets to broader regional electricity markets by creating ISOs, which gradually evolved into RTOs, through the delegation of dispatch authority.

In addition, addressing the varied organizational forms of regional markets, the U.S. introduced the Standard Market Design (SMD) framework based on the market design of the Pennsylvania-New Jersey-Maryland (PJM) electricity market. The introduction of SMD promoted the development of regional electricity market models towards greater uniformity and provided effective technical support for the consolidation and expansion of regional electricity markets.

Currently, the U.S. electricity market mainly comprises 10 regional electricity markets. Among these, the Midcontinent Independent System Operator (MISO) covers the widest trading area, spanning 15 states in the central U.S. and parts of Canada [63].

3) CHINA

The development of regional electricity markets in China has also undergone significant and challenging exploration. Specifically, this process can be divided into three stages.

a: INITIAL EXPLORATORY STAGE OF THE REGIONAL ELECTRICITY MARKET

In 2002, the first round of electricity market reform was initiated. The "Electricity System Reform Plan" first proposed the idea of "initially establishing competitive and open regional electricity markets" based on regional power grids [64]. However, at that time, the conditions for building regional electricity markets were not met in terms of policy, market development drivers, technical conditions, and grid infrastructure. Consequently, for the next decade, the development of regional electricity markets in China remained stagnant.

b: INITIAL ESTABLISHMENT STAGE OF PROVINCIAL MARKET

In 2015, a new round of electricity system reform was initiated in China, with the release of the document "Several Opinions on Further Deepening the Reform of the Electricity System" and related supporting documents [65]. This round of electricity market reform began with market establishment at the provincial level, rather than focusing on regional markets. Although the new electricity reform policy also proposed the concept of dividing the electricity market into regional and provincial (or municipal) electricity markets, with regional electricity markets involving power market optimization over larger national and specific ranges, the initial focus was primarily on developing provincial-level electricity markets. Subsequently, provinces successively issued their own market rules, leading to rapid development in the electricity market.

c: ESTABLISHMENT STAGE OF THE REGIONAL MARKET UPON THE CONTINUOUS IMPROVEMENT OF THE PROVINCIAL MARKET

With the continuous improvement of provincial-level market establishment, China has begun to explore further optimization of electricity resources on a larger scale. Especially with the introduction of the "Dual Carbon" energy strategy in 2019, the demand for integrating intermittent renewable energy sources over larger areas has increased. Since 2020, China has issued a series of policy documents to promote the establishment of a unified national electricity market. In February 2020, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) issued the "Implementation Opinions on Promoting the Independent and Standardized Operation of Electricity Trading Institutions [66]", which explicitly proposed "promoting market integration and accelerating the development of a unified electricity market nationwide to facilitate the optimized allocation of electricity resources on a larger scale."

On January 18, 2022, the NDRC and NEA of China issued the "Guiding Opinions on Accelerating the development of a Unified National Electricity Market System", which aims to strengthen the hierarchical unified electricity market system, steadily promote the establishment of provincial/regional electricity markets, guide the coordinated operation of electricity markets at all levels, and promote orderly cooperation and opening among markets across provinces and regions.

With the increasing demand for integrating new energy sources over a larger scale, the establishment of regional electricity markets in China has made rapid progress, particularly in the southern region. Currently, a regional market system comprising "medium- and long-term + spot + auxiliary services" has been established.

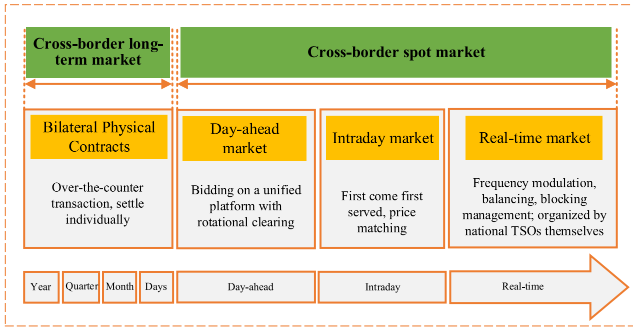

FIGURE 8. Architecture of the European Unified Electricity Market.

B. MARKET STRUCTURE AND TRADING MODES

1) MARKET STRUCTURE OF TYPICAL REGIONAL ELECTRICITY MARKETS

The framework of the European unified electricity market is illustrated in Fig. 8. From the perspective of time scale, the European unified electricity market includes four main aspects: cross-border bilateral physical contracts, day-ahead market, intra-day market, and ancillary services with real-time balancing market [67].

The PJM regional electricity market in the United States is one of the typical regional markets internationally, and inter-state transactions within the region use a "unified market" structure. PJM has been a joint venture corporation since as early as 1927, with historical inertia conducive to forming a fully integrated internal electricity market for transactions and dispatch. Therefore, it can more smoothly establish a regionally unified electricity market for transactions and dispatch. Currently, PJM has developed into the largest regional electricity market in the United States, covering 13 states and the District of Columbia.

The PJM electricity market primarily uses a combination of long-term price contracts and spot market centralized bidding. The electricity market is composed of medium and long-term, day-ahead, hour-ahead, and real-time markets, with traded products including electricity, ancillary services, financial transmission rights (FTRs), and capacity. In the medium and long-term market, transactions mainly involve electricity, capacity, and financial transmission rights. Meanwhile, the spot market primarily handles transactions for electricity and ancillary services. The market framework is depicted in Fig. 9.

In recent years, China's regional electricity markets have experienced rapid development. There are currently two main market architectures in place. The first is the Southern Regional Unified Electricity Market, consisting of five provinces: Guangdong, Guangxi, Yunnan, Guizhou, and Hainan. This market architecture is similar to the U.S. PJM Regional Electricity Market and has established a market system comprising both "medium and long-term (power energy as the traded commodity) + spot market (power energy and ancillary services as traded commodities)." The Southern Regional Electricity Market is currently in

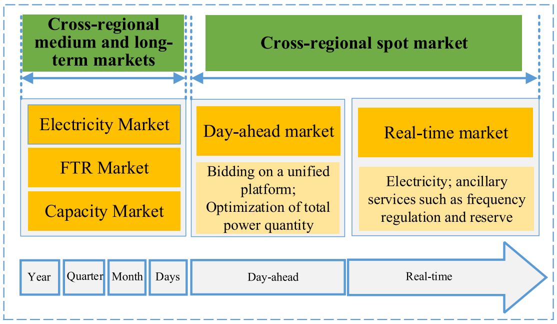

FIGURE 9. Architecture of the U.S. regional electricity market.

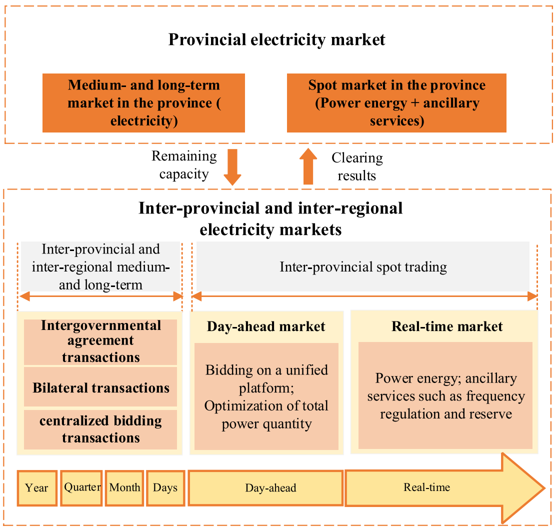

FIGURE 10. Cross-regional and cross-provincial electricity market structure in China.

the draft consultation stage and has not yet commenced actual operations. The second market architecture involves the development of a cross-provincial incremental trading market based on provincial markets, as depicted in Fig. 10. As shown in the figure, the surplus capacity of the provincial market can participate in transactions with other provincial markets in the inter-provincial market. The inter-provincial market includes the inter-provincial medium- and long-term market and the inter-provincial spot market. The inter-provincial medium- and long-term market consists of government-agreed, bilateral, and centralized bidding transactions. The inter-provincial spot market includes the day-ahead market and the real-time market. Currently, the predominant approach is the second framework, which serves as a transitional model from provincial electricity markets to a regional unified electricity market.

2) TRADING MODE

The political background and organizational structure of market establishment have determined that the European unified electricity market and the U.S. regional electricity market (unified electricity market between different regions) have adopted the trading mode of "unified market, unified clearing", which also determines China's adoption of the trading mode of "unified market, two-tier market" or "incremental trading across regions".

a: POLITICAL BACKGROUND

From a political perspective, the European Union (EU), as a highly integrated regional economic and political organization, aims to achieve free trade and circulation of various goods among its member countries. Therefore, to eliminate barriers to trade and circulation of electricity as a commodity among countries, the European Parliament and European Council have issued a series of directives that set specific requirements at the legal level for the organizational structure, trading modes, and regulatory mechanisms of electricity markets in each country. This is intended to further promote the gradual coupling of electricity trading among member countries.

However, considering that grid dispatch involves issues related to national security and sovereignty, the European Council has not put forward further integration requirements for grid dispatch among countries, retaining the Transmission System Operators' (TSOs) dispatch authority over their respective national grids. This approach has kept the development of the European market on a path of "trading integration with decentralized dispatch."

In contrast, the United States, as a federal country, has a long history of joint grid dispatch within regional power systems. Therefore, when designing standardized market frameworks, the Federal Energy Regulatory Commission (FERC) of the United States fully considered the physical characteristics of regional grid dispatch and established a power market framework that aligns with economic principles and operational realities of the power system. FERC has promoted the ISO/RTO model with regional grid dispatch as its core, ensuring that the market evolves along a path of "integrated trading and dispatch" during development.

For China's electricity market, given the country's economic and social development with provinces as the main units, the electricity industry has long operated on a provincial basis, forming a power supply pattern based on provinces. The current situation of power supply and demand balance within provinces has led to a certain level of closure and local autonomy in the establishment of provincial electricity markets. The frequent occurrence of "inter-provincial barriers" presents challenges to further integrating the electricity market.

b: MARKET ORGANIZATION

In terms of organization, the establishment of the European unified electricity market is led by the European Council. In the early stages of market development, the European Council clarified the role of Transmission System Operators (TSOs) in electricity system operation and required each member state to establish independent national regulatory authorities. As the market further integrates and harmonizes, the European Council specified that seven major regional exchanges take turns to be responsible for market clearing, and established two institutions, the Agency for Cooperation of Energy Regulators (ACER) and the European Network of Transmission System Operators for Electricity (ENTSO-E), to enable highly centralized coordination and management of the European unified electricity market.

In the United States, the development of regional electricity markets is primarily overseen by the Federal Energy Regulatory Commission (FERC). Although the FERC established basic characteristics and functions for Regional Transmission Organizations (RTOs) in regional grid dispatch and market transactions through Order No. 2000, it did not design corresponding coordination mechanisms specifically for coupling between regional electricity markets.

In China, the development of the electricity market is guided by relevant documents from the central government. This involves the establishment of national and provincial-level electricity trading institutions separated from grid enterprises, responsible respectively for inter-provincial and intra-provincial market transactions. National and provincial electricity dispatching institutions are responsible for the operation of various levels of power grids. Each province designs different models of electricity market transaction rules based on its provincial and grid conditions. Therefore, from the perspective of practical conditions, it is challenging in the short term for the trading model of China's regional electricity market to adopt the "unified market, unified clearing" model used in European and U.S. regional electricity markets,

C. COORDINATION MECHANISMS BETWEEN DIFFERENT MARKETS

Designing the market coordination mechanism is an essential part of ensuring the smooth and stable operation of each market. This section primarily analyzes the market coordination mechanisms of cross-regional trading in Europe, the United States, and China based on their clearing mechanisms and organizational timing.

1) EUROPEAN ELECTRICITY MARKET

The clearing mechanism of the European day-ahead electricity market is not the same as that of the intraday market. The clearing of the day-ahead electricity market is carried out by a variety of electricity exchanges such as the European Power Exchange (EPEX), the Nordic Power Exchange (Nord pool), the European Energy Exchange (EEX) and others on a bi-weekly rotational basis, and the clearing process during the rotational cycle is carried out on the same trading platform. The clearing process uses the Price Coupling of Regions (PCR) mechanism, which relies on a unified electricity price coupling algorithm called Euphemia. This algorithm calculates the operating day's detailed electricity generation and consumption plans for each hour, along with cross-border transmission capacities and trading prices. Therefore, the day-ahead market clearing essentially adopts a centralized optimization model based on "unified market, unified clearing".

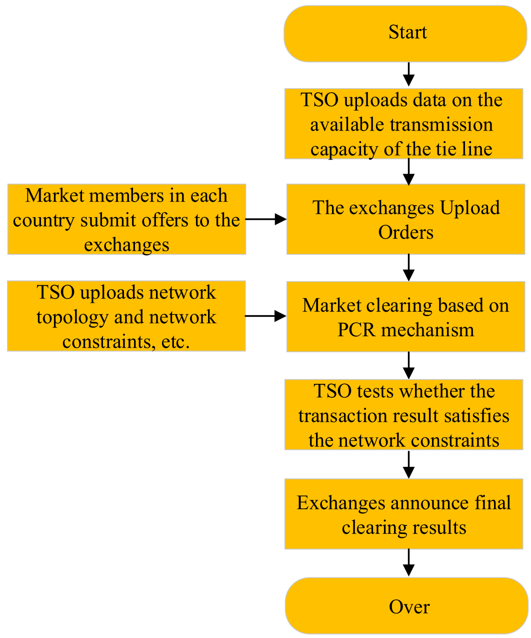

FIGURE 11. **Coordinated process of day-ahead market clearing in Europe.**

The coordination process for the day-ahead market is shown in Fig. 11, and the specific coordination organization process is as follows: (1) Based on the transmission capacity limits of the contact line and the cross-border bilateral physical contract (based on the cross-border transmission plan communicated by the market members), the TSOs of each country calculate the available transmission capacity (ATC) of the corridors between the subregions and submit it to the market coupling system. (2) Each market member submits bid orders to its respective power trading organization within a specified timeframe. The electricity trading organizations then aggregate and submit the compiled orders to the market coupling system. (3) The rotating electricity trading organization operates the market coupling system, optimizing the clearing process based on ATC and the submitted orders. This involves calculating the transaction outcomes for all orders, the clearing prices for each price zone, and the commercial flows between price zones. Each power exchange is required to formulate a cross-border transmission plan based on the clearing results and submit it to the relevant TSO. (4) The electricity trading organization compiles and publishes market transaction information.

The European intraday market adopts the aggregated trading model similar to the stock market, The trading process is as follows: (1) During market opening hours, market participants can list orders in the Intraday Trading System (ITS), which includes the direction of the order (buy/sell), the quantity of electricity, the price and other information. (2) The system automatically matches orders based on certain principles: if a newly entered buy order has a price higher than the lowest price of sell orders in the system, or if a newly entered sell order has a price lower than the highest price of buy orders in the system, then automatic matching occurs and a transaction takes place. Otherwise, the order remains in the system awaiting a match.

In terms of the relationship between the clearing results and grid operation and production arrangements, the market clearing results are loosely coupled with grid operation and production arrangements. From the perspective of grid operation, only the available transmission capacity constraints of the transmission cross section between price zones are considered in the day-ahead and intra-day markets, and the market clearing results are not used in the dispatch and operation commands of market players, and do not directly determine the starting and stopping of the units or the output of the units. Due to the adoption of the mechanism of balancing units of responsibility, the market players, based on the clearing results of the market in each period and according to the total balancing demand for the resources they own, choose to combine their production schedules (Based on the total balancing demand of their resources, market players choose to combine their production schedules (including starting and stopping of units, etc.) or buy and sell electricity in the subsequent market segments to match the total amount of trading transactions in different time-sequence markets.

2) U.S. ELECTRICITY MARKET

As one of the 8 major regional electricity markets in the United States, PJM is interconnected with other regional markets such as MISO. Although PJM operates internally across multiple states as a regional electricity market, it also engages in cross-regional transactions with other RTOs. The coupled coordination mechanism between PJM and MISO is analyzed here in terms of the PJM and MISO real-time energy markets.

The cross-regional transactions between PJM and MISO follow the Joint Operation Agreement (JOA). In the JOA model, each RTO (such as PJM) will be equivalently represented as a proxy node by another RTO (such as MISO) connected through a connecting line when conducting analysis related to cross-regional transactions. The price and constraint information of the proxy node will be provided by MISO. In the real-time trading process, it is necessary to set one of the RTOs as the monitoring RTO, which is responsible for trading and tidal current adjustment. For example, MISO is the monitoring RTO, and when it finds that the tie line tidal current P_{line} may have the problem of overrunning the limit, MISO adds this tie line constraint to the security constraint scheduling software, sets its tidal limit to an appropriate value, and calculates to get the shadow price of the tie line tidal current constraint, P_{shadow} as well as the tidal current ΔP_{line} (MW) that MISO requests to reduce from the current market of PJM and other data are transmitted to PJM.

The cross-market transaction coordination process is shown in Fig. 12. Due to changes in MISO's boundary conditions, PJM's boundary conditions may also change. PJM incorporates MISO's requirements into its secure economic dispatch constraints, setting the flow limits on tie lines to be the current market flow minus the amount requested by the monitoring RTO (MISO). If PJM has sufficient adjustment capability, it will redispatch to meet MISO's flow requirements, aiming for a marginal cost equal to MISO's shadow price. Subsequently, the boundary conditions (shadow prices, maximum transfer limits, etc.) on the tie lines between the two control areas are communicated back to MISO. In the following scheduling cycles, MISO can continue to request PJM to adjust its flows up or down.

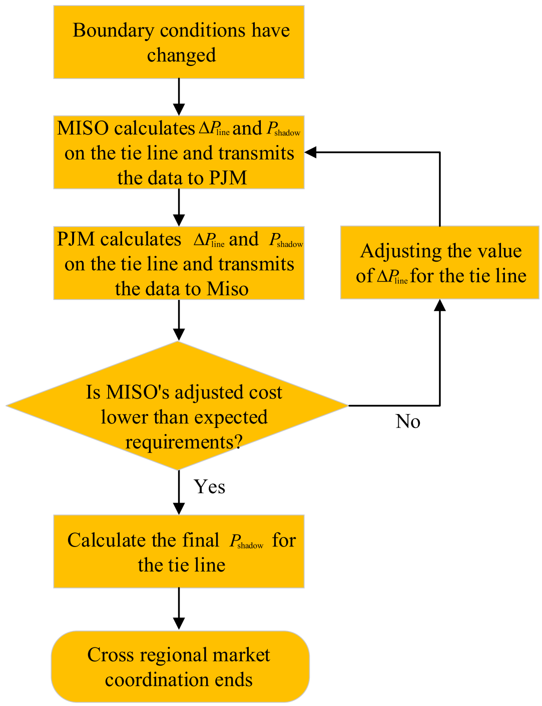

FIGURE 12. Cross-regional market coordination process in the United States.

Throughout coordinated scheduling, the two RTOs will continue to share current and shadow price information. If both RTOs have sufficient redispatch capability, the process concludes when the shadow prices of the two RTOs converge to the most cost-effective redispatch solution, i.e., when MISO's self-adjusted dispatch cost is lower than the cost of coordinated dispatch by PJM.

The relationship between the clearing results in the regional electricity markets in the United States and the grid operation and production arrangements is more closely integrated compared to the unified electricity market in Europe. In the U.S., the day-ahead market primarily determines the scheduling of unit start-up and shutdown, while the real-time market specifies the dispatch of generating units.

3) CHINESE ELECTRICITY MARKET

As previously mentioned, the current cross-regional power market in China operates under two models. One model is the unified clearing mechanism used by the Southern Regional Power Market, where each province's power generation and consumption plans, transaction settlements, and other outcomes are calculated by a single clearing platform. This model is similar to the regional power markets in the United States, so its market coordination mechanisms will not be elaborated here. The other model involves incremental spot trading between provinces or regions. Under this model, the coordination between cross-regional trading clearing results and intra-provincial trading clearing works as follows: the provincial dispatch center issues a pre-schedule for interconnection lines as a boundary for intra-provincial preliminary clearing. After determining cross-regional trading demands, the national dispatch center and network dispatch center organize cross-regional spot trading, achieving the first linkage between intra-provincial and cross-regional transactions. The results of cross-regional spot trading, combined with medium- and long-term curves, serve as the boundary for the formal intra-provincial clearing. Based on the constraint, intra-provincial spot markets and auxiliary service markets are cleared, achieving the second linkage between cross-regional and intra-provincial transactions.

In terms of the coordination process of China's inter-area trading market, the inter-area spot trading was organized daily for 96 periods of spot trading on an operating day, which mainly includes information announcement, trade declaration, centralized bidding, market clearing and generation schedule preparation, and the release of trading information, and the specific process is shown in Fig. 13. The inter-provincial intra-day spot trading is organized in 12 trading sessions with 2 hours as a trading cycle, and temporary trading can be organized when there is still a surplus demand for power transmission or power purchase after the release of the results of this trading cycle, but it is necessary to ensure that the results of the clearing will be issued to the provincial dispatcher before T-60 (T is the starting moment of the trading session). The inter-provincial intra-day spot trading includes information announcement, submission of quotations, inter-provincial spot clearing, formulation of inter-provincial transmission schedule, and issuance of results, etc. The specific process is shown in Fig. 14.

D. TRANSMISSION COST RECOVERY MECHANISMS ACROSS REGIONS

1) EUROPEAN ELECTRICITY MARKET

The allocation mechanism for cross-border transmission capacity in Europe is a crucial mechanism to ensure fair competition in the cross-border market, enhance market operation efficiency, and promote optimal resource allocation. The transmission capacity allocation mechanism in the European power market has undergone three stages, each corresponding to different cost recovery mechanisms.

Before 2001, the capacity of cross-border transmission channels was allocated using a "first come, first serve" model. This involved selling contracts for cross-border transmission capacity based on a fixed price schedule and clearing transmission capacity according to the order of market bids. In terms of cost recovery, the transmission costs were primarily recovered by selling the cross-border transmission capacity at the fixed prices determined by the postage stamp method.

During the regional electricity market development phase from 2001 to 2007, the increasing scale of cross-border transmission made the "first come, first serve" model inadequate for reflecting the value of transmission capacity during high load periods. Consequently, it was gradually replaced by the "explicit auction" mechanism. The explicit auction mechanism, organized by the Joint Allocation Office (JAO), involved auctions for cross-border transmission capacity, which typically included yearly, quarterly, monthly, and intra-day auction cycles. Regarding cost recovery, the costs of cross-border transmission were mainly recouped in two parts: one is the investment and construction cost and the loss cost of transmission lines, which is mainly recovered through the inter-TSO compensation (ITC); and the other is the operation and maintenance cost, which is mainly recovered through the way of explicit auction. However, the explicit auction mechanism had its inefficiencies. The separate markets for auctioning transmission capacity and trading electrical energy could lead to mismatches between auctioned capacity and actual available capacity, and even result in reverse power flows.

After 2007, to address the issues brought about by explicit auctions, Europe gradually introduced the implicit auction mechanism. This approach optimizes and clears cross-border transmission capacity in conjunction with electrical energy trading. The implicit auction mechanism effectively avoids mismatches between auctioned capacity and actual available transmission capacity, as well as reverse power flows. Additionally, the market clearing prices comprehensively reflect the value of both electrical energy and cross-border transmission capacity, providing more accurate price signals for market participants. Currently, the Nordic Nordpool market fully adopts the implicit auction mechanism, while other markets use a combination of implicit and explicit auctions. In terms of cost recovery, network loss costs and investment and construction costs are still recovered through the cross-border ITC. Under the implicit auction mechanism, operation and maintenance costs are primarily recovered through congestion surplus. Specifically, when cross-border transmission corridors experience congestion, leading to price differences between regions, congestion surplus revenue is generated. This revenue is collected by the transmission system operators who own the transmission capacity of the congested corridors.

E. ELECTRICITY MARKET IN THE U.S.

The transmission pricing mechanism in the U.S. regional electricity markets adopts a contribution-based transmission service cost allocation mechanism. The overall approach is to first allocate the costs of inter-regional transmission based on function and purpose, then determine the allocated costs of

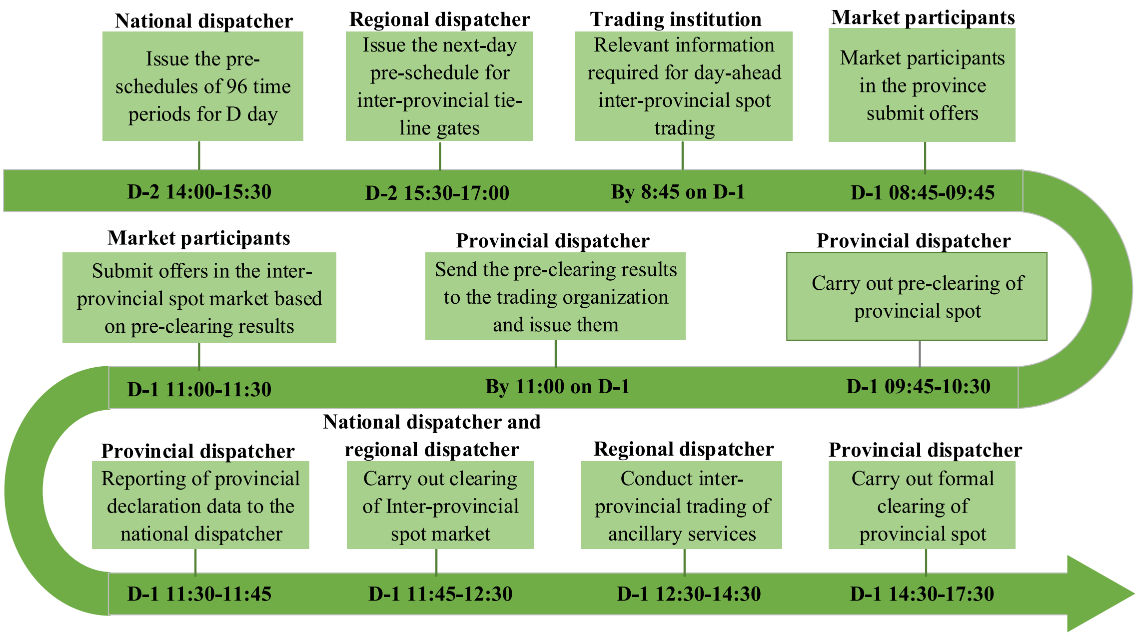

FIGURE 13. Cross-regional day-ahead spot market coordination process in China.

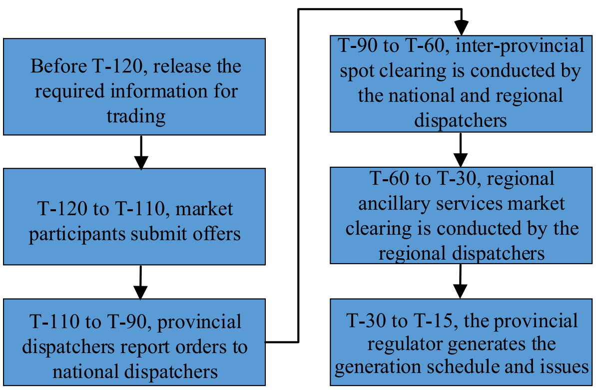

FIGURE 14. Cross-regional real-time spot market coordination process in China.

inter-regional and intra-regional transmission to each region according to relevant rules, and finally allocate the costs that need to be shared within each region to specific entities according to relevant rules. The specific steps are as follows:

First, allocate the costs of inter-regional transmission to each sub-region based on the following criteria: (1) Based on the degree of contribution to improving the stability of system operations in each regional market; (2) Based on the proportion of generation costs and electricity consumption costs reduced by each regional market; (3) Based on the benefits of alleviating congestion in each regional market, etc.

Then, determine the allocated costs within each region based on the following rules for both inter-regional and intra-regional transmission costs: (1) For transmission costs below 110kV, directly allocate to market participants within the region; (2) For transmission costs above 110kV, Costs for enhancing system security are allocated based on the distribution coefficient of DC power flow; Costs for enhancing system economic efficiency are allocated based on the proportion of benefits brought to market participants within the region; (3) For transmission costs of 345kV double circuit and 500kV and above, 50% of the costs are allocated based on functionality (same method as for transmission costs above 110kV); he remaining 50% of the costs are allocated based on the postage stamp method for non-coincident system peak load.

Finally, allocate transmission costs to market participants and establish transmission prices. When establishing transmission prices, corresponding pricing mechanisms are designed for the network integration transmission service (NITS) and point-to-point transmission service (PTPTS) involved in transactions. NITS refers to transmission service provided by an electricity utility to customers of electricity within a regional market, where the service is charged for capacity only, i.e. priced in the form of a single capacity tariff. Generally, it is calculated based on the sum of annual transmission permit revenues of various transmission companies within the transmission region and the annual maximum coincident load of the transmission region, with the calculation formula as follows:

$$\rho_{NITS} = \frac{D_{\text{con}}}{365} \times \frac{W_{\text{annual}}}{P_{\text{aumax}}} \tag{1}$$

where, ρ_{NITS} refers to the price that market members are required to pay for transmission services on the utility network; D_{con} is the extent to which market members contribute to the peak load in the region; W_{annual} presents the sum of the annual permitted revenues of the transmission companies in the transmission region; P_{aumax} represents the maximum annual simultaneous load for the transmission area.

Point-to-point transmission service is a transmission service provided by an electricity utility for cross-market trading entities to transmit electricity between subregional markets, and is charged to entities participating in cross-market electricity trading based on the delivery capacity and capacity rate, which is calculated according to the following formula:

$$\rho_{\mathrm{PTP}} = C_{\mathrm{PTP}} R_{\mathrm{PTP}} \tag{2}$$

where, ρ_{PTP} refers to the price for point-to-point transmission services; C_{PTP} is the capacity reserved for point-to-point transmission service; R_{PTP} denotes capacity rate. The value of the capacity rate can be divided into yearly, monthly, weekly, daily and other types of divisions according to the service cycle, and the size of the rate corresponding to different service cycles is different.

1) ELECTRICITY MARKET IN CHINA

After the new round of power market reform in 2015, China has continued to improve the formation mechanism of cross-province and cross-region transmission prices. The Pricing Measures for the Transmission of Electricity for Cross-province and Cross-region Special Projects (for Trial Implementation) released in 2017 suggests that the form of cross-province and cross-region transmission prices is determined according to function. Transmission projects primarily serving transmission functions are priced based on a single electricity price (determined according to the annual total cost of inter-provincial and inter-regional transmission services and the transmitted electricity volume) and are collected with transactions. Projects primarily serving interconnection functions are priced based on capacity tariffs (determined according to the postage stamp method) and are shared jointly by the seller province and the buyer province.

To further define inter-provincial and inter-regional transmission projects, the ''Inter-provincial and Inter-regional Special Transmission Project Pricing Measures'' were issued in 2021. It specifies that inter-provincial and inter-regional transmission projects refer to cross-regional power grid projects primarily serving the function of power transmission, as well as intra-provincial transmission projects within regions where the sending and receiving ends are clear and the direction of power flow is fixed. These projects are subject to a single-part tariff.

F. COMPARATIVE ANALYSIS OF TYPICAL CROSS-REGIONAL ELECTRICITY MARKETS

Table 2 provides a comparative analysis of typical interregional electricity markets. The market clearing characteristics are highlighted here. The European electricity market is designed to ensure a high degree of transparency and liquidity in the market, and the use of simplified network models helps to reduce the requirements for market members. In addition, the European market supports complex and diverse market member offer models, and the clearing model that supports coupled operations in the day-ahead market is already a complex mixed-integer planning problem, and the current computational scale of the solution is already facing a large challenge, and if a network-wide physical model is used to market clearing, it may face exceeding the capacity of the technology to support it. The clearing results of the U.S. regional electricity market are precise to the production operation arrangements of the smallest physical units of electric resources, such as unit start-up and shutdown, unit output, and the maximum frequency modulation of units. This poses a high level of difficulty in clearing, and market participants face significant challenges in understanding the market clearing results. China's cross-regional power trading out of the price matching approach, when the number of market players is increasing, the order of magnitude of the market out of the market will grow exponentially, and the efficiency of the market out of the market will be greatly reduced. As the ''unified market'' model has not yet been practically applied in the SREM, it is still in the stage of being drafted for comments.

IV. RECOMMENDATIONS FOR THE DEVELOPMENT OF CROSS-REGIONAL ELECTRICITY TRADING MARKETS

This section first summarizes and analyzes the problems existing in the further development of cross-regional trading markets in typical regional electricity markets, and provides corresponding solutions. Then summarizes the common issues that need to be focused on in the cross-regional trading market in terms of the basic structure and market model, market coordination mechanism, transmission cost recovery mechanism, etc., to provide a theoretical basis for other countries or regions in the world where there is a need to build a cross-regional trading market, and to promote the optimization allocation of energy resources on a larger scale.

A. INDIVIDUAL CHALLENGES AND RECOMMENDATIONS IN VARIOUS COUNTRIES

The cross-regional electricity markets in the United States and Europe have been developing for many years and have matured in terms of basic architecture, market models, market coordination mechanisms, and transmission cost recovery mechanisms. The key to further development of cross-regional markets in Europe and the United States in the future lies in technological conditions, with the main focus being on clearing algorithms. As for the cross-regional electricity market in China, in addition to the technical challenges mentioned above, the key to further integration of cross-regional electricity markets lies in breaking down inter-provincial barriers. The following section analyses the challenges of cross-regional market development in Europe, the United States and China, and proposes corresponding solutions.

TABLE 2. Comparative analysis of typical cross-regional electricity markets.

Name	Europe	America	China
Political background	As a regional economic and political organization, the market establishment of the European Union is led by the European Council	As a federal country, the market establishment in the United States is carried out by the Federal Energy Regulatory Commission	Dominated by the central government, the electricity industry is a provincial entity with strong inter-provincial barriers
Market Structure	Common market	Unified market	Both common market and unified market
Market trading modes	unified market, unified clearing	unified market, unified clearing	unified market, unified clearing; unified market, two-tier clearing
Organizations	Different exchanges rotate the market clearing, TSOs are responsible for scheduling operations, ACER and ENTSO-E are responsible for coordination	RTO/ISO is responsible for market clearance and scheduling operations, lacking regional market coordination agencies	Inter-provincial and intra-provincial transactions are organized by national and provincial trading agencies, respectively, and scheduling agencies at all levels are responsible for hierarchical scheduling
Characteristics of market clearing	A simplified network model is adopted; supports market members in adopting multiple offer patterns	Market clearing results are precise to the production and operation arrangement of the smallest physical unit of power resources	Cross-regional transactions are cleared using price matching, and data will grow exponentially when there is a large number of market players
Coordination with sub-regional markets in trading timing	The day-ahead market is organized by a unified clearing; intraday organization of supplementary trading in the day-ahead market; real-time balancing services are organized by TSOs	No sub-regional markets	Pre-clearing in the province, then clearing cross-regional transactions and finally formal clearing in the province
Relationship between trading results and schedules in cross regional markets	Does not directly determine generation and consumption schedules; needs to consider self-balancing requirements	Trading results directly determine power generation and consumption schedules	Indirectly; power generation and consumption schedules; results of inter-regional tradings need to be superimposed on the results of market clearing in the province
Transmission cost recovery mechanisms	Combination of explicit and implicit auctions, except for the Nordpool market, which uses a uniform implicit auction mechanism	A mechanism for sharing transmission service costs based on the degree of contribution	Fixed-rate with volume tariff

1) ELECTRICITY MARKETS IN EUROPE AND THE UNITED STATES

Due to the simple capacity constraints of interconnection lines of interconnection line in the market clearing process of the European unified electricity market, the requirements for clearing algorithms have not significantly increased with the expansion of market scale. However, as cross-border transmission channels are constructed and the degree of cross-border grid coupling increases, the trading volume of the European unified electricity market continues to grow. In countries where centralized dispatch of electricity resources is partially adopted, the balancing responsibility units are equivalent to generating units. If their physical characteristics are not considered, they may face excessive self-balancing pressure. For these reasons, the European unified electricity market will increasingly take into account fundamental constraints on the operation of the power system, mainly in the form of sensitivity-based security constraints on the transmission cross-section, as well as physical operating characteristics of different types of power sources, such as unit start-ups and stops, minimum operating times, ramp rates, etc., which will be embodied in a variety of forms of flexible product declarations. As a result, the clearing algorithms of the European electricity market may also face challenges beyond technical support capabilities.

The centralized clearing model used in the U.S. regional electricity markets requires specific consideration of the physical parameters of nodes in the power network and the operating parameters of generating units. As the market scale continues to grow, the number of nodes and generating units that the clearing algorithm needs to consider increases significantly. Taking MISO as an example, its coverage includes over 40,000 computational nodes and more than 1300 generating units in the power network. The scale of the optimization problem is enormous, making it challenging for the clearing algorithm to meet convergence requirements within a reasonable time frame. Therefore, the complexity of market optimization models and the computational capabilities of clearing algorithms greatly constrain the further integration of the U.S. regional electricity markets.

Therefore, further development of cross-regional electricity markets in both the United States and Europe requires addressing issues related to clearing algorithms. To improve the computational speed of large-scale power systems and achieve fast real-time optimization control while considering the need for user privacy protection, it is necessary to ensure information security at the algorithm design level, in addition to using a ''decomposition-coordination'' architecture to improve computational efficiency. Strengthening research and application of clearing algorithms, determining reasonable sets of interregional shared communication information, and using boundary phase angles or interconnection line flows as coordination variables for iterative computation can help address the challenges of computational efficiency and optimality.

2) ELECTRICITY MARKET IN CHINA

As mentioned above, in addition to the SREM, other provinces and regions of the inter-regional transaction have adopted the ''incremental trading'' mode at present. In the future, whether cross-regional transactions can be shifted from the ''incremental trading'' mode to the ''unified market, unified clearing'' mode in the Southern Regional Market, the most critical and the first issue to be resolved is how to break down inter-provincial barriers. China's electricity sector has long operated on a provincial balance basis, employing traditional methods of managing electricity generation and usage. In the context of a significant economic downturn and an oversupply of electricity, some regions, to protect their interests, intervene in cross-regional transactions by imposing restrictions on purchased electricity volume and prices, thereby undermining the integrity of the electricity market. With the continuous deepening of the new round of electricity market reform, it is imperative for the country to strengthen overall planning, adopt a national perspective, and rationally balance the interests of various regions, thus breaking down the barriers to inter-provincial transactions. To address the issues, the following three recommendations are proposed.

Firstly, establish cross-regional supervisory agencies and independent regulatory bodies. The supervision of regional electricity markets goes beyond the jurisdiction of local governments. Regional supervisory agencies can be integrated into national administrative bodies to exercise supervisory, coordination, and inquiry regulatory functions, propose regulatory suggestions, promote reforms, and improve regulatory capabilities. There is a need to establish dedicated regulatory departments for regional electricity markets, equipped with adequate personnel, a reasonable professional composition, experienced talent, stable, sufficient, and independent sources of income, and the ability to hire third-party consultants when needed.

Secondly, strengthen the supervision of market entities' trading behaviors to ensure fair competition in the market. Improve regulations for the supervision of regional electricity markets, clarify and refine the types, criteria, identification standards, harm determination, enforcement procedures, punitive measures, and relief gradients of monopolistic agreements, unfair competition behaviors, and mergers and reorganizations that ''may significantly reduce competition.'' Utilize specialized knowledge and methods to identify unfair trading behaviors. In particular, remain vigilant towards agreements, interest group alliances, collective boycotts, and market segmentation practices aimed at reducing competition that may be reached within power generation and utilization group enterprises, as well as between seller and buyer provinces.

Finally, on the basis of ensuring the effective implementation of electricity market supervision and lawful and reasonable temporary interventions, rectify local governments' improper subsidies to local enterprises or the use of administrative power to restrict and exclude market competition. For instance, local governments should not interfere in market transactions by setting designated market prices or price reduction targets. They should reduce practices such as artificially setting unreasonable supply-demand ratios for transactions or organizing special transactions for specific industries. Rectify the tendency of local governments to artificially create interprovincial barriers in the electricity market. This includes eliminating regulations that prohibit enterprises from purchasing electricity from other provinces and only allowing local enterprises to participate in transactions.

B. COMMON RECOMMENDATIONS FOR OTHER COUNTRIES

1) CHOICE OF MARKET STRUCTURE AND TRADING MODES

The selection of market structure and trading models must be analyzed based on practical circumstances. For regions where trading institutions are already established and the electricity system is relatively mature, creating a fully unified and singular cross-regional trading center that also considers both trading and dispatch functions poses significant challenges. Specifically, the following issues arise: (1) Conflicts with the existing dispatch operation system, grid balancing responsibilities, and full division of unit scheduling. (2) Issues such as power supply characteristics and transmission constraints of subregional grids cannot be characterized in detail, and there may be a large difference between the unified clearing results and the dispatch and operation arrangements that take reliability into account. From the perspective of market operation efficiency, the operability of implementation is low. (3) If a detailed grid model covering the entire grid is established, taking into account the operating characteristics and transmission constraints of all subjects, the complexity and technical support capability of the entire grid clearing will face major challenges.

The choice of market structure and trading mode needs to be analyzed in the context of the actual situation. For areas where subregions have already established their trading institutions and have relatively well-developed electricity systems, it is more difficult to establish a fully unified and unique cross-regional trading center that takes into account both trading and scheduling functions. Specifically, the following problems exist: (1) There may be conflicts with the existing dispatch operation systems, grid balancing responsibilities, and the overall allocation of unit dispatching. (2) Issues such as power supply characteristics and transmission constraints of subregional grids cannot be characterized in detail, and there may be a large difference between the unified clearing results and the dispatch and operation arrangements that take reliability into account. The unified clearing results may significantly differ from the dispatch operations that consider reliability. (3) Establishing a detailed grid model that covers the entire network and considers the operational characteristics and transmission constraints of all entities would face major challenges in terms of complexity and technical support capabilities.

Against this background, the "joint market" model becomes the optimal choice for cross-regional electricity trading. This model can accommodate the different operational methods, trading rules, and dispatch rules of each sub-region, maintaining the existing structure of sub-regional electricity markets. For countries or regions that have not yet established trading institutions, adopt a joint dispatch mechanism, or have minimal barriers between sub-regions, a unified market rule and clearing platform can be established following the practices of the United States or Europe to optimize resource allocation.

2) MARKET COORDINATION MECHANISMS

Based on the analyses in Section I and Section II, it can be seen that market coordination mechanisms need to be analyzed in terms of market structure and trading patterns. Specific analyses are presented below.

a: COORDINATION MECHANISMS UNDER THE UNIFIED MARKET MODE

For the unified market, generation and consumption schedules and tariffs are formed on a unified platform, and there is no interface between sub-regions. The market coordination relationship under this mode mainly considers the connection of markets of different time series. Specifically, this includes the following two approaches.

The first approach involves a certain degree of coupling in the clearing process between successive and preceding markets. In the day-ahead market, clearing is based on the available transmission capacity of the transmission section already occupied by medium- and long-term bilateral contracts. Similarly, the intraday market clearing must further consider the available transmission capacity occupied by the day-ahead market clearing. Regarding the relationship of market clearing results, in each sequential market, market participants determine their current buying and selling needs based on the output plans of their own generation and consumption resources, and then declare the incremental electricity they intend to trade. These transactions must be physically executed, and the trading contracts have a "physical attribute," meaning that the total electricity awarded in all markets represents the actual electricity that must be delivered or purchased. Therefore, there is no direct connection between the clearing results of successive markets and the preceding market.

The second is that the different time series markets only consider the settlement linkage, i.e., in the form of Contract for Difference (CFD), but there is no linkage at the time of clearing. In the day-ahead market clearing, the next day's generation and consumption arrangements are re-optimized without considering the results of medium- and long-term contracts. For the day-ahead market clearing results, the real-time market re-optimizes the unit output arrangement based on the day-ahead startup and shutdown schedules. Under this model, the trading contracts in each time-sequenced market have "financial attributes". The medium- and long-term market, the day-ahead market and the real-time market reflect the linkage of the three through differential settlement, i.e., the medium- and long-term contracted power is settled at the medium- and long-term contracted price; the deviation of the contracted power from the medium- and long-term contracted power in the day-ahead spot market is settled at the day-ahead spot market's clearing price; and the deviation of the real-time market's power from the day-ahead spot market is settled at the real-time market's clearing price.

The European electricity market adopts the first type of convergence, and through the "balancing mechanism" to resolve the difference between the actual power generation and consumption of market members and the contracted power, the imbalance of market members by the imbalance mechanism for settlement. The U.S. electricity market adopts the second approach. There is no absolute "good or bad" distinction between different mechanisms; they generate different economic signals and welfare distributions. Each country or region needs to determine the appropriate method based on specific circumstances.

b: COORDINATION MECHANISMS UNDER THE JOINT MARKET MODE

For the joint market, besides considering the alignment of clearing results or timing in different time sequences within sub-regional markets (referring to the unified market model), it is also necessary to consider the coordination between different sub-regional markets. The specific alignment relationship needs to be determined based on the specific common market model.

For the "two-tier clearing" model, regarding the alignment of market clearing and timing, the priority is given to cross-regional transaction clearing, where the clearing results of cross-regional transactions serve as the boundary conditions for intra-regional clearing. Once the clearing results for cross-regional transactions are formed, the tie-line schedule is inputted into the market clearing program within the sub-regions, and the markets within the sub-regions conduct formal intra-regional power market clearing using the tie-line schedule as the market boundary. For the "incremental trading across regions" model, preliminary clearing procedures are first conducted within each sub-region. Based on the preliminary clearing results, the remaining capacity for cross-regional transactions is determined, and after conducting cross-market clearing, the results are used as the boundary for market clearing within the region. For the "participation of surplus capacity" mode, priority is given to clearing within the sub-region with surplus power resources, and the surplus generating capacity participates in the market clearing of the sub-region with scarce power resources, bidding for participation in the market together with other generating resources in the sub-region with shortage of resources.

Among the three modes mentioned above, since the ''two-tier clearing'' mode gives priority to inter-regional trading, it is not possible to guarantee that the demand for electricity in the sub-regions of the regions with surplus electricity resources can be met; the ''incremental trading across regions'' mode and the ''participation of surplus capacity'' mode can guarantee that the demand for electricity in the sub-regions can be met; however, the former mode is more practicable than the former mode.

3) TRANSMISSION COST RECOVERY MECHANISMS

To ensure the profitability of transmission channel investors and promote the sustainable development of cross-border markets, different transmission cost recovery mechanisms have been established in the European cross-border market, the US regional electricity market, and the Chinese regional electricity market. When designing the transmission cost recovery mechanism, the following steps can be adopted. Firstly, the market should combine the establishment of standardized and matching transmission and distribution electricity prices in the regional electricity market trading mechanism to ensure the recovery of transmission channel revenue and the sustainable development of the market; Secondly, addressing issues such as unclear division of transmission network functions, and separately calculating transmission prices. Lastly, guided by the principle of ''cost-sharing by beneficiaries,'' formulate transmission cost and network loss-sharing mechanisms to establish a rational transmission and distribution price recovery system.

V. CONCLUSION

Expanding the scope of electricity market transactions and optimizing resource allocation on a larger scale to enhance energy utilization efficiency has become the development direction of the international electricity market. Firstly, this study analyzes feasible solutions for key mechanisms of cross-regional electricity markets, including basic architecture, transaction models, market coordination mechanisms, and transmission pricing mechanisms. The aim is to provide readers with a comprehensive understanding of different mechanisms' feasible solutions while allowing them to gain a deeper insight into the mechanism design schemes of typical regional markets. Secondly, the study reviews the mechanism designs of the European unified electricity market, U.S. regional electricity markets, and Chinese regional electricity markets in the context of cross-regional transaction markets, followed by a comparative analysis. Finally, the problems and corresponding solution ideas of typical regional power markets in the further development of cross-regional trading markets are summarized, and the problems that cross-regional trading markets need to focus on in terms of the design of different mechanisms are summed up in the hope of providing important references for the advancement of the development of cross-regional power markets.

For typical regional markets, the key to the further development of cross-regional markets in Europe and the United States lies in technological conditions, which are mainly reflected in clearing algorithms. For China's cross-regional electricity market, in addition to technological issues, the key to further integration of the cross-regional electricity market in the future is the ability to break down inter-provincial barriers. Additionally, when selecting the trading model, clearing mechanism, market coordination mechanism, and transmission pricing for the cross-regional electricity market, it is necessary to comprehensively consider the pace of market development, the feasibility of implementing market mechanisms, and the advantages and disadvantages of different mechanisms.

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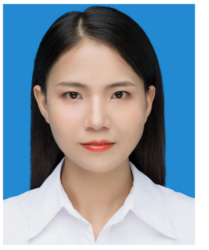

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