Analysis of the Impact of Different Hydropower Pricing Models on Unified Market Settlement in Hunan

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Abstract—This article introduces the basic situation of Hunan Province, where hydropower resources are relatively abundant. To reduce the impact of market reform, it is necessary to reasonably consider the evolution path of hydropower bidding mechanism. Therefore, this article first summarizes the hydropower participation modes in hydropower-rich areas. The results show that foreign countries have not set up special price competition mechanisms for the problem of hydropower and thermal power bidding together, while the impact of direct hydropower and thermal power bidding together needs to be considered in China, and related special mechanisms are introduced for this purpose. Then, the article introduces the form of agent purchase under unified settlement, and designs three pricing models: hydropower not participating in the market, hydropower participating in the market as a price taker, and hydropower adopting the excess profit distribution mechanism. Finally, a spot simulation model is used to conduct market clearing based on the actual boundary conditions of a certain day, and the electricity matching and cost situations under different bidding modes are analyzed. The results show that adopting the excess profit distribution mechanism has a certain effect on the market transition.

Keywords- electricity spot market; coal price volatility; high proportion of hydropower; spot market simulation; unit profitability

1 Introduction

Since the release of the "Document No. 9 on Power System Reform" in 2015[1], China's power market construction has achieved initial results. Currently, the Beijing Power Exchange, Guangdong Power Exchange, and 33 other provincial power exchanges have normalized the trading of medium and long-term market transactions. Eight first-batch spot pilot areas, such as Shandong, have completed trial runs of spot settlement, and second-batch spot pilot areas, such as Jiangsu, have completed simulation trials of spot markets. The process of market-oriented reform is gradually accelerating.

ICPDI 2023, September 01-03, Chongqing, People's Republic of China

DOI 10.4108/eai.1-9-2023.2338782

As a non-spot pilot province, Hunan Province's electricity market is mainly based on medium and long-term transactions, and the spot market has completed the design of relevant plans and is gradually promoting the trial operation of the spot market. Due to the large proportion of hydropower in its power structure and the fact that the variable cost of hydropower is much lower than that of thermal power units, different hydropower pricing mechanisms will have a significant impact on Hunan's social electricity costs. The National Document No. 809 issued in 2021 further clarifies the task of grid agent power purchase[2], making the matching process between power generation and consumption more complex, and further sorting out the relevant power components in settlement is necessary. Therefore, it is necessary to conduct research on different hydropower pricing models and further analyze their impact on unified market settlement in Hunan based on this.

Regarding the challenges of hydropower participating in the market, Luo Xinzhi introduced the resource endowment and characteristics of hydropower resources in Hunan in 2008, and proposed the advantages and disadvantages of hydropower participating in market competition[3]. Yang Qidong analyzed the challenges of Guangxi hydropower participating in the spot market[4]. Zhang Senlin sorted out the difficulties faced by hydropower units participating in market competition and designed three transaction schemes for hydropower and thermal power bidding together[5][6]. In terms of reference experience for hydropower mechanisms at home and abroad, Tang Yingling, Li Hua, and others introduced the basic market situation of countries such as Brazil and the mechanism of hydropower participating in market competition[7][8]. Lu Yi and others introduced the design ideas, models, and operating logic of the spot market during the abundant and scarce water seasons in Sichuan Province[9]. Xing Yuhui and others designed a set of organic, sequentially progressive, and mutually complementary thermal power mechanisms for the problem of low-cost hydropower and high-cost thermal power units bidding together on the Yunnan power market[10]. In terms of hydropower participating in cross-provincial and cross-regional transactions, Deng Yumin and others systematically studied how hydropower can participate in the spot market across provinces and regions[11], designed a physical execution mechanism for decomposing the long-term contracts of hydropower across provinces and regions, and proposed a market-based incremental bidding strategy for the day-ahead market, which is based on the value of water and opportunity cost. In terms of the model of hydropower participating in market transactions, Li Ling and others mathematically modeled the participation of cascade hydropower in market clearing[12], while Huang Chao and others briefly introduced the frequency regulation market[13]-[15]. Regarding the study of grid enterprise agent power purchase, scholars have discussed the cost settlement, business process, and optimization decision-making of grid enterprise agent power purchase[16]-[21]. Chazarra M and Ghadimi N has built a model for hydroelectric participating in the regulation market and energy market respectively[22][23]. However, most of the above research was conducted from a unilateral perspective, and no scholars have conducted research and analysis on the impact of different hydropower pricing models on market settlement.

This article will conduct an exploratory study on the impact of different hydropower pricing mechanisms on unified market settlement based on the actual province and network situation in Hunan Province and draw on the experience of domestic and foreign market construction. The remaining chapters of this article are arranged as follows: Chapter 2 introduces the basic situation of Hunan Province, Chapter 3 introduces relevant market key mechanisms related to

the research, proposes possible solutions, Chapter 4 conducts simulation analysis based on real data from Hunan Province, and Chapter 5 provides a summary of the entire article. The main contribution of this article is to sort out the advantages and disadvantages of different hydropower pricing mechanisms, make forward-looking judgments on the possible changes that may occur in Hunan's market settlement using real data, and provide reference for subsequent market construction in Hunan Province.

2 Hunan Province Basic Situation

2.1 Power structure in Hunan power grid

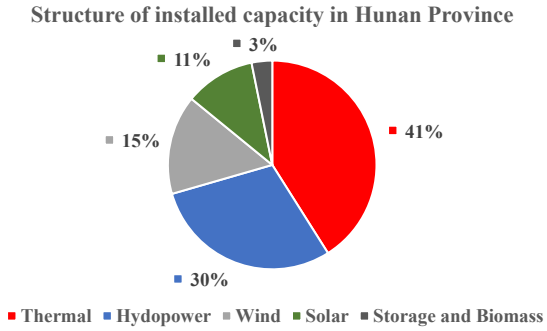

Figure 1. Hunan power grid power structure

In Hunan Province, the installed capacity is mainly dominated by thermal power and hydropower, accounting for over 70% of the total installed capacity in the province, while the proportion of wind power and photovoltaic installed capacity exceeds 20% and is gradually increasing as shown in Figure 1. According to the latest "Hunan Province Energy Development Report 2022"[24], as of the end of 2022, the province's power installed capacity was 58.41 million kilowatts. Among them, thermal power installed capacity was 23.96 million kilowatts, accounting for 41%; hydropower installed capacity decreased slightly to 17.231 million kilowatts, accounting for 29.5%; wind power and photovoltaic installed capacity were 8.995 million kilowatts and 6.367 million kilowatts respectively, with a total proportion of 26.3%. Currently, small-capacity units dominate the thermal power units, including six 1,000 MW coal-fired units and 37 coal-fired units with a capacity of over 300 MW, and only one 980 MW gas-fired unit. 80% of hydropower units do not have peak regulation capabilities, and only have 1,200 MW of pumped storage (Heimifeng). The cumulative installed capacity of energy storage is about 600 MW. Therefore, the overall regulation capacity of the Hunan power system is slightly insufficient.

2.2 Characteristics of resource endowment

Hunan Province has the characteristics of "lack of coal, no oil, insufficient gas, and limited potential for the development of new energy" in terms of overall resources, and it is a "dual-end" province in terms of energy and power grid. It has a high dependence on external energy and the situation of ensuring long-term power supply is severe [24]. Its total water

resources rank sixth in the country, with a per capita possession of 2,500 cubic meters, slightly higher than the national level. The water area is mainly composed of small water systems, which have certain advantages in water resources. Due to the large proportion of hydropower installed capacity, the grid has obvious seasonal characteristics of abundance and scarcity. Wind power has obvious anti-peak characteristics, with large output during low-load periods at night and small output during peak load periods, making it difficult to become a supporting power source for the power grid. During the flood season, the generation of hydropower and wind power overlaps, and there are difficulties in accommodating clean energy.

2.3 The construction situation of the market

In 2022, Hunan Province's total electricity consumption reached 223.55 billion kilowatt-hours, a year-on-year increase of 3.8%. The power supply of the power grid company reached 196.55 billion kilowatt-hours, a year-on-year increase of 4.4%. The purchased electricity reached 190.11 billion kilowatt-hours, a year-on-year increase of 6.4%. The sold electricity was 183.78 billion kilowatt-hours, a year-on-year increase of 6.1%. At present, the market system in Hunan Province is mainly dominated by the medium and long-term market, and the latest policy requirements for power market reform have been further implemented. The long-term market trading mechanism and supervision of Hunan power have been improved, and efforts are being made to expand the trading cycle and trading varieties, striving to shift from annual and monthly trading to continuous trading within a month. The spot market has formulated relevant construction plans and completed the first simulation operation in 2023. Inter-provincial spot trading has also been conducted in 2022. The auxiliary service market currently does not have a frequency regulation market or standby market. The main participating entities in various markets are thermal power units and new energy units, and hydropower units have not yet been included in the market unit category.

2.4 The necessity of research

There is a significant price difference between hydropower and thermal power in Hunan Province, with an average on-grid electricity price of 0.31 yuan/kilowatt-hour for hydropower after withdrawing from the medium and long-term market, while the monthly transaction price of thermal power is close to 0.54 yuan/kilowatt-hour. During the flood season, the large amount of hydropower reduces the purchasing cost, while the opposite occurs during the dry season. As an extremely important part of the Hunan power grid, with the gradual expansion of market-oriented opening-up and the realistic issue of hydropower consumption during the flood season, it is necessary to face the issue of hydropower participating in market bidding. In order to reduce the impact of market reform on the existing interest patterns, it is necessary to reasonably consider the evolutionary path of hydropower bidding mechanism based on research and analysis.

3 Key mechanisms in the market

3.1 Summary of the mechanisms for hydropower

Most foreign markets do not establish special price adjustment mechanisms for the co-bidding of hydropower and thermal power units, but treat the value of electricity generated by

hydropower and thermal power units fairly. Their approach mainly focuses on the adjustment of hydropower deviation power, market pricing models, and profit distribution methods. For example, Brazil, as a hydropower giant, proposed the "electricity rebalancing" mechanism, which centrally optimizes and dispatches the entire regional hydropower according to the concept of "shared benefits and shared risks" on the basis of ensuring the capacity of the designated units, improving the complementary and cascade compensation benefits of the river basin. Canada determines whether hydropower units participate in market pricing based on their own regulation performance, fully utilizing the advantages of regulation capacity of hydropower units with regulation ability through reasonable pricing strategies to achieve a reasonable profit and promote system peak shaving and valley filling. The reason why foreign countries can do this is that their market system is more abundant and perfect, and the market entities have more choices to obtain benefits such as auxiliary services.

In the domestic market, due to being generally in the initial stage, the profit channels for hydropower are relatively single, and the national level requires the full consumption of renewable energy and has assessment requirements for discarded water. If hydropower and thermal power units participate in co-bidding directly, on the one hand, hydropower may face the problem of abandoned water due to failing to win the bid, and on the other hand, the long-standing pattern of interests between hydropower and thermal power will change, which may cause an increase in social electricity cost. Therefore, special market mechanisms need to be proposed. For example, Sichuan has established a competition mechanism for the flood and dry seasons to maximize the consumption of hydropower resources through market means. Yunnan has proposed a market trading adjustment price subsidy mechanism, which also uses market means to form compensation costs for thermal power, avoiding difficulties in recovering investment costs for thermal power units.

Therefore, in the initial stage of hydropower pricing in Hunan Province, it can refer to some domestic practices, aiming to achieve full consumption and avoid significant changes in the interest pattern of the market entities as much as possible. When the market system gradually improves and the assessment of discarded water is gradually relaxed, foreign practices can be learned to directly co-bid hydropower and thermal power units, and more use can be made of inter-provincial and intra-provincial markets to promote the balanced consumption of surplus hydropower.

3.2 Settlement analysis under agent power purchase policy

In October 2021, the General Office of the National Development and Reform Commission issued a notice on the organization of agent power purchase by power grid enterprises, clarifying the implementation details of agent power purchase. In order to implement the policy, Hunan Province has issued a notice on the implementation details (temporary) of agent power purchase by power grid enterprises in Hunan Province.

Hunan Province has stipulated that the priority power sources include priority power sources within and outside the province and coal-fired power outside the province, which will continue to be purchased by power grid enterprises under the current price mechanism. Priority electricity users include residents, agricultural users, etc., and the original catalog electricity price mechanism will continue to be implemented. In terms of electricity matching order, according to the purchase price from low to high, priority is given to matching

electricity to residents and agricultural users; those with surplus electricity will be matched to agent power purchase users; and those remaining will be matched to users who participate directly in market transactions. When calculating the weighted average purchase price of directly participating market transaction users, the purchase price of this part of the electricity is determined based on the benchmark price of coal-fired power generation in Hunan Province. The electricity matching situation in Hunan Province is shown in Figure 2.

The implementation of the agent power purchase policy has made the original "planned and market" dual-track system more complex in terms of cost settlement, as shown in Figure 3. The formation of the agent purchase electricity cost for power grid purchase users is closely related to the matching of power generation and electricity consumption, and may be composed of both priority power generation and market electricity.

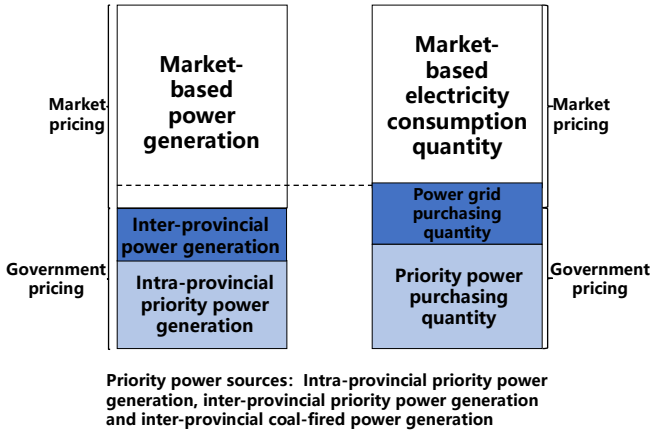

Figure 2. Schematic diagram of power matching in Hunan Province

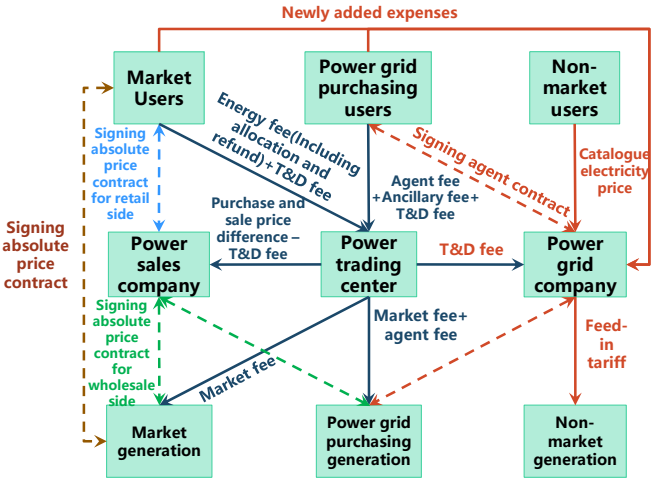

Figure 3. Cost distribution under the agent power purchasing model

3.3 Design and analysis of hydropower pricing models

1) Hydropower does not participate in the market

Under the existing trading mode, hydropower in Hunan Province is not included in the market unit category. Instead, it is treated as a low-cost priority power source and signs a fixed-price government-authorized contract with the power grid. It is prioritized for matching with the residential, agricultural users and as a source of agent power purchase by power grid enterprises, which is an important factor in ensuring lower electricity costs for the entire society. Under this mode, the hydropower output plan (curve) will be designated by the dispatch center and will serve as the boundary condition for the spot market clearing. Settlement will be based on the approved on-grid electricity price (lower than the benchmark on-grid electricity price for coal-fired power). However, since hydropower is not affected by market prices at all, the role of market-optimized adjustment of hydropower resources cannot be fully utilized, which is not conducive to the future construction of hydropower units (especially pumped storage units). Therefore, this mode is more suitable for the early stage of market construction.

2) Hydropower as a price taker

Under this mode, hydropower units can freely participate in medium- and long-term market transactions, and sign medium- and long-term transaction contracts with power purchasers. In the spot market, according to the forecasted maximum power generation capacity, they participate in the spot market by reporting quantity without price (default setting is the lowest price) to prioritize the clearance of power generation capacity, and the clearance price is the unified spot market clearance price. Essentially, this approach directly allows hydropower and thermal power units to compete on the same platform, which is beneficial for optimizing the allocation of hydropower resources. However, since there is a large difference in on-grid electricity prices between hydropower and thermal power units in Hunan Province, after the same platform competition, the marginal unit in the market is generally the higher-priced thermal power unit, which will lead to an increase in the overall electricity cost for society and hydropower companies obtaining excess profits, which is not conducive to the development of the power industry. Therefore, it is not recommended to use this method in the early stage of market construction in Hunan, when the profit path is relatively single. As the ancillary service market, capacity market, and the proportion of new energy installed capacity gradually increase, consider setting the pricing method for hydropower units to participate in the spot market according to their adjustment performance. For example, pumped storage units with adjustment capacity can report quantity and price to participate in spot market transactions.

3) Mechanism for the distribution of excess profits

Considering the price difference between hydropower and thermal power units mentioned above, it is difficult for them to compete directly on the same platform. Therefore, based on the condition of hydropower being a price taker, a mechanism is being considered to recover the excess profits obtained by hydropower as shown in equations (1) and (2). F_{exc} represents the excess profit fee, P_{exc}^{t} and Q^{t} are the unit price of excess profit and traded electricity quantity at time t. P_{ben}^{0} and P_{hyd}^{0} are the benchmark electricity price for coal-fired power

and hydropower, subscript 0 means fixed value. P_{clear}^{t} is the market clearing price at time t. The excess profit fee F_{exc} is distributed proportionately to all industrial and commercial users participating in the market based on the market trading volume. The idea behind this design is that when the market clearing price is high, hydropower units will not receive excessive profits, which to some extent compensates for the electricity costs of industrial and commercial users (the residential and agricultural users are not affected as they still follow the original catalog electricity price). When the market clearing price is low, this mechanism prevents hydropower units from earning too little and ensures that they still trade according to the original approved on-grid electricity price.

$$F_{exc} = \sum P_{exc}^{t} \cdot Q^{t} \tag{1}$$

$$P_{exc}^{t} = \min(P_{ben}^{0} - P_{hyd}^{0}, P_{clear}^{t} - P_{hyd}^{0}) \tag{2}$$

3.4 Mathematical Model of Electricity Market Clearing

The Security Constrained Unit Commitment (SCUC) and Security Constrained Economic Dispatch (SCED) programs are simply used to simulate the electricity spot market clearing. Equation (3) to (7) show the related SCUC model. The optimization objective is to minimize the system operation fee including the fuel costs $C_{i,t}$ and startup costs $C_{i,t}^{U}$, while the SCED model only including the fuel costs $C_{i,t}^{U}$. N is the number of units and NS is the number of sections. T is time counts. M is punish factor. SL_s^{+} and SL_s^{-} is the relaxation factor. Equation (4) is the power balance constraint where $T_{j,t}$ is the tie-line power and D_t is the load. Equation (5) is the power constraint where α is on-off binary variable. Equation (6) is the minimum on-off time constraint. Equation (7) is the sectional flow constraint where G is the related PTDF.

$$\text{Min} \sum_{i=1}^{N}\sum_{t=1}^{T}[C_{i,t}(P_{i,t}) + C_{i,t}^{U}] + \sum_{s=1}^{NS}\sum_{t=1}^{T} M[SL_s^{+} + SL_s^{-}] \tag{3}$$

$$\sum_{i=1}^{N} P_{i,t} + \sum_{j=1}^{NT} T_{j,t} = D_t \tag{4}$$

$$\alpha_{i,t} P_{i,t}^{\min} \le P_{i,t} \le \alpha_{i,t} P_{i,t}^{\max} \tag{5}$$

$$\begin{aligned} T_{i,t}^{D} - (\alpha_{i,t} - \alpha_{i,t-1}) T_D \ge 0 \\ T_{i,t}^{U} - (\alpha_{i,t-1} - \alpha_{i,t}) T_U \ge 0 \end{aligned} \tag{6}$$

$$P_s^{\min} \le \sum_{i=1}^{N} G_{s-i} P_{i,t} + \sum_{j=1}^{NT} G_{s-j} T_{j,t} - \sum_{k=1}^{K} G_{s-k} D_{k,t} - SL_s^{+} + SL_s^{-} \le P_s^{\max} \tag{7}$$

4 Simulation analysis

4.1 Simulation description

The spot market simulation work in this paper is carried out based on the market simulation platform of Hunan Provincial Economic Research Institute.

The data used in this study include the actual unit parameters of Hunan Power Grid, the load parameters, interconnection line power, and the maximum predicted output of renewable energy units on a certain day, as shown in Figure 4. Assuming that coal-fired and gas-fired units are market units, the pricing mode of hydropower units is classified and discussed under the condition of perfect competition in the market, that is, the quoted price of each unit is the marginal cost of the unit, and the unified price is quoted throughout the day, as shown in Table 1. The actual unit startup and other initial states are given at time 0, and the output of relevant planned units will be adjusted when new energy cannot be effectively consumed to ensure the balance of system load. The approved on-grid electricity price for hydropower units is temporarily set at 310 CNY/kWh, and the benchmark on-grid electricity price for coal-fired power is 450 CNY/kWh. Due to the lack of relevant medium- and long-term data and the need for simplified result analysis, the impact of medium- and long-term transaction volume is temporarily not included. It is assumed that all electricity transactions are formed only through the spot market, and the proportion of the market users, power grid purchasing users, and residential and agricultural users is balanced at 40%, 20%, and 40%, respectively. The unified priority power source price is assumed to be 300 CNY/kWh.

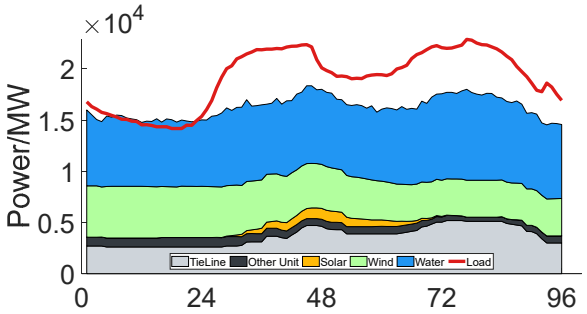

Figure 4. The Boundary Conditions of Market Simulation(a day)

Table 1. The bidding of various units

Unit Type		num	First bid price (CNY/MWh)	Incremental bid price for each segment (CNY/MWh)	bid segments
Coal	0-300 MW	14	369	5	10
	300-600 MW	15	342	5	10
	600-1000MW	16	320	5	10
Gas		1	600	50	10

Wind	111	Specified output	/	/
Solar	20	Specified output	/	/
Hydropower	154	0	0	10
Other	137	Specified output	/	/

4.2 Results and analysis

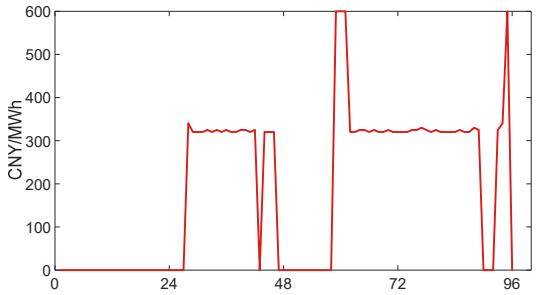

Figure 5. The Clearing Price in Spot Market

As different pricing methods for hydropower have no impact on the overall power generation pattern of the system, and the bid price for hydropower is zero when participating in the market, which does not affect the market clearing price essentially whether hydropower participates or not, the all-day spot market clearing price can be obtained as shown in Figure 5. Due to the smaller load in the early morning, and the large output of photovoltaic power at noon, the overall supply and demand of the system tend to be loose, and the total output of renewable energy can meet the system's demand without the need for additional electricity from thermal power units. However, in the morning and evening, as the electricity load increases, the power supply and demand of the system begin to tighten, and the marginal clearing units in the market become thermal power units, with the overall price fluctuating around 325 CNY/MWh.

Table 2. Electricity matching under different hydropower price modes

		Market users		**Agent users**		**Priority users**	
Actual demand /MWh		183892		91946		183892	
Matching situation		Plan	Market	Plan	Market	Plan	Market
Mode1	power quantity /MWh	114069	69823	91946	0	183892	0
	Cost/10^3 CNY	34221	19560	27584	0	55168	0
Mode2	power quantity /MWh	12	183880	31178	60768	183847	45
	Cost/10^3 CNY	3.6	37644	9353	16151	55154	14.5
Mode3	F_{exc} /10^3 CNY	-21024					

Table 3. Expenses under different water and electricity price models

Hydropower bidding mode	Total revenue of hydropower units/10^3 CNY	Cost of power purchasing for power grid purchasing users/10^3 CNY	Total social electricity purchasing cost/10^3 CNY
Mode 1	52465	27584	136533
Mode 2	34250	25504	118320
Mode 3	55274	25504	139344

The main difference between different hydropower bidding models is reflected in their impact on the cost settlement of different market participants. The power matching situation and overall cost situation have been calculated and summarized in Tables 2 and 3. When hydropower does not participate in the market, it will be used as a priority power source at a predetermined price to match the electricity demand of the residential, agricultural, and power grid purchasing users. At this time, the electricity demand of market users is mainly met by market units (coal-fired units). However, after hydropower participates in the market, hydropower units will no longer act as a priority power source but accept the fluctuation of spot market prices. At this time, power grid purchasing users need to buy electricity from the market to maintain the balance of electricity demand, and the degree of impact of market price fluctuations on their cost will increase.

Due to the decoupling of medium and long-term prices from spot prices in the existing market price system, there has been no significant increase in revenue for hydropower units when settling at spot market prices. In fact, due to the abundance of renewable energy most of the time, hydropower units settle at lower prices, reducing the total social electricity purchasing cost. However, the excess revenue distribution mechanism effectively reduces the difference in revenue between different pricing models, ensuring the revenue of hydropower units.

5 Conclusion

This paper has reviewed the situation in Hunan Province, introduced the domestic and international experience of hydropower participation in the market and the power grid purchasing mechanism in China, designed different pricing models for hydropower, and conducted relevant research and analysis. The results show that the hydropower excess revenue distribution mechanism is beneficial to the market transition and reduces the significant changes in the market interest pattern caused by direct entry of hydropower into the market.

Acknowledgment. This work is supported by State Grid Hunan Electricity Power CO. Research Project (Design and Research of Hunan Unified Electricity Market System Mechanism, B616A2230005)

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