Comparison of Domestic and Foreign Hydropower Consumption Mechanisms and Implications for Hydropower Participation in the Power Market in China

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Abstract. As a mature clean energy source, the market-based consumption of hydropower can give full play to its flexibility, which is in line with the trend of power market reform and is also an important way to realize the "carbon neutral" strategy. Hubei is a province with abundant hydropower resources and is one of the pilot provinces of electricity spot market of the second batch at the same time. Therefore, it is vital to study how hydropower enters the spot market. This paper compares the mechanisms of hydropower participation in the market at home and abroad. On this basis, three viable mechanisms for hydropower units to participate in spot market in Hubei are proposed. Besides, the advantages and disadvantages of different feasible ways and the scope of application of the corresponding units are analyzed, and relevant suggestions on the deviation settlement are also given.

Keywords: hydropower · clean energy · consumption mechanism · spot market

1 Introduction

The "China Development No. 9" in 2015 opened a new chapter of China's electricity system reform, requiring the acceleration of the establishment of a mechanism for determining energy prices mainly by the market [1]. In April 2021, the Notice [2] set up six regions, including Hubei and Henan, as the second batch of spot market pilots. In the context of the "double carbon" target, the proportion of renewable energy in the power system will continue to increase [3]. However, because of its intermittent and fluctuating power output, if the system is not flexible enough, renewable energy will not be able to fully consume. Therefore, market-based incentives to provide system flexibility on the power side, load side and energy storage are the key means to achieve full consumption of a high proportion of renewable energy. Hydropower is the second largest conventional energy source in China and plays an essential role in the domestic power system. However, there is uncertainty about the water supply for hydropower. Since the beginning of

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summer in 2022, Sichuan and Hubei have experienced rare droughts, and the Yangtze River and its tributary basins have experienced scarce water supply, which severely limited hydropower generation in many provinces. However, hydropower is a mature clean energy which owns excellent regulatory capacity. The flexible dispatching of existing hydropower can enhance the system's ability to consume wind and photovoltaic power. Considering flexibility of hydropower in the design of market rules can effectively reduce the cost of wind and photovoltaic power consumption, which is important for ensuring energy security, achieving the goal of carbon emission reduction in the Paris Agreement and promoting economic and social development [4, 14].

At present, most of global power markets have formulated corresponding mechanisms to promote the development of clean energy according to their own market structure characteristics, and the demand for clean energy consumption has been fully considered in the power market rules. In order to design the mechanism for hydropower participation in the power market, scholars at home and abroad have conducted a lot of researches on this issue. At present, there are three main ways for hydropower to participate in the market: participate in the market together with other units according to the same rules [5–8], participate in the market by the "unified dispatch of hydropower" [9, 10] and participate in the market as a price-taker [11].The installed hydropower capacity in China is in the first place around the world, but there is still little research on hydropower participation in the power market at present. Reference [12] proposed that hydropower should participate in the spot market directly. Reference [13] took the penalty of abandoned hydropower into consideration based on the traditional clearing model, so as to effectively reduce the amount of abandoned water and promote the consumption of hydropower. Reference [14] proposed the idea of market-based hydropower consumption in China and framework for a market-based hydropower trading system. Reference [15] proposed a model for incremental offers in the market by day for hydropower across provinces and regions. Reference [16] designed high-water and low-water spot market mechanism according to the characteristics of Sichuan Province. With the continuous development of the spot market, hydropower has attracted much attention in the rule-making of the power market, and the relevant rules need to be continued to be explored and studied.

The distribution of water resources in China has obvious regional characteristics, and hydropower resources are richer in southwest and central China, mainly in Sichuan and Hubei. However, the structure of the power market in Hubei is complex, featuring complex inter-provincial currents, diverse dispatching relationships, large differences in hydropower abundance and output, and close coupling of hydropower gradients, etc. At present, how to design a suitable market mechanism for hydropower units is not yet clear and how to use the market mechanism to guide the efficient use of hydropower resources is an urgent issue to be resolved. Therefore, it is crucial to study how hydropower enters the market.

The major contribution of this paper is the viable mechanism for hydropower units in Hubei to participate in the spot market which provides strong support for the construction of electricity spot market in Hubei.

The rest of the paper is organized as follows. The domestic and foreign hydropower consumption mechanisms are summarized in Sect. 2. The rules of domestic and foreign

hydropower consumption mechanisms are compared in Sect. 3. The implications for hydropower participation in the spot market in Hubei are proposed in Sect. 4. Finally, the paper is concluded in Sect. 5.

2 Domestic and International Hydropower Consumption Mechanism

2.1 Brazil

Brazil is rich in hydropower resources, with hydropower meeting more than three-quarters of its electricity needs [17]. Considering the characteristics of its energy structure, Brazil has adopted the Energy Relocation Mechanism (ERM) to optimize the allocation of water resources in the national interconnection system to fully utilize its hydroelectric advantages, reduce the risk of energy shortage, and improve the efficiency of hydroelectric utilization while ensuring the reliability of power supply [18].

The ERM is implemented through the National Electricity Dispatching Center (Operador Nacional do Sistema, ONS), and is based on the principle of transferring surplus power from hydropower plants that generate more than the guaranteed capacity to those that do not reach the guaranteed capacity. The "guaranteed capacity" is the minimum amount of power generation allocated to each hydropower plant by the government to ensure that the system-wide load demand is met, based on the capacity, hydrological conditions and differences in the periods of abundant and dry water. The ERM is mandatory for hydropower plants dispatched by ONS with installed capacity of 50 MW or more, while small hydropower plants can participate selectively [9]. The ERM essentially allocates hydrological risk to each hydropower plant in the national interconnected system.

The Generation Scaling Factor (GSF) is the ratio between the total generation capacity and the guaranteed output of a power plant under the ERM and is calculated once a month. When GSF is low, there is a deviation between the actual power generation and the contracted electricity, and the deviation amount is settled according to the deviation settlement price which is determined by the Brazilian Power Exchange based on the generation capacity, load demand, fuel prices and weather conditions of each hydropower plant [19].

2.2 The Unite States

In the U.S., hydropower accounts for only 7% of its total electricity production, but provides about 40% of the black start resources and offers ancillary services such as frequency regulation and reserve ancillary service, significantly increasing the flexibility of the power system [20].

The PJM (Pennsylvania-New Jersey-Maryland, PJM) market stipulates that in the day-ahead energy market, hydroelectric power is supposed to be self- scheduled, while storage sources such as pumped storage can be self- scheduled or participate in the day-ahead market scheduled by Independent System Operator (ISO) [21]. At present, hydropower mainly participates in the auxiliary services market to provide frequency

regulation and reserve ancillary services, and when certain units submit offers, PJM has the right to adjust the capacity of hydro units for economic operation [5].

The clearing rule of PJM regulation market is based on the opportunity cost of units, ranking regulation resources in order of preference price, with the lowest cost resources required to provide regulation, synchronized reserve service along with electric energy. The PJM market compensates hydro units that are scheduled by ISO to provide regulation service based on the unit opportunity cost, which is a measure of the revenue lost of units that cannot fully participate in the electric energy market by providing regulation service [22]. Since hydro units are not required to make energy offers to operate on a scheduled basis, the opportunity cost is calculated differently than for conventional units, as follows:

$$|LMP - ED| \times GENOFF \tag{1}$$

Where *LMP* is the predicted hourly regional marginal price; *GENOFF* is the difference between economic dispatch and frequency regulation capacity; *ED* is the average value of *LMP* of hydro units during peak and valley hours.

When there is water abandonment among the hydropower units, *ED* is set to 0 and opportunity cost is determined by *LMP*. The day-ahead *LMP* is used to estimate the opportunity cost of the hydropower unit, while the real-time *LMP* is used to settle the opportunity cost of the loss afterwards.

2.3 Canada

Canada's installed hydropower capacity ranks fourth in the world, and has many large hydroelectric power plants with good regulation capacity, and hydroelectricity accounts for about 60% of its electricity production [23]. Hydropower accounts for approximately 60% of its electricity production. In the Canadian electricity market, the development of hydropower, its share of electricity production and the price of electricity varies from province to province. The structure of the Canadian electricity market in each province can be divided into the following two categories.

- Vertically integrated markets, such as British Columbia and Quebec, are dominated by hydroelectric power generation and have open wholesale power markets where hydroelectric producers provide power to hydroelectric companies under power purchase agreements and do not provide retail services.
- Reformed and restructured competitive markets, such as Alberta and Ontario, established ISOs to manage the transmission system and set wholesale market prices, moving away from a centralized regulatory model. Relying primarily on fossil fuels and nuclear power, electricity prices are high, so market reforms were undertaken to reduce control and increase market competition. Among them, Ontario adopted a hybrid regulatory competition model and Alberta adopted a mandatory power pool model.

The Canadian electricity market has established a relatively refined clearing model, which considers the relationship between hydroelectric power plants in terms of the

hierarchical dispatch, and sets different rules for hydroelectric power plants with different regulation capacity, in which large hydroelectric power plant with strong regulation capacity participate in the market as a price-maker, and run-of-river power plant with weak regulation capacity participate as a price-taker [11]. In addition to some special rules, hydropower participate in the market together with thermal units according to the same rules. In the Ontario electricity market, hydro companies participating in the market are required to submit information required by the IESO (Independent Electricity System Operator, IESO), including operating dead zones, maximum number of daily starts and minimum output [24]. Due to the advantages of cheap hydropower, each province bordering the U.S. have some cross-country power trading, mainly in the northeastern U.S., where most of the power exported is shared between the ISO-NE (ISO New England, ISO-NE) and NYISO (New York ISO, NYISO) markets [25].

2.4 Norway

Norway is interconnected with Sweden, Finland and Denmark to form the Nordic electricity market, and the Nordic electricity market is also interconnected with other European regions such as the Netherlands, Germany and Russia [26]. The high share of hydropower in Norway's electricity supply and the large amount of electricity exported, as well as the large storage capacity, are important features of the Norwegian hydropower system. Therefore, the cross-border interconnection, the mature grid and the abundant hydropower resources make Norway's power system very flexible, thus reducing the negative impact of fluctuations in power generation between seasons and years [27].

In the Norwegian electricity market, hydropower has entered the market to compete. During the summer period, when Norwegian reservoir inflows are high but load demand is low, electricity exports are highest; during the winter period, when reservoir inflows are low but load demand is high, electricity imports are highest, and electricity prices rise. Therefore, cross-border power trading moderates the increase in electricity prices in Norway in winter and maintains higher electricity prices in summer. In addition, cross-country power trading can provide relatively low-cost electricity in low-water years and increase the value of electricity in high-water years [28].

2.5 China

In the first batch of domestic electricity spot market pilots, only hydropower from Zhejiang, Gansu and Sichuan provinces are currently competing in the market. As for Zhejiang Grid, provincial hydropower is seen as the provincial spot market boundary and is a price-taker in the spot market. The cross-province and cross-region hydropower is partly represented by Zhejiang Grid (e.g. Three Gorges and Southwest Hydropower) and partly implemented as the spot market boundary (e.g. Xiluodu Hydropower). For Gansu Grid, the provincial hydropower is also seen as the provincial spot market boundary and is a price-taker in the spot market. The cross-province and cross-region hydropower is physically implemented as the provincial spot market boundary. For Sichuan Grid, provincial hydropower participates in the hydropower spot market. The cross-province

and cross-region hydropower is carried out as provincial spot market boundary according to relevant rules. Inter-provincial hydropower that cannot be executed in the spot market is settled by "Contract of Difference" [29].

3 Comparative Analysis of Domestic and Foreign Hydropower Consumption Rules

Due to the differences in electricity market patterns and the proportion of hydropower in different countries, there are also differences in the approaches for hydropower used to enter the market. In summary, there are three main types:

- Participate in the market together with thermal and other power. For example, Norway, Canada, etc.
- As a price-taker. For example, run-of-river hydropower in Ontario.
- Unified dispatch of hydroelectricity. For example, Brazilian electricity market.

Hydropower enters the market together with thermal and other power sources, and no special rules are set for hydropower in the power markets which own abundant hydropower. In the Canadian electricity market, large hydropower with strong regulation capacity competes in the market, and run-of-river power plants with weak regulation capacity participate in the market as price-taker. The Brazilian electricity market considering the characteristics of its own energy structure, implements national unified dispatch which can share the hydrological risk.

In addition, each country has taken the operational characteristics of hydropower into account in the rule-making of electricity market. For instance, in the energy pricing method, most countries use marginal cost pricing, while Brazil uses the market clearing price after the ONS unified dispatch, and in the type of contract, most countries use contract trading method for hydropower, and spot trading only accounts for a minority.

With the development of the electricity market, the real-time balancing market is beneficial to the real-time participation of hydropower plants in market transactions according to the incoming water. In addition, because hydropower units have good operating performance such as flexible start and stop, hydropower enterprises in various countries can obtain revenue by participating in auxiliary service market.

4 Implications for Hydropower Consumption in Hubei Power Market

The electricity market structure in Hubei is relatively complex and has significant geographical characteristics. Firstly, there are various power plant dispatching relationships, including state regulation, network regulation, provincial regulation and non-regulation units. Secondly, there are large differences in the regulation capacity of hydropower plants, including multi-year regulation, annual (seasonal) regulation, daily (weekly) regulation and run-of-river power plants, and it is difficult to coordinate between hydropower plants with different regulation performance. Most of the reservoir power stations, in

addition to power generation, also need to undertake comprehensive social services, such as flood control, irrigation and shipping. Thirdly, the relationship between the gradient hydropower is complex and there is a time lag dependency relationship problem. The last is the lack of regulation capacity because of the lacking unit capacity with excellent regulation capacity.

4.1 Principles of Hydropower Participation in Market Competition

In China's "unified market, two levels of operation" of the electricity market system, Hubei Province should be in accordance with the "three conducive" principle of building the electricity market, and implement "three co-ordination" [30]. Therefore, hydropower needs to enter the market according to the following principles:

- Adhere to security and stability. Power generation enterprises need to meet operation technical standards, grid scheduling and other requirements [31] to ensure the reliable supply of electricity.
- Adhere to unified dispatching. The hydropower units should obey the relevant regulations of scheduling management, ensure the system safety in the market operation mode, and arrange the way of their participation in the market according to the dispatching authority of the hydropower units.
- Adhere to scientific regulation. To ensure market fairness, market force testing of hydropower units entering the spot market is needed to prevent power generation groups from conspiring to change the market clearing price.
- Adhere to the overall balance. Hydropower stations should be given priority to meet the comprehensive social tasks of flood control, shipping, irrigation, etc. On this basis, the reasonable organization of the distribution of electricity involved in the market.
- Adhere to the principle of low-carbon and clean. According to [32], mechanisms for hydropower participation in the spot market should be established and improved, full consumption of hydropower resources should be achieved as far as possible, and the proportion of hydropower entering the market should be gradually liberalized.

4.2 Difficulties and Challenges Faced by Hydropower Units Participating in the Spot Market

There are four main difficulties and challenges for hydropower units in Hubei to participate in the spot market.

- Large deviation of long-period power generation forecast. Long-period water forecast must consider the system's load demand and flood control, shipping and other water scheduling requirements, so the forecast deviation is large.
- The diversity of dispatching authority is difficult to coordinate. There is diversity and incompatibility in the dispatching authority among hydropower units in Hubei and there are also differences in reservoir capacity regulation performance and power station functions.

- Clean energy consumption in the spot market has special characteristics. When entering the spot market, the upstream and downstream hydropower stations may have inconsistent bidding results or winning power bids. The run-of-river power plants without regulation capacity may not win the bid, resulting in the water abandonment.
- Auxiliary service market and spot market need to be reasonably connected. The auxiliary services such as frequency regulation and reserve which are provided between provinces, cannot be reasonably compensated through the "two rules" [33, 34] and the auxiliary service market.

4.3 Viable Mechanisms for Hydro Units to Participate in the Spot Market

Combining the characteristics of hydropower units in Hubei Province, three feasible ways for hydropower units to participate in the spot market are proposed, including government direct purchase contract, as price-maker or price-taker.

Government direct purchase contract: Hydropower units do not participate in the spot market and are given priority in power generation on the basis of ensuring system safety [35, 36]. The price mechanism of government direct purchase contracts is divided into two types: fixed contract and index-based contract.

Fixed contract: Fixed contract price is a fixed contract price for the government to settle the contracted electricity, and all units covered by the contract have a uniform price. In the initial stage of the spot market, the government approved tariff for the same period can be used.

The fixed contract mechanism is easy to operate and conducive to a smooth market transition, but the spot market price signal cannot be transmitted to the hydropower units, making it difficult to play the advantages of flexible regulation of hydropower units and reducing the efficiency of market operation.

Index-based contract: On the basis of the fixed contract price, the spot market price correction index is introduced which can correct the fixed contract price. The expression is:

$$P = x \times P_N + (1 - x) \times P_C \tag{2}$$

Where P is the index contract price and x is the weighting share of the spot price to the price correction of the index contract, whose value is in the range of 0 to 1 and is determined according to the incoming water quantity, installed capacity and regulation capacity of different hydropower units. P_N is the real-time spot market clearing price and P_C is the price of a fixed contract signed by the government.

The index-based contract mechanism introduces market price signals into contract price with different weights, which effectively guides hydropower enterprises to adapt to market competition while ensuring their income and controlling market force, making the price signals play a guiding role in optimizing the output of hydropower units to a certain extent, which is conducive to advancing the process of participation in the spot market for hydropower units.

Government direct purchase contract mode is a way for government to effectively suppress the market force of hydropower units, stabilize the market price of electricity while also ensuring the output of hydropower units, which has less impact on the

adjustment of the benefits of individual market players. However, the power and price of hydropower units are less influenced by the market, which is not good for price signals to guide the optimal allocation of hydropower resources. At the early stage of spot market, this participation mechanism is suitable for power stations with cross-provincial consumption of electricity, such as Three Gorges Power Station and Gezhouba Power Station.

Participate in the spot market as a price-maker: Hydropower units declare full power to participate in the spot market bidding, optimizing the clearing together with all types of units. The power dispatching agency is supposed to consider factors such as the constraints of each unit for grid and the operational safety, and takes the maximization of social welfare as the optimization goal [37] to make clearing to get the local node price of different time in the day-ahead market. The real-time market adopts the information declared by the power generation enterprises in the day-ahead market to clear out [38]. The market unit settlement adopts the "double settlement" mode, which means the deviation between the day-ahead spot trading curve and the medium-term and long-term decomposition curve is settled according to the day-ahead spot price, and the deviation between the actual generation and consumption curve and the day-ahead spot trading curve is settled according to the real-time spot price.

This participation mechanism can return the hydropower unit output to the power commodity properties to find the true value of electricity, but the declared output is possible not to win the bid and hydropower consumption has a certain risk. This mechanism is suitable for hydropower stations with annual regulation and above regulation performance, such as Shuibuya, Geheyan power station, etc. This type of power station has excellent regulation performance and reservoir storage capacity all over the year. In the case of unsuccessful bids in the spot market, it can reduce water abandonment through reservoir regulation, promoting the optimal allocation of hydropower resources, thereby reducing the total cost of electricity to society.

Participate in the spot market as a price-taker: This mode can ensure the winning bid of hydropower units and realize the effective consumption of hydropower resources. The hydropower units only need to declare the 96-point power generation forecast curve of the next day before the day-ahead market closes according to the future power output forecast, and carry out centralized and optimized clearing with all types of units. The real-time market adopts the information declared by the power generation enterprises in the day-ahead market for clearing [38]. The market adopts the "double settlement" mode for the settlement of units.

This participation mode is consistent with the current scheduling mode which is easy to operate and manage and can also ensure full consumption of clean energy, but the units can only passively accept the market clearing price, and cannot play the advantages of the spot market. Therefore, this method is suitable for daily (weekly) regulating power plants and run-of-river power plants, such as Gaobazhou, etc.

5 Conclusion

It is an inevitable trend for hydropower which is one of the major power sources in electricity production to participate in market competition. The proportion of hydropower

generation in Hubei has exceeded 50%, and the reasonable participation of hydropower units in the market is crucial to the construction of power market in Hubei and even in China. Taking the characteristics of hydropower in Hubei into account, this paper compares the mechanisms of hydropower participation in the market at home and abroad, and analyzes the difficulties and challenges of hydropower participating in the spot market in Hubei. Besides, the paper proposes the principles and three feasible ways of hydropower participation in the market in Hubei including government direct purchase contract, as price-maker or price-taker, and also discusses the characteristics of different feasible ways and the corresponding scope of applicable units which can provide strong support for the construction of electricity spot market in Hubei.

In the process of designing the spot market mechanism, the characteristics of hydropower resources should be fully considered, and the construction of the spot market should be steadily promoted under the principle of playing the decisive role of the market and the guiding role of the government, in compliance with the law of market development, so as to finally realize the market-based consumption of hydropower.

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