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COMMENTS

Zhongkai FENG, Wenjing NIU, Chuntian CHENG, Jianzhong ZHOU, Tao YANG

China’s hydropower energy system toward carbon neutrality

Abstract Wind and solar powers will gradually become dominant energies toward carbon neutrality. Large-scale renewable energies, with strong stochasticity, high volatility, and unadjustable features, have great impacts on the safe operation of power system. Thus, an advanced hydropower energy system serving multiple energies is required to respond to volatility, with expanding role from a “stable energy supplier” to a “flexible efficiency regulator”. Future research and application can be considered from three aspects: 1) system expansion (e.g., the construction of large-scale hydropower/renewable energy bases in China, the construction of transnational hydropower energy internet, and the functional transformation of traditional hydropower reservoirs and generating units); 2) efficiency promotion (e.g., advanced intelligent forecasting, multi-objective operation, and risk management methods); and 3) supporting measures (e.g., market reform, benefit compensation and policy mechanism, technical standards, and laws and regulations).

Keywords hydropower system, carbon neutrality, artificial intelligence

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Zhongkai FENG (✉), Tao YANG
College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China; Yangtze Institute for Conservation and Development, Hohai University, Nanjing 210098, China
E-mail: myfellow@163.com

Wenjing NIU
Bureau of Hydrology, ChangJiang Water Resources Commission, Wuhan 430010, China

Chuntian CHENG
Institute of Hydropower and Hydroinformatics, Dalian University of Technology, Dalian 116024, China

Jianzhong ZHOU
School of Civil and Hydraulic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

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1 Introduction

Recently, the Chinese government outlined the strategic map for carbon peak until 2030 and carbon neutrality until 2060 under the new development philosophy (Ren et al., 2021; Song et al., 2022; Zhao et al., 2022). To achieve this great goal, renewable energies (e.g., hydropower, wind, and solar energies) will play increasingly important roles in constructing a low-carbon and efficient interconnected energy system (Griffiths and Sovacool, 2020; Millot et al., 2020). The total installed capacities of hydropower, wind power, and solar power of China have reached approximately 370, 282, and 254 GW in 2020, respectively. According to the national medium- and long-term development program for the power system, the installed capacities of wind and solar energies will reach about 1440 and 2160 GW in 2050, respectively (Cheng, 2021). However, it is difficult to absorb large-scale wind and solar energies with high volatility, strong stochasticity, anti-peak shaving, and unadjustable features (Li et al., 2016; Shuai et al., 2020; Liu et al., 2021; Sattich et al., 2021; Zhou et al., 2022). As the shares of renewable energies increase sharply, it becomes difficult to guarantee the energy supply and antijamming ability of power systems due to some practical problems, like the inadequate flexibility of energy, the incomplete market mechanism, the limited transmission capacity, and the complex interaction of multiple electronic devices.

Unlike other countries in the energy structure transition process, China has the world’s largest hydropower energy potential, with approximately 694 GW of theoretical reserves of hydropower resource. In the past decades, China exerted great efforts into promoting hydropower development for energy conservation and emission reduction. The total installed capacity of hydropower is estimated to reach approximately 450 GW in 2030 and 550 GW in 2050. Under the new strategic map, the role of hydropower industry has experienced unprecedented and enormous changes to satisfy the practical requirements of renewable energies. Thus, the future researches on hydropower system should be intensified toward carbon neutrality.

2 Hydropower role expansion from power supplier to flexible efficiency regulator for stabilizing renewable energies

Traditionally, hydropower takes full advantage of the abundant regulation storage to reallocate the natural river flow and satisfy the operation requirements of the involved management departments. Compared with other energy resources, hydropower has the unique advantages of strong stability, low pollutant emission, and high flexibility and reliability, promoting its rapid expansion throughout the world. However, energy resources and electricity load are unevenly distributed in China, that is, the load consumption is mainly provided by the central and eastern regions, while hydropower energy is mainly located in southwestern provinces, like Sichuan, Tibet, and Yunnan. To effectively enhance the energy utilization efficiency, several huge hydropower bases and large-scale west-to-east power transmission projects have been built for energy production and power transmission, promoting nationwide connectivity and the interprovincial interaction of hydropower systems. Consequently, hydropower usually plays the part of energy supplier in a power system.

To respond to the dynamic injection of large-scale wind and solar powers, considerable energy with flexible, stable, and controllable features is required to effectively smoothen the frequent power fluctuations and the peak–valley loads of electrical power systems. Among all the known energy resources, hydropower may thus far be the only choice for this responsibility (Musa et al., 2018; Wang et al., 2018; Kung and Mu, 2019). On one hand, more than half of the planned huge hydropower bases are centralized in the southwest regions and Yangtze River basin of China, whereas multiple carryover storage hydropower reservoirs have been put into operation. The relative centralization of hydropower energy leads to favorable rolling development convenience, while reservoirs with superior adjusting abilities can provide multiscale (like hourly, daily, weekly, monthly, and yearly) high operational flexibility. On the other hand, nearly all the hydropower resources in central and eastern China have been developed, while the utilization of the southwest hydropower bases waiting for exploitation is a challenge due to complicated hydrological condition and engineering geological environment. The hydropower share in electric systems will continuously decrease with the increase of renewable energies in the coming decades, but its significance will keep rising. Thus, China's hydropower energy system will exhibit some unique features in the new situation, like 1) transnational and trans-regional integration with multiple energies, 2) open sharing in connecting energy island and information wisdom, 3) role re-establishment from stable energy supplier to flexible efficiency regulator, 4) multi-dimensional cooperation among various stakeholders, 5) panoramic scheduling for promoting comprehensive benefits, and 6) functional complementation at multiple temporal–spatial scales.

3 Possible strategies for the hydropower energy system toward carbon neutrality

In the future, large-scale flexible hydropower energy will be necessary to satisfy the operational requirements of wind and solar energies. The following measures in Fig. 1 may be conducive to fully exploiting the potentials of the hydropower system toward carbon neutrality, including scale expansion for increasing the total installed capacities of available domestic and overseas hydropower bases, efficiency promotion for improving the operation and management levels of the hydropower system, and supplementary measures for providing comprehensive support for the hydropower system.

- **Scale expansion for increasing flexible hydropower share**

(1) Domestic construction of a large-scale complementary hydropower energy system. On the basis of previous research findings, the complementary operation of multiple energies (like hydropower, wind, and solar energies) can not only effectively improve the resource utilization efficiency but also promote healthy and sustainable economic development. As the world's largest hydropower base, the hydropower corridor in upper and middle Yangtze River accounts for approximately a quarter of the total potential installed capacity of China's hydropower industry, providing a solid foundation for hydropower energy bases and water resource pools. Furthermore, due to their vast territory, suitable altitude, and low population density, the northwest, north, and northeast (3N) regions of China, with abundant high-quality wind and solar energy resources, are regarded to be among the most important and promising renewable energy bases (Musa et al., 2018; Wang et al., 2018; Kung and Mu, 2019). For instance, the wind power resources in the 3N regions account for 80% of the onshore wind power resource reserves of China, while the annual illumination time exceeds 2200 h. Obviously, forming the renewable energy corridor in the 3N regions of China is of great value. Thus, domestic emphasis can be placed on the construction of an interconnected network of multi-energies complementary bases in Yangtze River basin and the 3N regions of China, where the huge hydropower reservoirs are set as the cornerstone power resources to respond to the time-varying wind and solar power outputs.

(2) Overseas construction of transnational hydropower energy internet. With an interconnected transmission network, the power generation in resource-intensive areas can be easily transferred to consumption intensive regions, which is helpful in promoting balanced

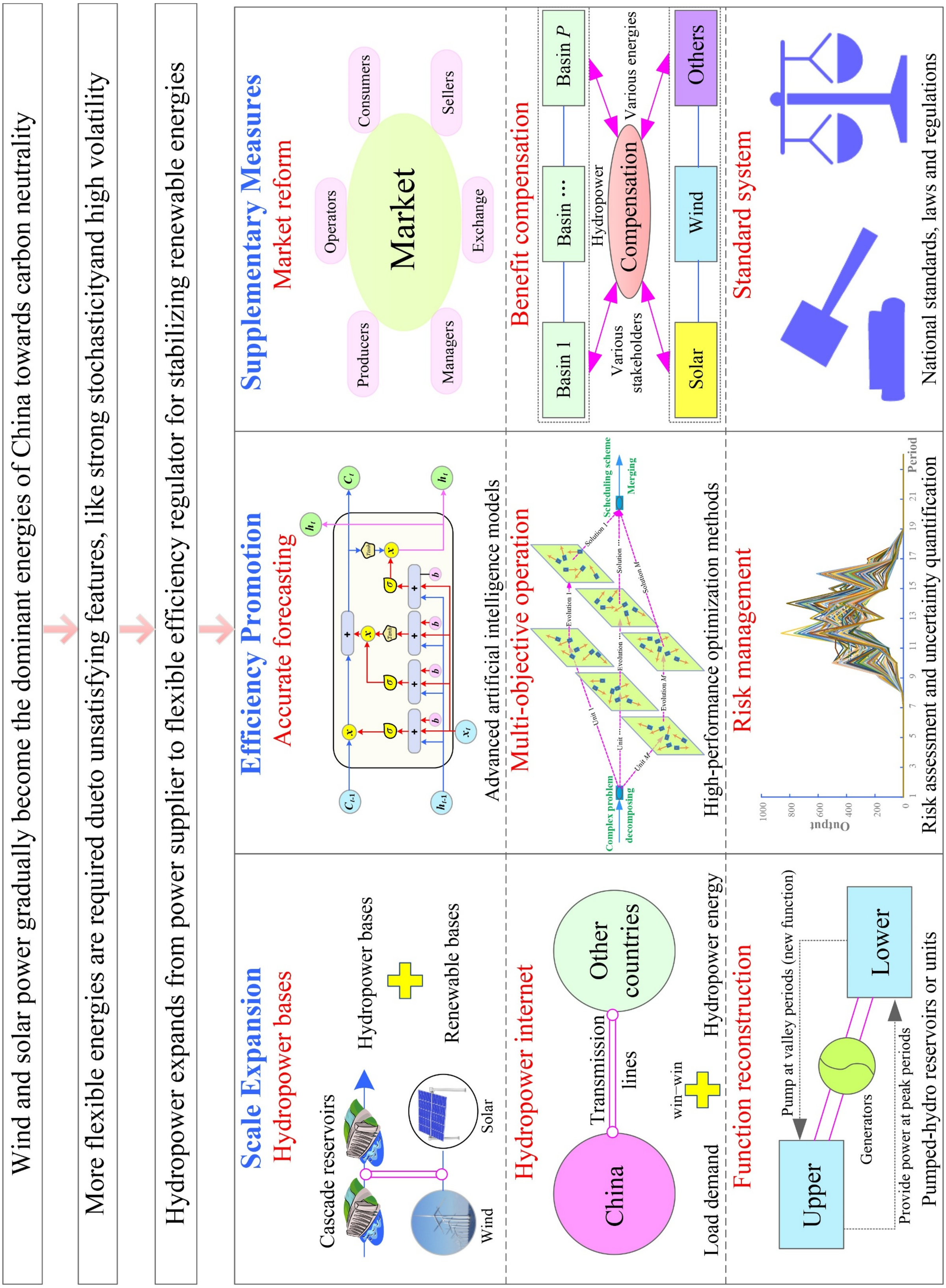

Fig. 1 Summary of possible strategies for hydropower energy system toward carbon neutrality.

economic development and achieving win–win situations among different regions. In recent years, China's hydropower services have achieved fruitful results within the Belt and Road Initiative strategy, and several huge world-class hydropower stations adhering to the highest technical standards of the local "Three Gorges Project" have been put into operation, like the Neelum–Jhelum hydroplant in Pakistan and the Shweli cascade hydroplants in Myanmar. As one of the world's most competitive hydropower countries, China, with an advanced comprehensive technical strength, has occupied more than 70% of the overseas hydropower market and nearly all the large and medium-sized hydroelectric projects in the world, popularizing hydropower as a national business card. Thus, an effective transnational interconnected hydropower energy internet can be constructed, where abundant energies and huge energy demands between all friendly states and China can be tightly connected to improve the global economic efficiency and achieve the mutual benefit goal.

(3) Function reconstruction of conventional hydropower reservoirs and generating units for improving operation flexibility. Most of the traditional hydropower reservoirs and generators can only undertake the tasks of power suppliers and fail to satisfy the demand response requirements at valley-load or low-efficiency periods, which may reduce the operational flexibility and lead to waste of produced renewable energies. Thus, to satisfy the dynamic load balance, traditional hydroplants can install more reversible hydropower generators or be transformed to pump-storage power stations at appropriate locations. Through this approach, except for providing electricity at peak–load periods, hydropower generators can use unabsorbable renewable energies to pump water from a lower-storage reservoir (or riverway) to an upper-storage reservoir, improving the resources utilization efficiency on the premise of mitigating the frequent load fluctuation.

- **Efficiency promotion for improving hydropower operation benefit and flexibility**

(1) Advanced forecasting and simulation models. Generally, accurate forecasting of power generation ability is one of the most important preconditions in determining the scheduling schemes of hydropower and renewable energies (Feng et al., 2022). Given the influences of meteorological factors, wind and solar outputs often possess strong stochasticity, volatility, and intermittent features, increasing the difficulty of high-accuracy forecasting. Owing to the rapid development of computer technologies, the working condition information (like observation, monitoring, transmission, and processing) can be timely collected in the entire production process, providing a strong data foundation. Furthermore, artificial intelligence methods using well-designed mathematical models are enjoying increasing popularity for various engineering problems due to their strong generalization abilities and high learning rates. Thus, the essential spatial–temporal output features and future evolutionary laws of both hydropower and renewable energies should be intensively analyzed, while advanced artificial intelligence can be dynamically integrated to develop effective forecasting and simulation models to provide accurate input information for operation models.

(2) Multi-objective operation optimization methods. In the spatial scale, hydropower and renewable energies are often under the management of multiple departments with different interests or demands, like regional or provincial power grids and power generating companies. Thus, various scheduling requirements (like power generation, navigation, environment protection, and flood control) and physical constraints (like load regulation, market contracts, ecological flow, and water level) should be simultaneously considered in the modeling process. The modeling and optimization difficulty usually shows an exponential growth with the increasing number of grid-connected power stations and generators. In terms of time scale, the entire decision-making process of the hydropower system can be split into a set of relatively-independent but tightly-coupling sub decisions. When creating the latest scheduling scheme, the comprehensive information should be fully considered in the daily work, while the dynamic implementation deviation at the current-scale scheme should be used to adjust the future operating boundaries of the upper-scale scheme. Mathematically, the operation of the hydropower system, which is characterized by multiple stakeholders, complex scheduling requirements, and time-varying physical constraints, belongs to a typical multi-objective constrained optimization problem, as well as an international hotspot in many research fields. Thus, efficient multi-objective operation optimization methods can be developed to quickly provide feasible compromise schemes for decision-making.

(3) Risk management methods. In practice, hydropower and renewable energies are affected by many uncertain factors (like water/rain regimens, decision-makers' experience and preferences, and engineering maintenance) that follow different manifestation patterns, influence scopes, and transmission paths. Meanwhile, the occurrence frequencies and influence ranges of extreme weathers and hydrological events are increasing owing to the comprehensive influences of human activities and climate changes. The new trend makes obvious changes in the data consistency and internal relationship of some important factors (like runoff, wind speed, and solar radiation), increasing the operational risk under the changing environment. Generally, scientific uncertainty quantification is helpful in identifying various risk factors, building the risk indicator set, and making adaptative decisions in different scenarios. Thus, more effective risk assessment and uncertainty quantification

methods can be developed to maximize the comprehensiv benefits of the hydropower system.

● **Supplementary measures for supporting hydropower healthy development**

(1) Market reform for enhancing global consumption ability. In the past few years, the historical experience of the world's power industry has proven that a healthy electricity market can effectively improve the energy allocation efficiency and guarantee a reliable power supply. In the new era of energy revolution, the improvement of the electricity market is the primary goal of nearly all developed countries. However, a mature electricity market has not been fully achieved in China. To bridge this practical gap, a unified, open, competitive, and orderly national electricity market should be constructed as soon as possible. Through the guidance function of the electricity market, more social capital investments can be gained, the marginal electricity prices can be reduced, the participation degree and market competitiveness of renewable energies can be promoted, and the demand response willingness and consuming ability of end-users can be increased.

(2) Benefit compensation and policy mechanism for promoting allocative efficiency. On one hand, the large-scale consumption of renewable energies inevitably aggravates the peak shaving pressure of the hydropower system, which harms the operation benefit of the hydropower enterprise. On the other hand, the working roles of hydroplants in the power system have positive correlations with the regulation capabilities, where hydroplants with a superior performance tend to undertake the peak regulation tasks, while those with poor regulation storage can work in the base-load zones. When responding to load demands, great interest contradiction often exists between hydropower and renewable energies, and between regional and provincial power grids. Hence, suitable benefit compensation strategies and innovative complementary policies that consider multiple factors (like peak/valley periods and flood/dry seasons) can be developed to arouse the enthusiasm for cooperation between energy sources of different stakeholders.

(3) Standard system improvement for guaranteeing operation safety. As is well-known, nothing can be accomplished without norms or standards. However, the power system may suffer from accidents due to multiple energy equipment, devices, and technologies with different standards. Thus, unified standards, laws, and regulations at the national levels, like technical regulation rules for generation integration and the emergency response of renewable energy, should be established. For instance, the voltage and frequency resistance performance of renewable energies should be consistent with that of synchronous generators, which is conductive to providing sufficient peak load and frequency/voltage regulation capabilities for the power system. Through this approach, more hydropower and renewable energies can be absorbed in a healthy manner.

Besides, with the booming development of modern sciences and technologies, growing frontier approaches and engineering practices are constantly appearing in different disciplines (Hu et al., 2020; Kaluarachchi, 2021; Zhang and Ariaratnam, 2021). For instance, deep learning has sharply promoted the development of many research fields, like time series forecasting, image recognition, and speech identification. Thus, attention should be also paid to emerging theories, tools, strategies, policies, and other effective measures to provide new possibilities for improving the overall efficiency of the hydropower system.

4 Conclusions

In the carbon neutrality era, the role of hydropower is expanding from the "stable energy supplier" to the "flexible efficiency regulator", which will produce a hydropower energy system that connects transnational and trans-regional multiple energies. To help realize this goal, this study proposes three aspects of focus, namely, the strategy level (system expansion for increasing flexible hydropower share), the operation level (efficiency promotion for enhancing hydropower benefit and flexibility), and the policy level (supporting measures for guaranteeing hydropower healthy development).

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