MATEC Web of Conferences **410**, 01017 (2025) https://doi.org/10.1051/matecconf/202541001017
MENEC 2025

Study on the Development Trend of Hydroelectric Power Generation

Huiyu Luo*

Liuzhou Tieyi High School, Liuzhou, Guangxi, 545007, China

Abstract. As a clean and renewable energy source, hydropower occupies an important position in China's energy transition. This paper systematizes the technical principles, development status, advantages, and challenges of hydropower and looks forward to its prospects. The study points out that China is rich in hydropower resources and has sufficient technological reserves, but the development rate is low and needs to be upgraded urgently. Currently, hydropower development is facing problems such as institutional monopoly, thermal power competition, and ecological conflicts, which need to be solved through power market reform, optimization of scheduling mechanisms, and promotion of integrated development of river basins. At present, China's hydropower installed capacity continues to grow, with high-power units and intelligent technology to promote the upgrading of the industry, but we need to pay attention to the ecological impact and the challenge of uneven regional resources. In the future, the construction of hydropower bases in the west and the layout of pumped storage power plants will become a key focus, helping to realize the goal of carbon neutrality. This paper emphasizes that hydropower has economic, social, and environmental benefits, and its sustainable development needs to be driven by both policy support and technological innovation.

1 Introduction

As one of the most mature renewable energy technologies, hydropower has been widely used worldwide. The hydropower industry has made remarkable progress over the past decades, and hydropower not only provides a significant amount of clean energy globally but also plays an important role in grid peaking and energy storage.

With the continuous progress of science and technology, hydroelectric power generation technology is undergoing important innovations. Modern hydropower plants have not only made technological improvements in major equipment such as turbines and generators but have also made significant progress in hydraulic engineering and automation control. For example, new composite materials (e.g., epoxy powdered mica) have been used to replace traditional materials, reduce the thickness of the insulation layer, and improve the efficiency of heat dissipation in the stator windings, resulting in an increase in power generation capacity of 10-15% [1].

* Corresponding author: wendy@stu.msu.edu.kg

These technological advances have enabled the widespread development and utilization of low-fall and conventional hydropower and unconventional hydropower. The research objective of this paper is to explore the technological path and sustainable development strategy for the efficient utilization of hydro energy resources. By analyzing key topics such as the evolution of hydraulic turbine technology, the impact of hydropower plant construction on river basin ecology, and the optimization of an intelligent dispatching system, the central role of hydropower in the clean energy transition is revealed.

2 Principles and applications of hydroelectricity generation

2.1 Principles of hydroelectric power generation

The basic principle of hydroelectric power generation is to use the water level of the fall (potential energy) to make the water flow under the action of gravity (kinetic energy) to drive the turbine blade rotation, and the turbine, through the mechanical transmission, drives the generator to generate electricity. Among them, the pump of the hydraulic circuit is the source of energy, and at the end of the whole link, the water flow will be lifted up to the high water level, completing a circuit cycle.

2.2 Hydroelectric applications

2.2.1 Dam-type hydropower plants

A dam-type hydroelectric power plant is a typical model of a water conservancy project that utilizes dam-building technology to concentrate the head of water to generate electricity. It forms a reservoir by damming a river and converts the potential energy of natural water flow into electricity. The core principle lies in the fact that the dam congests the upstream water level, creating a significant water level difference between the dam and the downstream river, driving the turbine to generate electricity. Depending on the relative position of the plant and the dam, dam-type hydropower plants can be categorized into two types: behind-the-dam type and riverbed type, each of which has its own unique engineering characteristics and application scenarios.

Behind-the-dam hydropower plants use the dam as the main water retaining structure, with the plant arranged on the downstream side of the dam and generating power by diverting water through pressure pipes. This type of design is suitable for high-head scenarios, such as the Three Gorges Hydropower Station, where the concrete dam body bears all the upstream water pressure and the plant only needs to focus on power generation. The advantage of behind-the-dam hydropower plants is that they allow for the construction of large reservoirs for multi-year runoff regulation, with comprehensive benefits such as flood control and navigation. However, the construction of high dams is often accompanied by large inundation losses and ecological impacts.

Riverbed hydroelectric plants integrate the plant with the dam, with the plant itself acting as part of the water retaining structure and being directly subjected to upstream water pressure. This type of design is mostly seen in low to medium-head scenarios, such as the Gezhouba hydroelectric power plant, which utilizes a riverbed-type structure to generate power in the middle reaches of the Yangtze River in a gentle stretch of the river. The advantage is that it saves the cost of the water retaining building and eliminates the need for a specialized diversion pipeline, but the small reservoir capacity results in limited runoff regulation, and the power generation efficiency is greatly affected by the fluctuation of the natural flow rate.

As the main form of traditional hydropower generation, the dam-type hydropower plant occupies an important position in the global energy system. Not only can they realize the peak and frequency adjustment of the power system through reservoir regulation and ensure the stability of the power supply, but they also play a key role in the comprehensive management of river basins. However, as the demand for ecological protection and low-carbon transition intensifies, the inundation costs and ecological risks of high dams and large reservoirs are becoming increasingly prominent. In the future, dam-type hydropower development needs to take more account of environmental sustainability and explore the integration path with ecological restoration and intelligent scheduling technology.

2.2.2 Diversion-type hydroelectric power plant

A diversion-type hydroelectric power plant is an important technical means in the field of water conservancy engineering to convert natural water energy into electricity by concentrating the river drop through artificial diversion channels. Its core principle is to avoid the gentle section of the river, directly from the significant difference between the river or cross-basin diversion, the formation of the head of water required for power generation. Especially suitable for mountainous rivers with small flow but large drop terrain conditions. According to the diversion channel pressure form, the hydroelectric power plant is divided into two categories: unpressurized and pressurized.

The unpressurized system uses open channels or tunnels to convey the water flow to the pressure front pool, which is suitable for hilly areas with small water level difference scenarios. An example is the Manas terraced power station in Xinjiang, China. The pressurized system, on the other hand, diverts water through pressure tunnels or steel pipes, and the plant can be arranged underground, on the bank, or in the tail section. The first hub contains facilities such as barrages and sedimentation tanks, while the central diversion channel optimizes the head by cutting curves or cross-basin design, and the tail plant relieves the water strike pressure through a regulating chamber.

Compared to dam-type hydropower plants, diversion-type power plants do not require high dams to store water, avoiding the problems of reservoir inundation and migration and significantly reducing the unit cost. However, the nature of the unregulated reservoir results in limited water utilization, and power generation is greatly affected by seasonal runoff. Therefore, diversion-type power plants are often combined with hybrid designs, such as the Lubugu power plant, which is developed through the joint development of a dam and a diversion channel, taking into account the head and regulating capacity. In the context of the global clean energy transition, diversionary hydropower plants have become an important option for renewable energy development in mountainous areas by virtue of their small engineering volume and low ecological disturbance. Future technology trends include intelligent voltage regulation systems to optimize operational efficiency and underground plants with ecological flow relief facilities to reduce environmental impact. Through refined hydrological analysis and digital scheduling, diversion-type power plants will play a greater role in ensuring a balance between energy supply and ecological protection.

3 Hydroelectric power generation technology innovation and efficiency improvement

3.1 Hydraulic turbine and generator technology improvement

Cavitation, a unique phenomenon of hydrodynamics that includes complex characteristics such as phase change and compressible flow, has been one of the difficult research points in the field of hydraulic machinery. Cavitation inside the hydraulic turbine usually induces severe vibration, strong noise, and material spalling in the hydraulic turbine, which reduces the operation quality and life of the unit. Therefore, it has become an important research direction in the field of hydraulic turbines to identify the types of cavitation inside the turbine and to propose effective cavitation suppression measures.

Currently, most of the studies on turbine cavitation problems are based on the impact turbine, and the cavitation in the impact units usually appears in the needle valve of the nozzle and the water-cutting and splitting edges of the rotor [2, 3]. However, the specificity of their flow has led to their lesser study. In the past 20 years, the development of CFD technology has greatly contributed to the progress of chemical numerical simulation studies [4]. With the joint efforts of a large group of scholars, cavitation models and cavitation turbulence calculations have achieved fruitful results, and a series of cavitation models based on different principle equations, such as the Schnerr-Sauer model, the Singhal full cavitation model, the Zwart cavitation model, the IDM model and the DMBM model, have emerged [5-9]. These models laid the foundation for accurate simulation of cavitation flow in hydraulic machinery, making it possible to use numerical simulation instead of tests to assess the course of cavitation development in hydraulic machinery [10]. For example, the Ertan Hydropower Station cavitation repair project used C50 silica fume concrete repair technology combined with epoxy resin grouting to enhance cavitation resistance and optimized the construction process to ensure the strength of the bonding surface between the old and new concrete. The structural life of the repaired structure was extended for more than 5 years, and the cavitation resistance was improved by 80% [11]. At present, the attention of the research on numerical simulation of cavitation flow is still focused on the validation of the accuracy of numerical simulation results, and the proposal of a process for the validation of the accuracy of the cavitation simulation method will be the focus of the research for some time in the future.

3.2 Structural optimization design of the generator

The inefficiency of hydroelectric generators is the result of a combination of factors. Mechanical wear is one of the important reasons. In the process of hydroelectric power generation, the hydraulic turbine is in contact with the water body for a long time and rotates at a high speed, and its internal blades, bearings, and other mechanical parts will be subjected to the impact and friction of water. With the growth of operation time, these parts will gradually wear out, leading to a reduction in the rotation efficiency of the hydraulic turbine, thus affecting the process of converting mechanical energy into electrical energy by the generator.

Optimized design of structure is an important technical direction for the improvement of the hydroelectric generator, which can effectively improve the efficiency of the generator through the improvement of turbine design and magnetic circuit structure. In terms of hydraulic turbine design, the parametric study of blade airfoil is the key. By parameterizing the geometry of the blade airfoil, the performance of the airfoil can be controlled more precisely. For example, scholars at Hunan University used evaporative cooling technology to optimize the stator core through-tube structure to improve the heat dissipation efficiency and optimized the layout of copper tubes through unit sensitivity analysis to balance the electromagnetic and heat transfer performance. These measures solve the high-temperature problem of the 10 MW permanent magnet direct-drive motor and improve the overall operational stability [12]. These optimization measures can make the turbine maintain good working performance under various hydraulic conditions and improve the utilization rate of hydraulic energy. The improvement of the magnetic circuit structure is equally important. By optimizing the magnetic circuit design, the uniformity and stability of the magnetic field can be improved, and magnetic leakage and hysteresis loss can be reduced. For example, adopting a new magnetic circuit structure, increasing the thickness of the yoke and poles, and reasonably arranging the position of the poles can make the magnetic field distribution more uniform and improve the electromagnetic conversion efficiency of the generator. In some high-power hydroelectric generators, by optimizing the magnetic circuit structure, the volume and weight of the generator can also be reduced to lower the manufacturing and transportation costs.

4 Addressing challenges promoting quality development

4.1 Challenges facing hydropower generation

The first is ecological damage and biodiversity crisis, manifested in the significant impact of dam construction on the basin ecosystem. The Yangtze River Basin Water Conservancy Project has blocked the migration path of the Chinese sturgeon, and its population is on the verge of extinction. Dams along the Pacific coast of North America have reduced salmon reproduction rates by 70%, and mitigation measures such as fish ladders are difficult to offset the lethality of turbines on juvenile fish. Reservoirs inundate large areas of wetlands and forests, exacerbating habitat fragmentation, and soil erosion and eutrophication in reservoir areas further deteriorate water quality, creating a vicious ecological cycle. Secondly, there is the contradiction between economic cost and resource constraints, as the construction of hydropower plants faces high capital investment and long construction periods, and the limited capacity of a single unit (about 300MW) makes it difficult to match the large-scale power demand. The construction of the Salzburg Mountain Pumped Storage Power Station in Austria shows that new hydropower projects still need huge financial support. Meanwhile, although Southwest China has abundant hydropower resources, seasonal drought and rain fluctuations have led to unstable power generation (-21.8% annual cumulative decline), exacerbating the pressure on grid peaking [13].

Then, there is an imbalance between technological bottlenecks and policies, with traditional hydropower equipment relying on natural runoff and lacking flexibility. Under the monopoly structure of the power industry, the distortion of resource allocation by "protecting thermal power and emphasizing hydropower" has led to a waste of clean hydropower resources. The lagging regulatory system also exposes risks: many hydropower plants in China suffer from safety hazards due to the lack of professionalism of technicians and equipment maintenance mechanisms, constraining the efficient operation of the industry.

Finally, there are social conflicts and climate feedbacks, with migration and resettlement conflicts and the risk of disease transmission coming to the fore along with dam construction. Reservoir evaporation changes the regional microclimate and may induce secondary disasters such as earthquakes. Climate change creates double pressure: Austria is forced to upgrade its pumped storage facilities due to declining river levels, while extreme weather conditions exacerbated by global warming threaten the flood safety of hydropower plants, creating a vicious circle.

4.2 Responding to challenges

4.2.1 Development of intelligent hydropower systems

Big data technology provides strong support for the operation analysis and optimization of hydropower generators. By collecting and analyzing a large amount of operating data, the generator's operating model can be established, the operating state and performance trend of the equipment can be predicted, and the scientific basis for the maintenance and optimization of the equipment can be provided. For example, by analyzing the historical operation data of generators, the failure pattern and potential problems of the equipment can be found, and maintenance and replacement of components can be carried out in advance to avoid the occurrence of equipment failures; it is also possible to optimize the operation parameters of the generator according to the operation data of the generator, to improve the efficiency and output of the generator. Artificial intelligence technology has a broad application prospect in generator fault diagnosis and intelligent control. Through the establishment of an artificial intelligence model, the generator's operating data can be deeply learned and analyzed to identify the equipment's failure mode and causes of failure, and realize accurate fault diagnosis. In terms of intelligent control, artificial intelligence technology can automatically adjust the generator output according to the demand of the power grid and the operating status of the generator, realizing intelligent scheduling and operation and improving the stability and reliability of the power system.

4.2.2 Optimize hydropower generation using digital technology

Driven by digitalization, the formation of a holistic solution integrating multiple participants, positive design concepts, lean construction mode, multidimensional information models, multi-source sensing equipment, and intelligent analysis means is the main development trend of future design and construction integration [14]. Digital twin technology, as a result of the physical things in the objective world and their development laws being defined by software, can realize the Dynamic reconstruction, process simulation, and deduction analysis of physical models in digital scenarios is an inevitable choice to help design and construction integration to digitalization, integration, and refinement [15]. Currently, digital twin application research is still in its early stages, and the most representative open source platform is the iModel.js open source platform released by Bentley, which integrates value-added tools and services such as advanced augmented reality and mixed reality solutions from vGIS to ensure that managers can view the entire asset on the Web side, check status, perform analysis, and generate insights in order topredict and optimize the performance of design outcomes. However, this platform only guarantees universal applicability and does not provide customized solutions for specific industries. Therefore, how to realize the effective fit between digital twin technology and the integration of design and construction in hydropower engineering has become a future research priority.

At the turn of the century, with the rapid development and application of the Internet, the digitalization process of dams is fully integrated with Internet technology, prompting digital dams to mature from germination and gradually be practically applied in dam construction. A digital dam is based on modern network technology and real-time monitoring technology to realize the whole life cycle of the dam information in real time, online, with all-weather management and analysis, and the implementation of dynamic analysis of dam performance and control of the integrated system. Digital dam integration involves project quality, progress, construction process, safety monitoring, engineering geology, design information and other aspects of data, information; covering the owner, design, supervision and construction units, while integrating computer technology, management science and technology, information technology, etc., with the help of hardware and software, to achieve the management of massive information data; and coordination of various types of information within the relationship between the realization of the advantages of complementary, resource-sharing andComprehensive application of the system system, to enhance the level of dam construction management provides a scientific way.

5 Conclusion

By analyzing the current situation, technological progress, and development trends of hydropower, this paper points out the important role of hydropower in the global energy transition. The technical principles, environmental impacts, and economic benefits of hydropower are systematically analyzed, pointing out its central position in the renewable energy system. Through case comparisons, it is verified that optimized reservoir scheduling and ecological flow regulation can significantly improve power generation efficiency and reduce ecological costs. The study emphasizes that hydropower needs to be complemented with solar and wind energy to build smart microgrids to meet the challenges of climate change and energy transition. Despite environmental and social challenges, hydropower still has great potential for development through technological innovation and international cooperation. Future research can further explore the integration strategy between hydropower and other renewable energy sources, as well as should deepen the application of digital twin technology in the whole life cycle management of hydropower plants, explore the mechanism of cross-basin collaborative scheduling, and promote the development of hydropower in the direction of low-carbon, flexible and intelligent.

References

1. J. Y. Liu, Research on capacity expansion and transformation technology of hydro-generator sets. Electron. Paradise (16), 2 (2019)
2. C. J. Zeng, Y. X. Xiao, W. Zhu, Numerical simulation of cavitation flow characteristic on Pelton turbine bucket surface. Proc. Int. Symp. Cavitation Multiphase Flow (Beijing, 2015)
3. Y. Peng, Y. C. Zheng, Research on operation and maintenance of Pelton turbine runner. Sichuan Water Power **37** (S2), 64-65 (2018)
4. B. Ji, X. Luo, X. Wang, Unsteady numerical simulation of cavitating turbulent flow around a highly skewed model marine propeller. J. Fluids Eng. **133**, 011102 (2011)
5. G. Schnerr, J. Sauer, Physical and numerical modeling of unsteady cavitation dynamics. Proc. 4th Int. Conf. Multiphase Flow (New Orleans, 2001)
6. A. Singhal, M. Athavale, H. Li, Mathematical basis and validation of the full cavitation model. J. Fluids Eng. **124**, 617 (2002)
7. P. Zwart, A. Gerber, T. Belamri, A two-phase flow model for predicting cavitation dynamics. Proc. 5th Int. Conf. Multiphase Flow (Yokohama, Japan, 2004)
8. I. Senocak, W. Shyy, Interfacial dynamics-based modeling of turbulent cavitating flows. Part-1: Model development and steady-state computations. Int. J. Numer. Methods Fluids **44**, 975-995 (2004)
9. B. Huang, G. Y. Wang, Z. Y. Yu, Detached-eddy simulation for time-dependent turbulent cavitating flows. Chin. J. Mech. Eng. **25**, 484-490 (2012)
10. X. Luo, W. Wei, B. Ji, Comparison of cavitation prediction for a centrifugal pump with or without volute casing. J. Mech. Sci. Technol. **27**, 1643-1648 (2013)
11. X. Q. Luo, G. J. Zhu, J. J. Feng, Progress and development trends in hydraulic turbine technology. J. Hydroelectr. Eng. **39**, 1-18 (2020)
12. B. P. Shi, W. Cheng, X. L. Tan, Cavitation and repair of turbines in Ertan Hydropower Station. Sichuan Hydropower **33**, 5 (2014)
13. Z. R. Cheng, Y. Wang, J. Gao, S. D. Huang, L. Ruan, Optimization design of stator core tube structure of evaporative cooling wind turbine considering electromagnetic-heat transfer effects. Trans. China Electrotech. Soc. (6), 39 (2024)

14. S. R. Zhang, P. Q. Jiang, Z. Q. Wu, Advances in research of lean construction technology of integrated design and construction for hydropower projects: Exploration of digital twin application mode. J. Hydroelectr. Eng. **40**, 1-12 (2021)
15. C. Boje, A. Guerriero, S. Kubicki, Towards a semantic construction digital twin: directions for future research. Autom. Constr. **114**, 103179 (2020)