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Overview of the Development and Current Status of Pumped Storage Power Plants

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Industrialisation and overexploitation of forest resources have led to environmental crises, including climate warming and a sharp decline in biodiversity. To address these challenges, the world is actively pursuing carbon neutrality and carbon peaking. As the cornerstone of clean energy storage and conversion, pumped storage power plants have undergone a century of technological innovation, from reliance on manual labour to highly mechanised TBM construction, which has significantly improved construction efficiency and quality. However, the application of TBM in pumped storage power plant construction still faces many challenges. In the future, we will conduct in-depth research on the design and application of modularisation, standardisation and intelligence to overcome the existing challenges and promote the extensive and efficient development of pumped storage power plant construction.

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1. INTRODUCTION

After more than a century of industrialisation, overexploitation of forest resources and intensive expansion of agricultural production, the global climate pattern has undergone significant changes. Frequent climate events, such as global warming, are occurring, and the Arctic ice is experiencing significant and unprecedented changes. The once vast, thick and solid sea ice is gradually melting, and the summer ice cover is shrinking and becoming thinner every year (Fig. 1). This highlights climate change as a key challenge for human societies in the twenty-first century [1-4].Concurrently, ecological imbalances have accelerated the loss of biodiversity, thereby posing a significant threat to global sustainable development. In order to meet the challenges posed by climate change, the world is actively pursuing ambitious goals of carbon neutrality and carbon peaking [5-8]. These goals aim to control carbon dioxide emissions and realise green, low-carbon and sustainable development through profound changes in the industrial structure and energy system. Nevertheless, the attainment of carbon neutrality is a lengthy and intricate endeavor [9,10].

In this context, pumped storage power stations, with their distinctive energy storage capabilities, have emerged as a pivotal element in the advancement of clean energy integration, optimisation of grid operations and enhancement of system flexibility [11,12]. Pumped storage power stations (Fig. 2) can be built in the middle of mountains and forests, symbolising mankind's relentless pursuit of energy use and environmental protection, and demonstrating the perfect combination of human wisdom and the power of nature. It improves the grid-connection efficiency of intermittent renewable energy sources such as wind power and photovoltaic power, and significantly increases the utilisation rate of clean energy [13,14]. Furthermore, they reduce energy wastage due to the mismatch between supply and demand. The application of pumped storage power stations can also reduce the dependence on traditional fossil energy sources. This is particularly the case during peak hours of power demand, whereby they can be deployed to replace coal-fired and gas-fired power generation. It is estimated that the carbon reduction achieved by a pumped storage power station project with an installed capacity of 1,200 MW will be 97,407 t CO_2. This figure represents the total carbon reduction achieved by the project over the course of a year [15]. Consequently, the advancement of pumped storage power stations represents not only a manifestation of technological innovation but also a pivotal measure in the global response to climate change and the trajectory towards sustainable development [16-18].

Fig. 1. Glacier melting due to climate warming

Fig. 2. Pumped storage power station

2. INTRODUCTION TO PUMPED STORAGE POWER STATIONS

The milestone of the first pumped storage power station, the Neitra power station in Switzerland, has spanned more than a century since it was founded in 1882 at the end of the 19th century, witnessing the budding and initial development of technology in this field [19,20]. Thereafter, the construction of pumped storage power stations entered a slow phase of development, during which they were relatively small in size and simple in technology. Until about 70 years later, with the double drive of science and technology and energy demand, the construction of pumped storage power stations is experiencing an unprecedented rapid development phase, this trend is significantly reflected in the global scope, especially in the United States [21,22], Western Europe, Japan and other developed economies, due to the sharp rise in demand for electric power and the expansion of the load gap between the peaks and valleys, pumped storage power stations by virtue of its excellent peak-fill capacity to obtain a wide range of Application. Technology iteration is particularly rapid at this stage, from the initial four-machine combination (covering turbine, generator, pump and motor) gradually streamlined to three-machine (integrating turbine, power generation-motor and pump functions), and ultimately evolved into a more efficient two-machine reversible pump-turbine unit.

As the 21st century commenced, the global green transformation gathered pace, accompanied by the large-scale construction of renewable energy sources such as wind and solar energy (Fig. 3), and the wide application of ultra-high-voltage transmission technology. These developments served to reinforce the strategic value of pumped storage power stations. The scope of its functionality has expanded beyond the traditional roles of peak shifting and frequency regulation. It has become a pivotal component of the emerging energy storage system 22], offering indispensable flexibility and security enhancements to the power grid. In light of these developments, the construction of pumped storage power stations in China has accelerated considerably. China has become a global leader in the field of pumped storage power stations thanks to a combination of technological innovation and the accumulation of practical experience. The country has not only mastered the cutting-edge technology of pumped storage power station design, manufacturing and operation and maintenance, but has also established itself as a world-leader in this field. China currently leads the world in terms of both the number and quality of pumped storage power station projects that have been either operational or under construction. This has contributed to the optimisation of the global energy structure and the realisation of carbon neutrality. In terms of installed capacity, Hongping Power Station in Jiangxi (Fig. 4), China, is one of the largest pumped storage power stations in the world, with a total installed capacity of 2.4 million kilowatts.

Fig. 3. large-scale construction of solar energy facilities

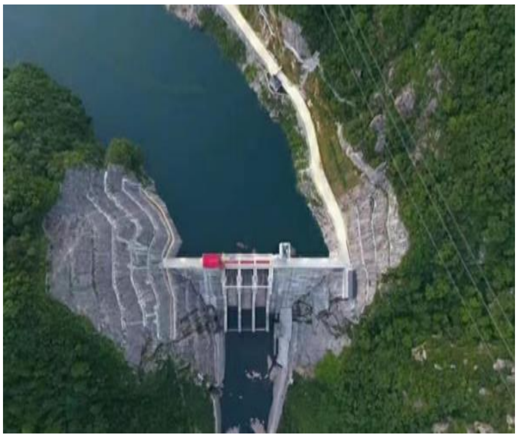

Fig. 4. Hongping pumped storage power station

With the future progress of science and technology, the application scope of pumped storage power stations will be further broadened, not only to continue to play a key role in the field of power system peak shifting and frequency regulation and energy storage, but also to actively explore diversified application scenarios such as seawater desalination, agricultural irrigation, urban water supply and so on, and to contribute to the global energy transition and sustainable development.

3. CONVENTIONAL CONSTRUCTION TECHNIQUES FOR PUMPED STORAGE POWER STATIONS

The underground engineering system of the pumped storage power station is of considerable scale, encompassing a multitude of caverns of varying dimensions. This inherent complexity gives rise to rigorous construction requirements, necessitating not only the deployment of a diverse array of heavy construction machinery but also the collaboration of personnel with specialized expertise in multiple domains [23].

In the traditional construction of pumped storage power stations, the principal mechanical equipment employed includes hand drills, frame drills, down-hole drills (Fig. 5), multi-arm carts (Fig. 6), climbing tanks, reverse well drilling rigs [24], disk saws, and so forth. The utilisation of manpower-assisted drilling and blasting technology, in conjunction with down-hole drills or hand drills, facilitates the slanting hole operation, thereby achieving the desired effect of ladder section blasting. In the excavation of horizontal holes, such as those required for traffic, ventilation, construction support, water diversion and tailwater tunnels, a combination of drilling rig carts and hand air drills is typically employed to facilitate precise drilling. In the excavation of water diversion inclined shafts or vertical shafts, the reverse shaft excavation technique is employed. In the context of anchor spraying support operations, the installation of anchor rods and grouting is a process that is overly dependent on manual operation, which in turn requires a significant input of manpower. In the context of grouting operations pertaining to water conveyance systems, the erection of scaffolding for the construction of grouting platforms is a manual process, as is the movement of these platforms.

The benefits of this range of construction methods lie in their extensive applicability to diverse rock strata types and their operational versatility. However, traditional construction methods for pumped storage power stations often face many challenges and drawbacks, most notably long construction periods, high environmental impacts and high costs. Conventional methods often require large amounts of manpower and resources for earthmoving, dam building, and construction of the water conveyance system, which are not only time-consuming and labour-intensive, but can also cause irreversible damage to the surrounding natural environment, such as destruction of vegetation and soil erosion. This reflects the relative lack of mechanisation in the traditional construction of pumped storage power stations. In addition, due to technical constraints and schedule pressures, it is often difficult for traditional construction methods to achieve optimal resource allocation and efficiency improvement, resulting in high overall costs [25,26].

Fig. 5. down-hole drill

Fig. 6. multi-arm cart

4. PUMPED STORAGE POWER STATION MECHANIZATION INTELLIGENT CONSTRUCTION TRANSFORMATION

The traditional construction mode of pumped storage power stations presents a number of challenges, including a low degree of mechanisation, an intensive manpower demand, a heavy cost burden, a high safety risk and a complex construction process. The rapid advancement of science and technology, coupled with the growing emphasis on efficiency and quality in engineering projects, has led to a notable acceleration in the mechanisation process in the field of pumped storage power station construction. This has been accompanied by the introduction of a plethora of sophisticated machinery and equipment. Among these, the full-section rock tunnel boring machine (TBM), which has been specifically designed for use in large-scale tunnel projects, shows considerable potential for application in the construction of traffic holes, ventilation system chambers, drainage passages, and inclined shaft sections of pumped storage power stations, among other contexts. The TBM's comprehensive ability to integrate the functions of excavation, slag removal, and instantaneous support, among others, has significantly accelerated the process of tunnel boring [27,28]. The construction efficiency of the TBM (Fig. 7) can be increased by a factor of three to four in comparison to the traditional drilling and blasting method, which represents a significant qualitative improvement in the overall construction progress of the pumped storage power station.

Fig. 7. Full-section rock tunnel boring machine

To date, there have been nearly one hundred instances of underground cavern construction utilising TBM equipment for pumped storage applications. As early as the 1960s, the world's first inclined shaft TBM, manufactured by WIRTH, was successfully deployed in the Corbes-LeChâtelard pressure inclined shaft project of the Emosson power station in Switzerland. The inclined shaft of the Shimogo pumped storage power station in Japan has a length of 485 metres, an inclination angle of 37 degrees, and was constructed using a TBM with a diameter of 3. The average depth of the excavation is 106 metres per month. The Katsunokawa Power Station in Japan features two distinct designs: an upper inclined shaft with a total length of 167 metres and a gradient of 48° and a lower inclined shaft with a total length of 768 metres and a gradient of 52.5°.The Parbati project in India comprises a sloping section of 1,500 metres with a gentler slope of 22 degrees, while the Innertkirchen project in Switzerland encompasses a sloping section of 1,015 metres with a slope of 35 degrees.

As the number of TBM applications in pumped storage projects continues to grow, researchers have come to recognise that the key to ensuring the safety and efficiency of TBM construction lies in its capacity to rapidly capture and effectively process vast quantities of data during excavation operations. This enables the realisation of science-based decision support. In essence, the TBM is actively integrating information technology and intelligent technology at the vanguard of innovation, with the objective of optimising construction efficiency, enhancing engineering quality assurance and ensuring construction safety. The implementation of an on-site vibration speed monitoring strategy provides crucial data for the deformation monitoring of neighbouring structures and the design of protective measures during the TBM tunnel boring process, exemplifying the utility of construction vibration management. In light of the difficulties posed by the prediction of complex geological formations, the optimisation of tunnel support strategies and the adjustment of tunneling parameters to suit specific strata, researchers have devised a technical blueprint for an intelligent TBM tunneling system. This has been successfully transformed into a technical system for practical application. Nevertheless, further investigation and technological advancement are required in pivotal areas, such as the development of efficient cooperative control mechanisms between multiple systems and the creation of intelligent decision-making algorithms for support strategies [29].

5. PROBLEMS ENCOUNTERED DURING THE CONSTRUCTION OF PUMPED STORAGE POWER STATIONS USING TBMS

5.1 High Construction Costs and Difficulties in Promoting Large Sets of Excavation Equipment

Although TBMs have demonstrated considerable advantages in the context of pumped storage engineering, including superior construction efficiency, notable enhancements to the operational environment, a highly developed mechanisation level and a significant reduction in the need for human resources, their high cost has emerged as a crucial consideration. Furthermore, the drilling and blasting construction system employed in pumped storage power stations for an extended period has reached a considerable degree of maturity and stability. This prevailing status quo constrains the extensive application of TBMs to a certain extent.

5.2 Poor Mechanization Universality

The intricate subterranean engineering system of a pumped storage power station comprises a multitude of tunnel structures, exhibiting notable discrepancies in section dimensions, length, inclination angle and geological context. However, the predominant focus of TBM construction technology on the excavation of single-diameter or slope tunnels inevitably results in constraints in addressing the diverse characteristics of tunnels. It is therefore essential to adapt the design of the TBM to the specific characteristics of each tunnel in order to ensure its optimal applicability and efficiency. This approach allows the TBM to accurately match and efficiently complete the task of tunnelling in a range of tunnel types.

5.3 Tbm Inclined Shaft Section Fall Prevention and Slag Discharge Difficulties

The fundamental operational mechanism of pumped storage power stations is the utilisation of the difference in water level to facilitate energy storage and conversion. This defining characteristic determines that the inclination

Fig. 8. Difficulty in discharging slag

Fig. 9. Scene of rock burst

angle of the inclined shaft section is typically set at a value exceeding 30°. The design of such a large inclination angle presents more rigorous technical challenges to the support and stabilisation system of the equipment, particularly the boot support device. Furthermore, although the TBM employed in inclined shaft boring can leverage the gravitational force of the slag to facilitate its discharge, the length of the inclined shaft section is frequently more substantial in pumped storage power station projects. This necessitates the implementation of a continuous and long-distance slag discharge operation (Fig. 8), thereby augmenting the construction complexity and difficulty [30,31].

5.4 Difficulty in Preventing and Controlling Rock Explosion Disasters

In comparison to the drilling and blasting method, the TBM construction method may be more prone to the occurrence of rock explosions under specific geological circumstances (Fig. 9) [32]. At present, microseismic detection technology is the predominant method employed in TBM construction projects. Despite its extensive range of applications, it is not without limitations when it comes to predicting the risk of rock explosions. In particular, the interpretation of microseismic data is frequently constrained by the subjectivity of artificial eigenvalue extraction, which may result in a lack of comprehension of the underlying correlation between microseismic activity and rockbursts. Furthermore, the current system for assessing the efficacy of rock explosion prevention and control measures is incomplete, and there is a dearth of systematic effect evaluation methods. This ultimately impairs the ability to control the accuracy of prevention and control strategies.

6. CONCLUSION

Pumped storage power stations, as a key infrastructure for clean energy storage and conversion, are actively promoting the reduction of fossil energy dependence, leading the energy system to a low-carbon, environmentally friendly transition path, and are of great significance in accelerating the realization of the goal of carbon neutrality.

As the scale of construction for pumped storage power stations continues to expand and the engineering complexity increases, TBMs are becoming increasingly important due to their high degree of construction mechanisation, excellent boring efficiency, low environmental impact and high-quality tunnel forming quality. It is therefore anticipated that TBMs will become the dominant force in the field of underground cavern construction for pumped storage power stations. As artificial intelligence and automation technology become increasingly integrated, the potential of TBMs will be further realised. The introduction of an intelligent control system will greatly enhance operational efficiency and precision, while reducing the risk of human operation and establishing a robust safety and stability barrier.

Nevertheless, the utilisation of TBM technology in the construction of pumped storage power stations is not without its own set of challenges. These include the high cost of equipment, the limited number of scenarios for which it can be applied, and the difficulties encountered in the construction of inclined shaft sections. In the future, our research will concentrate on the specialised areas of modularisation, standardisation and intelligent design of pumped storage underground caverns and TBM equipment, with the aim of facilitating the widespread application of TBM in the construction of pumped storage power stations.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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