Analysis of Technical Specifications and Application of Pumped-Storage Hydro Power

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Abstract: As an important form of hydroelectric energy storage, pumped storage plays a crucial role in balancing grid demand and promoting renewable energy integration. Its energy density and efficiency are significant indicators for measuring project effectiveness, yet these values are often lower than theoretical expectations due to various influencing factors. Nonetheless, through optimized management and technological upgrades, the energy utilization rate and lifespan of pumped storage power stations can be significantly improved. The application practices in China and the United States in the field of pumped storage indicate that this technology possesses long-term stability and high efficiency, which is of great significance for the sustainable development of power systems. The construction of pumped storage power stations requires thorough consideration of geographical elevation differences and reservoir capacity to achieve optimal energy storage performance. At the same time, the lifespan management and maintenance of facilities are equally important, especially in the inspection and replacement of critical components such as turbine rotor blades. Through regular maintenance and interventions, the service life of power stations can be extended, enhancing their economic benefits and performance. In the future, with technological advancements and experience accumulation, the energy density, efficiency, and lifespan of pumped storage power stations are expected to be further improved. Simultaneously, it is necessary to strengthen research and assessment of their environmental impacts to ensure they play a greater role in sustainable development. In conclusion, pumped storage is an efficient, reliable, and environmentally friendly energy storage technology, deserving wider application and in-depth research in power systems.

1 INTRODUCTION

Pumped Storage Hydroelectricity (PSH) or Pumped Storage Hydroelectric Power Stations (PHES) is a crucial form of hydroelectric energy storage for balancing grid demand (Rehman et al, 2015). As the largest-scale energy storage technology currently available, PSH holds a pivotal position in power systems due to its clean and pollution-free nature. It not only excels in peak shaving, frequency and phase modulation, and spinning reserve, but also plays a key role in optimizing the utilization efficiency of new energy in power systems, thereby enhancing the overall benefits of power generation. PHES, as a special type of hydropower station, stores energy by pumping water from a lower to a higher elevation using pumps, and releases this energy to generate electricity during peak power demand. When the grid load is low, it converts excess electric energy into water potential energy for storage; during peak load periods, this potential energy is converted back into electric energy to supply the grid, effectively storing and redistributing electricity over time. This process effectively regulates the dynamic balance between energy production, supply, and consumption, making it the most mature, reliable, economical, largest-capacity, and longest-lifespan energy storage solution in current power systems.

As the largest and most widely distributed energy storage method, PSH plays a crucial role in enhancing grid reliability, improving energy security, and promoting the integration of renewable energy. Its ability to efficiently store and regenerate energy makes it a crucial component in the transition to a

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more sustainable energy mix, helping to mitigate volatility and ensure the stability of grids heavily dependent on intermittent renewable energy sources such as wind and solar (Erixno et al, 2022).

The history of PSH development dates back to the late 19th century, when the world's first PSH was built in Switzerland. In the 1960s to 1980s, with the growth of energy demand and the development of the power industry, PSH construction entered a golden period of booming development, especially in developed countries and regions such as the United States, Western Europe, and Japan. However, after entering the 21st century, with the slowdown in economic growth and the rise of new energy sources, the development of PSH stations has slowed down somewhat. In recent years, however, with the adjustment of global energy structures and the demand for clean and low-carbon transitions, PSH stations have regained attention due to their unique flexible regulation characteristics, becoming an important means to ensure the stability of new energy generation and ushering in new development opportunities.

This paper investigates several technical indicators of PSH and identifies a lack of effective recording of energy density in PSH projects. It proposes suggestions to improve the construction cost and efficiency of PSH facilities, demonstrating the superiority of PSH as a well-tested energy storage method. Through quantitative analysis of PSH technology indicators (energy density, energy efficiency, equipment service life), analysis of practical cases in China and the United States, and comparison of actual data with theoretically calculated data, this paper conducts research on PSH technology.

2 THE OPERATING PRINCIPLE AND TECHNICAL INDICATORS OF PUMPED STORAGE

2.1 The Operating Principle and Components of Pumped Storage

The pumped storage system consists of two reservoirs at different elevations. When water flows from one reservoir to another (water discharge), it passes through turbines to generate electricity, converting its stored gravitational potential energy into electrical energy to meet corresponding power demands (Emmanouil et al, 2021). During periods of high electricity demand, when both electricity prices and demand are high, the stored water is released and converted into electricity through turbines (Hossain et al, 2020, Kucukali, 2014, Zhang et al, 2022)This process allows for a rapid response to fluctuations in energy demand and supply, making it a valuable tool for managing grid stability.

A typical pumped storage system includes the following components: upstream and downstream reservoirs (some projects may choose multi-level reservoirs), an upper reservoir which is usually a reservoir at a higher elevation or an artificially constructed water storage tank used to store pumped water during low grid load periods for power generation during peak load periods; and a lower reservoir, typically a river, lake, or sea area at a lower elevation, serving as a source of water for power generation and also meeting the need for water during pumping. The system also includes pump units for pumping water from the downstream reservoir to the upstream reservoir, large generator sets for power generation at the upstream reservoir, and turbine units for converting gravitational potential energy into mechanical energy. The mechanical energy is then converted into electrical energy through hydraulic turbines pushing generator blades. Additionally, the system may include structures such as flood gates and gratings to ensure safe and stable operation.

2.2 Types of Pumped Storage Hydroelectric (PSH) Systems

Research on the distribution characteristics of MPs usually covers several dimensions such as polymer type, size, abundance, and color. Most studies show that MPs in mangrove ecosystem sediments are mainly polyethylene (PE) and polypropylene (PP). In the mangroves of Sanya, Hainan, the main polymers are PP (42.10%) and PET (37.14%). In Colombia, PS is the main polymer, while in Guangdong, China and Singapore, PE and PP are the predominant polymers. The primary reason for the differences in polymer types is the variation in plastic elements . In Sanya, Hainan, the extensive use of textile fiber for fishing has resulted to a high local PET content. Regarding size, more than half of the MPs in Sanya, Hainan are large-sized MPs (1–5 mm), while more than 90% of the MPs in Singapore’s mangroves are less than 1mm9. The main reasons for this difference are differences in seawater flow and ocean current patterns in Sanya, as well as the substantial amount of plastic debris from local tourism that has not been degraded in time. In terms of abundance, the abundance of MPs in Sanya, Hainan is 67–228 items/kg, higher than 12.0–62.7 items/kg in Singapore. The interception effect of artificial forests is superior than that of natural forests, which is one of the reasons for the higher abundance in Sanya. In terms of color, white (transparent) MPs accounts for the largest proportion in global mangrove research, and in Sanya, Hainan, this proportion is as high as 89.04%. This is related to the large use of white plastic products and the fading of MPs during the diffusion process.

2.3 Technical Indicators and Calculation Formulas

2.3.1 Energy Density

Energy density refers to the amount of energy stored within a given volume or mass of a substance, commonly used to measure the energy contained in a unit volume or unit mass of a material. In the context of pumped storage hydropower, energy density, under an ideal model that neglects frictional resistance and various energy losses associated with Bernoulli's equation, can be simply understood as the total gravitational potential energy possessed by the upper reservoir divided by its total volume. However, in practical engineering applications, due to inevitable losses, the actual energy density will be significantly lower than the theoretically calculated value.

To calculate the energy density of a pumped storage hydropower plant, this study first needs to determine the hydropower potential P(W) and the corresponding reservoir volume V. Based on the given formulas and tabular data, the following calculations can be performed.

Firstly, this study assumes that H1 and H2 are transformed into a low-head pumped storage hydropower system (LCHES), where H1 represents the upper reservoir and H2 represents the lower reservoir. This study will utilize the data from H1 to calculate the energy density, as it possesses regulating capacity and a larger reservoir volume (Zhang et al, 2022).From Table1, the paper acquires the following data: Forebay water level range: [691 m, 745 m] Regulating reservoir Volume: $V = 20.37 \times 108\ m^3$ Installed capacity: 1040 MW

To simplify the calculations, this study selects an average flow rate Q, which is typically determined based on actual flow data or design flow. In this instance, a hypothetical value of $Q = 10000\ m^3/s$ is used, as it closely approximates the average flow rate of a large hydropower station in the western region of China.

Subsequently, this paper employs Equation (1) to calculate P(W)：

$$P(W) = Q \times H \times g \times \eta \times \rho \qquad (1)$$

Here， $g = 9.81\ m/s^2$， $\eta = 0.8$（80% efficiency）， $\rho = 1000\ kg/m^3$，Q represents the average runoff, and H denotes the head difference between the upper and lower reservoirs, which is simplified as their height difference.

$$P(W) = 10000\ m^3/s \times 54\ m \times 9.81\ m/s^2 \times 0.8 \times 1000\ kg/m^3$$

$$P(W) = 42{,}391{,}20000\ W = 4239.12\ MW$$

Now, this paper utilizes Equation (2) to calculate the energy density P：

$$P = \frac{P（W）}{V} \qquad (2)$$

$$P = 0.0208\ W/m^3$$

It should be noted that this is a simplified calculation based on the average flow rate Q and known data. In practical applications, the flow rate Q typically needs to be determined based on actual measurements or design data. Additionally, this calculation assumes that all energy can be effectively stored and converted, but in reality, due to various losses such as friction and leakage, the actual efficiency will be lower than the theoretical value.

Table 1. Basic characteristics of the cascade hydropower stations.

Hydropower Station	Regulation ability	Forebay water level range	Regulating reservoir Volume	Installed capacity
H1	Multi-year	[691 m, 745 m]	$20.37 \times 10^8\ m^3$	1040 MW
H2	Daily	[580 m, 585 m]	$0.31 \times 10^8\ m^3$	558 MW
H3	Daily	[483 m, 490 m]	$1.44 \times 10^8\ m^3$	880 MW

2.3.2 Energy Efficiency

During the pumping phase, the sequence of energy conversion is from electrical energy to mechanical energy and then to gravitational potential energy. In the generation phase, the sequence is reversed, with gravitational potential energy converted into mechanical energy and ultimately into electrical energy. During this stage, water from the upper reservoir passes through the pump-turbine to generate mechanical energy, driving the generator to produce power that is supplied to the grid. Conversely, during the pumping phase, electrical power from the grid drives an electric motor, converting it back to mechanical energy, which is used to pump water from the lower reservoir back to the upper reservoir for storage, via various systems.

Generally, the overall efficiency of the power station and the combined efficiency of the unit can be calculated using Equations (3) and (4), respectively:

Overall efficiency：

$$A=\frac{\text{On - grid energy}}{\text{Off - grid energy}}\times 100\% \qquad (3)$$

Comprehensive efficiency：

$$B=\frac{\text{Unit capacity}}{\text{Unit pumping water}}\times 100\% \qquad (4)$$

Taking an energy storage power station in China as an example, the actual electricity that the unit should generate is 1304.37 million kWh, and the electricity that the power station should deliver to the grid is 1,292.47 million kWh (Liu et al, 2023). Therefore, the actual combined efficiency of the unit (ηg) is 83.60%, and the actual overall efficiency of the power station (ηS) is 82.1%. As a result, when the conversion efficiency is only 75%-80%, the energy can typically be increased to over 80%.

2.3.3 Estimated Durability

During quantitative analysis, factors highly correlated with human intervention should be disregarded. Based on this principle, the service life of a typical pumped storage hydropower station (PSHs) primarily depends on two factors: the service life of the hydraulic turbine and the durability of the generator set. Since this project is also based on a hydraulic turbine, the calculation of the expected life of the turbine is equivalent to the service life of the pumped storage hydropower station. Considering a turbine rotor blade with an angular crack, the crack propagates along the interface between the blade and the crown, originating from the outlet edge of the blade's pressure side. Table 2 provides relevant technical parameters of the turbine rotor, and Table 3 presents the initial data for this evaluation.

Table 2. Related factors of the turbine

Parameter	Output, MW	Flow rate, m^3/s	Net head, m	Rotational speed, rpm	Runner diameter, m	Z_b, pcs	Z_g, pcs	Fr, hz	f_{Rst}, hz
R1	240	254	96	125	5.5	14	24	2.08	50
R2	255	285	100	125	5.58	15	24	2.08	50
R3	245	315	86	125	5.5	16	20	2.08	41.7

Under the influence of high-frequency loads, the point at which the crack begins to propagate rapidly corresponds to a crack length of 44.4 mm. The critical crack length, indicating imminent failure of the rotor blade, is 87.3 mm.

In this example, the allowable increase in crack length from the onset of rapid crack growth to the point of blade failure is approximately 42.9 mm. This equates to approximately 9.33 × 108 loading cycles at the RSI frequency, or approximately 6230 hours (roughly one year) of operational time. In contrast, under the influence of low-frequency loads, it takes approximately 71,000 hours (about ten years) for the crack to grow from its initial defect size of 3 mm to 44.4 mm. Notably, until the crack reaches a length of 44.4 mm, its growth is gradual, allowing for detection and repair during scheduled maintenance intervals (Georgievskaia, 2019). In summary, the lifespan of a PSH system without any maintenance should be at least 10 years.

Table 3. Initial data for the assessment

Parameter	Value
Kth, MPa·√m	2
KC, MPa·√m	80
Static stress value at design point without crack, MPa	150
Amplitude of dynamic stress intensity at design point without crack, MPa	9.1
Residual stress, MPa	100

3 ACTUAL APPLICATION IN CHINA AND US

3.1 Actual Application in China

Based on its energy storage principle, the energy storage capacity of pumped storage hydropower (PSH) is primarily proportional to the height difference and reservoir capacity between the two reservoirs. Due to the relatively minimal losses from water evaporation or infiltration, PSH systems exhibit a wide range of energy storage periods, ranging from a few hours to several years. Considering additional mechanical and transmission losses, the round-trip efficiency of PSH systems lies between 70% and 80%, and the expected service life is approximately 40 to 60 years, depending on the scale and design of each PSH plant (Qiang et al, 2023).

When comparing comprehensive nationwide statistical data with theoretical calculations, it was found that energy density varies among reservoirs and is often unrecorded in most projects. However, in terms of energy efficiency, the theoretical calculations closely align with actual conditions, demonstrating the simplicity yet effectiveness of the formula. In China, the actual expected lifespan of PSH systems exceeds 40 years. As mentioned in the previous chapter, this formula overlooks all human intervention factors. The ideal calculation represents only the minimum lifespan of a PSH system.

This implies that while the formula provides a basic, theoretical estimate of lifespan, the actual lifespan may be longer due to positive impacts from factors such as human intervention and maintenance. Therefore, in practical applications, regular maintenance and inspections can further extend the service life of PSH systems.

3.2 Actual Application in the US

The Taum Sauk Pumped Storage Hydropower Station, located in Missouri, USA, is a high-head pumped storage power plant constructed in 1963 with a capacity of 350 MW. In 1995, the station underwent an upgrade and retrofit to enhance its performance and efficiency. The objective of the retrofit was to significantly improve the plant's operational efficiency and reduce the time required from cold start to full load operation (Du, 2004).

To achieve these objectives, the design team enhanced the capabilities of the turbines and pumps without replacing the generators. During the retrofit, the team evaluated various rotor designs and ultimately selected a solution that effectively addressed leakage issues. Additionally, updates to the rotor's blade and structural design significantly improved the turbine's hydraulic performance and extended the expected service life. These improvements not only increased the plant's output by 90 MW, but also achieved a cost significantly lower than installing new gas-fired generators. Post-retrofit, the plant experienced significant improvements in operational frequency and efficiency, maintaining a high availability and successful start-up rate for several years (Du, 2004).

Concurrently, the retrofit of the Taum Sauk Pumped Storage Hydropower Station underscores the importance of technological upgrades and retrofits for PSH (pumped storage hydropower) systems. By updating equipment and technology, PSH systems can extend their service life, improve energy efficiency, and increase energy density, thereby enhancing their economic benefits and application potential in the renewable energy sector. Although US projects may lag behind in efficiency compared to Chinese PSH projects, the retrofit case of Taum Sauk provides valuable experience and insights for the development of PSH systems.

The retrofit case of the Taum Sauk Pumped Storage Hydropower Station exemplifies the crucial role of technological upgrades and retrofits in enhancing the performance and energy efficiency of PSH systems. By improving equipment and technology, the station has achieved efficient and reliable operation, providing valuable reference for the development of PSH systems. While PSH systems may have lower energy density compared to other energy storage methods, continuous technological innovation and optimization will ensure that PSH systems continue to play a significant role in the renewable energy sector.

4 SUGGESTIONS FOR THE FUTURE DEVELOPMENT OF PUMPED STORAGE HYDROELECTRICITY

During the research process, the author believes that pumped storage hydropower primarily faces issues such as low energy density, relatively large energy losses during conversion, slow conversion speed, and sluggish response. The proposed solutions are as follows:

(1) In future engineering applications, pumped storage hydropower can select geographical locations

with a greater relative elevation difference for planning. In regions with abundant water resources but difficult to construct, such as karst landscapes, it is possible to explore the utilization of naturally existing water bodies to build open-type pumped storage hydropower systems. The parallel connection of more generator sets can significantly enhance energy storage density.

(2) Pumped storage hydropower can be integrated with a wide range of renewable energy systems to build a comprehensive green energy system. Green energy sources such as hydropower, wind power, and solar power all exhibit significant diurnal and annual fluctuations. As a well-tested energy storage technology, pumped storage hydropower can store excess energy produced during high-production seasons of these technologies. As an essential energy storage facility in the power system, pumped storage hydropower plants play a crucial role in peak shaving, valley filling, and optimizing resource allocation. Improving their energy conversion efficiency is crucial, as it directly affects the economic and environmental performance of the power stations. To address this issue, the introduction of more efficient turbines and generator sets is the most significant solution, while more rational hydraulic design can also contribute to reducing energy losses to a certain extent.

(3) Additionally, pumped storage hydropower plants require higher flexibility and response speed. To achieve this, the introduction of intelligent monitoring and automated control systems becomes essential. These systems can monitor the real-time operating status of the power plants and automatically adjust operating strategies based on grid demand, ensuring the stability and reliability of power supply.

5 CONCLUSION

This study analyzes and calculates the theoretical calculation model of technical indicators related to pumped storage hydropower (PSH) technology and its practical applications in China and the United States. The typical energy conversion efficiency of PSH technology is approximately 80%, with an energy density mostly less than $1W/m^3$. The service life of its facilities is around 40 years, and with proper maintenance and upgrades, they can have an even longer lifespan. PSH technology is widely used due to its long facility lifespan, reliable operation, and relatively simple maintenance. However, its energy density and energy conversion efficiency are relatively low. Among the existing facilities in China and the United States, Chinese PSH facilities tend to have higher energy conversion efficiency due to their newer construction and the adoption of more efficient turbine units and generators. In terms of service life, many PSH units built in the early stages in the United States have reached their design life, but after mid-life extension and upgrades, they can continue to operate.

For the future application of PSH technology, it is necessary to select more suitable locations, which can be combined with the development of land consolidation technology in recent years. Building PSH facilities in regions such as karst landforms, where construction was difficult in the past but have significant topographic drops and abundant hydropower resources, can significantly increase energy density. At the same time, selectively replacing older turbine units and generators for some older PSH facilities and systemizing their maintenance work can result in higher facility lifespan and energy conversion efficiency.

This study fills the gap in the comparison of quantitative indicator data between related projects in China and the United States in PSH research, providing a reference for subsequent cross-country comparisons of similar energy storage technologies. This research will be beneficial for researchers in new energy and energy storage technologies who require quantitative calculation formulas and specific data for studying PSH. But this study focuses on providing relatively simple quantitative calculations, thus ignoring the influence of some hydraulic characteristics on turbine units, resulting in larger errors in the calculated energy density under small runoff or some extreme conditions. In subsequent research, more variables will be introduced to provide a more accurate calculation method or relevant correction coefficients.

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