Analysis and Prediction on the Development Potential of Pumped Storage Hydroelectricity in China in Ten Years (2022 - 2032)

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Abstract. Pumped Storage Hydroelectricity (PSH) is a very important method for energy storage. The cycle of water usage, starting with using excess energy, is of great significance for saving energy and improving social and economic benefits. This paper focuses on the analysis and prediction for the ten years' development potential of PSH in China. By analyzing the basic principles and computation methods to understand how PSH works. There are introductions and explanations of two huge PSH projects to determine the current advantages and suggest improvements. Based on China's current national conditions and geographical regions, PSH is suitable and being promoted to be developed, and it will help the country reach the objective of carbon peaking by 2030 and carbon neutrality by 2060. By comparing PSH to its potential competitor, Solid Gravity Energy Storage (SGES), the advantages of maturity and applicability of PSH in China allows PSH to be developed better. Therefore, the thesis evaluated the PSH's future development and concluded that this technology should be promoted in the future.

Keywords: Pumped Storage Hydroelectricity, Energy Storage, Sustainability

1. Introduction

In 2015, the United Nations formulated 17 global sustainable development goals, and countries around the world listed sustainable development as an important development for their countries in the future. In 2021, China adopted the 14th Five-Year Plan, and the National Energy Administration 2022 issued the "14th Five-Year Plan for Modern Energy System", which emphasized the importance of new energy development in the new power system, carbon neutrality. It is proposed that new energy generation will become the main power supply route of the power system. Greater volatility and instability are drawbacks of both solar and wind power. However, PSH plays an important role in the power grid system due to its large capacity and cleanliness [1].

Pumped-storage power plants have the characteristics of environmental friendliness, and their peak regulation, frequency regulation, and environmental improvement have a very strong role in the power grid [2]. Based on those features, this article will first describe the system principle, historical development, and future needs of pumped-storage power plants, analyze the current situation of foreign and Chinese pumped-storage power plants with examples, and combine the goals and objectives created by the 2030 carbon peak and 2060 carbon neutral statement. Influence, and analyze the development of PSH in the next ten years in the context of today's electricity market; finally, be optimistic about the development of PSH in China in the next ten years.

2. Overview of PSH

2.1. Working principles

PSH stations are allowed to store valuable electric power around the world. In some scenarios, the solar panel or wind turbine builds near pumped storage hydropower. During the day, the solar panel receives sunlight and generates electricity for people to use. Meanwhile, the excess energy from the solar panel or wind turbine will pump the water from lower elevation reservoirs to high elevations for storage purposes. During the nighttime, when there is peak electricity demand, the water stored in the high reservoir will be released through the Reversible Francis turbines in order to generate electricity for people to use [3].

The reason that made PSH a great sustainable energy storage form is the high accessibility of water. Unlike solar panels and wind turbines which are randomly affected by weather changes and periodically limited by diurnal variation, water is stored in the reservoir that can be accessed at any period of the day. PSH plants are able to deal with emergency situations, such as electricity blackouts and so on. Water is such an abundant resource on the earth. When water is stored in the reservoir, precipitation will balance the part of water evaporated to maintain a certain water level. Also, the lifetime of PSH plants is normally more than 40 years [3]. Therefore, there are advantages to the duration of energy storage, the flexibility of electricity supply, and high capacity. The general drawbacks of PSH technology are a long-term investment, long-period construction, and geographic restrictions.

2.2. Designing factors of PSH

It is easy to calculate the desired value for designing a PSH system by using several equations [4].

Engineers need to understand the computation process, which can help them to better understand the technology. First, use the energy equation to find the missing value in the system. p stands for the pressure, γ stands for the specific weight of water, which is in a standard 10-celsius degree situation, z stands for elevation, V stands for velocity, g stands for earth gravity, and stands for the pump and turbine head, and lastly the stands for the total head loss [4].

$$\frac{p_1}{\gamma} + z_1 + \frac{{v_1}^2}{2g} + h_p = \frac{p_2}{\gamma} + z_2 + \frac{{v_2}^2}{2g} + h_t + h_L \quad (1)$$

The flow rate Q could be calculated by using the velocity to multiply the cross-section area of the pipe [4].

$$Q = V \times A \quad (2)$$

Then calculate the mass flow rate by using water density and multiplying the flow rate Q [4].

$$\dot{m} = \rho \times Q \quad (3)$$

To find the total power that the turbine can generate, the formula uses the mass flow rate to multiply the earth's gravity which is 9.8 m/s, then times the net head loss and which is the system efficiency. Small hydropower will usually have around 85 % efficiency. The formula is demonstrated below [5].

$$P = \dot{m} \times g \times H_{netL} \times \eta \quad (4)$$

2.3. Head loss of PSH

The definition of Head loss is important to understand. Head loss really exists and must be considered by engineers and designers to design an accurate system. Head loss is caused by the friction resistance in the pipe system. When water either enters or exits the pipe, both processes may cause energy loss. Other factors include contraction or expansion, which means the pipe becomes larger or smaller. The larger or smaller pipe will cause different cross-section areas. Since the flow rate is the same throughout the pipe system, the velocity will change. A small cross-section area will

cause higher velocity, which is the opposite of the larger cross-section area pipe. Or when pipes have some bending or turns, all of these factors cause energy loss in the system [6].

3. The development and current status of PSH

The history of the Pump Storage Station started in 1882 in Zurich, Switzerland. After a few decades, Europe constructed a few small PSH plants. The first large PSH plant was completed in 1928, the Rocky River PSH plant in the US. This project first began using two separate pumps and a Francis turbine which can generate 24 MW of electricity [7]. Then in the mid of 19 century, the technology formed a shape that is the same as nowadays. The generator is on top, with the pump in the middle of the pipe and the turbine at the bottom. During this period, the PSH can generate about 59.5 MW of energy [8]. The development of technology provides the pump and turbine with more capacity to generate enormous energy.

At first, the traditional operation of PSH plants mainly focused on satisfying the load through the so-called coordination of water and heat. In recent years, China had large-scale development and utilization of emerging energy, and the configuration of PSH has gradually changed from a single focus on electricity load centers in the past. It has been developing to the power load center, energy base, sending end, and landing end.

3.1. Bath County Pumped Storage Station

The second largest hydro plant in the world is the Bath County Pumped Storage Station, located in Virginia. Bath County Pumped Storage Station generates power to supply approximately 750,000 homes [6]. During urgent situations or peak demand, workers opened the large valves in the powerhouse, which let the water flow down inside the pipe from the upper reservoir to generate enormous electricity. After that, the water flows into the lower reservoir for storage purposes in order to prepare for the next peak electricity demand. The maximum capacity of Bath County Pumped Storage Station is 3 million kW in less than 15 minutes with all six units online, which should deal with most of the situation [6]. Bath County Pumped Storage Station is not only a reliable electric generator power station but also their maximum effort was put into the creation of a green and sustainable environment for local species. For instance, the engineers monitored the water released from the storage station to guarantee the water quality, ensuring the health of aquatic species. Also, the 99 acres of the recreation area are used for managing the pollinators and building an ideal habitat for birds or small mammals. Besides, the area planted many trees and flowers, which helped combat climate change [6]. Therefore, if all the pumped storage stations could follow what Bath County Pumped Storage Station did, this technology could have a huge contribution to the global environment [6].

3.2. Hebei Fengning Pumped Storage Power Station

Currently, PSH is very widely used in China as an energy storage form. Fengning Pumped Storage Power Station is currently the largest PSH plant in China. The construction began in 2013. After 17 years of unremitting efforts, the Hebei Fengning Pumped Storage Power Station will be officially put into operation at the end of 2021. This is the largest pumped storage power station in the world [9].

The total installed capacity of the power station is 3.6 million kW, and it is developed in two phases, and the first phase has an installed capacity of 1.8 million kW. The upper reservoir of the power station has a storage capacity of 58 million cubic meters, and the lower reservoir has a capacity of 60.7 million cubic meters [10]. Once the power plant is finished, it will regulate the electricity grid between Beijing, Tianjin, and Tangshan. Fengning Pumped Storage Power Station has played a huge economic, social and environmental benefit after its completion [10]. At the same time, it has a better performance in absorbing cross-regional clean energy, which can better alleviate the energy problem in the northern region, and will be a powerful force in the future. Support the implementation of the "foreign power into Hebei" strategy [10,11].

Fengning Power Station has a huge storage capacity, which can store nearly 40 million kWh of new energy power at one time and can consume 8.7 billion kWh of new energy power in one year. High-intensity energy storage supports the safe and stable operation of the North China Power Grid, enhancing system regulation capabilities, quickly tracking new energy output, and playing a role in large-capacity energy storage [11]. Additionally, pumped hydro storage facilitates the grid integration of intermittent and seasonally variable renewable energy sources like wind and solar, making this technology the perfect complement to contemporary, clean energy systems. At the same time, this project can also serve carbon peaking and carbon neutrality well and plays a very important role in energy regulation.

For the disadvantages, firstly, the construction cost is high. It requires many infrastructures such as dams, pumping stations, power stations, and related pipelines, a lot of capital engineering, and a lot of maintenance [12]. As a large-scale water storage power generation project, this part will still be a very important difficulty for PSH cost operation in the future. Additionally, building the upper and lower reservoirs may change the original ecology to a certain extent and cause widespread flooding. Building artificial lakes or exploiting natural reservoirs have both significantly altered the living conditions of aquatic and land animals, upsetting the regional ecological balance. The problem of the system will be a problem that people need to pay attention to for a long time. The PSH facility is a large-scale energy storage project. If the local ecological environment cannot be well protected, it will easily cause soil erosion. In severe cases, it may cause flooding, which will affect the health of humans and nature's life safety [12].

3.3. Current PSH development in China

In general, China has more than 40 years of construction practice in PSH construction [13]. It is relatively experienced and advanced in the overall design and manufacture of the power station to the specific installation technology in the world. These experiences and technologies are conducive to reducing construction costs, thereby improving the competitiveness of power companies in the power market. Based on the existing conditions, China's current PSH development is in a positive stage [13,14].

4. Prediction of PSH Development in the next decade

It is difficult to make an accurate and exact prediction of the future development of PSH, including technology innovation and market share. Therefore, based on an analysis of national policies, features of PSH, and an analysis of another potential competitive technology, there is a general assumption that the development of PSH is encouraged and the market share of PSH will increase slightly or at least maintain the current ratio in the Chinese energy storage market in the next ten years. There are several factors that positively influence its present and future development.

Firstly, as mentioned, PSH is a long-history and well-developed energy storage form. It has a fast response time, high flexibility, high single-unit capacity, high energy efficiency, and ideal cost efficiency. Besides, PSH plants can effectively relieve the system peak regulation pressure, quickly stabilize the system frequency and phase modulation operation, and stabilize the system voltage. It is a backup power supply for power system accidents and can be used as the power grid black-start power supply and the first choice for large-scale energy regulation. In addition, PSH plants mostly have a long lifetime. According to EESI, the lifetime of PSH plants is around thirty to sixty years, which is relatively the highest compared with other current types of electricity storage forms [12]. Although the upfront investment and long construction period of PSH are criticized, considerable and ideal returns cannot be ignored. Meanwhile, the construction of the PSH plants is economically in line with the planned economy in China. Therefore, constructing PSH can be considered as one of the methods which are conducive to achieving the goals stated by Xi Jinping, President of the People's Republic of China, at the 75th Session of the United Nations General Assembly – "China will aim to

have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060." [15]. Afterward, there were policies and conferences that referred to advancing the development of PSH.

In the global response to climate change, China strives to achieve the goal of "emission peaking by 2030 and carbon neutrality by 2060". Consequently, there are policies supporting PSH development in China. For instance, the Outline of the People's Republic of China 14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives for 2035 states that it is required to accelerate the construction of PSH plants and the large-scale application of new energy storage technologies [16]. Additionally, in the ninth meeting of the Central Financial and Economic Affairs Commission, "build a new power system with new energy as the main body" was emphasized [17]. The plan and the objectives have made requirements in the policy. The direction of developing PSH was discussed at the conference. Soon afterward, on September 17, 2021, National Energy Administration announced a Medium- and Long-Term Development Plan for Pumped Hydro Storage (2021-2035). According to the plan, the installed capacity of PSH will reach at least 62 GW in 2025, and approx. 120 GW in 2030 [18] After the plans were announced and the meetings ended, the stocks of associated companies increased. PSH is currently in a trend with increasing concerns and investments in China, and the trend will last at least fifteen years.

Furthermore, there will be a possibility to see new technology showing in the energy storage market after ten years. In the traditional energy storage group, PSH is a typical and most common energy form from mechanical energy storage and gravitational potential energy storage. In this branch, there are two main types of storage forms, which are PSH and SGES. SGES can be considered as one of the potential competitors of PSH in the Chinese energy storage market in the next decade.

There are advantages of SGES, that PSH not includes. For instance, there is more flexibility in construction on location selection. PSH plants mostly require two reservoirs with high vertical terrestrial differences. The height of the vertical difference proportionally influences the energy transformation, from gravitational energy to kinetic energy, through the flow of water from the upper reservoir to the lower reservoir. For the SGES, it has much more advances in location selection. The company Energy Vault currently provides solutions for SGES plants, including EV1 and EVx plants. EV1 is a six-armed-crane-based SGES prototype. The EVx is more advanced, which illustrates the modular design and allows the utility scale of SGES plants to be more custom. Moreover, plants can be constructed close to the solar or wind power plants to reduce the energy loss during the transmission, and also, they can also be simply connected to the grid to improve dispatchability and grid stability [19]. Correspondingly, SGES plants do not need to be built in the natural environment, unlike PSH plants. They can mostly be built in industrial areas or suburban areas. Consequently, improving or reducing damage to the local ecosystem is beneficial. Because the area and space of the SGES plants are much smaller than that of the PSH plants, it hardly has any safety impacts on the residents living around. There is less worry about the potential harm caused by the shutdown of the power station.

Also, SGES has some advantages that PSH has as well, such as large storage capacity, high energy efficiency, long lifetime, and low cost of electricity [20]. Although there are multiple advantages of the SGES technology, several causes probably result in SGES not being competitive with PSH in the next decade. Firstly, SGES is not a completely mature technology. In the development of new technology. Financial support and long-term research are basic conditions. Correspondingly, large-scale applications of SGES and installations of plants usually require time to validate stability and security. Currently, there are no systematic supporting facilities, highly experienced builders, as well as skilled workers. It would be unrealistic to see large-scale installations of SGES plants on a large scale within ten years.

In addition, China has a long coastal line and many natural lakes. They are ideal conditions for selecting sites for PSH plants. Once minimizing the negative environmental impacts caused by PSH constructions, one of the most prominent advantages of SGES, the flexibility of site selection, is not particularly necessary. Compared with the high maturity of PSH, SGES is relatively young and highly

developable. Hence, in the Chinese market in the next decade, SGES will not have the potential to be competitive with PSH.

5. Conclusions

In conclusion, PSH is highly potential to be developed in China in the next decade. Based on the brief explanation of the working mechanisms of PSH, simple principles and long-term application make this technology very mature and stable. Introducing the representative schemes of PSH of different ages in two different regions helps to objectively understand the changes in the application and function of PSH plants, as well as the technical update of this technology. There is a lot of experience in the application of PSH in China. And both in terms of volume and environment, China is a country that is very suitable for large-scale use of PSH for energy storage. Meanwhile, many policies have given considerable support to the development of PSH in order to achieve the goal of "carbon peaking by 2030 and carbon neutrality by 2060". Therefore, based on these conditions, the development of PSH in China is at the right time and place in recent years and in the near future. Also, a comparison between the PSH and SGES was discussed, which showed the advances of PSH on its maturity adaptability in China. Therefore, the development of PSH in China within 10 years will be successful.

References

[1] Haiqing T, Jinhui G, Yu Z, et al. Regulation strategy for new energy participation in electricity trading based on cooperative game model [J/OL]. Modern Electric Power: 1-9 [2022] -09-26].

[2] Zhang Jianhui. Research on the boundary value of investment life based on generalized economic benefits of pumped storage power stations [J]. Journal of South-Central University for Nationalities (Natural Science Edition), 2022, 41(05): 636-640.

[3] How pumped storage hydropower works. (Energy.gov. (n.d.). Retrieved July 29, 2022, from https://www.energy.gov/eere/water/how-pumped-storage-hydropower-works)

[4] Elger D F, LeBret B A, Crowe C T, et al. Engineering fluid mechanics[M]. John Wiley & Sons, 2020.

[5] GE Renewable Energy. (n.d.). Pumped Hydro Storage. Pumped Storage. Retrieved August 13, 2022, from: https://www.ge.com/renewableenergy/hydro-power/hydro-pumped-storage

[6] Bath County Pumped Storage Station. Dominion Energy. (n.d.). Bath County Pumped Storage Station: Dominion Energy. Retrieved August 19, 2022, from: https://www.dominionenergy.com/projects-and-facilities/hydroelectric-power-facilities-and-projects/bath-county-pumped-storage-station

[7] Renewables First - The Hydro and Wind Company. (2017, November 14). How much hydropower power can I get - renewables first. Retrieved August 13, 2022, from https://www.renewablesfirst.co.uk/hydropower/hydropower-learning-centre/how-much-power-could-i-generate-from-a-hydro-turbine/

[8] Botterud, A., Levin, T., & V. Koritarov Argonne National Laboratory. (n.d.). Utility - scale energy storage to support higher penetration of variable renewable energy. Retrieved September 14, 2022, from https://ptfcar.org/wp-content/uploads/2019/11/01.IWE-USAID_PTF_Hirsch-3.pdf

[9] Fengning Pumped Storage Power Station [J]. Communist Party Member (Hebei), 2022(14):58.

[10] Weihua Y, Zezhong Z. From Gangnan to Fengning: Pumped Storage Power Station and Hebei [N]. Hebei Daily, 2022-05-12(011).

[11] Wantang Fei, Lijun Z, Rongda J, et al. Discussion on operation and maintenance mode of large-scale pumped storage power station in Fengning, Hebei [J]. Hydropower and Pumped Storage, 2020, 6(06):1-4.

[12] EESI. Fact sheet: Energy storage (2019) [EB/OL]. EESI, 2019. (2019). https://www.eesi.org/papers/view/energy-storage-2019.

[13] Kong Y , Kong Z , Liu Z , et al. Pumped storage power stations in China: The past, the present, and the future [J]. Renewable & Sustainable Energy Reviews, 2017, 71:720-731.

[14] Characteristics of China's Pumped Storage Power Stations and Prospects for Scenic Development [C]. 2008 Proceedings of China Hydropower Generation., 2008: 117-125.

[15] UN GAOR, 75th Sess., 4th plen. mtg., U.N. Doc A/75/PV.4 (Sept. 22, 2020)

[16] Xinhua News Agency. Outline of the People's Republic of China 14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives for 2035[EB/OL]. the State Council, the People's Republic of China, 2021-03-03. [2022-09-13]. http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm.

[17] Xinhua News Agency. Xi presided over the ninth meeting of the Central Financial and Economic Commission [EB/OL]. LI M. the State Council, the People's Republic of China, 2021-03-15. [2022-09-25]. http://www.gov.cn/xinwen/2021-03/15/content_5593154.htm.

[18] National Development and Reform Commission, NEA. Medium- and Long- Term Development Plan for Pumped Hydro Storage (2021-2035) Beijing, China: National Energy Administration, 2021: 6.

[19] Energy Vault. Solutions Gravity Energy Storage [EB/OL]. Transforming Utility Scale Gravity Energy Storage, n.d. [2022-09-25]. https://www.energyvault.com/gravity.

[20] Tong W, Lu Z, Chen W, et al. Solid gravity energy storage: A Review[J]. Journal of Energy Storage, 2022, 53.