Performance and economy analysis of distributed small-scale pumped storage power station

Wanting Liao¹, Yanchi Zhang¹, ⁴, Tian Ding¹, Jun Fang¹, Pengfei Ju¹, Da Xie² and Wenbo Zhao³

¹School of Electrical Engineering, Shanghai Dianji University, 201306 Shanghai, China
²School of Electrical Information and Electrical Engineering, Shanghai Jiaotong University, 200240 Shanghai, China
³State Grid Shanghai Jinshan Power Supply Company
⁴E-mail: zhangyc@sdju.edu.cn

Abstract. The installed capacity of clean energy represented by solar and wind power has increased by 77.5 times in the past 20 years. In 2019, it reached 1437GW, accounting for 35% of the total installed power generation capacity [1]. With large quantities of fluctuating renewable and new energy integrated, the power system has insufficient absorption capacity and needs more adjustable power sources. In this paper, the location limitation of centralized large-scale pumped storage power station (PSPS) is broken through and a distributed small-scale PSPS which can be widely constructed in load centers such as the east coast of China is proposed. Furthermore, the distributed small-scale PSPS is compared with large-scale PSPS and other kinds of energy storage technology in terms of installed capacity, discharge time, energy density, power density, life cycle, and per kilowatt hour (kWh) cost. The calculated results show that the energy density of distributed small-scale PSPS is about 10 times higher than that of large-scale PSPS, while the per kWh-cost of the two kinds of PSPS is close. In addition, the expected life cycle of distributed small-scale PSPS is higher than that of most energy storage technologies. For example, its life cycle is 4 times longer than that of battery-type storage. In conclusion, the performance and economy of distributed small-scale PSPS are both in the good level, so it has the potential to solve the problem of new energy consumption in China.

1. Introduction

Since the industrial Revolution, the extensive use of coal, oil and other fossil fuels, carbon dioxide emissions have increased year by year. According to the Global Energy Review 2021 released by the International Energy Agency (IEA), global energy demand will grow by 4.6% in 2021 and global energy-related CO₂ emissions will increase by 4.8% [2]. China, a major emitter of carbon dioxide, has announced a ‘3060’ planning about carbon issue to speed up its transition to green and low-carbon energy. This plan aims to peak carbon dioxide emissions by 2030 and become carbon neutral by 2060. This means that China, as the largest developing country in the world, will achieve the largest reduction in global carbon emissions and achieve carbon neutrality in the shortest time in the history of the world.

In order to meet the national carbon reduction targets, wind power, photovoltaic and other renewable energy will become the focus of China’s energy development. However, wind and solar energy are variable, so the power system needs a large amount of adjustable power. Energy storage with flat wave, peak regulation and other characteristics, is one of the best ways to solve the impact of new energy on...
the power grid. Pumped storage has a large capacity. China has built a number of large pumped storage power stations, such as Tianhuangping PSPS located in Zhejiang Province of China with an installed capacity of 1800MW, and Fengning PSPS located in Hebei Province of China with an installed capacity of 3600MW. According to Medium and Long Term Development Plan for Pumped Storage (2021-2035) released by the National Energy Administration, it is estimated that the pumped storage capacity will be put into operation in 2025 to more than 6200MW.

Researchers have done a lot of reports to expand the use of pumped storage power station. Reference [3] mentioned that RAG cooperated with Duisburg-Essen University to transform an abandoned coal mine into a 200MW PSPS in 2016. This research is a kind of reuse of existing space, but it is difficult to carry out widely due to the limitation of underground water storage technology. Reference [4] studied that the advantages of small and medium-scale PSPS in the construction and operation practice of East China, and shows that small and medium-scale PSPS will have a good prospect under a reasonable electricity price mechanism. Reference [5] studied that the operation mode of small and medium-scale PSPS. And it is concluded that small and medium-scale PSPS should adopt independent generator set management mode and two prices. The small and medium-scale PSPS mentioned in the above research are all megawatts. Although the site selection range is wider than that of large-scale PSPS over 1000MW, they still cannot be built in urban centers.

The distributed small-scale PSPS proposed in this paper can be widely built in the areas with rivers flowing, and the site selection restriction is low. It can cooperate with the grid for peak regulation, frequency regulation, with the economic operation of thermal power units.

2. Design and characteristics of distributed small-scale PSPS

2.1. Energy conversion process of large-scale PSPS

Figure 1 shows the energy conversion process of a PSPS. At night when the power consumption is low, the PSPS stores energy when there is a surplus of electricity generation. During daytime peak power consumption, in order to relieve the load pressure of the power system, the PSPS releases the water stored in the upper reservoir to generate electricity.

![Energy conversion process of PSPS](image)

**Figure 1.** Energy conversion process of PSPS.

2.2. Structure design of distributed small-scale PSPS

The design of distributed small-scale PSPS refers to the design idea of large-scale PSPS, and it carries out pumping and storage cycle through height drop. The structure of large-scale PSPS is shown in Figure 2(a). The distributed small-scale PSPS adopts steel tower structure, which is welded and assembled on the ground. When the shape of the steel tower conforms to the slope ratio of "123", the force on the tower can be uniform. The tower is built along the river or pool. The combined stainless steel water tank fixed at the top, as the upper reservoir of distributed small-scale PSPS. The structure is shown in Figure 2(b).
2.3. Characteristics of distributed small-scale PSPS

The power density (W/kg) generally refers to the rate at which the battery per unit quality can discharge energy. The power density of pumped storage (W/L) refers to the ratio between the total installed capacity of the pumped storage unit and the volume submerged when the reservoir of the power station is full. Energy density (Wh/kg) refers to the amount of energy stored per unit weight of the battery. The energy density of pumped storage (Wh/L) refers to the amount of energy stored per litre of water.

The formula for single discharge time of pumped storage power station is shown in Equation (1).

\[ h = \frac{V}{3600Q_m \cdot K_1} \]  

(1)

Where, \( h \) is the number of discharge hours; \( V \) is the capacity; \( Q_m \) is the water flow of pumping and storage unit; \( K_1 \) determined after considering working conditions, \( K_1=1 \).

The power generation formula of water turbine is shown in Equation (2).

\[ P = 9.81K_2HQ_m \]  

(2)

Where, \( K_2 \) is the energy conversion efficiency of hydraulic turbine, which is generally calculated as 0.97; \( H \) is the head height of pumped storage power station.

Power density calculation and energy density calculation formulas are shown in Equations (3) and (4).

\[
\begin{align*}
\text{Power density} &= \frac{\text{Total installed capacity}}{\text{The tank volume}} \\
\text{Energy density} &= \frac{\text{Power yield of single pumping storage}}{\text{The tank volume}}
\end{align*}
\]

(3)

(4)

The cost of distributed small-scale PSPS includes capacity cost and operation and maintenance cost. The capacity cost is the initial investment cost and is related to capacity, which is shown in Equations (5) and (6).

\[ C_E = \pi_k E_{\text{max}} \frac{(1 + r)Y_{\text{sto}} \cdot r}{(1 + r)Y_{\text{sto}} - 1} \]  

(5)

\[ E_{\text{max}} = P_{\text{max}} T_n \eta_{\text{pump}} \]  

(6)

Where, \( C_E \) is the apportioned annual value over the life cycle, \( \pi_k \) is the unit price of capacity; \( E_{\text{max}} \) is the maximum capacity; \( P_{\text{max}} \) is the maximum pumping power; \( T_n \) is the full pumping time; \( \eta_{\text{pump}} \) is the pumping efficiency; \( r \) is the discount rate, which is generally calculated as 9%; \( Y_{\text{sto}} \) is the lifetime.

The operation and maintenance costs are divided into fixed costs and variable costs, which is shown in Equation (7).
3. Performance and economy analysis of distributed small-scale PSPS

3.1. Comparison between distributed small-scale PSPS and large-scale PSPS

The performance and economy of the designed distributed small-scale PSPS are compared with those of a typical large-scale PSPS -- Tianhuangping PSPS, as shown in Table 1. Tianhuangping PSPS is the second largest PSPS in China, which has the installed capacity of 1800MW, the annual generating capacity of 3.16 billion kWh, the annual filling capacity of 4.286 billion kWh, and the annual generating time of 1755.6 hours. The station undertakes the task of peak cutting and valley filling of 3.6 million kW. The total cost of Tianhuangping PSPS is about ¥8 billion, excluding management costs [6]. According to the electricity price of Zhejiang Province, that is ¥0.4/kWh at the valley and ¥0.65/kWh at the peak, and the annual generating income of Tianhuangping PSPS is ¥340 million, which can be recouped by only generating electricity in about 23.5 years. The geographical location of Tianhuangping is shown in Figure 3.

![Figure 3. The geographical location of Tianhuangping PSPS.](image)

The parameters of the designed distributed small-scale PSPS are calculated as follows. Considering the bearing capacity of the water tower, it is expected to place a combined stainless steel water tank of 10m×10m×3m on the top of the tower. The tower is designed to be about 25m high. H110-WJ-42 vertical water turbine generator set with rated power of 50kW is selected, with the highest water head of 26m and the rated flow of 0.31m³/s. And it takes time from static to full discharge of the turbine is about 5 minutes, the 300L water is expected to be discharged in 17 minutes. It can be calculated from the formulas in Section 2.3 that the output capacity of single station is about 11.4kWh, the power density is 166.7W/L, and the energy density is 11.3Wh/L. The overall estimated construction cost is about ¥80,000, which can be recouped by only generating electricity in about 38.5 years.

The large-scale PSPS has low energy density, however its installed capacity is large and its service life is more than 80 years, so it will still be the main content of energy storage development of power system for a long time in the future. As can be know from Table 1 and Figure 4, the single installed capacity of distributed small-scale PSPS is far smaller than that of large-scale PSPS, but if a certain number of small-scale PSPSs are built, the pumping capacity may reach hundreds of millions of kWh.
Table 1. Comparison results of two kinds of PSPS [6].

|                       | Installed capacity | Energy density | Discharge time | Lifetime  | Return cycle |
|-----------------------|-------------------|----------------|----------------|-----------|--------------|
| Tianhuangping PSPS    | 1800MW            | 1.33Wh/L       | 4.81 hour/day  | about 80 years | 23.5 years   |
| Distributed small-scale PSPS | 50kW             | 11.3Wh/L       | 17 min/day     | about 50 years | 38.5 years   |

Figure 4. Performance radar diagram of Tianhuangping PSPS and distributed small PSPS.

In actual grid, multiple distributed small-scale PSPSs can be constructed to form PSPS cluster. The discharge time and discharge quantity of distributed small-scale PSPS cluster can be centrally controlled by the grid. The construction of distributed small-scale PSPS not only expands the installed capacity but also prolongates the discharge time.

According to the analysis in Table 1, the economy of the two kinds of PSPSs are low, their investment cost is high, and the return cycle is rather long, usually more than 20 years, which is restricting the development of PSPS. However, the economy brought by the PSPS cannot be simply evaluated by generating income, and its contribution to the stability of power system and the development of new energy is huge.

3.2. Comparison between distributed small-scale PSPS and various energy storage technologies

By comparing the parameters of various existing energy storage technologies, the feasibility analysis of distributed small-scale PSPS is shown in Table 2.

As can be seen from Table 2, the discharge time of distributed small-scale PSPS is minute level, and the calculated energy density and power density are 11.3Wh/L and 166.7W/L respectively. Its energy density is much higher than that of large-scale PSPS, while it is still smaller than that of batteries, which can reach hundreds of Wh/kg. The biggest advantage of distributed small-scale PSPS is its lifetime is about 50 years, far exceeding other types of energy storage. Its upfront investment cost is too high, while the cost per kilowatt cycle is low.

Meanwhile, since distributed small-scale PSPS can be widely built, the construction quantity is huge. If unified deployment can be made during peak/trough load, it will achieve the effect of not transferring megawatt level of energy storage. To sum up, the performance of distributed small-scale PSPS is at a good level. It can be used as energy or power based application according to different situations. Built on the power generation side, it can be used for load tracking to dynamically adjust the slowly changing...
continuous load to achieve real-time balance. Built on the grid side can be used to relieve line congestion, and built on the user side can reduce capacity cost management.

### Table 2. Performance comparison between distributed small-scale PSPS and various energy storage technologies [7, 8].

| Species                        | Installed capacity | Discharge time | Energy density | Power density | Life span (years) | Cost (Yuan/kWh Single cycle) |
|--------------------------------|--------------------|---------------|----------------|---------------|------------------|-----------------------------|
| Large pumped storage           | 100MW-5000MW       | 1-24 hours    | 0.5-1.5 Wh/L   | \             | 60-80            | 0.21-0.25                   |
| The lithium battery            | 0-100kW            | Minute-hour   | 75-200 Wh/kg   | 150-315 W/kg  | 5-10             | 67.5-650                    |
| Lead-acid battery              | 0-20MW             | Seconds – hour| 30-50 Wh/kg    | 75-300 W/kg   | 2-5              | 130-650                     |
| The flywheel energy storage    | 0-250kW            | Milliseconds  | 10-30 Wh/kg    | 400-1500 W/kg | about            | 19.5-162.5                  |
| Compressed air storage         | 5MW-300MW          | 1-24 hours    | 3-6Wh/L        | 0.5-2 W/L     | 20-40            | 13-26                       |
| Superconducting energy storage | 100kW-10MW         | Milliseconds  | 0.5-5 Wh/kg    | 500-2000 W/kg | 10-20            | \                           |
| Super capacitor                | 0-300kW            | Milliseconds  | 2.5-1.5 Wh/kg  | 500-5000 W/kg | about            | 13-130                      |
| Distributed small pumped storage | 0-100kW          | Minutes       | 11.3Wh/L       | 166.7W/L      | about            | about 0.38                  |

#### 3.3. Discussion of distributed small-scale PSPS development prospect

At present, the main problem restricting the development of the PSPS is the electricity pricing mechanism is not reasonable, the two-part electricity price is mostly used in the PSPS in China. The price of capacity electricity price is seriously low while the price of energy electricity price is rather high [9]. In addition, the peak-valley electricity price system is not complete and there is no compensation for the auxiliary service of the PSPS. Therefore, the enthusiasm of investment in the PSPS is low, which directly leads to the mismatch between the demand for PSPS and the construction speed.

The distributed small-scale PSPS can be built not only in cities, but also in rural areas to ensure the reliability of power supply. And it can be deployed by the grid, and their peak regulation and frequency regulation will be more accurate and faster than the large-scale PSPS. China needs to optimize the electricity price structure and consider three parts of electricity price: capacity price, energy price and auxiliary service price to improve the economy of distributed pumped storage power station.

#### 4. Conclusions

In this paper, a distributed small-scale PSPS which is not limited by geographical factors is first proposed, its overall steel tower structure is then designed, and its performance and economy is finally analysed through comparison. The main conclusions are as follows.

1. The designed small-scale PSPS performs the pumped-storage cycle through the height difference, realizing the energy conversion process. When the shape of the designed steel tower conforms to the slope ratio of "123", the tower body is uniformly stressed and can withstand a water tank with a capacity of 300 cubic meters at the top of the tower.

2. The performance and economy of distributed small-scale PSPS are relatively good. Its energy density is about ten times that of large-scale PSPS. Compared with other energy storage technologies, it has lower single cycle cost and longer lifespan.
(3) Due to the small installed capacity, single distributed small-scale PSPS does not contribute much to the power grid. However, it has long lifespan and can be widely constructed in load centers. If a certain scale of construction can be reached, it will have a huge effect on the stability of the grid and the consumption of new energy in the future.

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