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Research article

A method for optimizing the capacity allocation of a photovoltaic-pumped hydro storage system in an abandoned coal mine

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A R T I C L E I N F O

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A B S T R A C T

The enormous potential of the photovoltaic (PV) sector has aided in the faster attainment of China's "dual-carbon" aim. However, due to a scarcity of land resources and intermittent fluctuations in solar energy, it has been difficult to build large-scale PV bases, and existing PV systems also suffer from unstable power generation and seasonal fluctuations and are unable to be directly connected to the grid for use. However, abandoned mines with huge surface collapse zones and a large underground mining area offer a potential possibility for constructing photovoltaic-pumped hydro storage (PV-PHS) systems and limiting PV variations. Based on the abandoned mine pumbed hydro storage (AMPHS) potential assessment model and the optimized discrete wavelet decomposition algorithm, this study proposes a dynamic cycle optimization method for the PHS regulation capacity in an abandoned mine PV-PHS hybrid system. This approach is able to determine the optimal regulation capacity of AMPHS on a daily scale while limiting the volatility of the PV-PHS hybrid system. The method was applied to an abandoned mine PV-PHS hybrid system in Zaozhuang City, Shandong Province, and the optimal regulation capacity of the AMPHS was determined to be 88 MWh and 100 % elimination of PV generation volatility was achieved. This also reduces the economic cost by roughly 1.94×10^8 CNY. In addition, it is possible to store an average of 2.32 % of the PV power generated and to extend the power generation time by approximately 2.5 h per day. This research is critical for boosting the resource use of abandoned mines, and establishing the comprehensive usage model of new energy and abandoned mine resources.

1. Introduction

Many difficulties and challenges have arisen as a result of economic globalization, including global warming, harsh weather, and

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energy shortages. To address the global climate crisis, approximately 200 nations signed the Paris Agreement in 2015, which united global climate action, and several countries have since established carbon-neutral objectives [1]. At the United Nations General Assembly in 2020, the Chinese Government pledged to "strive to achieve carbon peaking by 2030 and carbon neutrality by 2060" [2]. It's a well-established fact that China is the world's largest producer and consumer of coal. According to China's National Bureau of Statistics, coal consumption has accounted for 55.3 % of China's total energy consumption in 2023. This implies that China could face even larger hurdles in meeting the "dual-carbon" target. One of the most important directions of China's future efforts will be how to more effectively guide the green and low-carbon transformation of energy. In terms of new energy, this requires China to promote the large-scale deployment of renewable energy sources such as photovoltaic (PV) and wind power. The instability of renewable energy sources due to seasonal and natural conditions has also become one of the great challenges for China's power grid [3].

The International Energy Agency recently released its annual report for 2023, which shows that last year the global installed capacity of PV power generation was about 375 GW, a growth of more than 30 % [4,5]. Among them, China is the world's largest PV market and product supplier [6]. However, most of China's large-scale PV bases are located in the northwest and southwest regions, while China's population and high electricity load areas are concentrated in the eastern and central regions, and there is a serious imbalance between the deployment of PV bases and the distribution of electricity demand [7]. Land resources are very tight in eastern and central China due to rapid economic development, while the deployment of PV projects requires large areas of land resources, and the contradiction between the two is also increasingly prominent. For that reason, the Chinese Government encourages the use of mine waste land for the construction of PV power plants [8]. As a result of the energy transition and de-capacification policies, China already has 13,000 abandoned mines [9], and the number of abandoned mines is expected to reach 15,000 by 2030 [10]. This provides large areas of abandoned mines, industrial plazas, and coal-mining collapse zones for the construction of PV projects [11,12]. In addition, with the large percentage penetration of PV, its intermittent character will cause great challenges to the security of the grid. At this point, energy storage systems are needed to play the role of peak shaving and valley filling to reduce the impact of PV instability on the grid [13–15]. The pumped storage power plant (PHS) has energy storage characteristics such as cleanliness, flexibility, fast start-up, and peak shaving [16]. In the context of China's energy system transforming to cleaner and more sustainable utilization, PHS is experiencing a period of rapid development [17]. Abandoned coal mines contain enough underground space and mining water, making them ideal for the development of PHS power plants [18,19]. Abandoned mine pumped hydro storage (AMPHS) has become a new trend in the development of energy storage systems for PV projects [20].

Numerous academics have discussed the PV-PHS hybrid system as a means of addressing the power grid stability issues brought on by the growing proportion of PV penetration. Some research focuses on the optimal configuration and dispatch operation of hybrid power generation systems combining PV-PHS and other power generation or energy storage technologies [21–24]. Yang et al. proposed a novel spatio-temporality-enabled parallel multi-agent-based dynamic dispatch method to solve the optimal scheduling problem of an Hydro-PV-PHS integrated system [25]. Guo et al. proposes a solar-wind-hydro hybrid power system with PHS-TES double energy storages, and investigates its optimal coordinated operation strategy and multi-objective selection problem with the objectives of minimizing the levelized energy cost and power supply loss probability [26]. These studies usually require a third power technology to compensate for the lack of PHS and suppress the volatility of PV. However, in the context of the Chinese government encouraging the use of abandoned mines to develop PV projects, the majority of future PV projects in China will be located within abandoned mine areas. As mentioned above, abandoned mines often have natural advantages for the development of PHS. Nevertheless, due to their geographical conditions and location limitations, it is often difficult to develop other power technologies. Therefore, the optimal configuration and dispatching operation method of the PV-PHS hybrid system, which is assisted by the third technology to suppress photovoltaic fluctuations, is not suitable for deployment and operation in an abandoned mine.

In addition, some scholars have studied the optimization of PHS configuration parameters in PV-PHS hybrid system for the purpose of smoothing PV fluctuations [27–29]. Zhang et al. presented a "rule-based" capacity control technique for cascaded hydropower–photovoltaic-pumped storage hybrid power generating systems, using statistical methodologies to realize pumped storage regulation capacity determination [30]. These studies usually use some complex mathematical models and neural network algorithms, which are computationally expensive and time-consuming. Moreover, current studies are usually based on one day or one week of PV power generation data with a small time period and do not adequately consider the impact of seasons on PV power generation. More significantly, these studies are aimed at conventional PHS, whereas the capacity configuration of AMPHS is limited by the underground space, and the parameter optimization methods for conventional PHS do not take into account the capacity constraints of PHS.

In order to address the problems in the current study, especially to complement the gaps in the current research on AMPHS. In this study, an abandoned mine AMPHS hybrid system was designed and modeled based on the aboveground and underground spaces that can be utilized in an abandoned mine. In this paper, with the goal of minimizing PV fluctuations, the objective function is established to improve the discrete wavelet transform algorithm (DWTA) to construct a PV fluctuation smoothing model. Subsequently, the potential assessment model of AMPHS is established based on the underground space resource assessment model of abandoned mine. Based on the complementary effect of PHS on PV fluctuation, this paper couples the PV fluctuation smoothing model and the potential assessment model of AMPHS, and constructs a dynamic cycle-round optimization algorithm for AMPHS regulation capacity with a period of days.

The contribution of this methodology is as follows: (1) This paper constructs a mathematical model based on a simple and lightweight DWTA, which is computationally fast. (2) The method proposed in this paper is a cycle optimization algorithm with a period of days, which can analyze data for any integer number of days. This approach extends the time horizon of the data, and for weather-sensitive PV power generation, it can be considered to include data from more seasonal climatic conditions, enhancing the reliability of the model. (3) This methodology evaluates the potential for capacity of AMPHS by utilizing the available subsurface space resources of abandoned mines as a limiting factor to constrain the regulating capacity of the AMPHS. In this way, this method fully considers the impact of the unique subsurface space resource characteristics of abandoned mines on the optimal configuration of PV-PHS hybrid systems. (4) This study proposes an optimal configuration method for the development of PV-PHS hybrid systems using abandoned mines, which provides a new direction for their transformational utilization.

2. Materials and methods

2.1. Abandoned mine PV-PHS hybrid system design

Fig. 1 depicts a hybrid abandoned mine PV-PHS system that was constructed using the surface and subterranean space resources of an abandoned mine. The system includes PV modules, a control center, pumped storage, and other components [31]. The PV power-generating module mostly uses the surface open space of abandoned mines to deploy solar PV arrays and construct PV power generation systems, such as abandoned mine tailing ponds, open-pit quarries, waste rock industries, mining subsidence zones, and so on [32]. The control center's role is to convert the underground PHS's operational status and adjust its pumping power to fulfill the requirements of managing the fluctuations in PV power production based on these fluctuations. The PHS module primarily makes use of abandoned mines' underground space resources, and it completes the PHS plant construction by selecting two abandoned roadways or mining regions with suitable height disparities as the upper and lower reservoirs of the PHS, respectively [33]. The roadway is a variety of access roads drilled during the coal mining process, used for mineral transportation, ventilation, drainage, and worker walking [34]. The underground mining area is the hollow left behind as a result of coal mining [35]. After a coal mine is closed or abandoned, both roadways and underground mining areas can provide spatial resources that can be utilized. A pressure pipe connects the two reservoirs, which are outfitted with pumps and turbines for energy storage and generation.

It is difficult to achieve the real-time and rapid adjustment function necessary for PV fluctuations using the fixed-speed reversible device employed in typical PSH [36]. In this study, we assume that variable speed constant frequency unit is used to construct AMPHS [37], and its flexible and fast reaction capability can provide real-time complementarity between PV and PHS [38]. The pumped storage power station enters a pumping state when the fluctuation in photovoltaic power generation within a given time period exceeds the standard requirements and shows an upward trend. The excess electricity generated by photovoltaic power generation is pumped through the pump turbine to move water from the lower reservoir to the upper reservoir for energy storage; the pumped storage power station is transformed into a power generation state when the fluctuation in photovoltaic power generation is greater than the standard requirements and shows a downward trend. Water from the upper reservoir is then transferred to the lower reservoir for power generation to make up for the shortfall of photovoltaic power generation. In this way, the goal of limiting PV power generation fluctuation can be achieved, PV power generation stability can be increased, the threat that PV power generation fluctuation poses to the safety of the power grid can be diminished, the efficient and safe use of PV and other new energy sources can be promoted, and the resourcefulness and energy reuse of abandoned mines can be encouraged.

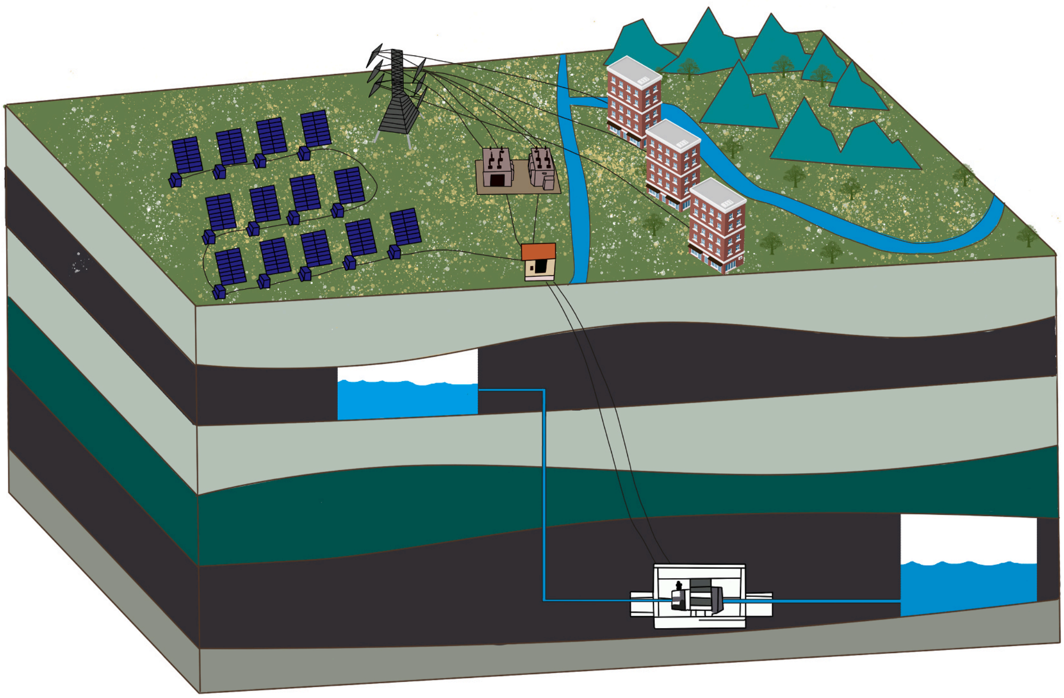

Fig. 1. Abandoned mine PV-PHS hybrid system structure diagram.

2.2. Framework of capacity allocation optimization methods for AMPHS

The restraining effect of the AMPHS plant on the fluctuation in PV system power generation is mainly determined by the efficiency of the pumps, the efficiency of the turbine, and the capacity of the upper and lower reservoirs. The use of variable-speed constant-

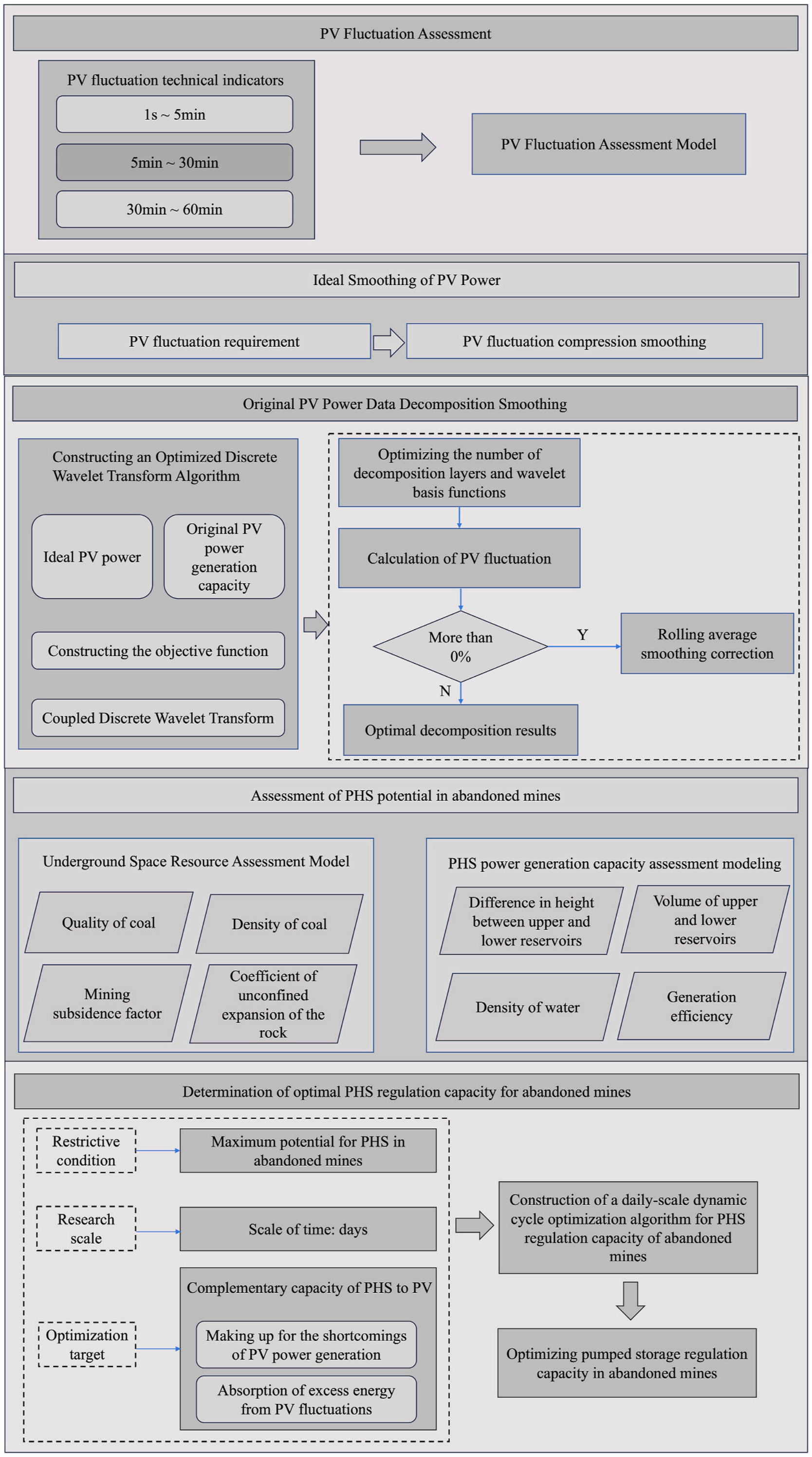

Fig. 2. Framework diagram of regulatory capacity optimization method for AMPHS.

frequency PHS units enables PHS to flexibly control the power of generation and storage, and the efficiency of pumps and turbines no longer becomes a key element affecting the effect of suppressing PV fluctuations in PHS power stations, whereas in the case of AMPHS, the capacity of upper and lower reservoirs has become a key factor restricting the ability of PHS to suppress PV fluctuations in an abandoned mine due to the limitation of underground space resources. Thus, the following procedures are followed in this study in order to optimize AMPHS regulation capability under suppressed PV fluctuation conditions. Fig. 2 illustrates the research framework.

Evaluate the PV system's fluctuations. The fluctuation of PV power at a given moment is determined by the power difference between that moment and the previous moment. The State Grid of China has clear technical requirements for grid-connected PV systems. The State Grid of China indicated that the power fluctuation of the PV system should not exceed 10 % of the installed capacity in the short term (1–5 min), 5 % of the installed capacity in the medium term (5–30 min) and 2 % of the installed capacity in the long term (30–60 min). Since the time scale of the PV generation data used in this study is 15 min, 2 % of the installed capacity is used as the limiting condition for PV fluctuations in this study. In this study, the overall volatility of the PV system is assessed using the ratio of the duration that the PV fluctuation exceeds the requirement over the entire power generation period to the duration of the power generation period. A detailed description of the model can be found in the *Appendix section1*.

Idealized smoothing of PV power. The idealized smoothing of PV power time series data is a step processing method based on time point. Based on the limiting parameters of PV power fluctuation, we adjust PV power one by one at time points. We replace the data of the original time node with the adjusted PV power data and then adjust the power data of the remaining time nodes sequentiall. See *Appendix section2* for details.

Construction of the PV power optimization model. However, PV power data that meets the fluctuation requirements can be obtained by the method of idealized smoothing. However, this method ignores the characteristics of PV power generation, and excessive smoothing may change the power generation ability of the PV system. The DWTA is a method of decomposing fluctuating signal data into high- and low-frequency data (see Appendix Fig.1), which is lightweight and rapid to compute [39]. In this study, the discrete wavelet transform algorithm is improved by constructing a loss function with the objective of idealizing the PV power and maintaining the generating capacity of the PV system. The improved DWTA guides the decomposition process of PV power data and determines the optimal decomposition result. In order to address the possible incomplete smoothing of discrete wavelet transform methods, this study uses rolling average as a post-processing method to cycle through time points that still exceed the fluctuation limit after smoothing. Details of the model can be found in the *Appendix section3*.

Estimation of the potential of AMPHS. The AMPHS utilizes two roadways or underground mining areas in an abandoned mine, which have height differences, to create upper and lower reservoirs for energy storage and discharge. The potential of the AMPHS is hence largely dependent on the volume of the underground mining areas or roadways utilized and the difference in height between them. In this study, the underground mining space that can be utilized in an abandoned mine was evaluated with reference to the calculation method of Xie et al. [40]. Based on the estimation of subsurface space, this paper evaluates the potential of AMPHS with reference to the methodology proposed by Bian et al. [41]. Since there are several underground spaces that can be utilized in the abandoned mine, we need to combine them two by two, calculate the capacity potential of each combination and take the maximum value as the capacity potential of AMPHS. (See *Appendix section4* for details)。

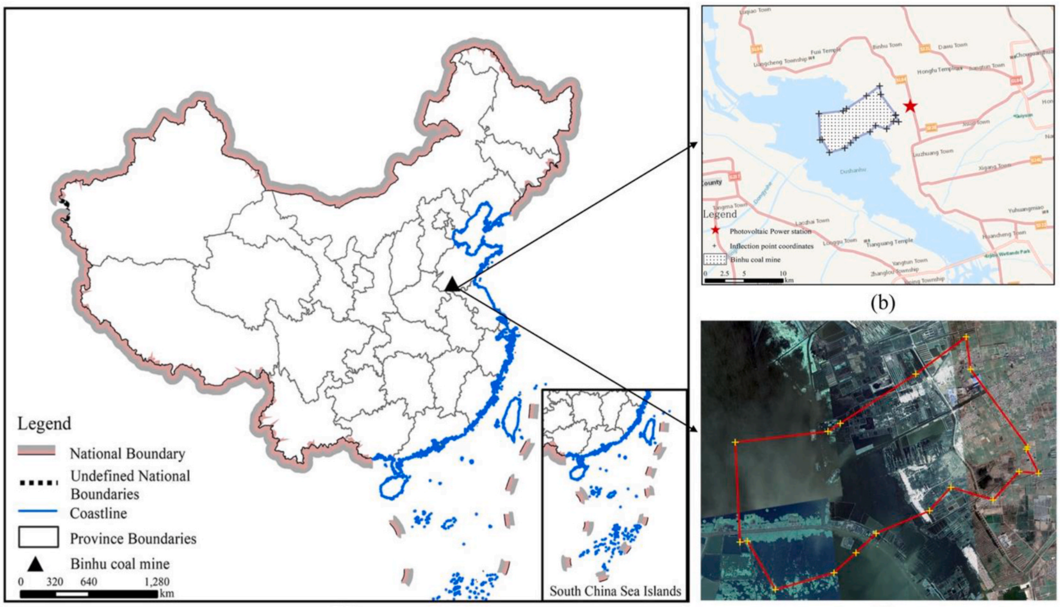

Fig. 3. Overview of the study area.(a) indicates the location of the mine in China; (b) indicates the administrative location of the mine; (c) indicates a satellite image of the extent of the mine.

Optimization of the capacity of AMPHS. According to the original PV power data and the optimized PV power data, it is possible to determine the complementary process between AMPHS and PV (See Appendix Fig.3). A The complementary process of AMPHS to PV can be explained as follows: When the original PV power is greater than the optimized PV power, the AMPHS needs to store the excess PV power; when the original PV power is less than the optimized PV power, the AMPHS needs to switch to the power generation state to make up for the shortage of PV power. Through the process described above, AMPHS can regulate original PV power to optimized PV power to meet fluctuation constraints. During each PV generation period (days are used as the generation period in this study), the regulation procedure of AMPHS is actually discharging and storing energy within the capacity range, which is a cumulative consumption process of the capacity by time node. Consequently, the potential of the capacity of the AMPHS determines the effectiveness of the AMPHS in regulating PV power. When the capacity of the AMPHS can meet the regulation demand, it is able to adjust the PV power to the optimized result; when the capacity of the AMPHS cannot meet the regulation demand, it is not able to completely adjust the PV fluctuation to the optimized result, and there may be some fluctuations that cannot be eliminated. However, when the potential of the AMPHS capacity is able to meet the regulatory demand, utilizing its full potential will result in a waste of resources and an increase in construction costs. We established a capacity allocation optimization method for AMPHS, considering the constraints on the potential of the capacity of AMPHS based on the regulation process of AMPHS on PV as described above, and determined the optimal capacity of AMPHS on a daily scale (See the *Appendix section5* for details). When long time series of PV power data are used (e.g., one year of PV power data), which reflect weather or seasonal variations, this method allows cyclic calculation of the daily-scale capacity allocation and selection of its maximum value as the optimal result, at which time the result can better realize the effect of AMPHS in regulating PV under different weather conditions.

3. Results

The method was validated using a coal mine in Zaozhuang City, Shandong Province, China, as an example. The geographical position of this coal mine is seen in Fig. 3(a)–(b) and (c). The coal mine is located in the western region of Tengzhou City, Zaozhuang City, China, and it began mining in 2005 and stopped in 2022, having mined a total of 16.434 million tons of coal resources. Coal mining activities caused a significant surface collapse area in the coal mine's southeastern section, which was repurposed to develop a 50 MW PV power generation plant. And the large amount of underground space resources left behind provides space resource advantages for the construction of the PV-PHS hybrid system. Consequently, this coal mine is selected to verify the method proposed in this paper to optimize the capacity allocation of AMPHS when AMPHS suppress PV fluctuations.

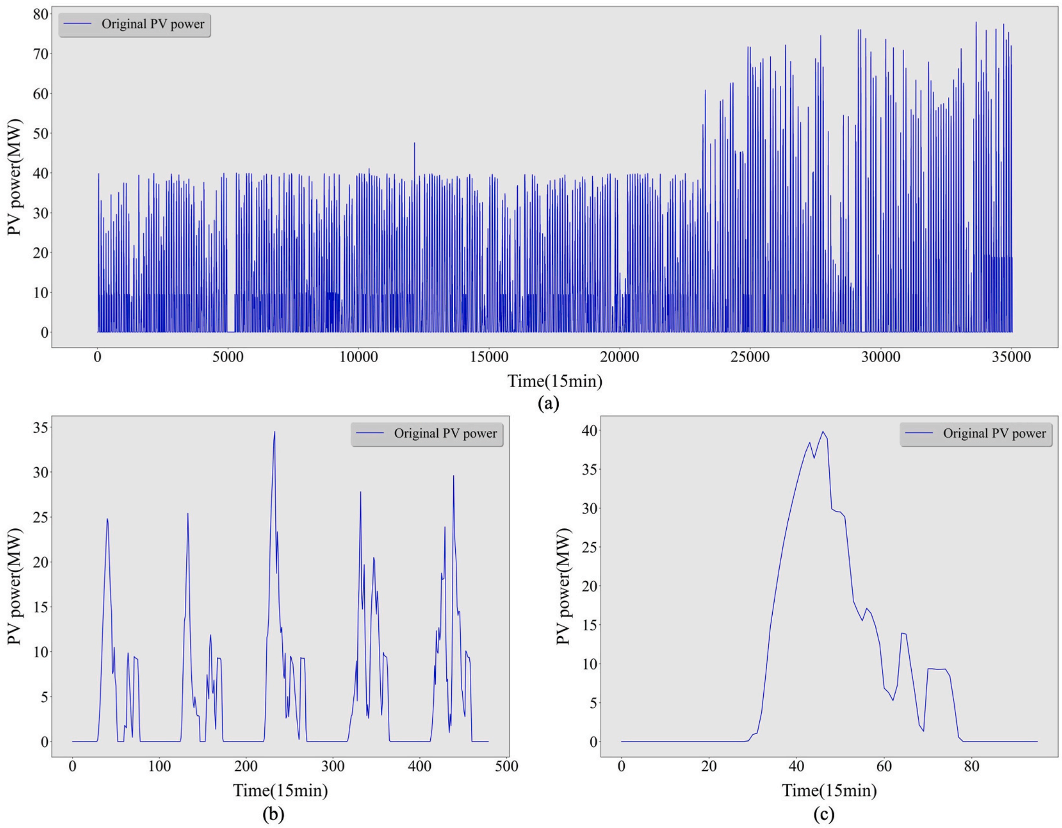

Fig. 4. PV power data in collapsed areas.(a) for one years; (b) for five days; (c) for one day.

3.1. Idealization of original PV power data

Since climatic conditions are some of the most important factors influencing PV fluctuations, this study chose PV power data from the case area over a one-year cycle to reflect changes in PV power generation during different seasons and climatic conditions to ensure that the optimal regulation capacity of the calculated AMPHS could cope with PV power fluctuations under complex weather conditions and to ensure the accuracy and universality of the results. Fig. 4 depicts the PV power data at 15-min intervals over a one-year cycle for the PV site in the case area's surface collapse zone. Fig. 4(a) depicts the PV power data for one year, whereas Fig. 4(b) and (c) depict the PV power curves for five days and one day, respectively. Fig. 4 depicts that the PV power data are approximated as a time signal data with a period of one day. The PV power can be considered as the amplitude of the signal data, and that the peak power generation of each day is concentrated in the time period from 10:00 to 12:00 when the solar radiation is at its strongest.

In accordance with the technical specifications of grid-connected PV power generation, the original PV power data are optimized. According to Appendix Table 1, as a result of the PV power data in this study being collected at 15-min intervals, the PV power fluctuation must not exceed 5 % of the installed capacity. As seen in Fig. 5, the ideal PV power data and PV power fluctuation data are obtained by using this as a restriction for idealized smoothing of the PV power data.

A comparison of the ideal PV power data and the original PV power data is shown in Fig. 5(a), and it can be seen that the volatility of the PV power curve is significantly reduced after the idealization process, but the overall PV power is lower than the original PV power, resulting in a loss in the PV system's generating capacity. A comparison between the ideal PV power fluctuation and the original PV power fluctuation is shown in Fig. 5(b), and it can be seen that the original PV power fluctuation is substantially higher than that required by the standard, with a fluctuation rate of 34.17 %. And the idealized processed PV power is within the standard requirement for the entire period, with a fluctuation rate of 0 %.

3.2. Smoothing of original PV power data

To smooth the original PV power data, the optimized discrete wavelet transform algorithm is employed, and in order to distinguish the wavelet basis function with the best smoothing effect more clearly, the smoothing loss value of each wavelet basis function is processed as follows:

$$T(P) = 1 - M(P) \tag{1}$$

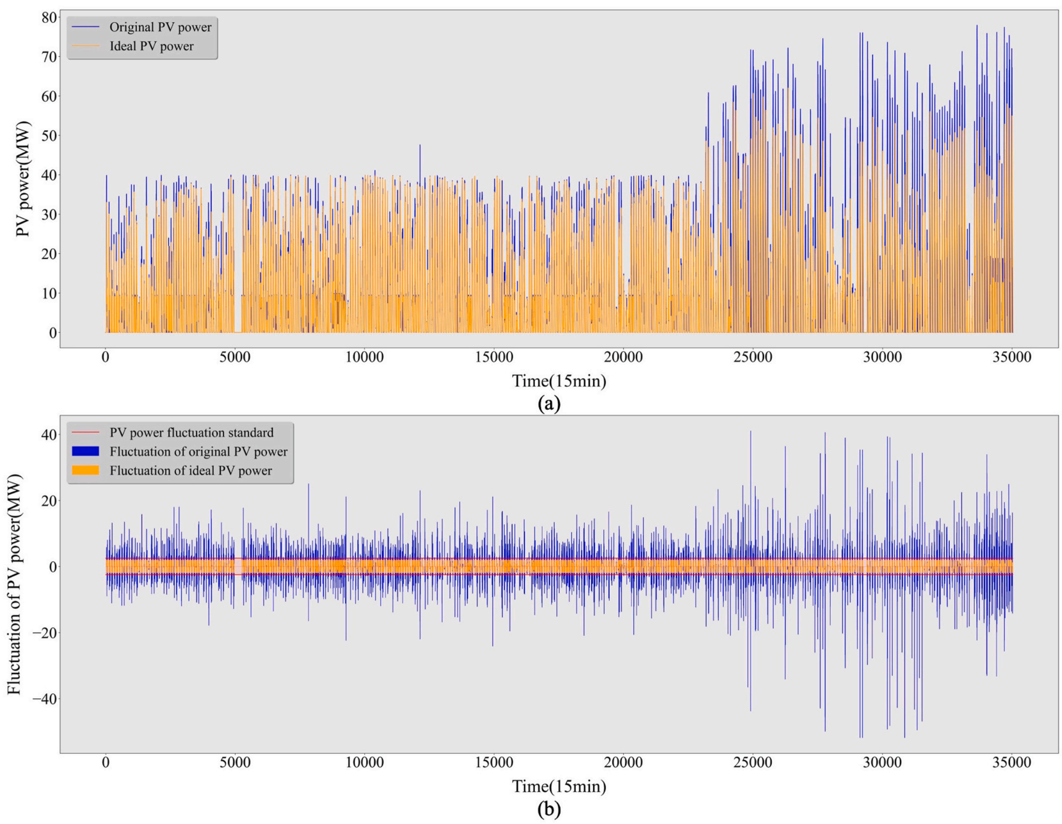

Fig. 5. Comparison of power(a) and fluctuations(b) of PV in ideal and original state.

where *M(P)* denotes the corresponding smoothing loss value of the wavelet basis function; *T(P)* denotes the smoothing effect of the wavelet basis function, and the larger the value of *T(P)*, the better the smoothing effect is. Fig. 6 records the smoothing effect of all wavelet basis functions.

The best smoothing results are obtained when the bior3.1 wavelet basis function is used for smoothing, as shown in Fig. 6. As a result, bior3.1 is used as the wavelet basis function in this research to smooth the original PV power, and the resulting smoothed PV power data and PV fluctuation data are shown in Fig. 7. And Fig. 7(a) indicates that the smoothed PV power data can still retain the trend and features of the original PV power, preserving the PV system's power generation capacity. The smoothed result achieved a good effect on the suppression of PV fluctuations on the basis of retaining the characteristics of the original PV power generation, which significantly reduces the value and frequency of PV fluctuations, but it cannot realize the effect of completely eliminating PV fluctuations, and fluctuations are still present in part of the time, with a fluctuation rate of 14.51 %, as shown in Fig. 7(b).

The rolling average method is then used to perform the cyclic correction, and the change in the PV power fluctuation rate during the correction process is depicted in Fig. 8, which shows that the fluctuation in PV power gradually decreases with the continuous iterative correction, and the fluctuation in PV power reaches 0 % after executing the rolling average 19 times.

Fig. 9(a) and (b) depict the adjusted results. It can be seen that the PV power data retain the characteristics of the original PV power generation after the rolling average correction, achieving a very good effect on the suppression of PV fluctuations, controlling the PV fluctuations all within the technical requirements, eliminating the residual PV fluctuations, and making the PV fluctuation rate 0 %.

3.3. Determination of optimal regulation capacity for AMPHS

There are six mining roadways in this coal mine, and the total volume of underground space that can be utilized is about 3.2 million m^3, which is combined two by two to calculate the regulating capacity of PHS, and the maximum regulating capacity of PHS in this abandoned mine is 153 MWh. The maximum regulation capacity of the AMPHS is utilized for dynamic cyclic correction of the smoothed PV power to obtain the optimal regulation capacity of the AMPHS on a daily scale, as shown in Fig. 10. This shows that the trend in the optimal regulated capacity on a daily scale for AMPHS is generally consistent with the trend in original PV power. The larger the average daily PV power, the greater the demand for the AMPHS's regulating capacity.

Fig. 11 depicts the evolution of PV system stability with AMPHS regulation capacity. It demonstrates that the optimal regulation capacity of an AMPHS is 88 MWh, the volume of underground space occupied by the upper and lower reservoirs of the corresponding AMPHS is 431,000 m^3, which can save approximately 2,769,400 m^3, and according to the AMPHS construction cost of 2.98×10^6 CNY/MWh [42], it can save approximately 1.94×10^8 CNY of economic cost. As shown in Fig. 11, the stability of the PV power

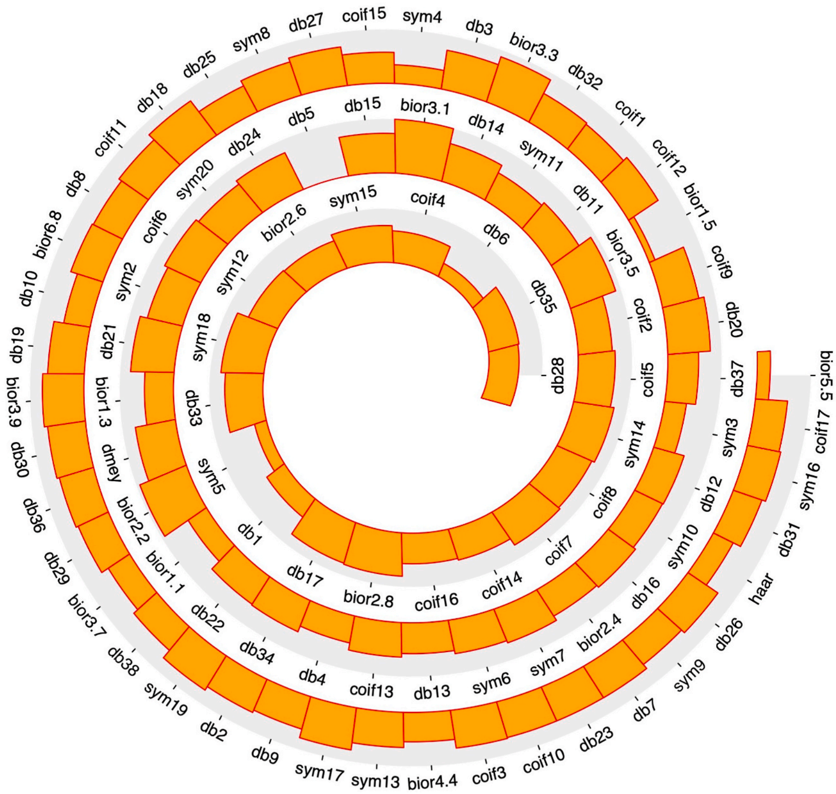

Fig. 6. Smoothing effect of wavelet basis functions.

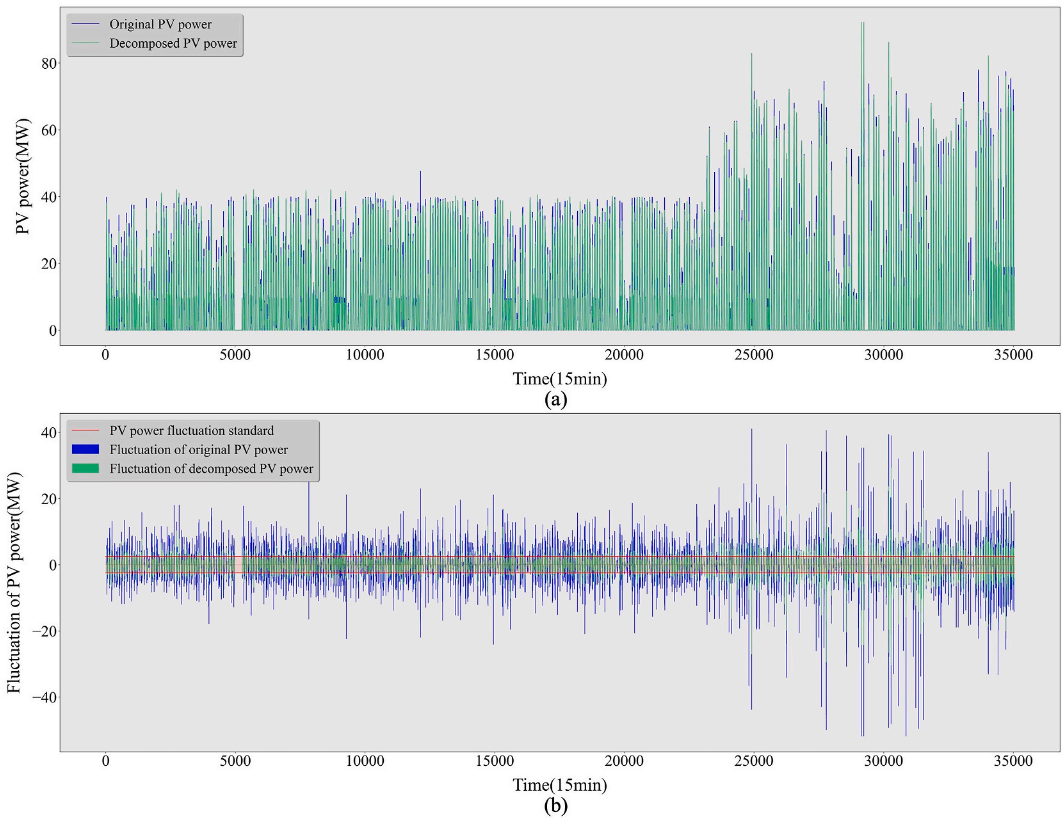

Fig. 7. Comparison of power(a) and fluctuations(b) of PV in post-decomposition and original state.

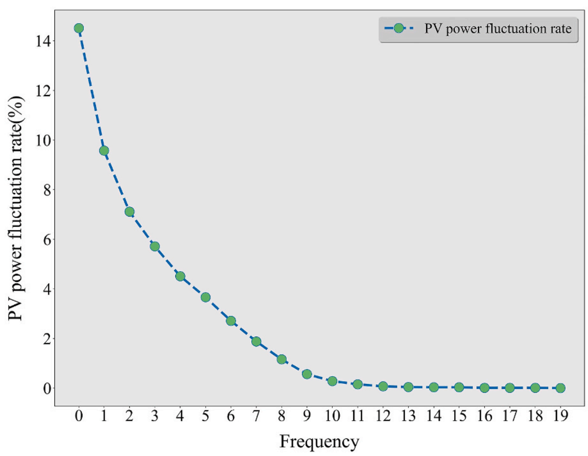

Fig. 8. Changes in PV power fluctuation rate during the correction process.

gradually increases as the regulation capacity increases. When the AMPHS's regulation capacity is substantial, the PV power stability increases at a more steady rate; however, when the AMPHS's regulation capacity is extremely small, PV power stability appears to increase quickly. This is due to the low demand for AMPHS regulatory capacity for the majority of the year, which has a greater influence on PV power fluctuation when it changes around smaller values.

The power data of the AMPHS over a one-year period are calculated using the original PV power data and the smoothed PV power data corresponding to the optimal regulation capacity of the AMPHS, as shown in Fig. 12(a). Fig. 12(b) and (c) show the power data of AMPHS over five days and one day, respectively. In the diagram, a vertical axis higher than 0 shows that the AMPHS is in the energy storage state, a vertical axis less than 0 indicates that the AMPHS is in the power generation state, and the region enclosed with the

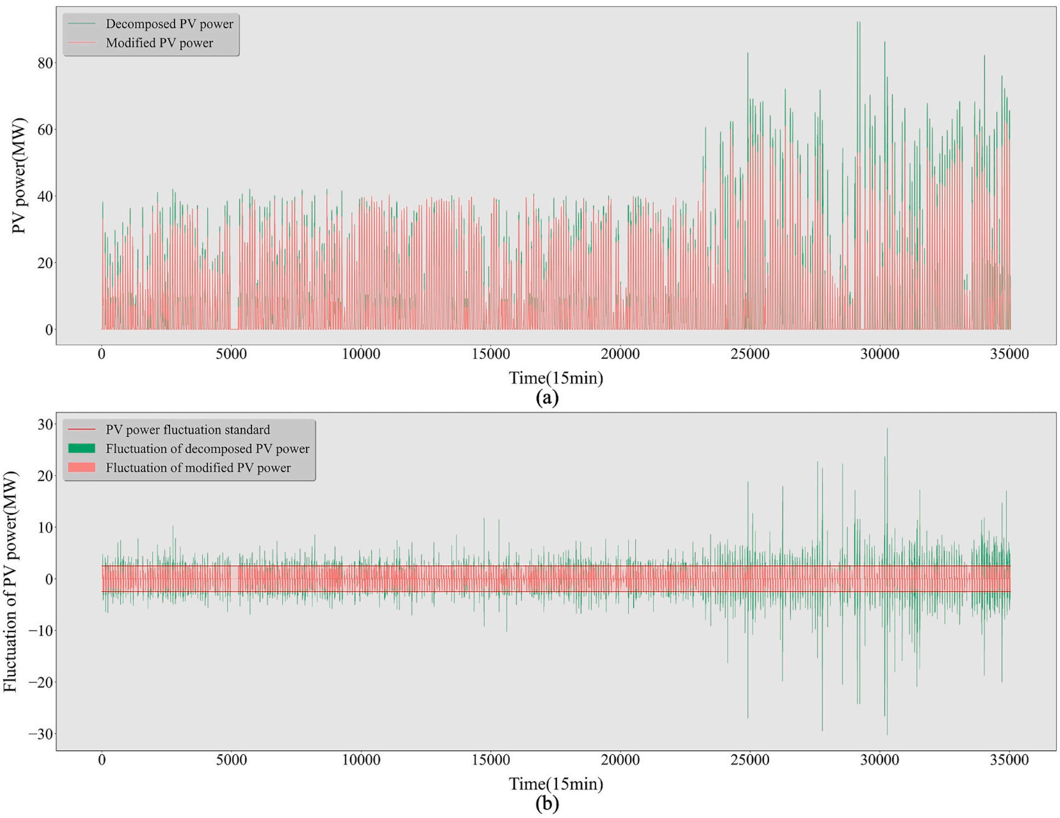

Fig. 9. Comparison of power(a) and fluctuations(b) of PV in corrected and original state.

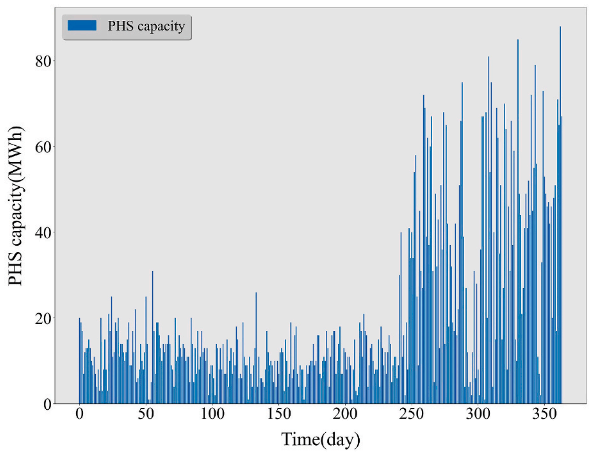

Fig. 10. Optimal regulation capacity of AMPHS on a daily scale.

horizontal axis represents the stored and released energy, respectively.

The statistics of excess energy stored by PHS in the abandoned mine every day are shown in Fig. 13(a). In the figure, the vertical axis greater than 0 indicates the energy remaining after smoothing the photovoltaic fluctuations after the excess energy absorbed by the photovoltaic system by the AMPHS; on the contrary, it indicates the energy that needs to be pre-stored in the AMPHS when the energy absorbed by the PHS cannot meet the photovoltaic fluctuation smoothing requirements of the day. According to the calculation, energy can be stored for an average of 1930.12 MWh annually, or 2.32 % of the PV system's total yearly power generation. The data for the daily energy stored in the AMPHS as a proportion of the PV system's total power generation are shown in Fig. 13(b). This percentage typically ranges from 1 % to 6 %, with an average of roughly 2.56 %.

The PV system is prone to rapid starts or pauses due to weather extremes and day/night alternation. Using the AMPHS to

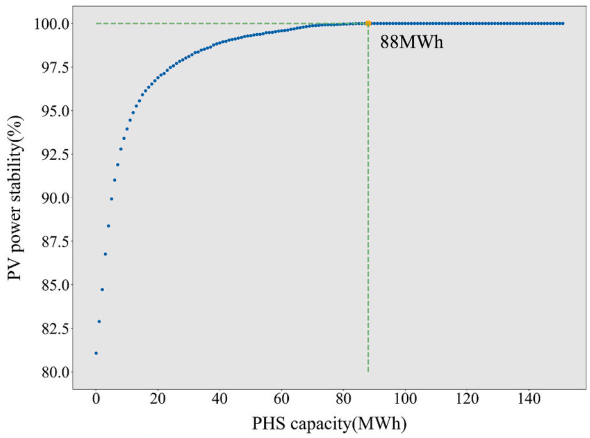

Fig. 11. The relationship between the stability of PV power and the regulation capacity of AMPHS.

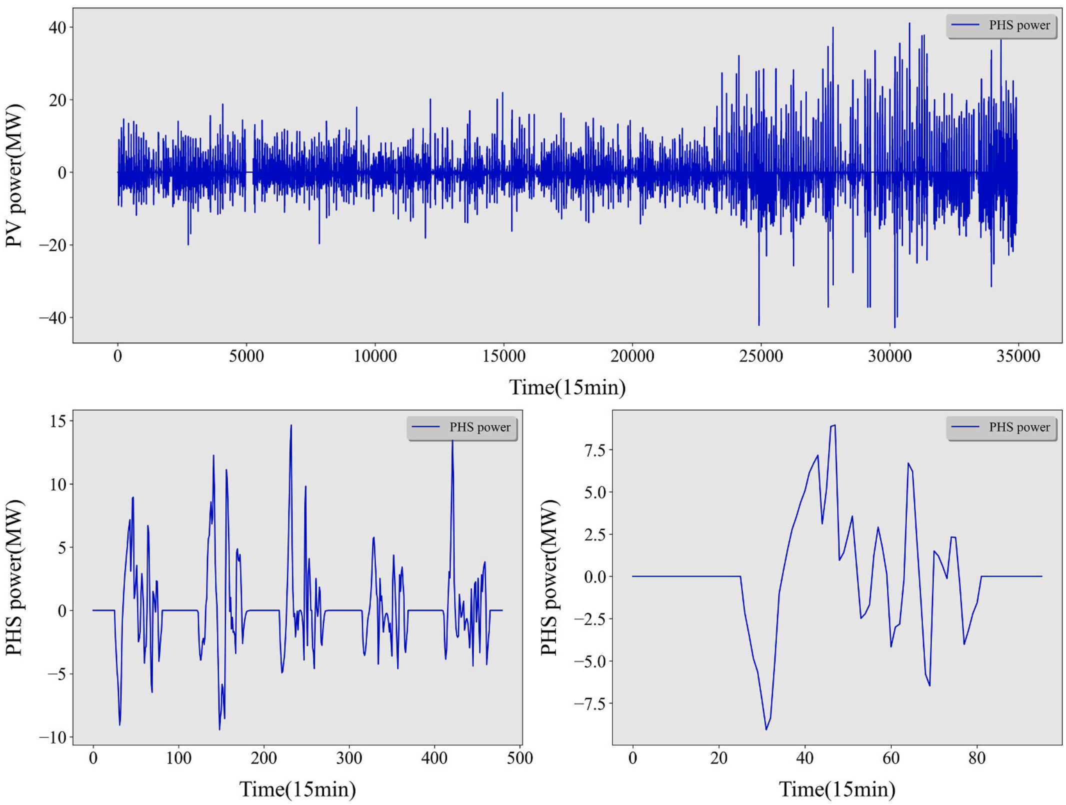

Fig. 12. Power of AMPHS.(a) for one year; (b) for five days; (c) for one day.

supplement the PV system will extend the PV-PHS system's power supply period. Fig. 14 depicts the extended time per day statistics for this mine when the optimal regulating capacity of AMPHS is applied. It demonstrates that the prolonged time per day is concentrated between 0.5 and 3 h, with an average extension of 2.5 h per day, extending the hybrid system's power generating time by approximately 876.75 h per year, or approximately 36 days.

4. Discussion and conclusion

In this study, the potential assessment model of AMPHS and the improved DWTA are coupled, and the complementary action mechanism of PHS on PV is used as a link to propose a capacity optimization allocation method for AMPHS when constructing a PV-PHS hybrid system using abandoned mines. Furthermore, in order to respond to the time effect of the abandoned mine PV-PHS hybrid

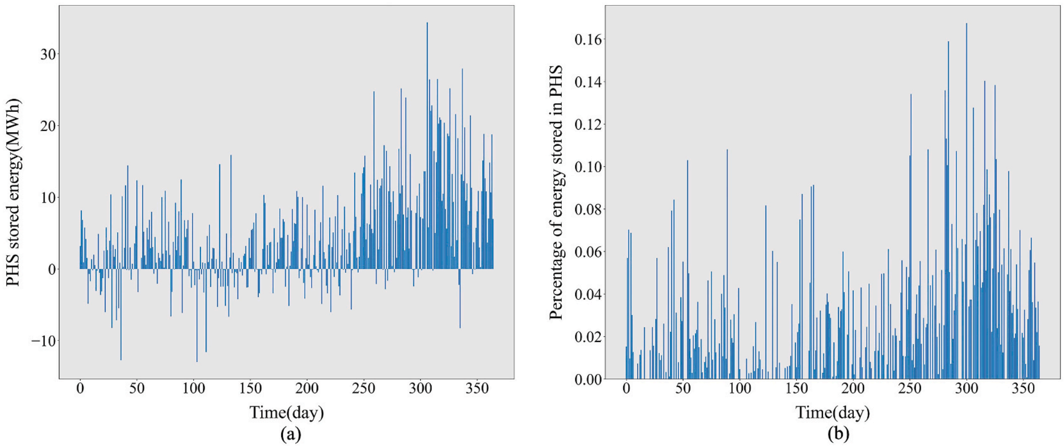

Fig. 13. Energy stored in AMPHS on a daily scale(a) and its percentage share(b).

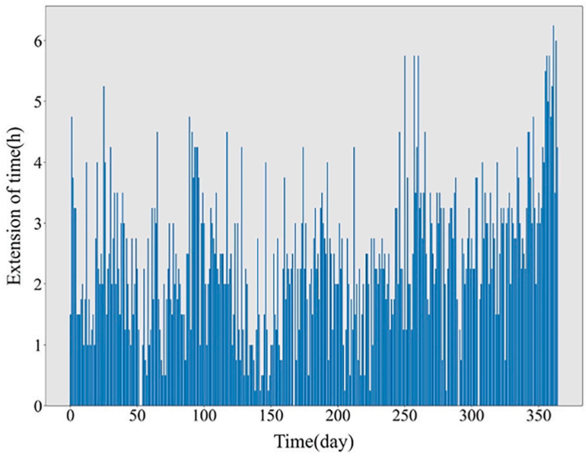

Fig. 14. Statistics of extended generation time of PV-PHS hybrid system in an abandoned mine.

system, the time scale of the optimization process is precisely modeled in this research, and a daily scale dynamic cycle optimization system is created. The method proposed in this study achieves the elimination of the volatility of the PV system and improves the stability of the PV-PHS hybrid system. In addition, the method determines the optimal capacity configuration of the AMPHS, which reduces the economic cost from the perspective of the construction scale of the AMPHS. This study applies the proposed optimization method for AMPHS regulating capacity to an abandoned mine in Zaozhuang City, Shandong Province. The findings indicate that, when combined with the PV base built in the collapsed area, the optimal AMPHS regulating capacity required by this coal mine is 88 MWh, and the volume of the occupied underground space is 431,000 m^3. This optimization method can achieve 100 % PV fluctuation elimination while saving 2,769,400 m^3 of underground space resources, resulting in a reduction of approximately 1.94×10^8 CNY in economic costs. Through the calculation of the optimized PV power, it can be seen that, compared to the current research on the optimization of PV-PHS hybrid systems, the method proposed in this paper not only eliminates the PV fluctuations but also retains the power generation characteristics of the original PV system. It does not result in a change in the system's power generation capacity due to the suppression of PV fluctuations. We compared a large number of PHS sites in China provided by the RE100 Group, Australian National University (http://re100.eng.anu.edu.au/), which essentially have tens or even hundreds of times the installed capacity of the AMPHS calculated in this study. But the selection and establishment of PHS sites is different from the research objective of this paper. The purpose of this paper is that we rely on the resource advantage of underground space of abandoned mines to suppress the fluctuation of PV systems in the context of land constraints in China and the Chinese government's encouragement of the use of abandoned mines for the development of PV projects. We try to establish a methodology that can determine the optimal amount of spatial resources, that is, the capacity of AMPHS, that can be provided by abandoned mines for the development of PHS. Therefore, our goal is to build smaller AMPHS with lower economic cost and realize better effect of suppressing PV fluctuation. In addition, this method achieves storage of about 1%–6% of the PV system's power generation per day, with an average of 2.3 % of the PV system's power generation per year. Furthermore, an examination of the daily scale optimized power curves reveals that the optimization method proposed in this study for the abandoned mine PV-PHS hybrid system can extend the power generation time of the PV system by 0.5–3 h per day, with an average prolongation time of 2.5 h.

The method also has some limitations at present. We did not further analyze the geological conditions and hydrological conditions of the underground space of the abandoned mine. And these natural conditions might affect our choice of roadways and mining areas. They may also affect the normal operation of AMPHS. In short, they can be a constraint to the construction of AMPHS. Incorporating them into our model is one of our future research directions.

Based on the above discussion of the results, this study makes the following three contributions: (1) this paper proposes a method for optimizing the capacity allocation of AMPHS in an abandoned mine PV-PHS hybrid system with the purpose of suppressing PV fluctuations; (2) the maximum suppression of PV fluctuations can be achieved by the method, and the power generation duration of the whole hybrid system can be extended by the complementary process of PHS and PV; (3) This paper proposes a data-driven mechanism for optimizing the capacity of AMPHS in a cycle of days, which can increase the model's consideration of more uncertainties by expanding the dataset in order to improve the reliability of the model results.

The results of the study are of great significance in guiding the development and reuse of abandoned mine resources under various scenarios, providing a new direction and model for the synergistic development and utilization of clean energy and abandoned mine resources, and playing a key role in realizing China's goal of carbon neutrality by 2060.

Data availability statement

Has data associated with your study been deposited into a publicly available repository? No.

Please select why. The authors do not have permission to share data.

CRediT authorship contribution statement

Chenglong Cao: Writing – original draft, Formal analysis. **Dong Jiang:** Writing – original draft, Supervision, Formal analysis. **Liu Yang:** Writing – original draft. **Gang Lin:** Writing – original draft, Supervision, Formal analysis. **Jingying Fu:** Formal analysis. **Xiang Li:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix ASupplementary data

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