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Feasibility and case studies on converting small hydropower stations to pumped storage

Yangqing Dan¹, Qingyue Chen¹✉, Daren Li², Wenhuan Bai^{3,4}, Weiming Zhou^{3,4}, Anyu Yang^{3,4} & Jia Yang^{3,4}

Hydropower, as a controllable energy source, plays a crucial role in supporting essential functions such as peak shaving, frequency regulation, and load reserve within modern power systems, thereby enhancing the overall economic efficiency and safety of these systems. This study utilizes data from small hydropower stations and advanced software algorithms to preliminarily evaluate the feasibility of converting conventional small hydropower stations in Zhejiang Province into pumped storage hydropower stations, with the province serving as the focal research area. Through comprehensive analysis and field investigations, Jiangshantou Hydropower Station has been selected as the pilot site for this conversion initiative. The proposed conversion scheme has been assessed, and predictions regarding annual operating hours, power generation, and energy consumption have been formulated. The analysis indicates that Jiangshantou Pumped Storage Hydropower Station will serve as the primary mechanism for power regulation. Furthermore, a small-scale integrated hydropower-wind-solar power system is proposed to ensure stable system output, improve the input-output ratio, and enhance the efficiency of renewable energy utilization.

Optimal locations for development have been identified, including a 6-hectare photovoltaic installation situated approximately 3.5 km from the dam, alongside a nearby elevated site suitable for wind energy generation. Tools such as SolarGIS and the Global Wind Atlas were employed to assess the solar and wind resources in the area, revealing that the site possesses abundant and stable solar resources, as well as favorable indicators for wind energy, making it an ideal candidate for photovoltaic and wind energy development. This research establishes a comprehensive framework for the conversion of conventional hydropower stations into pumped storage facilities, offering a model for medium-small scale pumped storage and distributed generation technologies. It is recommended to implement photovoltaic forecasting systems at the PV site to achieve more precise control over photovoltaic output and enhance the responsiveness of the pumped storage station to fluctuations in solar power.

Keywords Pumped storage hydropower, Small hydropower conversion, Renewable energy integration, Photovoltaic and wind resources, Energy system optimization

In its pursuit of both carbon neutrality and peak carbon emissions, China is rapidly accelerating the expansion of renewable energy, particularly solar and wind power, while actively constructing a modern power system that prioritizes these energy sources¹. By the close of 2023, wind and solar power capacities had grown to represent 16.5% and 15.2% of China's total installed capacity, respectively, while the share of thermal power had declined to 47.3%². Nevertheless, wind and solar energy contributed only 10.2% and 5.1%, respectively, to the country's overall electricity generation by the end of 2023³. This gap underscores the ongoing challenge of incorporating these variable and intermittent energy sources into the grid⁴. The intermittent nature of wind and solar power can lead to reduced system flexibility, inadequate disturbance resistance, and potential operational failures, posing significant challenges to the reliable operation of the power system^{5,6}. In order to reduce these effects and boost the proportion of renewable energy in power generation, studies are exploring various energy complementary systems, such as the combination of storage solutions and flexible generation facilities, is of substantial practical

¹Economic Research Institute of State Grid Zhejiang Electric Power Company, Hangzhou 310003, Zhejiang, China. ²State Grid Wenzhou Electric Power Supply Company, Wenzhou 325000, Zhejiang, China. ³National Research Institute for Rural Electrification, Ministry of Water Resources, Hangzhou 310003, Zhejiang, China. ⁴Research Center on Rural Hydropower, Ministry of Water Resources, Hangzhou 310003, Zhejiang, China. ✉email: qingyuechen163@163.com

value⁷. The “14th Five-Year Plan for Renewable Energy Development” outlines that by 2035, China aims to achieve basic modernization, with peak carbon emissions stabilizing and gradually declining thereafter. The plan sets ambitious targets, including a non-fossil energy consumption share of around 25% and a total installed capacity of wind and solar power reaching 1.2 billion kilowatts by 2030⁸.

To tackle these challenges, various multi-energy complementary systems are under investigation, including combinations like wind-solar-storage, wind-solar-thermal, and wind-solar-hydro^{9–13}. Hydropower, known for its high efficiency, flexible operation, and low unit output cost, can effectively support the new power system by balancing the variability of wind and solar power^{14,15}. Among the various hydropower technologies, pumped storage hydropower (PSH), which converts kinetic and potential energy between upper and lower reservoirs, has proven to be a reliable and cost-effective solution for energy storage and grid stability¹⁶. Pumped Storage Hydropower (PSH) is an essential renewable energy technology that balances electricity supply and demand within power grids. Although PSH projects involve high construction and operational costs, their long-term economic benefits are significant. These benefits include efficient energy storage and release, enhanced grid stability, and reduced operational costs for power companies during peak demand periods. According to the U.S. Department of Energy, PSH projects can provide system regulation services, such as frequency regulation, peak shaving, and price optimization, thereby positively impacting electricity markets¹⁷. Furthermore, PSH projects can stimulate local economic development by generating employment opportunities and providing stable electricity supply to communities¹⁸. In addition to PSH, other energy storage technologies, such as battery storage, compressed air energy storage (CAES), and thermal energy storage, offer unique economic benefits. Battery storage, particularly lithium-ion batteries, is known for efficient energy conversion and quick response time, though it incurs high costs. CAES provides high energy storage density and long lifespan but requires substantial equipment and maintenance expenses due to its technical complexity. Thermal energy storage offers high energy conversion efficiency and long lifespan but also involves significant equipment and maintenance costs. In conclusion, PSH and other similar models offer unique economic benefits across various scenarios¹⁹. Proper assessment and optimization can further enhance the economic advantages of these technologies, supporting the growth of renewable energy.

By the end of 2023, China had developed a PSH capacity totaling 40 million kW, with an extra 60 million kW actively being constructed, demonstrating the country’s increasing investment in this technology. The “Medium- and Long-Term Plan for Pumped Storage Development (2023–2035)” highlights a significant expansion of PSH capacity, aiming for a total installed capacity of 62 million kW by 2025 and 120 million kW by 2030²⁰.

Although the majority of PSH projects, both operational and under construction, are large-scale, there is growing interest in developing medium- and small-scale systems, particularly in resource-abundant areas like Hubei, Zhejiang, Jiangxi, and Guangdong. Considering the rising focus on environmental conservation and the significant time and financial resources needed for large-scale projects, converting existing conventional hydropower stations into small-scale PSH facilities offers a practical alternative²¹. This approach not only leverages existing reservoir capacities but also enhances the integration of distributed solar and wind power²².

By focusing on the transformation of small hydropower stations, this research aims to explore the feasibility and constraints of converting conventional hydropower stations into hybrid PSH facilities, and to assess the potential of small-scale PSH systems in supporting distributed renewable energy sources. This study will utilize data from small hydropower platforms to analyze the feasibility and constraints of such conversions and assess the potential benefits of integrating small-scale PSH with distributed renewable energy. The results are anticipated to provide important insights for optimizing energy storage and enhancing the efficiency and sustainability of renewable energy systems. Although existing research has extensively covered the integration of renewable energy sources with energy storage technologies, there remains a significant gap in specifically addressing the feasibility and constraints of such conversions in small-scale hydropower systems. This research fills this gap by providing a detailed analysis of the technical and economic feasibility of such conversions, without focusing on optimization or simulation aspects.

Methods

System objectives

The objective of small-scale PSH integrated with wind-solar hybrid systems is to utilize the PSH facility as the primary regulatory mechanism to stabilize overall power output, ensuring reliable system performance while optimizing the use of renewable energy sources. Given the significant variability in the outputs of photovoltaic (PV) and wind power, PSH stations can leverage stored water energy by releasing it through turbines during peak load periods. This process mitigates fluctuations in PV and wind generation, aids in managing higher system peaks, maintains supply reliability, and enhances overall system economics. During low demand periods, electricity generated by PV and wind sources is stored by pumping water into an upper reservoir. The operational principles of this system are illustrated in Fig. 1.

To ensure the reliability of the hybrid power generation system, it is crucial to optimally design the capacities of its various components. Current research on the capacity configuration of hydro-wind-solar hybrid systems encompasses various optimization objectives, including operational efficiency, flexibility, and economic viability. The implementation of hydro-wind-solar hybrid systems should be tailored to meet unique local conditions and practical engineering requirements. Based on existing research, conventional hydropower stations, typically small-scale and funded by private capital, are often converted into PSH stations with the aim of reducing investment while enhancing output. To optimize the design of the complementary system, we established a three-tier objective model with the primary goals of ensuring stable system output, maximizing the input-output ratio, and maximizing the utilization of wind and solar energy. The weights were assigned in descending order of importance. The three-tier objective model is designed to clarify the system design goals for converting conventional small hydropower stations into hybrid pumped storage hydropower (PSH) facilities. The first

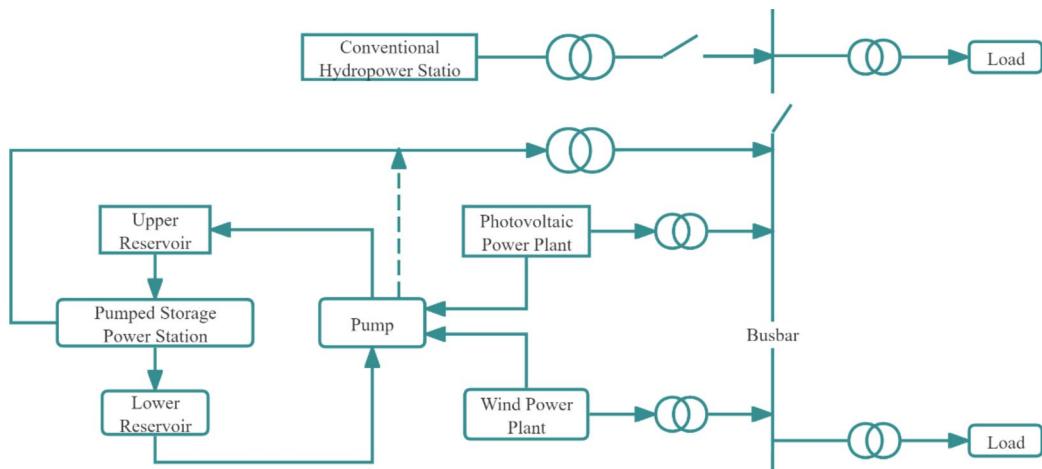


Fig. 1. Principle diagram of small-scale PSH with wind-solar hybrid power system.

tier of the model aims to ensure stable system output, with a weight of 0.5. The primary objective here is to maintain the stability of the overall system output and minimize fluctuations that could impact the grid. This is achieved by coordinating the output of different energy types during the design process, such as using pumped storage to balance load variations when wind and solar power are highly variable. The stable system output is crucial for reliable operation and consistent energy supply. The second tier focuses on maximizing the input-output ratio, with a weight of 0.3. This goal is centered on optimizing the economic efficiency of the system and maximizing the return on investment. It involves analyzing the input and output of each energy component to optimize resource allocation and ensure maximum economic benefits. For instance, by selecting the most cost-effective combination of energy sources, the system can achieve higher economic performance. The third tier aims at maximizing the utilization of wind and solar energy, with a weight of 0.2. This objective prioritizes the consumption of wind and solar power outputs and implements storage and scheduling strategies to reduce curtailment. For example, surplus wind and solar power can be stored in energy storage devices for use during peak demand periods. This maximization of renewable energy utilization helps in reducing dependency on non-renewable sources and promoting sustainability. By integrating these three tiers into the feasibility assessment, the model provides a comprehensive framework that ensures reliable operation, economic viability, and efficient use of renewable energy sources in the retrofitted hybrid power generation system.

Data sources

The foundational database for conventional hydropower is critical for analyzing the conversion to PSH. The small hydropower data platform contains essential information for over 46,000 hydropower stations nationwide. Among these, more than 25,000 are located across eight provinces within the Yangtze River Economic Belt: Jiangsu, Anhui, Jiangxi, Zhejiang, Hunan, Hubei, Guizhou, Sichuan, Chongqing, and Yunnan. Collectively, these provinces account for over 50% of the country's electricity production. This platform provides detailed data, including the latitude and longitude of powerhouses and dams, the rivers where the stations are located, installed capacity, historical generation data, dam height, reservoir capacity, development methods, and ownership forms.

Crucial meteorological factors, such as wind speed, solar radiation, air density, and temperature, serve as fundamental indicators for assessing the potential of wind and solar power generation. Given the challenges of acquiring data from meteorological stations and field measurements, this study employs computer simulation tools to evaluate wind and solar resources near PSH facilities and to identify optimal locations for wind-solar development. The Earth's atmospheric system functions as a complex, nonlinear structure. Advances in atmospheric detection technologies enable large-scale numerical simulations, supported by high-performance computing clusters and weather research and forecasting models, to replicate atmospheric circulation processes on medium to large scales, facilitating the analysis of meteorological data across distances ranging from several meters to thousands of kilometers. This approach is currently a primary method for macro-regional wind energy resource research.

This study utilizes wind energy resource forecast data provided by the Global Wind Atlas platform. Developed by the World Bank, this platform offers global wind resource maps and hourly time series data at heights of 50 to 150 m through numerical simulations. The data is validated against wind speed measurements from over 250 global sites, ensuring high accuracy. While ground-based radiation measurements are the most precise method for obtaining solar resource data, establishing local solar observation points and integrating long-term meteorological station data to estimate future solar radiation is time-consuming and computationally intensive. Furthermore, the sparse distribution and limited number of ground observation stations constrain practical usage. Consequently, the primary method for acquiring solar resource data relies on satellite remote sensing through physical inversion techniques. Among the commonly used solar radiation simulation tools—NASA, Meteonorm, and SolarGIS—SolarGIS offers the highest spatial resolution of 250×250 m, with time resolution at monthly, daily, and hourly levels, and has a long-term database exceeding ten years. Therefore, we selected

SolarGIS for solar resource analysis. SolarGIS combines satellite remote sensing data with radiation transfer simulations, leveraging satellite imagery and geographic information technology, utilizing advanced scientific algorithms to perform simulations of global solar radiation reflection, yielding essential solar radiation data, including Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Radiation (DIF). Additionally, detailed meteorological parameters such as temperature, atmospheric pressure, average wind speed, and wind direction are provided. Comparative analyses indicate that the error between GHI data and ground measurements ranges from 8 to 15%.

Technical route

The primary focus when converting conventional hydropower into PSH facilities is to optimize power generation metrics and extend utilization hours. Concurrently, the examination of wind and solar resources aims to improve the integration capacity of wind-solar power systems. The overall technical route is as follows:

Data collection and analysis: Gather information on hydropower stations located in Zhejiang Province and assess the feasibility of transforming these stations into PSH facilities. Narrow the scope to target research areas at the district level. Conduct further analyses and on-site investigations to establish pilot conversion stations and evaluate conversion plans. **Resource data collection:** Collect wind and solar resource data for the target area, including topography, digital elevation models, geological information, land cover distribution, and human activity data such as nature reserves, transportation infrastructure, and settlements. Create a comprehensive database to support resource analysis. Identify preliminary sites and utilize geographic information digital calculations, multi-resolution fusion, and multi-type mixed computation techniques to obtain wind-solar resource data and assess key indicators. **Capacity configuration assessment:** Analyze the capacity arrangement for integrating PSH systems with wind-solar hybrid systems.

Study area selection

Overview of hydropower, wind, and solar energy resources in Zhejiang Province

Zhejiang Province, located in southeastern China along the coast, is characterized by a subtropical monsoon climate, with an average annual rainfall of approximately 1600 mm, indicating an abundance of water resources. The province's diverse landscape consists of 74.6% mountainous areas, 5.1% water bodies, and 20.3% flatlands, sloping from the southwest to the northeast. Major river systems include the Qiantang, Ou, and Yong Rivers. Zhejiang holds significant potential for hydropower development, particularly in small-scale hydropower. By the end of 2020, the province had established 2861 hydropower plants with a combined installed capacity of 4.11 million kW, achieving a resource development rate of 88%²³.

Zhejiang also benefits from favorable solar energy potential, with annual sunlight utilization hours ranging from 1200 to 1400 h, making it well-suited for the development of photovoltaic (PV) power stations. During the 13th Five-Year Plan period, PV capacity expanded rapidly, reaching 25.39 GW by 2022, nearing the province's established targets. Wind energy resources are primarily concentrated in offshore, coastal, and mountainous regions, with wind speeds decreasing as one moves inland²⁴. Consequently, the focus of wind energy development has shifted towards offshore wind farms due to the limited availability of onshore resources. Zhejiang is actively pursuing the conversion of conventional hydropower into PSH systems and is exploring the integration of hydropower, wind, and solar energy, capitalizing on its abundant natural resources and robust environmental foundations.

Climate and topography analysis of the study area

Climate

Pan'an County is located in a subtropical monsoon climate zone, characterized by warm and humid conditions with abundant rainfall. The winter and summer monsoons alternate significantly, resulting in distinct seasonal variations. Due to the complex terrain, there is a considerable diurnal temperature range. The annual average temperature ranges from 13.9 °C to 17.4 °C, with the lowest temperatures occurring in January (2.0–4.3 °C) and the highest in July (25.6–28.8 °C). Spring and autumn are relatively long, while summer is short. The area experiences limited sunshine, frequent cloud cover, and notable microclimatic variations.

Geology and topography

Pan'an County is predominantly characterized by mid-to-low mountain terrain, classified as a purely mountainous region. Influenced by the Tianmu, Kuaiji, and Xianxialing mountain ranges, the region has a high and complex topography with overlapping mountain ranges. The central and southern parts of the county are higher in elevation, with Qianmeijian, the highest peak, located at the border with Xianju County, reaching an altitude of 1314 m. The western part is lower, with the lowest point being the Jiexigou Valley in the northeast, at an altitude of 150 m, resulting in a relative elevation difference of 1164 m.

The geological structure of Pan'an County predominantly consists of Mesozoic Upper Jurassic volcanic rock series, followed by Cretaceous terrestrial clastic rocks, Quaternary loose sediments, and minor Tertiary basalts. The geology is primarily characterized by fault structures, including NNE-SSW, NE-SW, E-W, and N-S oriented fault systems. The peak ground acceleration in the planning area is less than 0.05 g, with a characteristic period of 0.35 s for the seismic response spectrum. The basic seismic intensity is lower than level IV, indicating good regional stability. The topography encompasses soil, rocks, and groundwater, which influence factors such as foundation bearing capacity, soil erosion, and geological hazards. The main soil types in Pan'an County include red soil, yellow soil, lake soil, and paddy soil, characterized by sandy, loamy, and clayey textures, offering good bearing capacity and drainage performance. Groundwater in Pan'an County is categorized into loose pore water, red bed pore-fissure water, and bedrock fissure water, primarily replenished by atmospheric precipitation and surface water. The groundwater level is relatively low, and the hydrogeological conditions are simple. Common

meteorological disasters in Pan'an County include heavy rainfall, typhoons, and high temperatures. Due to the complex terrain and abundant mountains and hills, soil erosion is severe. Heavy rainfall can lead to mountain floods, debris flows, and landslides. The county is significantly affected by typhoons, with strong winds and heavy rains during typhoon events causing substantial damage.

Current status of hydropower development in the study area

Pan'an County is situated at the intersection of the Tiantai, Kuaiji, Kuocang, and Xianxia mountain ranges. It is the source of several tributaries, including the Jinhua River, which is part of the Qiantang River system, the Chengtan River, part of the Cao'e River system, the Hao Creek, part of the Ou River system, and the Yong'an and Shifeng Creeks, part of the Jiao River system. The rivers within the county are radially distributed, characterized by short and steep courses, large riverbed slopes, and significant fluctuations in water levels. These are typical mountainous rivers, highly influenced by precipitation, experiencing rapid rises and falls during floods, and minimal flow during dry seasons, with smaller streams prone to interruption. The total water resources in the county amount to 1.085 billion cubic meters. As of the end of 2023, there were a total of 51 small hydropower stations in Pan'an County. Among these, 7 stations were scheduled for rectification or immediate decommissioning, 44 stations were under rectification, and none were retained without modification. Post-rectification, there were 44 operational hydropower stations. An analysis of the installed capacity of the operational stations shows that 25 stations (56.8%) have an installed capacity of less than 1000 kW, accounting for 19.6% of the county's total installed capacity. There are 18 stations (40.9%) with an installed capacity between 1000 kW and 5000 kW, representing the largest share at 62.9% of the total installed capacity. The county's largest hydropower station has an installed capacity of 10,000 kW. In terms of construction timeline, 30 stations (68.2%) were built and commissioned before 2003, accounting for 45.3% of the total installed capacity. In contrast, 14 stations (31.8%) were built and commissioned in or after 2003, accounting for 54.7% of the total installed capacity.

Overview of power source construction in the study area

By the end of 2023, the total installed capacity of power plants at 110 kV and below voltage levels in Pan'an County was 231.235 MW. This capacity primarily comprises hydropower stations, photovoltaic power stations, and wind power, with hydropower accounting for 22.34%, photovoltaic power stations for 21.09%, and wind power for 56.57%. The specific installation situation of each type of power station is as follows:

Hydropower stations By the end of 2023, Pan'an County had 44 hydropower stations with a total installed capacity of 51.665 MW, accounting for 22.34%. Among these, six stations had a larger reservoir capacity, with a combined installed capacity of 16 MW.

Photovoltaic power stations As of the end of 2023, the total installed capacity of photovoltaic power stations in the county was 48.77 MW, accounting for 21.09%. It is projected that by the end of 2023, an additional 100 MW will be added, and approximately 300 MW will be added during the "14th Five-Year Plan" period, further increasing the proportion of photovoltaic power.

Wind power Pan'an County's current total installed capacity of wind power is 130.8 MW, accounting for 56.57%.

In 2023, the maximum load for the whole society in Pan'an County was 135,400 kW, the total electricity consumption was 663 million kWh, and the electricity sales amounted to 610 million kWh. The power supply reliability rate (RS-3) was 99.9685%, the comprehensive line loss rate for 110 kV and below was 5.8%, the line loss rate for 10 kV and below was 6.08%, the comprehensive voltage qualification rate was 99.908%, and the rate of one household, one meter was 100%, with a total of 124,200 users. The State Grid Pan'an County Power Supply Company is responsible for the construction, operation, development, and power supply tasks of the county's power grid. It is a directly managed county-level power supply enterprise under the State Grid Zhejiang Electric Power Company, covering a supply area of 160.2 km² and serving a population of 182,100.

PSH conversion analysis

Site selection analysis

Using ArcGIS geospatial analysis software, a preliminary site selection process was developed based on constraints, including an elevation difference approximating a head greater than 100 m and a distance-to-head ratio (L/H) relaxed to less than 30. The data sources included vector point data for reservoirs with capacities exceeding 100,000 cubic meters in Zhejiang Province, vector line data for rivers, vector polygon data for administrative boundaries, and GDEM V3 30 m resolution DEM raster data. A preliminary algorithm for site selection to convert conventional hydropower stations into PSH facilities was created, resulting in the identification of pairs of power stations that meet the criteria. The results, as depicted in the Fig. 2, show 298 pairs linked by lines throughout the province. Most pairs are concentrated in the southwestern and central mountainous counties of Zhejiang, such as Songyang, Suichang, Pan'an, Xianju, Wencheng, Taishun, Cangnan, and Tiantai, which possess the geographical attributes required for constructing PSH stations due to their varied terrain and significant elevation differences. Some pairs are clustered, allowing a single station to potentially be paired with several nearby stations for PSH construction.

Preliminary GIS analysis indicates that the northwest corner of Pan'an County contains five pairs of stations that fulfill the elevation difference and distance-to-head ratio constraints, qualifying it for further analysis. The rivers in Pan'an County exhibit a radial distribution with short source lengths, steep riverbed slopes, significant water level variations, and notable precipitation impacts. These rivers, typical of mountainous regions, are prone to flood surges and declines, experiencing low runoff during dry periods, with smaller streams frequently

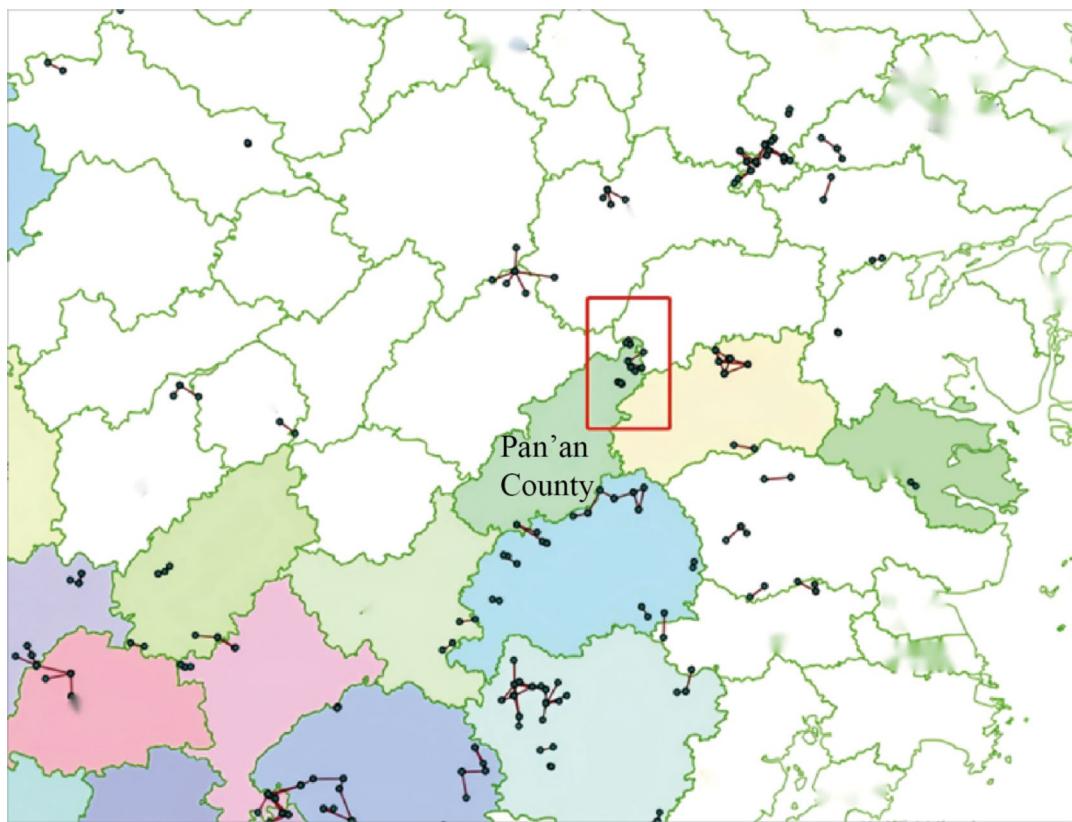


Fig. 2. Preliminary analysis results of Zhejiang Province Conventional Unit to PSH GIS.

facing flow interruptions. The total water resources in the county amount to 1.085 billion cubic meters. The foundational data for small hydropower stations in Pan'an County is sourced from the Yangtze River Economic Belt Cleanup and Rectification Platform. This includes essential information on the stations and their water sources, such as installed capacity, development mode, ownership, coordinates of powerhouses and dams, dam height, reservoir capacity, catchment area, and dam type. Data analysis from the platform shows that Pan'an County has 51 small hydropower stations, of which 7 have exited service due to cleanup and rectification, and 44 are currently undergoing rectification, with none retained. Thus, after cleanup, 44 stations remain operational. Among these, 25 stations have an installed capacity of less than 1000 kW, accounting for 56.8% of the stations and 19.6% of total installed capacity; 18 stations have capacities between 1000 and 5000 kW, representing 40.9% of the number of stations and 62.9% of total installed capacity; and one station has a maximum capacity of 10,000 kW.

Regarding construction years, 30 stations were built before 2003, representing 68.2% of the total number and 45.3% of installed capacity. Fourteen stations were constructed in 2003 or later, accounting for 31.8% of the total number and 54.7% of overall installed capacity. Functionally, 26 stations have comprehensive uses, such as flood control, irrigation, and water supply, while 18 are dedicated solely to power generation. Preliminary analysis indicates that the small hydropower stations in the county are characterized by small individual capacities, a high number of stations, and older construction periods, many of which serve multiple purposes. Based on the screening criteria, all current stations in Pan'an County were summarized, and terrain location information was determined using 1:10,000 topographic maps. River segments served as the research units, and preliminary screening identified resource points meeting the basic conditions for PSH utilization. Using 1:10,000 topographic maps and vector data, the horizontal distances between tiered reservoirs were measured, and reservoir characteristic data, such as normal storage level and dead storage level, were consulted to calculate the maximum, minimum, and average heads, along with the distance-to-head ratios for the PSH stations. Brief parameters are presented in Table 1 (detailed information of the power station is presented in Table A.1 (see Appendix A of [Supplementary Material](#))).

Refinement of criteria for selecting PSH station sites

The guidelines for enhancing the site selection process for PSH stations are informed by design and planning standards, along with insights from both domestic and international facilities. The essential criteria for site selection include:

Moderate head difference: The average height difference (H) between the upper and lower reservoirs is crucial for site selection. PSH relies on the potential energy of water, with an optimal height difference typically ranging from 300 to 600 m. While a greater elevation improves energy conversion efficiency, it complicates site

Power station name	Reservoir name	Catchment area (km ²)	Total reservoir capacity (10 ⁴ m ³)	Installed capacity (kW)	Annual power generation (10 ⁴ kW·h)	Design head (m)	Water diversion flow (m ³ /s)
Yujinxia Power Station	Yujinxia Reservoir	30.25	258.8	2400	588	101	3.45
Wuzhangyan Level 1 HPP	Wuzhangyan Reservoir	106.2	2163	2400	632.1	35	9.68
Sanqli Power Station	Sanqli Reservoir	131.4	115	10,000	2550.1	98	11.84
Santiao Power Station	Santiao Reservoir	162.6	147	4000	955.9	28	14.37
Chengxi Power Station	Xiafan Reservoir	3.13	119.31	100	38.7	24	0.14
Dongwushanhe Power Station	Dongwu Reservoir	57.85	538.3	1260	254.2	33	6.74
Jiangshantou Power Station	Leigunkou Reservoir	51.76	660	3200	640.8	43	0.57
Matikeng Power Station	Matikeng Reservoir	8.5	390	200	81.9	40	0.83
Huaxi Power Station	Huaxi Reservoir	21.67	490.6	1260	43.9	78	2.16
Longtanxi Level 2 HPP	Longtanxi Reservoir	17.45	98	1890	298.64	103	1.953
Dalu Power Station	Dalu Reservoir	3.85	125.41	150	10.97	20.8	1.1
Chatan Power Station	Chatan Reservoir	59	307.78	1200	194.4	27	4.83

Table 1. Site selection table for PSH utilization in Pan'an County.

Combination	Upper reservoir	Lower reservoir	Height-to-distance ratio	Elevation difference (m)	Straight-line distance (km)
1	Xiafan Reservoir	Santiao Reservoir	13.28	283	3.76
2	Wuzhangyan Reservoir	Sanqli Reservoir	24.47	146	3.57
3	Wuzhangyan Reservoir	Santiao Reservoir	26.6	258	6.86
4	Xiafan Reservoir	Sanqli Reservoir	31.46	171	5.38
5	Jiangshantou Reservoir	Shuangxi Reservoir	31.65	79	2.5

Table 2. Hydropower station combinations with the smallest distance-to-height ratio.

selection and increases equipment pressure and costs. Conversely, a lower height difference requires larger water flows, raising construction costs per kilowatt. Thus, maintaining an appropriate height difference is a primary consideration.

Appropriate distance-to-head ratio (L/H): The distance-to-head ratio (L/H)—the horizontal distance (L) between the intakes of the upper and lower reservoirs relative to the average head (H)—is critical for minimizing hydraulic losses and construction costs. An optimal L/H ratio not exceeding 10 is preferred. A higher ratio increases investment costs and efficiency losses due to longer conveyance systems, while an excessively low ratio complicates system arrangements and stability at tunnel inlets and outlets.

Supplementary water sources: While PSH relies on its own water cycles, losses from evaporation, leakage, and ice formation may necessitate additional water supply. The ideal site should be within a watershed large enough to exceed the maximum water level of the lower reservoir, ensuring continuous operational supply.

Reasonable dam height: The lower reservoir typically requires a larger surface area, thus necessitating a relatively modest dam height. In contrast, the upper reservoir, often located in valleys or mountainous areas, requires a higher dam to meet volume conditions. However, excessive dam height significantly raises investment costs, with heights typically not exceeding 100 m for economic feasibility.

Geological conditions: Extensive underground excavation and construction necessitate careful consideration of terrain, geological layers, rock structure, and stability. Geological conditions influence leakage rates, structural stability, and project feasibility. Sites should be distanced from seismic zones and regions of poor stability, requiring thorough engineering investigations for existing reservoirs under consideration for conversion.

Geographical location: Ideally, sites should be close to power grid load centers to facilitate efficient energy delivery, with surrounding infrastructure—including roads and transportation—favorable for construction.

Based on these principles, further analysis and screening of the preliminary selected reservoir sites have identified several candidates for potential conversion into PSH stations, summarized in Table 2.

The Jiangshantou Power Station was selected as the primary focus of this research for several reasons: (a) With an installed capacity of 2×1600 kW, the Jiangshantou Power Station ranks fourth in Pan'an County and includes a significant regulating reservoir with a normal capacity of 6.4 million cubic meters, thereby ensuring robust regulatory capabilities, despite lacking integrated utilization functions. (b) The downstream Shuangxi Reservoir, a regulating reservoir for the Shuangxi Hydropower Station, can be modified to effectively meet regulatory needs. (c) Both the upstream and downstream cascade stations are owned by the same entity, facilitating ease of operation scheduling and policy coordination, with the owner demonstrating a strong commitment to construction. (d) Upgrading the Jiangshantou Power Station to incorporate PSH would negate the need for a new water conveyance system, as only a pumping unit installation is required, thereby reducing retrofitting costs.

Parameter calculation

In the study of PSH utilization, key parameters and indicators are critical for calculation and analysis, categorized into three main groups: hydrological and reservoir characteristics, dynamic characteristics, and major structures.

The hydrological and reservoir features of the upper and lower reservoirs include nine key indicators: catchment area above the dam site, average annual runoff, total reservoir capacity, normal water level, reservoir capacity at normal water level, dead water level, dead storage capacity, cut-off depth, and effective capacity. The dynamic characteristics of the PSH station consist of nine indicators: total installed capacity, average annual energy output, average annual energy consumption for pumping, design flow rate, volume of water for power generation, maximum head, minimum head, average head, and key structural components. Key structural design parameters for the pump station include design flow rate and design lift, which are essential for evaluating the feasibility, efficiency, and overall performance of the PSH facility, serving as guidance for both design and operational planning.

Located in Pan'an County, the Jiangshantou Power Station utilizes the existing Leigunkou and Shuangxi Reservoirs as its upper and lower reservoirs, respectively. Leigunkou Reservoir, classified as a Type I small reservoir, is situated in Shuangxi Township within the upper reaches of the Xixi River in the Qiantang River Basin. The dam site is 24 km from Pan'an County, with a catchment area of 51.76 km² above the dam and an average annual runoff of 48.1 million cubic meters. The reservoir has a total capacity of 6.6 million cubic meters, a normal storage level of 322.5 m corresponding to a capacity of 6.4 million cubic meters, and a dead water level of 300 m with a capacity of 909,500 cubic meters, resulting in an effective storage capacity of 5.4905 million cubic meters. The station operates under a mixed development mode with an installed capacity of 3200 kW, comprising two units, a design head of 70.5 m, a design discharge rate of 2.687 m³/s, and an average annual energy generation of 6.408 million kWh. The lower reservoir, Shuangxi Reservoir, also classified as a Type I small reservoir, is located in Shuangxi Township, Pan'an County, in the upper reaches of the Xixi River in the Qiantang River Basin, approximately 18 km from Jingning County. This dam site primarily serves power generation. The upstream catchment area covers 112.71 km², yielding an average annual runoff of 103.7 million cubic meters. The total reservoir capacity is 338,000 cubic meters, with a normal storage level of 236.8 m, corresponding to a capacity of 202,000 cubic meters. The dead water level is recorded at 227.7 m, with a capacity of 52,000 cubic meters, leading to an effective storage capacity of 150,000 cubic meters. This station operates under a mixed development model with an installed capacity of 1890 kW across three units, a design head of 36.6 m, a design discharge rate of 5.32 m³/s, and an average annual power generation duration of 2006 h.

The horizontal distance between the upper and lower reservoirs is 2500 m, with a maximum head of 94.8 m, a minimum head of 63.2 m, and an average head of 79 m, resulting in a height-to-distance ratio of 31.65, which is advantageous for the development of a PSH facility. Therefore, the construction of a new pumping station is necessitated. The water conveyance system will utilize the existing water pipeline of the station, with a designed discharge of 2.687 m³/s and a design lift of 75 m, as detailed in Table 3. The design head is determined through site investigation, terrain elevation difference measurement, head loss calculation, operational condition analysis, environmental and social impact assessment, economic analysis, safety and feasibility verification, and scheme optimization, ensuring that it meets technical, economic, and environmental requirements.

Estimation of energy storage generation and absorbed energy

Analysis of operation time and power generation

Based on the data provided by the owner, Fig. 3 summarizes the power generation and operational hours of the Jiangshantou Hydropower Station over a 14-year period, from 2007 to 2020.

Based on the data provided, the Jiangshantou Hydropower Station demonstrates an actual multi-year average power generation of 6.408 million kWh, coupled with an average utilization time of 2003 h annually. Notably, peak power generation constitutes approximately 95% of this total, amounting to about 1903 h, while off-peak power generation accounts for approximately 200 h.

According to the current peak and off-peak periods defined by the Zhejiang power grid, peak demand occurs from 8:00 AM to 10:00 PM, while off-peak periods extend from 10:00 PM to 8:00 AM the following day. This results in a daily peak duration of 14 h, totaling 5110 h annually (365 days × 14 h/day), with off-peak periods lasting 10 h daily, aggregating to 3650 h annually (365 days × 10 h/day).

PSH stations typically leverage off-peak periods to pump water into an upper reservoir and subsequently generate electricity during peak demand times. Given that this project involves mixed development without an increase in generating capacity, it is critical to ensure that the new pumping and generating operations do not disrupt the existing power generation schedule. Specifically, pumping operations will be suspended during the rainy season, typhoon events, and periods when the upper reservoir is at a high water level, prioritizing power generation from natural inflows.

Under optimal conditions, the station could potentially allocate up to 3207 h (5110 h–1903 h) for PSH during peak power generation. Applying an 80% utilization factor, the actual PSH generation time would be 2566 h (3207 h × 80%). Given a 1:1 ratio between pumping and generating time, the station would also have 2566 h available for pumping. Consequently, the total annual operational time for this project amounts to 7135 h, calculated as 2003 h of existing operation, plus 2566 h for pumping, and 2566 h for electricity generation. Out of the total 8760 h available in a year, 1625 h are designated for flexible operation.

Calculation of additional power generation and unit cost of electricity

A PSH station redistributes off-peak electrical energy into peak electrical energy rather than generating new electricity. During periods of low grid demand, excess off-peak electrical energy is utilized to pump water from the lower reservoir to the upper reservoir, effectively storing it as potential energy. When demand peaks, this stored water is released from the upper reservoir through turbines to generate electricity, which is then supplied

No.	Project name	Unit	Parameter
I	Hydrology and Reservoir Characteristics		
1	Upper Reservoir		
(1)	Catchment Area Above Dam	km ²	35
(2)	Average Annual Runoff	10,000 m ³	6650
(3)	Total Reservoir Capacity	10,000 m ³	303.75
(4)	Normal Water Level	M	650
(5)	Reservoir Capacity at Normal Water Level	10,000 m ³	259
(6)	Dead Water Level	M	625.5
(7)	Dead Storage Capacity	10,000 m ³	25
(8)	Drawdown Depth	M	24.5
(9)	Effective Reservoir Capacity	10,000 m ³	234
2	Lower Reservoir		
(1)	Catchment Area Above Dam	km ²	82.43
(2)	Average Annual Runoff	10,000 m ³	15,662
(3)	Total Reservoir Capacity	10,000 m ³	389.5
(4)	Normal Water Level	M	468.8
(5)	Reservoir Capacity at Normal Water Level	10,000 m ³	260
(6)	Dead Water Level	m	446
(7)	Dead Storage Capacity	10,000 m ³	32
(8)	Drawdown Depth	M	22.8
(9)	Effective Reservoir Capacity	10,000 m ³	228
II	Kinetic Characteristics		
(1)	Installed Capacity	kW	8000
(2)	Design Flow Rate	m ³ /s	2.78
(3)	Maximum Head	M	204
(4)	Minimum Head	M	156.7
(5)	Average Head	M	180.4
III	Main Structures		
1	Pumping Station		
(1)	Design Flow Rate	m ³ /s	2.78
(2)	Design Head	M	75

Table 3. Project characteristics for the Jiangshantou power station's conversion to PSH.

back to the grid. The energy absorbed during the pumping cycle and the energy generated during discharge can be represented by the following formulas:

$$E_P = \frac{H_P V_S}{367.2 \eta_p} \quad (1)$$

$$E_T = \frac{H_T V_S \eta_t}{367.2 \eta_p} \quad (2)$$

where E_P is pumping energy consumption (kWh); E_T is generated electricity (kWh); V_S is regulated water volume (m³); H_p is average pumping head (m); H_T is average generation head (m); η_p is Operating efficiency under pump conditions; η_t is Operating efficiency under generating conditions. And the overall efficiency of a single cycle can be expressed as:

$$\eta = \frac{E_T}{E_P} = \frac{H_T}{H_P} \eta_t \eta_p \quad (3)$$

The overall efficiency of a PSH station is influenced by the operational efficiencies of several components, such as the pump, turbine, generator motor, main transformer, and water conveyance system. This overall efficiency can be expressed as:

$$\eta_t = \eta_a \eta_b \eta_c \eta_d \quad (4)$$

$$\eta_p = \eta_e \eta_f \eta_g \eta_h \quad (5)$$

where η is comprehensive efficiency; η_a , η_b , η_c , η_d are the operational efficiency of the power station's water conveyance system, turbine, generator, and main transformer under the generating condition, respectively.

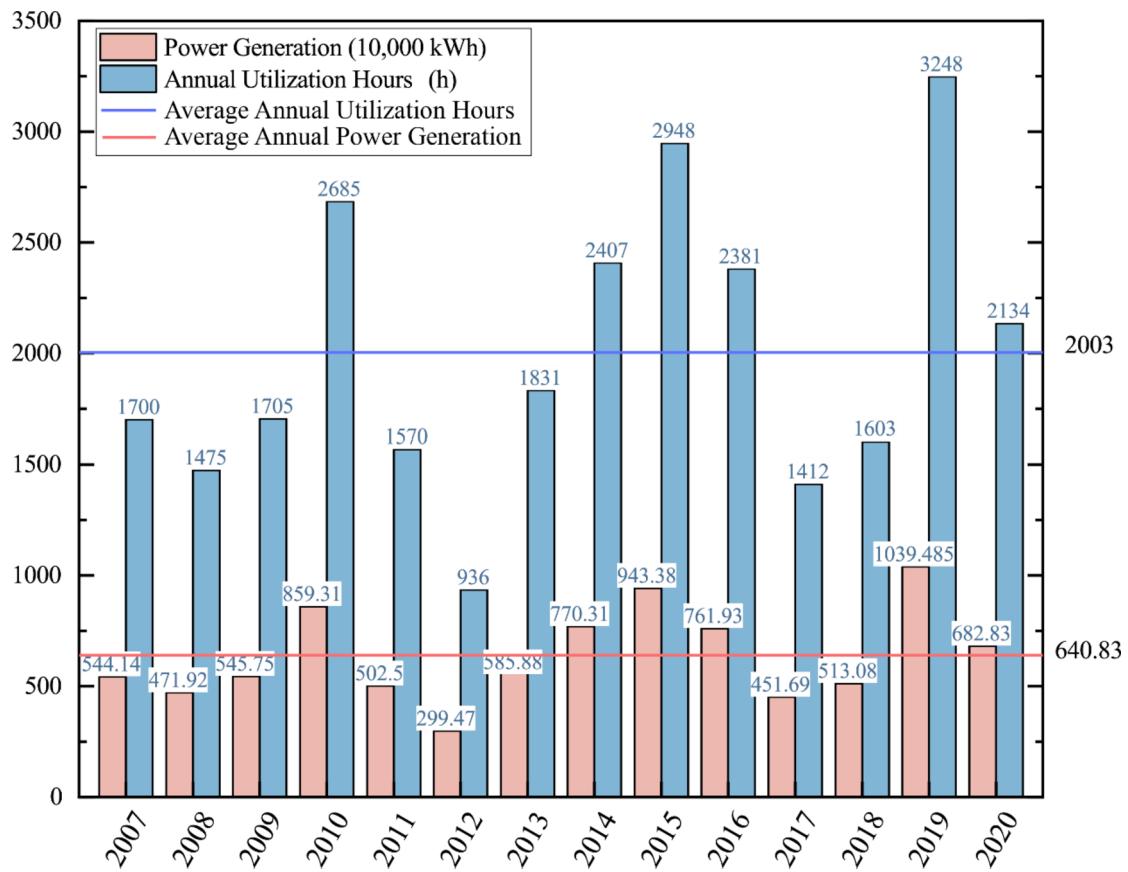


Fig. 3. Power generation data of Jiangshantou Hydropower Station from 2007 to 2020.

Based on practical engineering data, their values are taken as 0.96, 0.9, 0.95, and 0.995, respectively; η_c , η_p , η_g , η_h are the operational efficiency of the power station's water conveyance system, pump, motor, and main transformer under the pumping condition, respectively. Based on practical engineering data, their values are taken as 0.96, 0.88, 0.95, and 0.995, respectively.

Since the head losses in the water conveyance system under both generating and pumping conditions are already considered in η_a and η_e . Both H_p and H_T denote the average value of the elevation difference in water levels between the upper and lower reservoirs, where H_p equals H_T . Consequently,

$$\eta = \eta_t \eta_p = 0.652 \quad (6)$$

Based on the previously calculated additional peak power generation time of 2566 h, the additional peak power generation capacity for this project is $2566 \times 3200 = 8.21$ million kWh. The absorbed off-peak energy is $8.21/0.652 = 12.59$ million kWh. The cost per kilowatt-hour is $1/0.652 = 1.534$ kWh.

Analysis of solar and wind resources

Around the PSH station, it is crucial to evaluate various factors, including solar and wind resources, climatic conditions, geographical features, land use patterns, and relevant policies and regulations. This comprehensive analysis is essential for assessing resource availability, determining the economic feasibility of investments, and establishing site viability.

Analysis of exclusionary constraints

Construction constraints encompass areas designated as basic farmland, water source protection zones, nature reserves, significant mineral deposits, military zones, airports, and cultural heritage sites. Regions classified as ecological red lines—such as nature reserves, forest parks, wetland parks, scenic areas, and essential farmland—are off-limits for development, presenting substantial barriers to the advancement of solar and wind resources. In Pan'an County, there is one ecological red line nature reserve alongside three nature parks: the Dapan Mountain National Nature Reserve, the Dapan Mountain National Scenic Nature Park, the Dapan Mountain Provincial Forest Nature Park, and the Qixian Lake Provincial Wetland Nature Park. Importantly, the Jiangshantou PSH station is situated outside any ecological red lines and does not involve critical mineral deposits or cultural heritage sites. Furthermore, there are no nearby airports or military zones. Satellite imagery reveals that the area surrounding the PSH station is predominantly forested, with a few scattered villages and minimal residential development. According to SolarGIS data, the population density in the region is approximately 41 individuals

per square kilometer, indicating a relatively low density. Consequently, the impact of solar and wind energy development on local residents is expected to be minimal.

Site selection

Given the limited availability of meteorological stations and field data for measuring solar and wind resources, this report employs SolarGIS and the Global Wind Atlas to assess and evaluate the solar and wind potentials in proximity to the PSH station, with the aim of identifying suitable sites for solar and wind development. According to GB/T42766-2023 “Photovoltaic Power Generation Solar Energy Resource Assessment Specification”, “Wind Farm Site Selection Technical Provisions” and other standard specifications, to minimize transmission line investments, site selection should prioritize locations as close to the PSH station as feasible^{25,26}. The PSH station has been marked on the resource analysis platform, and a preliminary site selection criterion of a 20 km radius has been established. Satellite imagery indicates that the area surrounding the PSH station features hilly terrain with varying elevations, a few scattered villages, and high vegetation coverage, with an approximate elevation of 550 m.

Preliminary site selection for photovoltaic systems

Considering environmental protection, ecological conservation, and agricultural production, photovoltaic sites should ideally be situated on unused land, such as barren or abandoned industrial areas. Based on the understanding that a photovoltaic power station requires 23 to 30 acres for every 1000 kW of installed capacity, the Jiangshantou PSH station, which has a capacity of 3200 kW, maintains a 1:1 ratio between photovoltaic and storage capacity. Two large exposed areas, as depicted in Fig. 4, have been selected: one located approximately 3.5 km from the dam site with an area of 0.06 km², and another situated about 2 km from the dam site with an area of 0.036 km². This report will focus on the 0.06 km² exposed land as the primary subject of analysis, hereafter referred to as “the site.”

Wind power site selection

Given that Zhejiang Province has concentrated on offshore wind power and has not approved land-based wind projects for several years, this study suggests selecting a highland near the photovoltaic site adjacent to the PSH station for wind power development²⁷. Figure 5 illustrates the establishment of 30-m contour lines utilizing the GDEM V3 30 m digital elevation model in ArcGIS, with the ridge of the photovoltaic site identified as the preliminary location for wind turbine placement.

Slope and aspect analysis

Terrain significantly influences photovoltaic power stations, particularly in terms of slope, aspect, and gradient. Optimal slopes of 5–30° facilitate the installation and maintenance of photovoltaic modules, enhancing power generation efficiency. The slope aspect and gradient impact the angle and spacing of photovoltaic supports,

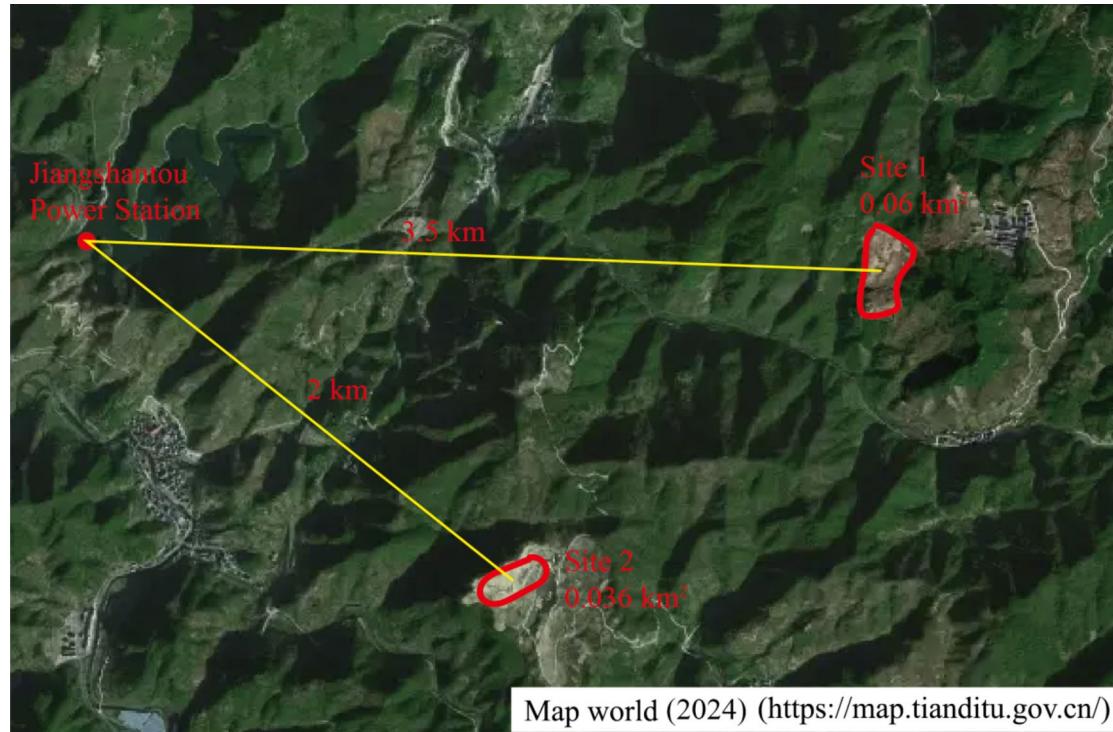


Fig. 4. Preliminary selection of solar PV site satellite imagery.

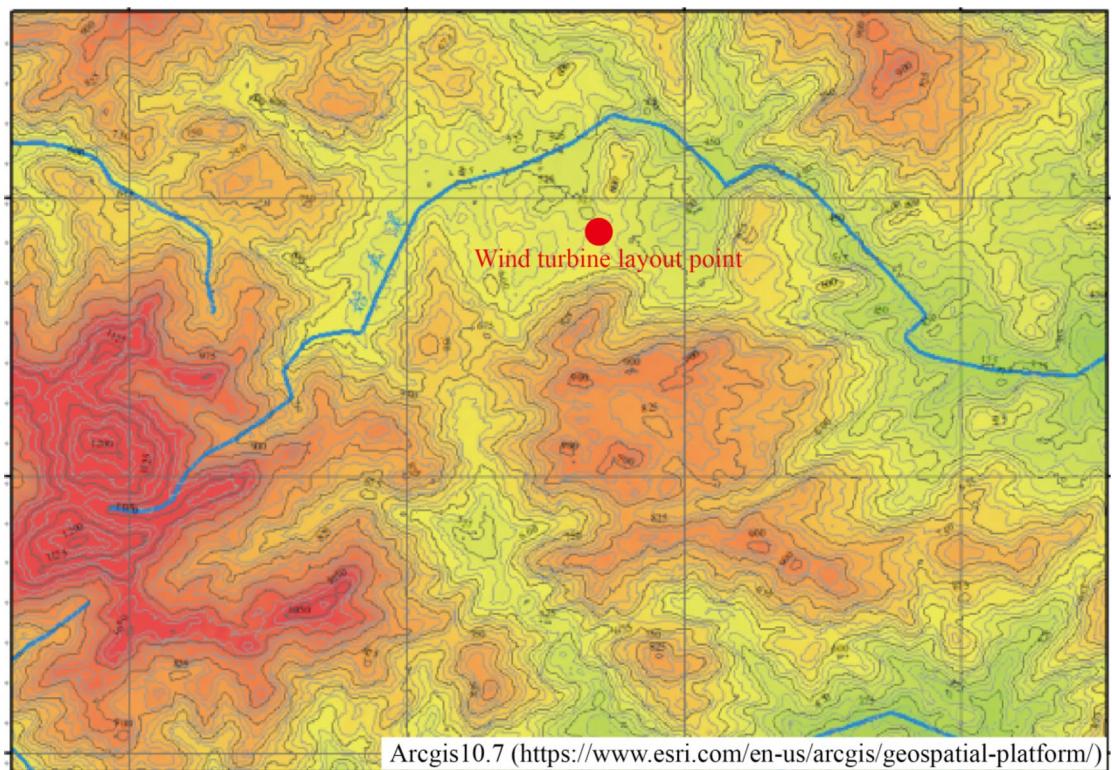


Fig. 5. 30-meter contour map of the solar PV site.

thereby affecting power generation per unit area. Figures 6 and 7 illustrate the analysis of slope aspect and gradient (0°–90°) using the GDEM V3 30 m digital elevation model in ArcGIS. At the potential sites, gradients range from 5°–10°, with an aspect oriented towards the southeast. Additionally, the presence of elevated mountains to the south raises concerns about potential shading.

Solar resource analysis

Solar photovoltaic power generation is highly dependent on solar radiation, with performance, efficiency, and losses affected by various meteorological factors. This section examines long-term variations in solar radiation, humidity, wind speed, and precipitation to evaluate solar resource conditions. Utilizing the SolarGIS online solar resource analysis tool, Table 4 presents key solar radiation and meteorological parameters for the potential sites. The annual averages include: Global Horizontal Irradiance (GHI) at 4695.1 MJ/m², Direct Normal Irradiance (DNI) at 3174.3 MJ/m², Diffuse Radiation (DIF) at 2609.3 MJ/m², and an average annual temperature of 16.4 °C.

Monthly radiation and meteorological statistics

Table 5 summarizes the monthly solar radiation and meteorological values, including annual averages. The total radiation on the horizontal plane begins to rise in January, peaks in July, and subsequently declines through December. The scattering ratio remains relatively stable throughout the year. According to software estimates, the optimal tilt angle for solar panels is 23°. Meteorologically, the highest monthly average temperature occurs in July, reaching approximately 27 °C, with interannual variations displaying a normal distribution. Wind speeds exhibit relatively stable monthly fluctuations.

Optimal tilt angle/GTLopta: 23°/180°.

Daily radiation and meteorological statistics

Tables 6 and 7 provide the average hourly data for total radiation on the horizontal plane and direct normal radiation, illustrating daily changes in solar radiation patterns. Daily variations reach their peak between 11:00 and 13:00 h, exhibiting increasing trends before this peak and decreasing trends afterward. Monthly variations indicate that the highest radiation levels occur in July, followed by August, with corresponding trends of increase and decrease observed before and after these months.

Based on solar resource predictions from SolarGIS, the potential site receives an annual average total radiation of 4695.1 MJ/m², categorizing it as a high solar resource area, thus suitable for photovoltaic power station development. It is advisable to deploy solar radiation monitoring instruments at the project site in the next phase for continuous observation over a year, while also collecting data from the nearest long-term meteorological station on solar radiation, sunshine hours, sunshine percentage, precipitation, and temperature. This will enhance the accuracy of power generation calculations and investment analysis by refining and validating the SolarGIS assessment results.

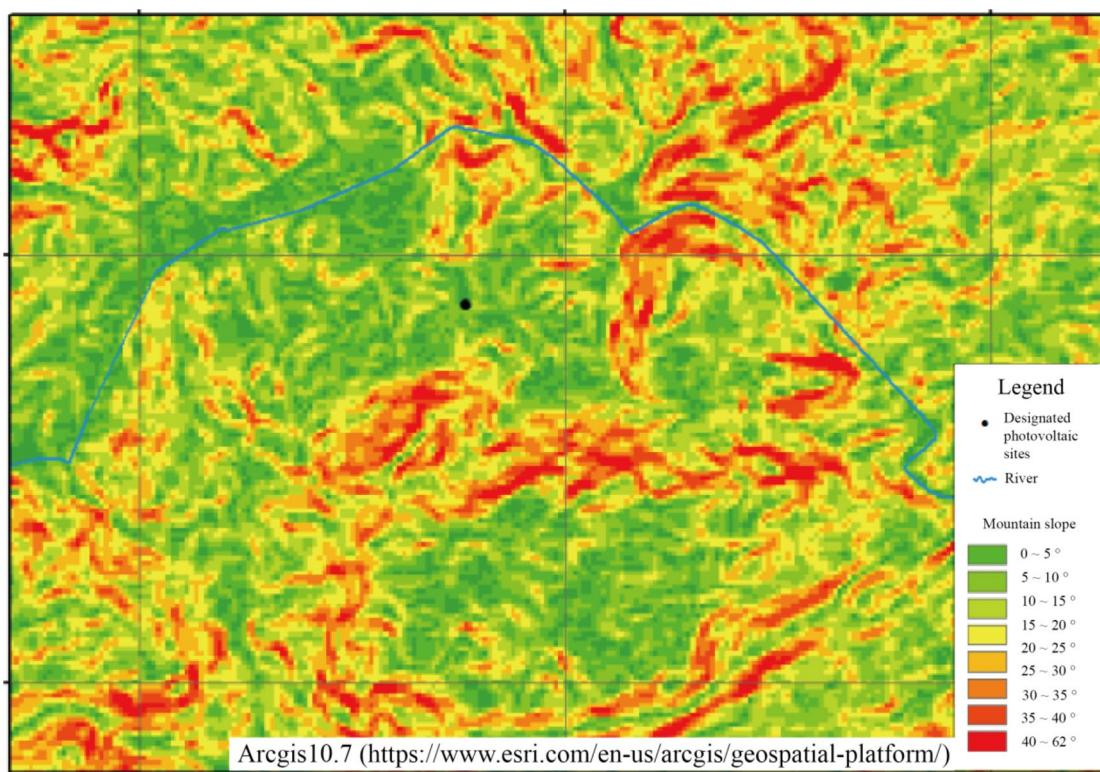


Fig. 6. Slope analysis map of the solar PV site.

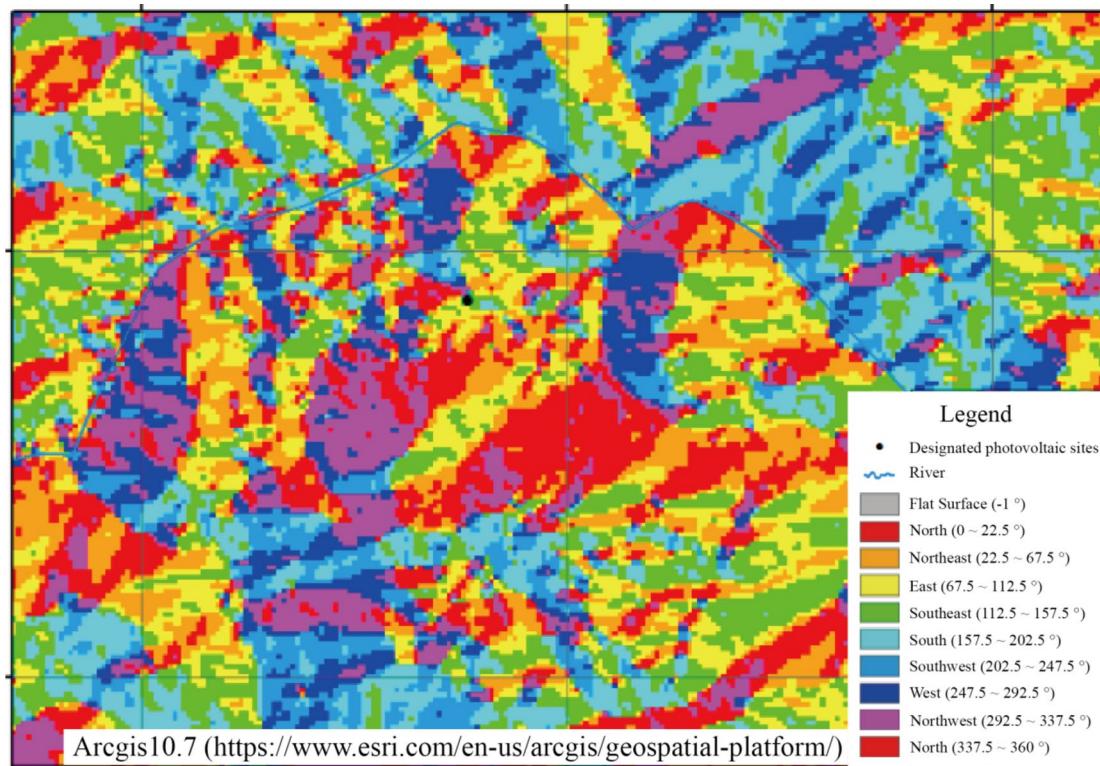


Fig. 7. Aspect analysis map of the solar PV site.

Parameter	Value	Unit
Total horizontal radiation	4695.1	MJ/m ²
Direct normal radiation	3174.3	MJ/m ²
Horizontal diffuse radiation	2609.3	MJ/m ²
Diffuse ratio	0.556	
Optimal tilt angle radiation	4902.3	MJ/m ²
Optimal tilt angle	23	Degrees
Wind speed	1.9	m/s
Temperature	16.4	°C
Cooling degree days	971	Degree-days
Heating degree days	1547	Degree-days

Table 4. Primary solar radiation and meteorological parameters of the potential site.

Month	GHI (MJ/m ²)	DNI (MJ/m ²)	DIF (MJ/m ²)	D2G	GTLopt (MJ/m ²)	TEMP (°C)	WS (m/s)	CDD (degree-days)	HDD (degree-days)
1	247.7	218	137.3	0.554	304.2	5.2	1.8	0	398
2	273.8	198.4	159.1	0.581	313.5	7	1.9	0	310
3	373.4	234	217.1	0.581	398	10.8	1.9	0	224
4	433.9	248.8	250.8	0.578	432.9	15.9	1.9	11	74
5	498.1	275.3	287.5	0.577	471.2	20.4	1.8	77	3
6	416.6	198.5	264.2	0.634	384.1	23.5	1.6	166	0
7	596.3	400.3	294.5	0.494	555.8	27.2	1.9	285	0
8	538.6	351.9	283.7	0.527	526.4	26.6	1.9	266	0
9	408.1	255.9	233.1	0.571	423.7	22.7	1.9	141	0
10	367.6	275	200.7	0.546	414.9	17.7	1.9	27	36
11	268.1	239.3	142.9	0.533	326	12.7	1.8	0	158
12	272.9	279	138.5	0.507	351.7	6.9	1.8	0	344
Annual	4695.1	3174.3	2609.3	0.556	4902.3	16.4	1.9	971	1547

Table 5. Solar radiation and meteorological parameters.

Wind resource analysis

Key metrics for evaluating wind resources include average wind speed, wind energy density, wind energy utilization factor, wind direction frequency distribution, and wind energy intensity. Wind power density, which combines wind speed, its distribution, and air density, serves as a crucial composite indicator for assessing wind resources. This data can be sourced from the Global Wind Atlas database, which provides comprehensive wind energy information from 1979 to the present. Figure 8 illustrates the Global Wind Atlas interface.

Figures 9 and 10 illustrate that the predominant wind direction at the prospective site is from the southwest, followed by the south and west, with other directions exhibiting relatively low frequencies. In regions classified within the top 10% for wind strength, the average power density is measured at 296 W/m², while the top 50% displays an approximate average of 210 W/m². The minimum average power density is approximately 150 W/m². The average wind speed in these high-strength areas is 6.04 m/s for the top 10%, around 5.25 m/s for the top 50%, with a minimum recorded wind speed of approximately 2.5 m/s. Over the years, wind speed shows relatively stable fluctuations, although deviations may occur in certain years. Monthly trends reveal lower wind speeds in December, whereas daily patterns indicate elevated speeds at night and decreased speeds during the day, maintaining consistent trends throughout each month.

According to projections from the Global Wind Atlas, the annual average wind speed at an elevation of 100 m at this site is approximately 5.25 m/s, predominantly from the southwest. The average power density in the top 10% of the strongest wind regions is 296 W/m², while the top 50% exhibits a value of around 210 W/m². This wind resource is deemed suitable for wind power development; however, as resource estimation tools provide simulated forecasts, further validation through on-site investigations and wind measurement data collection is recommended in the next phase.

Capacity configuration analysis

Based on evaluations of wind and solar resources, terrain characteristics, meteorological factors, and various constraints, the renovated Jiangshantou PSH station is recommended as the primary adjustment output mode for establishing a hybrid hydropower and photovoltaic system. This system benefits from favorable resource and geographical conditions. To ensure economic and safe operation, it is essential to optimize the functioning of the PSH units and manage the smoothing control of wind and solar outputs. Typically, these units operate during periods of low electricity demand to store water, generating power during peak demand. During periods of high

Time Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00-01												
01-02												
02-03												
03-04												
04-05												
05-06					3	22	29	20	8	0		
06-07	1	20	78	122	120	144	110	68	37	7	0	
07-08	30	64	128	195	236	221	295	257	193	157	89	37
08-09	142	175	238	310	353	309	437	399	316	279	207	176
09-10	234	274	341	430	475	399	569	520	421	385	296	283
10-11	307	351	421	511	549	451	653	592	493	449	355	360
11-12	348	398	474	548	577	475	674	615	512	486	381	397
12-13	346	410	475	532	567	466	651	601	494	459	365	384
13-14	322	379	440	485	519	440	612	570	458	414	331	346
14-15	257	315	366	400	432	371	510	482	376	327	254	264
15-16	168	223	260	291	318	283	385	357	268	214	153	158
16-17	63	113	142	171	195	181	248	219	148	85	43	41
17-18	1	13	39	62	90	94	125	90	31	2		
18-19			2	7	18	20	6					
19-20												
20-21												
21-22												
22-23												
23-24												
Daily total	2220	2716	3346	4018	4463	3857	5343	4826	3779	3294	2482	2446

Table 6. Hourly average of total solar radiation on a horizontal surface (Wh/m²).

water availability, such as the rainy season or typhoon season, they function like conventional power generation units. Conversely, during dry spells or when the upper reservoir's water level is low, they serve as storage units.

To ensure the scientific and economic viability of a multi-energy complementary system, it is crucial to determine the capacity configuration of hydropower, wind, and solar components appropriately. The complementary model includes both dispatch complementarity and real-time control of rapid fluctuations within a daily cycle. Given the relatively small proportion of wind power, this project primarily focuses on analyzing hydropower and solar resources, considering constraints related to water availability and grid transmission capacity. The annual variation in water volume at the Jianguantou station aligns closely with the typical curve of photovoltaic output, suggesting effective complementary regulation. The gradual fluctuations in photovoltaic output will be managed by the PSH units, while rapid fluctuations due to cloud cover will be adjusted using lithium iron phosphate (LiFePO₄) batteries. To ensure reliability, it is advisable to allocate 10–20% of capacity for LiFePO₄ batteries, with a capacity ratio of PSH to photovoltaic systems greater than 1 considered optimal.

Temporal complementarity analysis of wind, solar, and hydropower

Pan'an County, located in the central subtropical region, exhibits a monsoon climate characterized by distinct seasonal variations influenced by the interplay between continental and marine air masses. This region experiences significant seasonal wind shifts, marked by cold winters and hot summers, notable monsoon fluctuations, large daily temperature ranges, moderate annual temperatures, abundant heat, and substantial rainfall. The plum rain season is particularly characterized by heavy precipitation, and extreme weather events, such as floods, hail, and strong winds, occur frequently. Meteorological data from Pan'an indicate that the average annual temperature is 16.4 °C, with January being the coldest month (averaging between 2.0 and 4.3 °C) and July the hottest (averaging 25.6 to 28.8 °C). The highest recorded temperature is 40.6 °C, while the lowest is -15.2 °C. Annual sunshine hours range from 1645 to 1716 h, with an average of 178 rainy days per year, resulting in an average annual rainfall of 1551.8 mm. Data from the Anwen Rain Gauge Station indicate a maximum recorded rainfall of 81.0 mm in one hour, 264.9 mm in 24 h, and 413.0 mm over three days. Rainfall is primarily concentrated from April to July, with notable precipitation also recorded from August to October.

Time Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00-01												
01-02												
02-03												
03-04												
04-05												
05-06						18	27	28	14			
06-07					17	68	108	91	183	154	85	31
07-08				54	119	147	163	125	275	247	176	174
08-09	166	158	170	194	213	155	341	304	222	231	218	238
09-10	219	202	213	245	263	191	392	345	258	278	261	305
10-11	253	240	247	273	279	210	401	343	274	294	285	343
11-12	271	259	265	279	278	201	379	323	269	313	293	361
12-13	272	261	261	271	274	193	345	311	259	301	287	349
13-14	264	248	248	252	257	186	343	310	254	280	275	326
14-15	235	224	222	216	224	161	304	280	220	248	242	287
15-16	187	186	178	179	182	135	258	242	187	206	193	224
16-17	88	121	118	126	131	96	198	184	135	108	76	67
17-18		15	37	54	77	68	139	97	29	0		
18-19												
19-20												
20-21												
21-22												
22-23												
23-24												
Daily total	1954	1968	2097	2304	2467	1838	3587	3153	2369	2464	2216	2500

Table 7. Hourly average of normal direct radiation (Wh/m²).

Trends in water surface evaporation in Pan'an show an increase from east to west, although the variation is minimal. Based on evaporation data from the Anwen Rain Gauge Station (1980–2000), the maximum annual evaporation recorded was 1038.2 mm in 1994, while the minimum was 716.5 mm in 1999, yielding an average annual evaporation of 916.7 mm. Monthly average evaporation peaks in July at 154.0 mm and reaches its lowest point in January at 25.3 mm. As referenced in sections “[Estimation of energy storage generation and absorbed energy](#)” and “[Analysis of solar and wind resources](#)” concerning solar and wind energy, substantial rainfall occurs during the plum rain season in Pan'an, but solar radiation diminishes due to cloud cover, despite elevated average wind speeds. In autumn, rainfall decreases, but solar radiation conditions improve, while average wind speeds remain stable. Winter sees reduced rainfall, with December offering good solar radiation conditions and February displaying high average wind speeds.

Overall, significant seasonal complementarity among water, wind, and solar energy exists in Pan'an, highlighting its suitability for integrated multi-energy development.

Conclusion

This paper employs data from small hydropower stations and software algorithms to preliminarily assess the feasibility of converting conventional small hydropower stations in Zhejiang Province into PSH stations. The research is focused on Pan'an County, selected as the area for detailed analysis and field investigation. The Jiangshantou Hydropower Station is identified as a pilot site for evaluating the conversion scheme, which includes estimates of increased annual operating hours, power generation, and energy consumption. The conversion analysis identifies the Jiangshantou PSH Station as the primary method for power regulation. Plans are underway to develop a small-scale PSH system that integrates both wind and solar energy, aimed at ensuring stable output, enhancing the input-output ratio, and optimizing the utilization of renewable resources.

Efforts are being made to identify suitable locations for distributed wind and solar installations. A preliminary selection for photovoltaic (PV) sites has been made, encompassing an area of 6 hectares situated approximately 3.5 km from the dam site. Given the prolonged absence of approved onshore wind projects in Zhejiang Province, a high-altitude location near the PV site is designated for wind energy analysis. Tools such as SolarGIS and the Global Wind Atlas are utilized to evaluate solar and wind resources in the vicinity, alongside considerations of

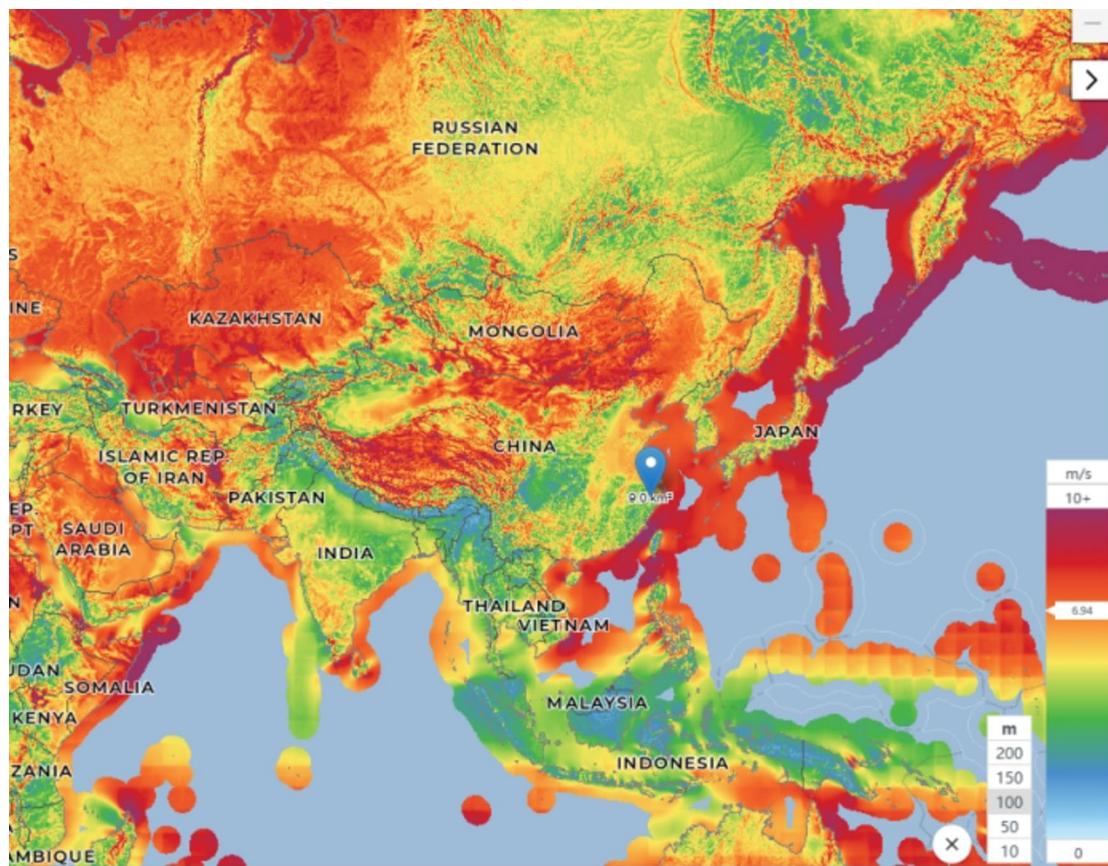


Fig. 8. Global Wind Atlas global wind energy resource database interface.

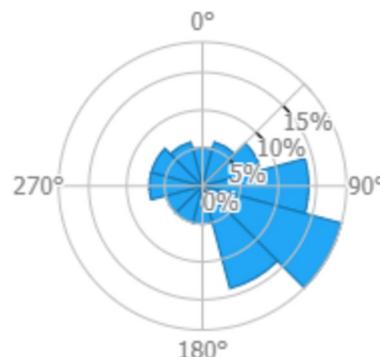


Fig. 9. Wind direction frequency rose diagram for alternative sites.

meteorological, geographical, land use, policy, and regulatory conditions. The assessment indicates that the site possesses relatively rich and stable solar resources appropriate for PV station construction, as well as favorable wind speed and power density indicators, thereby making it suitable for wind energy development.

The pilot project establishes a framework and methodology for transforming traditional hydropower stations into PSH facilities, utilizing PSH as the principal method of power regulation. Additionally, it fosters a small-scale integrated power system combining hydropower, wind, and solar energy, serving as a demonstration for converting conventional hydropower stations into medium-small PSH facilities and exploring distributed generation and small-scale PSH technologies.

This research aims to rapidly assess the technical and economic feasibility of potential sites for PSH projects, providing a foundation for more detailed studies and investment decisions. This approach helps save time and resources by identifying promising project areas. Additionally, our methodology aids in optimizing resource allocation, especially in emerging markets and regions with uncertain resources, enabling decision-makers to more effectively distribute exploration and development resources. Furthermore, the screening tool provides

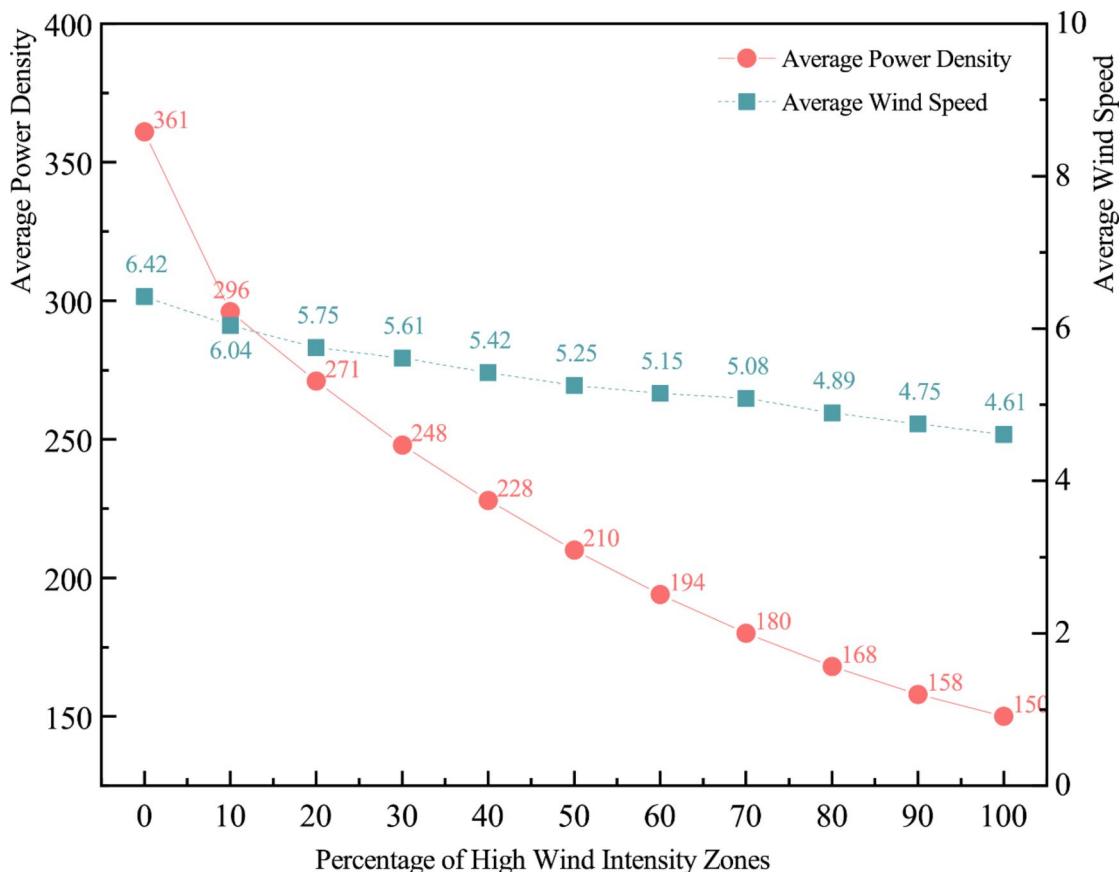


Fig. 10. Average power density and average wind speed map for alternative sites.

scientific support for governments and relevant organizations, considering resource, environmental, and economic factors to formulate more rational energy development plans. However, our methodology has certain limitations. Currently, it lacks detailed economic analysis, such as calculations for benefit-cost ratio (BCR), internal rate of return (IRR), and net present value (NPV). Comprehensive economic evaluation of PSH projects requires in-depth analysis combining grid modeling and financial metrics, which is the focus of our future research. Moreover, our current methodology is based on simplified assumptions and does not fully consider all operational and environmental factors, such as market price fluctuations and long-term climate impacts on water resources. These factors could significantly affect the feasibility and economics of the projects. Our methodology primarily focuses on static analysis and does not include dynamic scheduling and real-time control optimization models. The operation of PSH involves complex real-time decision-making and scheduling strategies, which require more advanced models and algorithms for optimization. Looking ahead, we plan to integrate detailed economic analysis models, including BCR, IRR, and NPV calculations, to comprehensively evaluate the economic viability of PSH projects. By incorporating advanced grid modeling techniques, we aim to simulate the performance and economic benefits of PSH under different operational scenarios. Additionally, we will expand our research scope to assess the long-term environmental and climate impacts on PSH projects, ensuring their sustainability and reliability.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Author contributions

Yangqing Dan and Qingyue Chen wrote the main manuscript text. Daren Li and Wenhuan Bai contributed to investigation. Weiming Zhou contributed to data analysis, Anyu Yang provided critical revisions, and Jia Yang prepared Figs. 4, 5, 6 and 7. All authors reviewed and approved the final manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Q.C.

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