

Article

Optimal Flexibility Dispatching of Multi-Pumped Hydro Storage Stations Considering the Uncertainty of Renewable Energy

Xinyi Chen ¹, Pan Wu ¹, Hongyu He ¹, Bingbing Song ¹, Kangping Qin ¹, Xiaobi Teng ¹, Fan Yang ^{2,*} and Dongdong Li ²

¹ State Grid East China Branch, Shanghai 200120, China; chen_xy@ec.sgcc.com.cn (X.C.); wu_p@ec.sgcc.com.cn (P.W.); he_hy@ec.sgcc.com.cn (H.H.); song_bb@ec.sgcc.com.cn (B.S.); qin_kp@ec.sgcc.com.cn (K.Q.); teng_xb@ec.sgcc.com.cn (X.T.)

² College of Electric Power Engineering, Shanghai University of Electric Power, Shanghai 200090, China; lidongdong@shiep.edu.cn

* Correspondence: yangfan@shiep.edu.cn

Abstract: With the continuous increase in the penetration rate of renewable energy, the randomness and flexibility demand in the power system continues to increase. The main grid side of the power system vigorously develops pumped hydro storage (PHS) resources. However, the current PHS station scheduling method of a fixed time period and fixed power has lost a certain flexibility supply. In this paper, an optimal dispatching model of multi-pumped hydro storage stations is proposed to supply flexibility for different regions of the state grid in east China. Firstly, the credible predictable power (CPP) of renewable energy is calculated and the definition of flexibility demand of a power system is given. The calculation model for flexibility demand is established. Secondly, considering the regional allocation constraint in the state grid in east China, a non-centralized model of multi-PHS within the dispatch scope is established. In the model, the constraints of storage capacity of different hydropower conversion coefficients of each PHS station is considered. The flexibility supply model of PHS stations to each region of the state grid in east China is established to realize reasonable flexibility allocation. Then, by combining the PHS station models and the flexibility demand calculation model, the optimal dispatching model for the flexibility supply of multi-PHS stations is established. Finally, based on the network dispatching example, the effectiveness and superiority of the proposed strategy are verified by a case study.

Keywords: pumped hydro storage (PHS) station; flexibility; flexible scheduling; power system; renewable energy



Citation: Chen, X.; Wu, P.; He, H.; Song, B.; Qin, K.; Teng, X.; Yang, F.; Li, D. Optimal Flexibility Dispatching of Multi-Pumped Hydro Storage Stations Considering the Uncertainty of Renewable Energy. *Symmetry* **2024**, *16*, 1404. <https://doi.org/10.3390/sym16101404>

Academic Editor: Yongji Cao

Received: 20 September 2024

Revised: 15 October 2024

Accepted: 17 October 2024

Published: 21 October 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

With the “dual carbon” goal proposed, the installed capacity of renewable energy resources in the power system will continue to increase. As a result, the penetration rate of new energy continues to increase. The superposition of renewable energy resources and load fluctuations leads to an increase in the risk of instability in the power system. Therefore, for the stable operation of the power system, the power system needs to have a stronger ability to cope with uncertainty and volatility. The “symmetry” between electricity production (power generation) and electricity consumption can be regarded as an ideal state, namely that the two are fully matched in quantity and highly synchronized in time. In order to achieve this state, the power system needs flexible scheduling strategies and efficient energy storage technology to cope with the instability of intermittent energy, such as wind and solar energy, on the power generation side, as well as the random fluctuations of load on the power side.

At present, scholars have adopted various methods to deal with the uncertainty of new energy in the optimization scheduling process. The predicted power is utilized directly in most instances for calculating when developing the day-ahead dispatch. References [1–3]

predict the power of renewable energy resources (RERs) through different methods, which eventually improves the accuracy of RERs' prediction in long- and short-time scales. On this basis, a more appropriate dispatch can be developed. However, these studies ignore the degree of fluctuations of RERs.

In addition, in order to measure the ability of the power system to cope with volatility, the concept of "power system flexibility" was proposed. In 2008, the International Energy Agency (IEA) proposed the concept of "power system flexibility", which reflects the ability of a power system to cope with large fluctuations in demand and supply. The stronger the flexibility, the stronger the ability to cope with fluctuations within the system; that is, the stronger the ability to maintain system stability [4]. Power system flexibility is defined in [5] as the ability of a system to call on its own resources to meet the load changes in the grid. In [6,7], power system flexibility is the ability to respond to load fluctuations at various time scales and maintain the standard level of system reliability. Therefore, there is still no unified definition of power system flexibility, but in general, the flexibility of the power system is the ability to dispatch various flexible resources in the power system and maintain system stability per unit time.

By the end of 2022, the total installed capacity of PHS stations approved under construction was 121 million kilowatts in China. However, at present, there is no commercial consensus on the dispatch of PHS units in the power system, especially the coordinated dispatch with other units. At the same time, the potential for the flexibility supply of PHS stations themselves is not sufficient. Therefore, some studies have focused on the more adequate dispatch of PHS stations. In [8], the authors study the optimal operation evaluation criteria, considering factors such as energy diversification and allocation, based on the research results of PHS-based energy systems in recent years. In [9], the authors establish an operation dispatching model with the goal of minimizing the running cost of the PV-PHS system. In [10], the authors combined PHS with residential buildings to study the technical and economic feasibility. In [11], the authors conducted a study on the optimal dispatch and management of seawater PHS stations with the goal of maximizing operating profits. However, the common limitation of these studies is that they all aim for optimal dispatching with the goal of economic optimization, and do not consider the flexibility balance between supply and demand in the dispatching process.

In [12–15], the lowest cost is taken as the optimization goal, so that the combined operation of wind power and pumped storage combined unit model is established. In [16], the authors examined the dispatching of PHS resources in coordination with other resources. In [17], the authors proposed a novel deterministic PSH model that considers the transition time and trajectory between three states of PHS units in look-ahead dispatch. In [18], the authors proposed a novel coordination strategy of wind and PHS units for a fast and reliable self-healing process. In these studies, the operation and dispatch models of PHS stations are established, but the reserved time constraints between the working conditions of PHS stations and the storage capacity constraints of different hydropower conversion coefficients are not considered. At the same time, only one PHS station is considered in these studies to provide or absorb power to the grid, or model pumped storage power plants intensively. The issue of multiple PHS units and supply flexibility for multiple regions is not considered. In actual operation, when the multi-PHS stations supply flexibility to multiple regions, it is necessary to consider the regional allocation constraints.

In order to address the shortcomings in the current research, the main objectives of this study are as follows:

- (1) CPP is calculated based on predictive data of RERs. In view of the current problem of inconsistent definition of the flexibility of power systems, this study defines the flexibility demand of power system as the change in net load per unit time, and propose a formula model for calculating flexibility demand at multiple time scales;

- (2) Design the refined operation model of PHS stations. This study summarizes the PHS unit models in previous studies and combines the actual operation characteristics of PHS stations to further refine the operation models of PHS stations.

(3) Propose the optimal flexibility dispatching model of multi-PHS stations. Based on the optimal matching of the flexibility supply of PHS stations and the flexibility demand of each region, the objective function is established. To integrate the different regional allocation constraints of different PHS stations to different regions, the flexibility supply of PHS stations to different regions was quantified, and the flexibility supply model of PHS stations was established. The effectiveness of the proposed method is verified by a case study.

2. Optimal Flexibility Dispatching Model of Multi-PHS Stations Considering the Uncertainty of Renewable Energy

In this study, an optimal flexible scheduling model for multi-PHS stations considering the uncertainty of renewable energy is proposed. On the basis of considering the uncertainty of the renewable energy forecast, the net load series is calculated, and then the flexibility demand is obtained. According to the actual operation characteristics of PHS stations, a refined operation model of PHS stations is established. Considering the power allocation constraints caused by the actual situation, the flexibility supply of different regions is calculated. Finally, the flexibility demand and supply are best matched to achieve the optimal flexible dispatching, and the economy of the flexibility supply mode is compared with that of the thermal power flexibility supply. The overall research framework is shown in Figure 1.

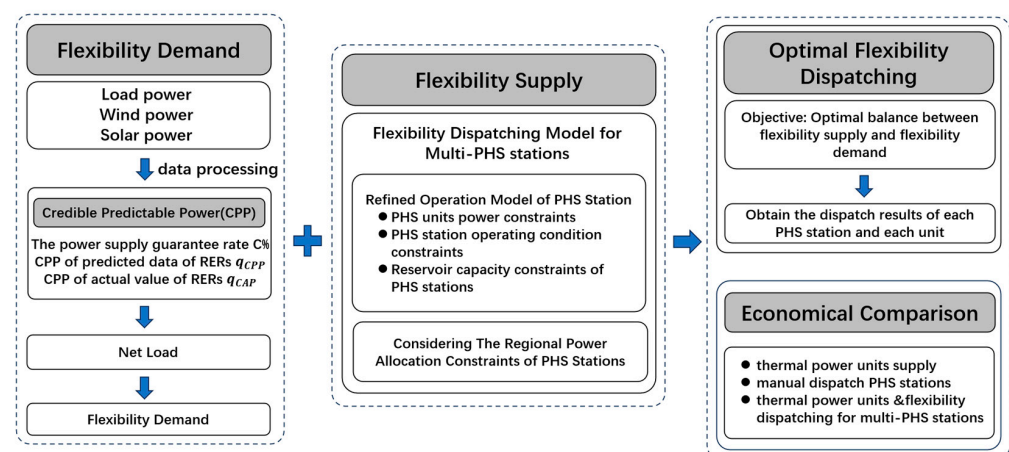


Figure 1. Overall research block diagram.

3. Flexibility Demand of Power System

In this study, power system flexibility is defined as the ability of the power system to cope with power changes and maintain stability, and flexibility demand is defined as the amount of change per unit time of net load. At the same time, the forecasted uncertainty of renewable energy is considered. Flexibility has both upward and downward directions, and the values and characteristics of flexibility are different. For the demand for flexibility in different directions, the flexible supply in different directions needs to be balanced with it.

3.1. Calculation of CPP

The CPP of RERs is defined as the minimum level of output that renewable energy forecasts can reach with a certain probability C%. This probability C% is also referred to as the power supply guarantee rate. This value represents a high-confidence prediction of energy output, reflecting the overall characteristics of renewable energy. The formula for calculating the CPP of RERs is as follows:

$$F(x) = \int_{-\infty}^x \hat{f}(s) ds \quad (1)$$

$$q = F^{-1}(x)|_{x=1-C\%} \quad (2)$$

where $F(x)$ is the cumulative distribution function of the dataset, the dataset is predicted data or actual value of RERs, $\hat{f}(s)$ is the probability density function of the dataset, $F^{-1}(x)$ is the inverse function of $F(x)$, q is the CPP of the dataset within power supply guarantee rate $C\%$, and $C\%$ is the percentage of confidence that ensures RERs can reliably output as planned.

Applying (1) and (2) and using the predicted data of RERs, the CPP of the predicted data of RERs q_{CPP} can be calculated. Applying (1) and (2) and using the actual value of RERs, the Credible Actual Power (CAP) q_{CAP} can be calculated, i.e., CPP of actual value of RERs.

Furthermore, the incorporating ratio of RERs participating in dispatching is given by:

$$\beta = \frac{q_{CAP}}{q_{CPP}} \quad (3)$$

In the dispatching process, all forecasted renewable energy power is replaced by P^{new} .

$$P^{new} = \beta \cdot P^{new_h} \quad (4)$$

where P^{new} is the renewable energy power used for dispatching, including wind power P_t^{wind} and solar power P_t^{solar} ; P^{new_h} is the original forecast data obtained from the wind or solar plants.

3.2. Formula Model for Calculation of Power System Flexibility Demand

3.2.1. Net Load Time Series Calculations

The net load is the power of the power system load demand minus the output power of renewable energy, and the net load can reflect the superposition fluctuation of load and renewable energy. The net load, at the same time, depends on the load demand power and the renewable energy output power at that time. The net load of the power system is calculated as follows:

$$P_t^{net} = P_t^{load} - P_t^{wind} - P_t^{solar} \quad (5)$$

where P_t^{net} is the net load value at time t . P_t^{load} , P_t^{wind} , and P_t^{solar} are the required load power, the output power of wind power, and the output power of photovoltaics at time t , respectively.

3.2.2. The Flexibility Demand

The flexibility demand at different time scales is the amount of change in the net load per unit time, and the flexibility demand at different time scales is also different. The flexibility demand at different time scales is calculated as follows:

$$P_t^{flex} = P_{t+a}^{net} - P_t^{net} \quad (6)$$

where P_t^{flex} is the flexibility demand of the t period. P_{t+a}^{net} is the predicted net load value corresponding to the next scheduling period; if the sampling interval of the forecast data is the same as the time of the scheduling period, a takes 1.

The value of the flexibility demand calculated according to Equation (6) is divided into positive and negative values, which are used to distinguish the direction of the flexibility demand, with a positive value indicating an upward flexibility demand and a negative value indicating a downward flexibility demand. The following formulas can be used to distinguish between upward and downward flexibility demand:

$$P_{t,s}^{flex_up} = \begin{cases} P_{t,s}^{flex}, & P_{t,s}^{flex} > 0 \\ 0, & P_{t,s}^{flex} \leq 0 \end{cases} \quad (7)$$

$$P_{t,s}^{flex_dn} = \begin{cases} 0, & P_{t,s}^{flex} > 0 \\ P_{t,s}^{flex}, & P_{t,s}^{flex} \leq 0 \end{cases} \quad (8)$$

where $P_{t,s}^{flex_up}$ and $P_{t,s}^{flex_dn}$ are the upward flexibility demand and the downward flexibility demand for period t under time scale s , respectively.

4. Flexibility Dispatching Model for Multi-PHS Stations

4.1. Set Dispatching Variables

- Power generation/pumping condition status variables $U_{i,t}^{gen}/U_{i,t}^{pm}$: Boolean variables. Indicate the power generation/pumping status of the i th PHS unit in the t period. A value of 0 indicates that the PHS station is not in the power generation/pumping condition, and a value of 1 indicates that it is in the power generation/pumping condition.
- Generating power $P_{i,t}^{gen}$: Real variables. Indicate the power generated by the i th PHS unit in the t period.
- The amount of water remaining in the upstream/downstream reservoir $E_{n,t}^{up}/E_{n,t}^{dn}$: Real variables. Indicate the water volume of the upstream/downstream reservoir of the n th PHS station in the t period.
- Number of power generation/pumping starts $K_{i,d}^{gen}/K_{i,d}^{pm}$: Integer variables. Indicate the number of power generation/pumping conditions started on day d for the i th PHS unit. $K_{i,d}^{gen}$ represents the number of power generation conditions started on day d for the i th PHS unit. $K_{i,d}^{pm}$ represents the number of pumping conditions started on day d for the i th PHS unit. This variable can be calculated and represented by the power generation/pumping condition state variable.

4.2. Refined Operation Model of PHS Station

In order to make the PHS station more accurate in the dispatching process, we must fully consider the various operation characteristics of the PHS station in the actual operation. In this study, we designed a refined operation model of the PHS station. The PHS unit has the characteristics of fast start and stop, fast climbing speed, etc. PHS units can be converted under three working conditions: power generation, pumping, and shutdown, corresponding to the state of transmitting power, absorbing power, and neither emitting nor absorbing power. As a result, PHS stations are able to provide flexibility in both upward and downward directions. However, the PHS units in the same PHS station cannot be in both power generation and pumping conditions at the same time. None of the PHS units in the entire dispatch scope can be in power generation and pumping conditions at the same time. Since the PHS unit cannot directly jump from the pumping condition to the power generation condition, nor can it jump from the power generation condition to the pumping condition, when the pumping and power generation conditions are converted, an interval of dispatching period is required.

A PHS station is usually equipped with multiple PHS units and has an upstream reservoir and a downstream reservoir. PHS units in the same PHS station share the same upstream and downstream reservoirs. The volume of the upstream reservoir determines the time when the PHS station can generate electricity, and the amount of water in the downstream reservoir determines the time when it can be pumped. However, the basic downstream reservoir capacity is much larger than the upstream reservoir capacity, so in most cases, the effective reservoir capacity of the upstream reservoir of the PHS station is mainly considered. At the same time, there is a dynamic equilibrium relationship between the upper and downstream reservoirs of PHS stations, and different PHS stations have different hydropower conversion coefficients due to the different heights of the drop between the upstream reservoir and the downstream reservoir. The constraints contained in the refined operation model of PHS station are as follows:

1. PHS units power constraints

(1) Power generation constraint:

$$P_{i,min}^{gen} \leq P_{i,t}^{gen} \leq P_{i,max}^{gen} \quad (9)$$

where $P_{i,min}^{gen}$ is the minimum stable power generation power of the i th PHS unit, and $P_{i,max}^{gen}$ is the maximum power generation power of the i th PHS unit, $i = 1, 2, \dots$.

(2) Pumping power constraint:

$$P_i^{pm} = P_{i,t}^{pm} \quad (10)$$

where P_i^{pm} is the rated pumping power of the i th PHS unit.

2. PHS station operating condition constraints

(1) Different working conditions are not simultaneous constraints:

$$U_{i,t}^{gen} + U_{j,t}^{pm} \leq 1 \quad (11)$$

where $j = 1, 2, \dots$, and m is the number of PHS units within the dispatch scope.

(2) Condition conversion reservation time constraints:

$$\begin{cases} U_{i,t}^{gen} \leq 1 - U_{i,t-1}^{pm} \\ U_{i,t}^{pm} \leq 1 - U_{i,t-1}^{gen} \end{cases} \quad (12)$$

(3) Prevent the operating condition changes sudden constraints:

$$\begin{cases} (1 - U_{i,t-1}^{gen}) \cdot U_{i,t-2}^{gen} + (1 - U_{i,t-1}^{pm}) \cdot U_{i,t}^{gen} \leq 1 \\ (1 - U_{i,t-2}^{gen}) \cdot U_{i,t-1}^{gen} + (1 - U_{i,t}^{gen}) \cdot U_{i,t-1}^{pm} \leq 1 \end{cases} \quad (13)$$

$$\begin{cases} (1 - U_{i,t-1}^{pm}) \cdot U_{i,t-2}^{pm} + (1 - U_{i,t-1}^{gen}) \cdot U_{i,t}^{pm} \leq 1 \\ (1 - U_{i,t-2}^{pm}) \cdot U_{i,t-1}^{pm} + (1 - U_{i,t}^{pm}) \cdot U_{i,t-1}^{gen} \leq 1 \end{cases} \quad (14)$$

(4) Specified time shutdown constraints:

$$U_{i,t}^{gen} + U_{i,t}^{pm} = 0 \quad (15)$$

(5) The maximum number of starts under the same working condition in one day constraints:

$$K_{i,start,min}^{gen} \leq K_{i,d}^{gen} \leq K_{i,start,max}^{gen} \quad (16)$$

$$K_{i,start,min}^{pm} \leq K_{i,d}^{pm} \leq K_{i,start,max}^{pm} \quad (17)$$

where $K_{i,start,min}^{gen}$ and $K_{i,start,max}^{gen}$ are the minimum and maximum number of starts of the i th PHS unit in a day, respectively. $K_{i,start,min}^{pm}$ and $K_{i,start,max}^{pm}$ are the minimum and maximum number of pumping starts in a day for the i th PHS unit, respectively.

$$K_{i,d}^{gen} = \sum_{t=1}^T (1 - U_{i,t-1}^{gen}) \cdot U_{i,t}^{gen} \quad (18)$$

$$K_{i,d}^{pm} = \sum_{t=1}^T (1 - U_{i,t-1}^{pm}) \cdot U_{i,t}^{pm} \quad (19)$$

where T is the number of time slots dispatched.

(6) Minimum running time constraint for power generation:

$$(X_{i,t-1}^{gen,on} - T_i^{gen,on}) \cdot (U_{i,t-1}^{gen} - U_{i,t}^{gen}) \geq 0 \quad (20)$$

where $X_{i,t-1}^{gen,on}$ is the continuous operation time of the i th PHS unit in the t period. $T_i^{gen,on}$ is the minimum continuous operation time of the i th PHS unit under power generation conditions. The formula for calculating $X_{i,t-1}^{gen,on}$ is as follows:

$$X_{i,t}^{gen,on} = (1 - U_{i,t-1}^{gen}) \cdot U_{i,t}^{gen} + U_{i,t-1}^{gen} \cdot U_{i,t}^{gen} \cdot (1 + X_{i,t-1}^{gen,on}) \quad (21)$$

(7) Minimum running time constraint for pumping:

$$(X_{i,t-1}^{pm,on} - T_i^{pm,on}) \cdot (U_{i,t-1}^{pm} - U_{i,t}^{pm}) \geq 0 \quad (22)$$

where $X_{i,t-1}^{pm,on}$ is the continuous pumping time of the i th PHS unit in the t period. $T_i^{pm,on}$ is the minimum continuous operation time of the i th PHS unit under pumping conditions. The formula for calculating $X_{i,t}^{pm,on}$ is as follows:

$$X_{i,t}^{pm,on} = (1 - U_{i,t-1}^{pm}) \cdot U_{i,t}^{pm} + U_{i,t-1}^{pm} \cdot U_{i,t}^{pm} \cdot (1 + X_{i,t-1}^{pm,on}) \quad (23)$$

(8) PHS unit start-up constraint:

$$\sum_{i=1}^{I_n} U_{i,t}^{gen} - \sum_{i=1}^{I_n} U_{i,t-1}^{gen} \leq 1 \quad (24)$$

$$\sum_{i=1}^{I_n} U_{i,t}^{pm} - \sum_{i=1}^{I_n} U_{i,t-1}^{pm} \leq 1 \quad (25)$$

where I_n is the number of PHS units in the n th PHS station.

3. Reservoir capacity constraints of PHS stations

(1) Upstream reservoir and downstream reservoir constraints:

$$\begin{cases} E_{n,min}^{up} \leq E_{n,t}^{up} \leq E_{n,max}^{up} \\ E_{n,min}^{dn} \leq E_{n,t}^{dn} \leq E_{n,max}^{dn} \end{cases} \quad (26)$$

where $E_{n,min}^{up}$ and $E_{n,max}^{up}$ are the minimum capacity and maximum capacity of the upstream reservoir, respectively. $E_{n,min}^{dn}$ and $E_{n,max}^{dn}$ are the minimum capacity and maximum capacity of the downstream reservoir, respectively.

(2) The dynamic balance of upper and lower storage capacity constraints:

$$\begin{cases} E_{n,t}^{up} = Q_{n,t}^{pm} - Q_{n,t}^{gen} + E_{n,t-1}^{up} \\ E_{n,t}^{dn} = -Q_{n,t}^{pm} + Q_{n,t}^{gen} + E_{n,t-1}^{dn} \end{cases} \quad (27)$$

where $Q_{n,t}^{pm}$ and $Q_{n,t}^{gen}$ are the amount of pumped water stored and the power generation displacement in the t period of the n th PHS station, respectively.

Under the power generation condition of the PHS unit, the gravitational potential energy of the water is converted into electrical energy, and under the pumping condition, the electrical energy is converted into the gravitational potential energy of the water. Therefore, there exists the following relationship between power generation and pumping power of PHS stations and the amount of drainage and pumped water:

$$\begin{cases} P_{n,t}^{gen} = \eta_n^{gen} \cdot Q_{n,t}^{gen} \\ P_{n,t}^{pm} = \eta_n^{pm} \cdot Q_{n,t}^{pm} \end{cases} \quad (28)$$

where $P_{n,t}^{gen}$ is the total power generated in the t period of the n th PHS station, and its value is equal to the sum of the power generated by all PHS units in the t period of the n th PHS station. $P_{n,t}^{pm}$ is the total pumped power of the n th PHS station in the t period, and its

value is equal to the sum of the pumping power of all PHS units in the t period in the n th PHS station. η_n^{gen} and η_n^{pm} are the water-electricity conversion coefficient under the power generation condition and the water-electricity conversion coefficient under the pumping condition of the n th PHS station, respectively.

The water-electricity conversion coefficient η_n^{gen} of the PHS station under power generation conditions indicates a power generation capacity of 1 m^3 water conversion per unit of water consumed under power generation conditions, and the calculation formula is as follows:

$$\eta_n^{gen} = \frac{\eta_n^{tur} \cdot Q_n^{gen} \cdot h_n^{gen} \cdot \rho \cdot g}{e} \quad (29)$$

where η_n^{tur} is the average turbine efficiency of the n th PHS station. Q_n^{gen} is the unit of water volume, the value is 1 m^3 . ρ is the density of water, usually 1000 kg/m^3 . h_n^{gen} is the height of the drop between the upstream reservoir drainage outlet and the downstream reservoir of the n th PHS station; in m , e is the unit of electricity and the value is $e = 1 \text{ MWh} = 3.6 \times 10^9 \text{ J}$. Therefore, the water-electricity conversion coefficient of the PHS station under the power generation condition mainly depends on the height of the drop between the upstream reservoir drainage outlet and the downstream reservoir of the PHS station.

The water-electricity conversion coefficient η_n^{pm} under the pumping condition of the PHS station represents the amount of electricity consumed by pumping 1 m^3 of water to the upstream reservoir under the pumping condition, and the calculation formula is as follows:

$$\eta_n^{pump} \cdot \eta_n^{pm} \cdot e = h_n^{pm} \cdot Q_n^{pm} \cdot \rho \cdot g \quad (30)$$

$$\eta_n^{pm} = \frac{h_n^{pm} \cdot Q_n^{pm} \cdot \rho \cdot g}{\eta_n^{pump} \cdot e} \quad (31)$$

where η_n^{pump} is the average pump efficiency of the n th PHS station. h_n^{pm} is the height of the drop from the downstream reservoir pumping port to the upstream reservoir of the n th PHS station; in m , Q_n^{pm} is the unit of water volume and the value is 1 m^3 .

4.3. Flexibility Supply for Different Regions

The flexibility supply of the PHS station to different regions is calculated by the final dispatch power of each PHS station. The dispatching power generation and pumping power of each PHS station are calculated by the working condition of each unit of each PHS station and the power generation and pumping power.

The final dispatch power generation/pumping power of each PHS station is determined by the power generation/pumping state variable and the power generation/pumping power. $P_{n,t}^{gen,end}$ and $P_{n,t}^{pm,end}$ are the dispatch generation power and pumping power of the n th PHS station during the t period, respectively. The calculation formulas are as follows:

$$P_{n,t}^{gen,end} = \sum_{i=1}^{I_n} U_{i,t}^{gen} \cdot P_{i,t}^{gen} \quad (32)$$

$$P_{n,t}^{pm,end} = \sum_{i=1}^{I_n} U_{i,t}^{pm} \cdot P_{i,t}^{pm} \quad (33)$$

The formulas for calculating the upward and downward flexibility supply obtained by each region in each dispatching period are as follows:

$$F_{t,r}^{up,supply} = \sum_{n=1}^N p_{n,r} \cdot P_{n,t}^{gen,end} \quad (34)$$

$$F_{t,r}^{dn,supply} = \sum_{n=1}^N p_{n,r} \cdot P_{n,t}^{pm,end} \quad (35)$$

where $p_{n,r}$ is the allocation ratio of the pumped power distribution from the n th PHS station to area r .

The flexibility supply variables obtained by each region in each dispatching period can be calculated as shown in Figure 2.

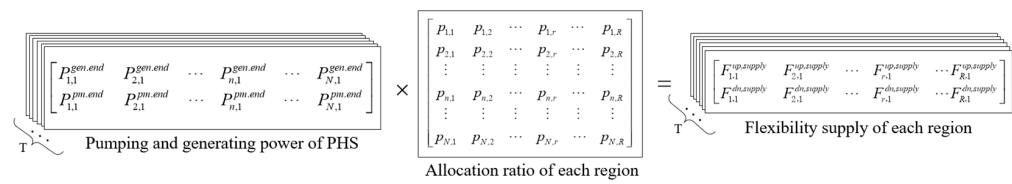


Figure 2. Schematic diagram of the flexibility supply variables.

In order to prevent the oversupply flexibility of PHS stations and the reverse increase in flexibility demand, the flexibility supply needs to meet the constraints of preventing excessive flexibility supply:

(1) Upward flexibility supply constraints: The upward flexibility supply of PHS stations to each region cannot exceed the upward flexibility demand of this region; otherwise, there will be an excess of upward flexibility supply. The expression is as follows:

$$P_{t,r}^{flex_up} - F_{t,r}^{up,supply} \geq 0 \quad (36)$$

where $P_{t,r}^{flex_up}$ is upward flexibility demand in the t period of r area. $F_{t,r}^{up,supply}$ is t period upward flexibility supply to the r area.

(2) Downward flexibility supply constraints: The downward flexibility supply of PHS stations to each region cannot exceed the downward flexibility demand of this region; otherwise, there will be excessive downward flexibility supply. The expression is as follows:

$$F_{t,r}^{dn,supply} - P_{t,r}^{flex_dn} \geq 0 \quad (37)$$

where $F_{t,r}^{dn,supply}$ is t period downward flexibility supply to the r area. $P_{t,r}^{flex_dn}$ is downward flexibility demand in the t period of r area.

4.4. Objective Function

In order to achieve the optimal supply flexibility of PHS stations, it is necessary to best match the flexibility supply of PHS stations with the flexibility demand of each region. That is, the difference between the flexibility supply of PHS stations to each region and the flexibility demand of each region needs to be as small as possible. In this study, the matching degree between the flexibility supply of PHS stations and the flexibility demand for each region is quantified by the difference between the flexibility supply of PHS stations and the flexibility demand of each region.

The objective function considers the influence of PHS stations on the flexibility supply of different regions in different modes, and the flexibility supply of PHS stations to each region needs to be calculated according to a certain allocation ratio.

The difference between upward flexible demand and upward flexible supply is calculated as follows:

$$F_{diff}^{up} = \sum_{r=1}^R \sum_{t=1}^T (P_{t,r}^{flex_up} - F_{t,r}^{up,supply}) \quad (38)$$

where F_{diff}^{up} is the deviation between upward flexibility demand and upward flexibility supply within the dispatching scope, i.e., the upward flexibility demand after the PHS supply and the upward flexibility. R is the total number of regions within the dispatching scope.

The difference between downward flexibility demand and downward flexibility supply is calculated as follows:

$$F_{diff}^{dn} = \sum_{r=1}^R \sum_{t=1}^T (F_{t,r}^{dn,supply} - P_{t,r}^{flex_dn}) \quad (39)$$

where F_{diff}^{dn} is the difference between the downward flexibility demand and the downward flexibility supply within the dispatching scope, i.e., the downward flexibility demand after the PHS supply and the downward flexibility.

Based on the above formula of flexibility supply and demand, considering the flexibility supply of PHS, including upward flexibility supply and downward flexibility supply, the optimal matching of flexibility supply and demand in each region by each PHS station is taken as the objective function of day-ahead dispatching, and its expression is as follows:

$$\min F = \min (F_{diff}^{up} + F_{diff}^{dn}) \quad (40)$$

The value of the decision variable that enables the objective function to be minimized is the dispatch result that supplies the optimal flexibility for PHS.

5. Materials and Methods

In order to verify the effectiveness of the model established in this study, a regional power grid in East China was used as an example system for simulation analysis. There are 4 regions in this dispatching scope, with a total of 10 PHS stations including 48 PHS units, with a total installed capacity of 13,700 MW. Different PHS stations have different flexibility supply patterns for each region, so the pumped and power generation power are allocated according to different proportions. The total installed capacity of wind power is 29,553.9 MW, and the total installed capacity of photovoltaic is 34,922.5 MW. The peak daily load of the system is 344,522 MW.

5.1. Flexibility Demand

The 3-day flexibility demand is calculated based on the 3-day renewable energy and load forecast data, as can be seen in Figure 3. The flexibility demand above the horizontal axis of the coordinate system is the upward flexibility demand. The flexibility demand below the horizontal axis is the downward flexibility demand. And the flexibility demand in different directions needs to be met by the flexibility supply in the corresponding direction. However, too much flexibility supply will lead to an inverse increase in the demand for flexibility, so the best match between flexibility supply and demand is required.

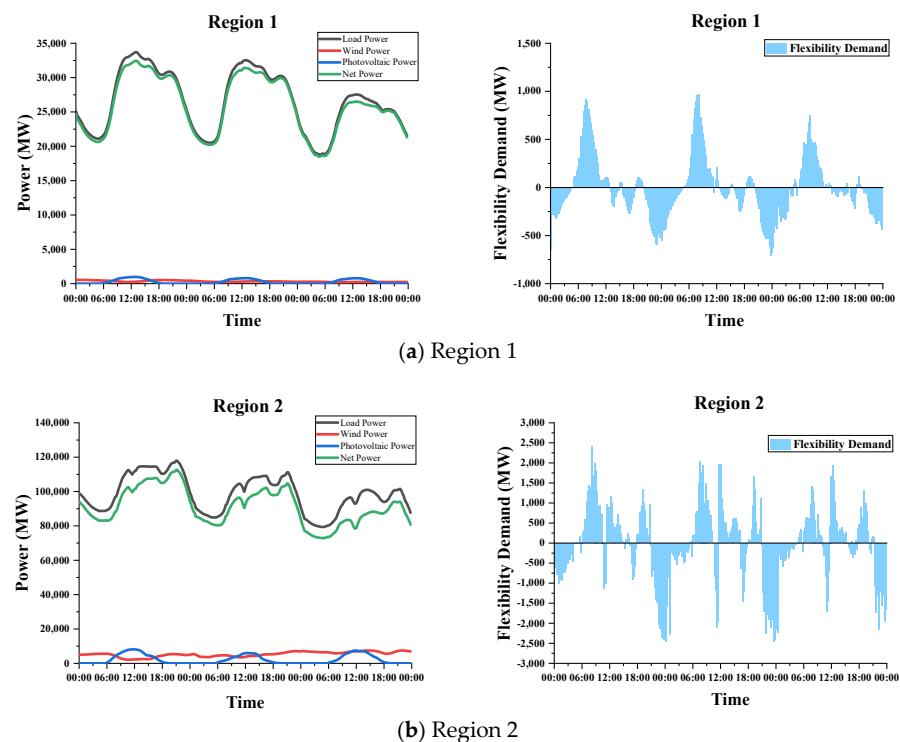


Figure 3. Cont.

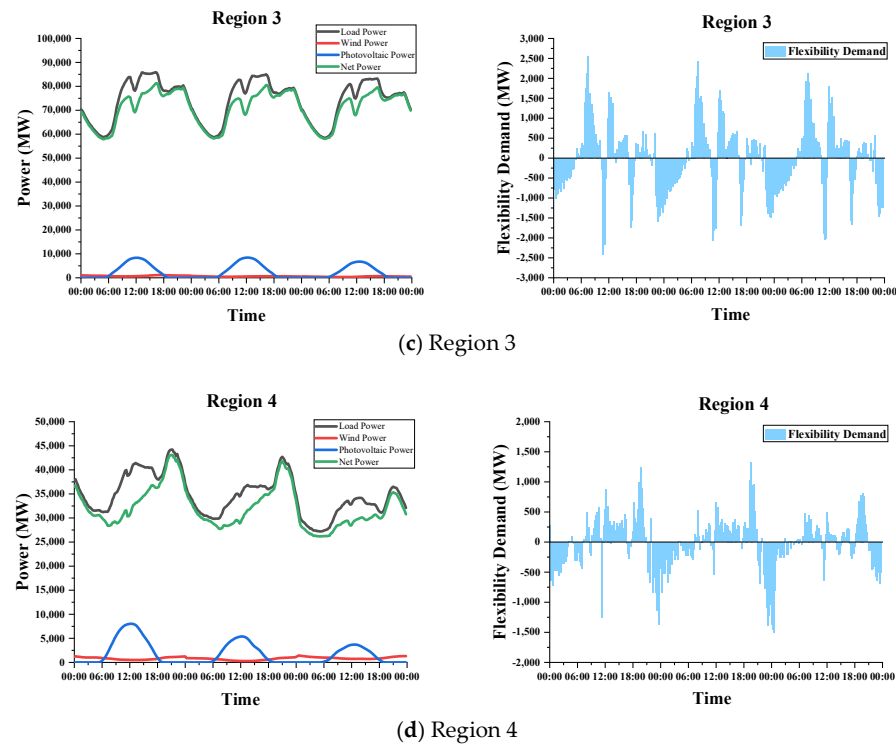


Figure 3. Forecast data curves and flexibility demand of regions.

5.2. Flexibility Supply

The main parameters of the PHS station include the number of units and the power of a single unit, as shown in Table 1.

Table 1. Parameters of each PHS station.

PHS Station Number	Number of Units	Single Generating Power (MW)	Single Pumping Power (MW)
1	6	300	315
2	4	300	312
3	4	375	380
4	6	350	380
5	4	250	275
6	4	150	165
7	6	300	315
8	4	300	330
9	4	250	270
10	6	300	269

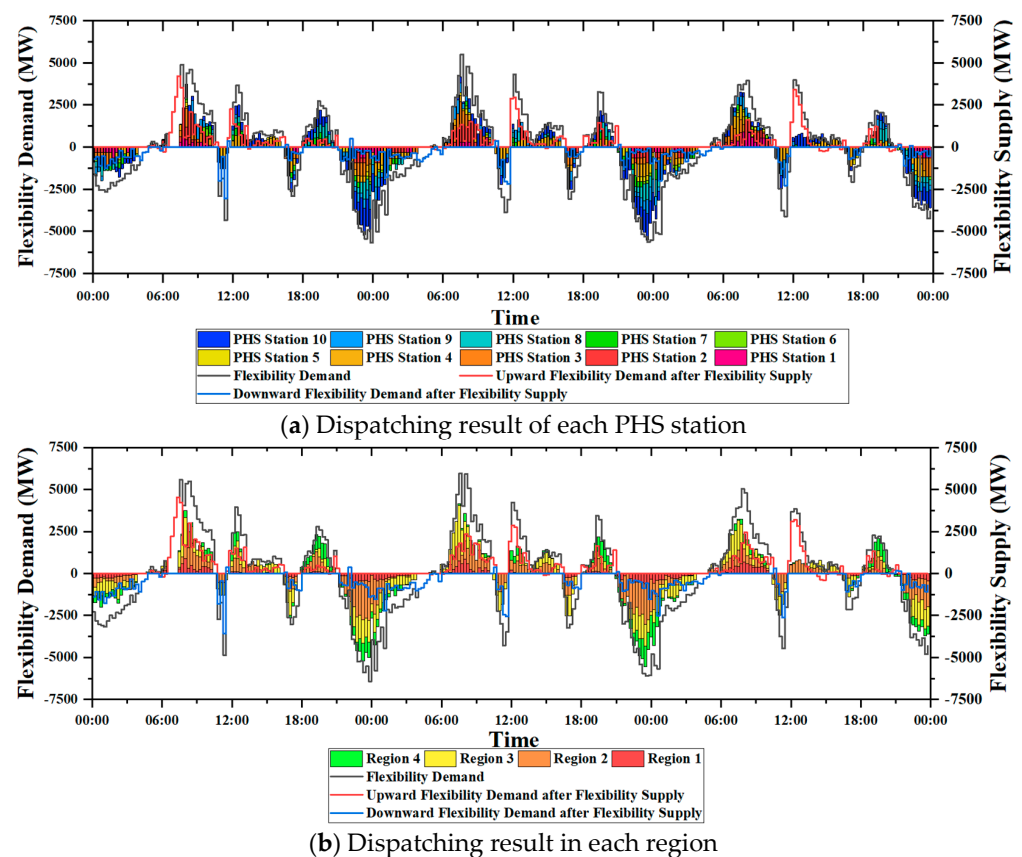
Due to factors such as the price model of PHS stations and the contracts signed between grid operators and PHS stations, the flexibility supply patterns of PHS stations to each region are also different, and the different regions have different regional constraints.

Table 2 shows the distribution ratio of each PHS station to each region under different regional allocation constraints.

The simulation dispatching results of each PHS station are shown in Figure 4, where the horizontal axis represents the time, the vertical axis represents the generation power or pumping power of each PHS station, the positive power represents the generation power, and the negative power represents the pumping power.

Table 2. PHS station allocation ratio to each region.

PHS Station Number	Allocation Ratio (%)			
	Region 1	Region 2	Region 3	Region 4
1	33.33	27.78	27.78	11.11
2	41.67	0	58.33	0
3	12.67	0	87.33	0
4	0	0	100	0
5	50	0	0	50
6	50	0	0	50
7	27	18	0	55
8	0	0	0	100
9	0	100	0	0
10	0	100	0	0

**Figure 4.** Dispatching result of dispatching scope.

The dispatching results show that the optimized dispatching model for PHS flexibility can realize the output dispatching of PHS stations, and conform to the operation characteristics of PHS stations, for example, the power generation and pumping conditions are different in the same time period, the multiple cycles of power generation and pumping in the dispatching period, and the limited number of starts and stops in one day is not exceeded.

Figure 4a shows the matching of flexibility demand and flexibility supply in the whole dispatching scope. The black curve represents the flexibility demand in the whole dispatching scope, the red curve represents the upward flexibility demand after the flexibility supply of the PHS station, the blue curve represents the downward flexibility demand after the flexibility supply of the PHS station, and the different colors in the histogram represent the flexibility supply of different PHS stations. Figure 4b shows the flexibility

supply of PHS stations to each region, and the different colors in the histogram represent the flexibility supply of PHS stations to each region.

The simulation results show that the histogram can basically cover the area enclosed by the black curve and the coordinate axis, and the flexibility supply by the PHS station in this dispatching scope can basically meet the overall flexibility demand. At the same time, the upward and downward flexible supply of PHS electricity has basically not exceeded the limit. There is a constraint to prevent the oversupply of flexibility in the constraints of the flexibility dispatching model of the PHS station, because the solver is used to solve the optimization problem. The convergence accuracy is set to 0.01% in order to prevent the solution time from being too long. In order to find a feasible solution and make the strict constraints feasible, the solver automatically adds relaxation in the solution process, so in some cases, the flexibility oversupply constraint is violated in a few periods in the simulation results, but the degree of violation is acceptable.

Figure 5 shows the supply and demand of flexibility in each region. The black curve represents the flexibility demand of each region, the red curve and blue curve represent the upward and downward flexibility demand after the PHS station flexibility supply to each region, respectively. The histogram represents the flexibility supply of PHS stations to each region. This flexibility supply is calculated by the allocation ratio under regional constraints.

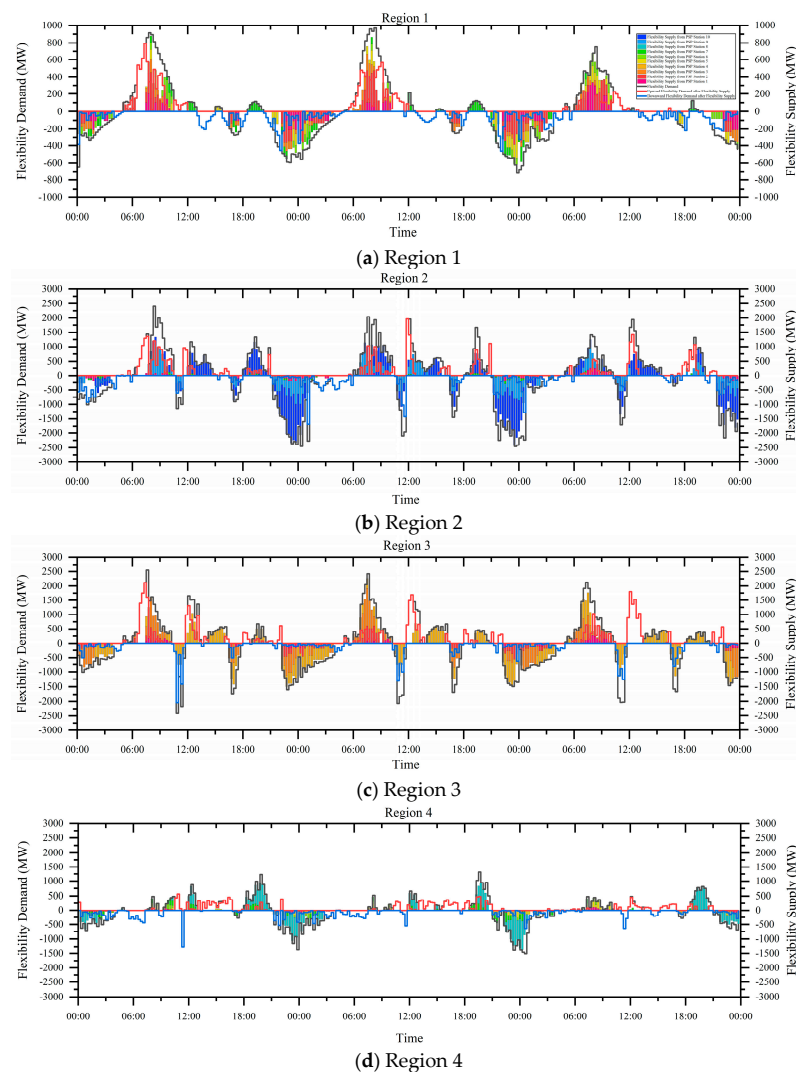


Figure 5. The flexibility supply of PHS stations to each region.

Through the flexibility supply and demand of each region, it can be deduced that the matching of flexibility supply and flexibility demand in each region can be completely matched in most cases. Moreover, it can be observed that some dispatching periods are limited by the actual operating conditions of PHS stations, and it is difficult to achieve a complete match between flexibility supply and demand.

5.3. Flexibility Supply Costs

In order to quantify the economics of the dispatch model proposed in this study, the following three dispatching modes are set up, along with the flexibility supply from PHS stations and thermal power units.

Case1: All flexibility supply is from thermal power units. Figure 6 shows the flexibility supply of the thermal power units, the upward flexibility of the thermal power unit is the region enclosed by the red curve and the 0 coordinate axis, and the downward flexibility of the supply is the area enclosed by the blue curve and the 0 coordinate axis.

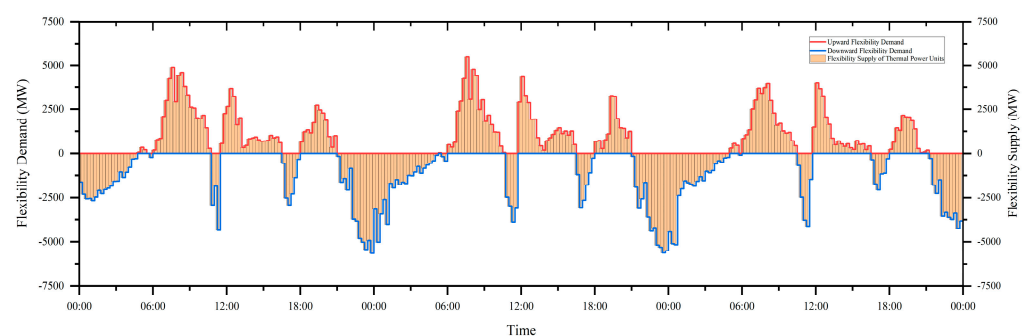


Figure 6. Case1 dispatching result.

Case2: The supply flexibility of PHS stations is added, manual dispatching to dispatch PHS stations is used, and the remaining flexibility supply is derived from thermal power units. Figure 7 shows the flexibility supply of manually dispatched PHS stations, the histogram represents the flexibility supply of each PHS station, and the area enclosed by the red curve, the blue curve and the 0 coordinate axis shows the flexibility supply of thermal power units required. The area enclosed by the blue curve above the zero axis and the 0 axis is the reverse increase in the downward flexibility demand caused by the operation of the PHS unit, and the area enclosed by the red curve below the zero axis and the 0 axis is due to the reverse increase in the upward flexibility demand caused by the operation of the PHS units.

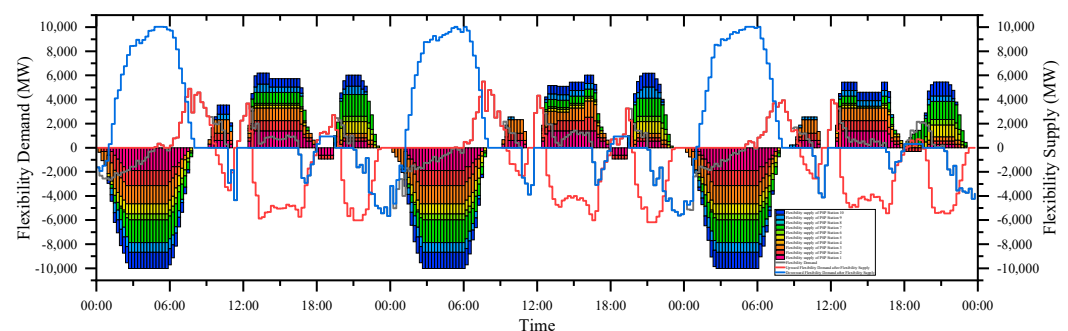


Figure 7. Case2 dispatching result.

Case3: PHS stations supply flexibility is added, and the PHS station flexibility optimization dispatching model proposed in this study is used to dispatch PHS stations. Figure 8 shows the flexible supply of PHS stations using the model proposed in this study. The histogram represents the flexibility supply of PHS stations, and the area enclosed by

the red curve, the blue curve, and the 0 coordinate axis shows the flexibility of thermal power units supply required.

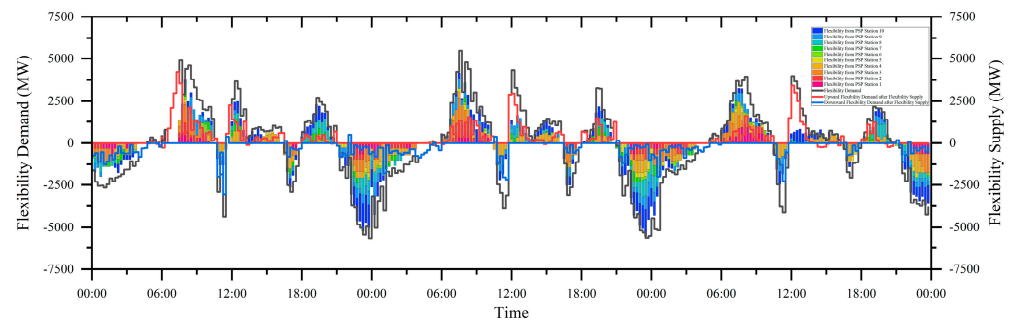


Figure 8. Case3 dispatching result.

The economics are evaluated by quantifying the cost of power generation for the flexibility supply of each case. The method of quantifying the cost of flexible supply is simplified as follows:

(1) Thermal power units: When the supply is indicative of an upward flexibility, it is necessary to climb up the slope to increase power generation, that is, to increase the power generation on the basis of the original power generation plan, and the flexibility supply cost is positive. The downward flexibility supply causes the need to climb down to reduce the power generation capacity, that is, the power generation is reduced on the basis of the original power generation plan, and the cost of flexibility supply is negative.

(2) PHS unit: When the supply is indicative of an upward flexibility, it needs to generate electric energy under the power generation condition, and the flexibility supply cost is positive. When the supply of a downward flexibility is required, it needs to consume electricity in pumping conditions, and the cost of flexible supply is positive.

The cost of flexibility supply of thermal power units is set to be 0.35 CNY/kWh, and the cost of flexibility supply of PHS units is 0.35 CNY/kWh under pumping conditions and 0.21 CNY/kWh under power generation conditions.

The economic comparison in different cases is shown in Table 3. Through comparison, it is found that the cost of flexibility supply only through thermal power resources is obviously higher, and the cost of flexibility supply is significantly lower after adding PHS resources. In Case3, the PHS stations have more flexibility supply, which greatly reduces the flexible supply pressure on the thermal power station. At the same time, the PHS station's dispatching strategy in this study greatly reduces the cost of power generation and dispatching. Therefore, the optimal scheduling strategy proposed and the PHS power station model established in this paper are effective.

Table 3. Economic comparison.

Case	Resource Type	Upward Flexibility Supply (MW)	Downward Flexibility Supply (MW)	Cost of Flexibility Supply (CNY)
Case1	Thermal units	3,663,015.68	3,655,076.08	6.4033×10^8
Case2	PHS stations	542,103	686,743	9.4668×10^7
	Thermal units	781,093.17	662,304.99	
Case3	PHS stations	138,256.82	175,022	2.5680×10^7
	Thermal units	208,252.24	172,739.11	

6. Conclusions

With the continuous improvement of the penetration rate of renewable energy in the power system. The flexibility demand of power systems is also increasing, it is more difficult

to balance the supply and demand of power system flexibility, and flexible resources are required to play a greater role. In recent years, PHS resources have not only been vigorously developed, but also possess the advantages of pollution-free, low-cost, and fast regulation. In this study, according to the actual operation characteristics of PHS units, a refined operation model of PHS is established. The optimal dispatching model for PHS flexibility is established with the goal of optimal matching of flexibility supply and flexibility demand in the different flexibility supply patterns of multi-PHS stations. The results show that the proposed method can realize the optimal flexibility of multi-PHS power station supply to multiple regions in East China. At the same time, this method can satisfy the matching of flexibility supply and flexibility demand, and make the PHS stations' dispatching more reasonable. This optimal flexibility dispatching method improves the utilization rate and flexible supply of PHS power stations and demonstrates favorable economic characteristics.

Author Contributions: Conceptualization, X.C. and P.W.; methodology, H.H. and B.S.; software, K.Q. and X.T.; validation, X.C.; investigation, X.C. and X.T.; writing—original draft preparation, F.Y.; writing—review and editing, X.C., X.T. and D.L.; supervision, H.H. and B.S. All authors have read and agreed to the published version of the manuscript.

Funding: The work is sponsored by Science and Technology Project of East China Branch of State Grid (Grant No.: SGHD0000DKJS2310440).

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy reasons.

Conflicts of Interest: Xinyi Chen, Pan Wu, Hongyu He, Bingbing Song, Kangping Qin and Xiaobi Teng were employed by The State Grid East China Branch. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Wang, W.; Dou, F.; Cheng, J.; Jiang, Z.; Shi, L.; Wu, F. A modeling method for a wind and photovoltaic joint power probability model. *Power Syst. Prot. Control.* **2020**, *48*, 22–29. [\[CrossRef\]](#)
2. Wang, S.; Yu, J. Joint Conditions Probability Forecast Method for Wind Speed and Wind Power. *Proc. CSEE* **2011**, *31*, 7–15. [\[CrossRef\]](#)
3. Liu, Y.; Li, W.; Liu, C.; Zhang, D. Mixed Skew Distribution Model of Short-term Wind Power Prediction Error. *Proc. CSEE* **2015**, *35*, 2375–2382. [\[CrossRef\]](#)
4. IEA. *Empowering Variable Renewables-Options for Flexible Electricity Systems*; International Energy Agency: Paris, France, 2008. [\[CrossRef\]](#)
5. Lannoye, E.; Flynn, D.; O'mally, M. Evaluation of power system flexibility. *IEEE Trans. Power Syst.* **2021**, *27*, 922–931. [\[CrossRef\]](#)
6. Holttinen, H.; Tuohy, A.; Milligan, M.; Lannoye, E.; Silva, V.; Müller, S.; Sö, L. The flexibility workout: Managing variable resources and assessing the need for power system modification. *IEEE Power Energy Mag.* **2013**, *11*, 53–62. [\[CrossRef\]](#)
7. Lu, Z.; Li, H.; Qiao, Y. Power System Flexibility Planning and Challenges Considering High Proportion of Renewable Energy. *Autom. Electr. Power Syst.* **2016**, *40*, 147–158. [\[CrossRef\]](#)
8. Mahfoud, R.J.; Alkayem, N.F.; Zhang, Y.; Zheng, Y.; Sun, Y.; Alhelou, H.H. Optimal operation of pumped hydro storage-based energy systems: A compendium of current challenges and future perspectives. *Renew. Sust. Energ. Rev.* **2023**, *178*, 113267. [\[CrossRef\]](#)
9. Kusakana, K. Optimal operation scheduling of grid-connected PV with ground pumped hydro storage system for cost reduction in small farming activities. *Energy Storage* **2018**, *16*, 133–138. [\[CrossRef\]](#)
10. Lin, S.; Ma, T.; Javed, M.S. Prefeasibility study of a distributed photovoltaic system with pumped hydro storage for residential buildings. *Energy Convers. Manag.* **2020**, *222*, 113199. [\[CrossRef\]](#)
11. Cavazzini, G.; Benato, A.; Pavesi, G.; Ardizzon, G. Techno-economic benefits deriving from optimal scheduling of a Virtual Power Plant: Pumped hydro combined with wind farms. *J. Energy Storage* **2021**, *37*, 102461. [\[CrossRef\]](#)
12. Zhang, G.; Chen, Y.; Zhang, J.; Tang, N.; Niu, Y. Research on optimization of day-ahead dispatching of wind power-photovoltaic-hydropower-thermal power-pumped storage combined power generation system. *Acta Energetica Solaris Sin.* **2020**, *41*, 79–85.
13. Zou, J.; Lai, X.; Wang, N. Mitigation of wind curtailment by coordinating with pumped storage. *Proc. CSEE* **2015**, *39*, 2472–2477. [\[CrossRef\]](#)
14. Ma, Z.; Wang, D.; Zhang, H.; Wang, Y.; Dong, H. Two-stage optimal dispatching based on wind-photovoltaic—Pumped storage-thermal power combined power generation system. In Proceedings of the 2019 IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2), Changsha, China, 8–10 November 2019; pp. 1714–1719. [\[CrossRef\]](#)

15. Zhao, J.; He, Y.; Fang, Y.; Weng, Y.; Ma, W.; Xiao, S.; Liang, Y. Multi-Source Optimal Dispatch Considering Ancillary Service Cost of Pumped Storage Power Station Based on Cooperative Game. *Energy Rep.* **2021**, *7*, 173–186. [[CrossRef](#)]
16. Xia, S.; Ding, Z.; Du, T.; Zhang, D.; Shahidehpour, M.; Ding, T. Multitime Scale Coordinated Scheduling for the Combined System of Wind Power, Photovoltaic, Thermal Generator, Hydro Pumped Storage, and Batteries. *IEEE Trans. Ind. Appl.* **2020**, *56*, 2227–2237. [[CrossRef](#)]
17. Wang, S.; Liu, J.; Chen, H.; Bo, R.; Chen, Y. Modeling State Transition and Head-Dependent Efficiency Curve for Pumped Storage Hydro in Look-Ahead Dispatch. *IEEE Trans. Power Syst.* **2021**, *36*, 5396–5407. [[CrossRef](#)]
18. Golshani, A.; Sun, W.; Zhou, Q.; Zheng, Q.P.; Wang, J.; Qiu, F. Coordination of Wind Farm and Pumped-Storage Hydro for a Self-Healing Power Grid. *IEEE Trans. Sustain. Energy* **2018**, *9*, 1910–1920. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.