Multi-Objective Short-Term Optimal Dispatching of Cascade Hydro–Wind–Solar–Thermal Hybrid Generation System with Pumped Storage Hydropower

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Abstract: Aiming to mitigate the impact of power fluctuation caused by large-scale renewable energy integration, coupled with a high rate of wind and solar power abandonment, the multi-objective optimal dispatching of a cascade hydro–wind–solar–thermal hybrid generation system with pumped storage hydropower (PSH) is proposed in this paper. Based on the proposed system, the scheduling operation strategy takes into account the complex restrictions of cascade hydropower as well as the flexibility of the PSH. According to various scenarios, the NSGA-II approach is adopted to address the optimization problem, minimizing the system’s residual load variation and operation cost. The Pareto solution sets are contrasted and evaluated, applying the TOPSIS with CRITIC weighting. Additionally, the scheduling output of thermal power, cascade hydropower, and PSH is given in terms of different scenarios. The results demonstrate that the allocation of PSH to a hybrid energy system can significantly reduce the operation cost and the fluctuation in the residual load.

Keywords: cascade hydropower; hybrid generation system; optimal dispatching; pumped storage

1. Introduction

Wind, solar, and hydropower are instances of renewable and clean energy that have been extensively generated and employed as a consequence of the depletion of fossil fuels and global environment pollution [1,2]. As the energy structure continues to diversify, electric power dispatching is encountering increasingly difficult problems. Improving the amount of renewable energy consumed by the power grid and lowering the detrimental impact of wind and solar output’s extreme fluctuation and interruptions on system stability are critical challenges [3–5]. In the existing power system, the thermal power plant is limited by carbon emission and climbing constraints, and its consumption and adjustment capacity for renewable energy are limited [6], resulting in massive wind and photovoltaic abandonment. Cascade hydropower is a clean, efficient renewable energy source with an enormous regulation capacity, flexible start–stop, and enhanced peak regulation advantages. In addition, hydropower, as a good regulatory power source, can effectively smooth the fluctuations in photovoltaic and wind power generation [7,8]. It is expected to play an essential part in the future in facilitating large-scale renewable energy consumption and multi-energy complementary operations [9]. Therefore, it is of great significance that we understand the optimal dispatch of cascade hydropower combined with multiple energy sources.

Recently, there have been many achievements in research on the optimal scheduling of multi-energy complementary systems. Representative multi-energy hybrid systems mainly include hydro–solar systems [10,11], hydro–wind systems [12,13], hydro–wind–solar systems [14,15], and so on. In the hydro–solar hybrid systems, Luo et al. [16] dealt with the randomness of photovoltaic output based on the fuzzy clustering method, considered the constraints of power grid section, and constructed the scheduling model of a
hydro–photovoltaic hybrid system with the goal of achieving the maximum consumption of electricity. However, historical data clustering requires a set of scenes with uncertain variables to be determined in advance, and its computational accuracy is affected by the number of scenes. Based on the Longyangxia large hydro/PV hybrid power system in Qinghai Province of China, Li et al. [17] proposed a long-term dispatching model for an integrated hydro-PV hybrid system considering the smoothness of the power output process and the annual total power generation simultaneously. In hydro–wind hybrid systems, in order to solve the uncertainty of wind speed and water inflow, Xiao et al. [18] proposed a model for determining the optimal spinning reserve capacity of the hydro–wind–thermal combined system to improve the reliability of the optimal operation. However, the PSO algorithm adopted in this paper requires a high initial value setting and is easy to fall into the local optimal. Wang et al. [19] proposed the scheduling principle of prioritizing wind power output and using the adjustability of hydropower to cope with the randomness of wind power. But, this paper deals with only conventional hydropower stations. In hydro–wind–solar hybrid systems, Ye et al. [20] established an index framework to evaluate the complementary characteristics of a hydro–wind–solar combined system. Aiming to achieve the maximum storage capacity of the cascade reservoir and minimum wind and light abandonment, Zhang et al. [21] established an optimal dispatching model for the complementary operation of the wind–PV–hydro complementary system in the Yalong River region and studied the influence of complementary operation on the water level and generation flow. However, this research process did not take into account the output characteristics of cascade hydropower and the effect of water flow delay between hydropower stations in detail. Wei et al. [22] studied the short-term optimal scheduling of hydropower stations coordinating wind and solar power stations participating in system peak shaving. Yin et al. [23] used Monte Carlo and scene clustering methods to deal with the uncertainty of wind and photovoltaic power and established a random optimal scheduling model of the combined system, including wind power, photovoltaic, cascade hydropower, and thermal power.

However, because the output of the hydropower station is limited by many complex constraints such as incoming water, reservoir volume, and discharge flow, its intraday output cannot absorb the excess renewable energy output in the system in a timely manner, resulting in a certain abandonment of wind and photovoltaic. Therefore, the employment of energy storage technology is an effective method to solve the power scheduling issue and increase the entire energy utilization. The PSH is flexible and reliable, which is the most mature and practical large-scale energy storage method in the power system. Numerous academics have conducted related studies since the PSH has been thought of as a supplement to the combined system. Wang et al. [24] presented a day-ahead optimal scheduling model of a combination system with wind, solar, thermal, and pumped storage, taking the deep peak shaving of thermal power units into consideration, with the goal of reaching the power grid with a high proportion of renewable energy. However, the constraint part of the model is too simple, and the description of the algorithm’s solution process is insufficient. Zhang et al. [25] established an economic evaluation model of a wind–PV–pumped Storage combined system with a different installed capacity considering carbon emissions. Luo et al. [26] proposed a two-stage optimal scheduling approach with a wind–solar–pumped storage–thermal combined system to lower the operational cost and minimize the active output deviation of the pumped storage unit. Others [27,28] configured PSH in the multi-energy complementary system and studied the combined system, including wind power, photovoltaic, hydropower, thermal power, and pumped storage power stations. Nevertheless, these studies merely considered conventional hydropower and a single objective function. The complicated restrictions of cascade hydropower stations are taken into account in this paper.

Multi-criteria decision analysis (MCDA) is an important field of decision-making disciplines, which is of great significance to solve the multi-objective optimization problem of energy systems. The main methods include WSM [29], AHP [30], TOPSIS [31], BWM [32],
and so on. Among them, TOPSIS is a comprehensive evaluation method for multi-attribute decision analysis by ranking the closeness between multiple evaluation objects and ideal solutions [33]. Bognár et al. [34] proposed the AHP-TOPSIS-based PRISM method, which can be applied more widely for practical decision-making problems than the previous PRISM approaches. Zeng et al. [35] improves the TOPSIS by introducing the Mahalanobis distance and Pearson correlation coefficients. In contrast to subjective weighting methods, the CRITIC method comprehensively considers the difference in and correlation of each indicator without relying on subjective judgments [36]. Combining the TOPSIS method on the basis of the weights obtained by CRITIC can improve the objectivity and accuracy of the multi-objective solution.

Based on the above analysis, most of the existing research focused merely on the cascaded hydropower or PSH to smooth the power fluctuations caused by wind and photovoltaic grid connection. However, few studies considered the combination of PSH in the combined system with cascade hydropower stations. With the PSH’s characteristics of peak shaving and valley filling, the complementary advantages of the combined system are further improved. This paper explores the optimal dispatching of a multi-energy hybrid generation system that includes both cascade hydropower and PSH, aiming to mitigate the impact of power fluctuation caused by large-scale renewable energy integration and improve the consumption of renewable energy.

The main contributions of this paper are as follows:
(1) This paper proposes a multi-objective optimal dispatching model of a cascade hydro–wind–sol–thermal hybrid generation system with pumped storage hydropower, which takes into account the complex restrictions of cascade hydropower and the flexibility of the PSH.
(2) In order to improve the computational speed of the initialization process, the discharge of each cascade hydropower station is selected as the bottom decision variable to form the feasible region, and the dispatch output of every station is chosen as the upper variable to participate in the genetic variation in the population.
(3) Based on the dispatching operation strategy proposed in this paper, the optimization results under four different scenarios are compared. As a result, PSH can exert the advantage of peak load shifting to significantly reduce the operation cost and the residual load fluctuation while improving the renewable energy consumption rate.

And the multi-energy complementary system with four cascade hydropower stations in a regional power grid is studied. The simulation results show that the PSH can effectively reduce the operation cost of the hybrid generation system and decrease the rate of wind and photovoltaic abandonment. Furthermore, with the operating characteristics, it can further stabilize the residual load fluctuation in the system and improve the stability of the thermal power supply.

The remainder of this paper is organized as follows. Section 2 introduces the optimal dispatching model of the hybrid generation system. The solving method and the operation strategy are proposed in Section 3. Section 4 introduces the materials and dispatching scenarios in the analysis. Section 5 presents the results and discussion. And conclusions are presented in Section 6.

2. Short-Term Optimal Dispatching Model of the Hybrid Generation System

2.1. Objective Functions

2.1.1. Objective Function $F_1$: The Lowest Operation Costs

There are many factors to consider in the calculation of integrated operation costs, including the fuel cost $C_f$ and the pollutant penalty cost $C_p$ of the thermal power plant, the operation and maintenance cost of power stations $C_s$, the power abandonment penalty cost $C_d$, and the start-up and shutdown loss cost of PSH $C_h$.

$$\min F_1 = \min \left( C_f + C_s + C_p + C_d + C_h \right)$$  \hspace{1cm} (1)
• Fuel cost of thermal power units $C_f$

The operating cost of the thermal power unit is a convexity quadratic function of its output.

$$C_f = \sum_{t=1}^{T} \sum_{i=1}^{N_g} w \left[ a_i \left( P_{gi}^t \right)^2 + b_i P_{gi}^t + c_i \right]$$

(2)

where $T$ is the dispatching period. $N_g$ is the number of thermal power units. $a_i$, $b_i$, and $c_i$ represent the coal consumption coefficient of thermal power units [37]. $P_{gi}^t$ represents the output power of unit $i$ in the $t$ period, and $w$ is the coal price.

• Penalty cost for pollutant emissions $C_p$

$$C_p = q_g \sum_{t=1}^{T} \sum_{i=1}^{N_g} \left[ a_{i0} + a_{i1} P_{gi}^t + a_{i2} \left( P_{gi}^t \right)^2 + a_{i3} \exp(a_{i4} P_{gi}^t) \right]$$

(3)

where $a_{i0}$-$a_{i4}$ are the emission coefficients of the $i$th thermal power unit. $q_g$ is the penalty cost coefficient of pollutants such as SO$_2$ and NO$_X$ [38].

• The maintenance cost of the power stations $C_s$

$$C_s = \sum_{t=1}^{T} \left( C_{hp} \sum_{j=1}^{N_h} P_{hj}^t + C_{wt} P_{WT}^t + C_{pv} P_{PV}^t + C_{pg} P_{PG}^t \right)$$

(4)

where $P_{hj}^t$, $P_{WT}^t$, $P_{PV}^t$, and $P_{PG}^t$ represent the output of cascade hydropower, wind farms, photovoltaic, and PSH during the $t$ period, respectively. $P_{PG}^t > 0$ indicates that the power station is running in the power generation state, while $P_{PG}^t < 0$ is in the pumping state. $C_{hp}$, $C_{wt}$, $C_{pv}$, and $C_{pg}$ are the maintenance coefficients of the corresponding power stations [39].

• The penalty cost of power abandonment $C_d$

$$C_d = \sum_{t=1}^{T} \theta P_{new}^t$$

(5)

where $P_{new}^t$ is the sum abandonment power of wind and photovoltaic in the $t$ period, and $\theta$ is the penalty coefficient of power abandonment.

• Start-up and shutdown loss cost of PSH $C_h$

$$C_h = y_t^p \left( 1 - y_{t-1}^p \right) + y_t^p \left( 1 - y_{t-1}^p \right) C_{h,on} + y_{t-1}^p \left( 1 - y_t^p \right) + y_{t-1}^p \left( 1 - y_t^p \right) C_{h,off}$$

(6)

where $y_t^p$ and $y_{t-1}^p$ are Boolean variables representing whether the unit is in pumping condition or power generation condition, respectively. And where 1 is yes and 0 is no. $C_{h,on}$ and $C_{h,off}$, respectively, refer to the loss cost of a single opening and closing of PSH [40].

2.1.2. Objective Function $F_2$: The Smallest Residual Load Fluctuation

The peak regulation effect of cascade hydropower and PSH to smooth the net load fluctuation after wind and photovoltaic connected to the grid is expressed by the variance of the system residual load.

$$\min F_2 = \min \left( \frac{1}{T} \sum_{t=1}^{T} \left( L_t - \bar{L} \right)^2 \right)$$

(7)

$$L_t = P_L^t - P_{WT}^t - P_{PV}^t - \sum_{j=1}^{N_h} P_{hj}^t - P_{PG}^t$$

(8)
\[ \mathcal{L} = \frac{1}{T} \sum_{t=1}^{T} L_t \]  

(9)

where \( F_2 \) is the mean square error of the system residual load. \( P_L^t \) is the load power. \( L_t \) and \( \mathcal{L} \) represent the system residual load power and the average system residual load, respectively.

### 2.2. Constraints

#### 2.2.1. System Power Balance Constraints

Under the premise of ignoring the network loss, the system power must always be balanced.

\[ \sum_{i=1}^{N_g} P_{gi}^t + \sum_{j=1}^{N_h} P_{hj}^t + P_{WT}^t + P_{PV}^t + P_{PG}^t = P_L^t \]  

(10)

#### 2.2.2. Operational Constraints of Thermal Power Units

\[ p_{t, \text{min}}^{gi} \leq p_t^{gi} \leq p_{t, \text{max}}^{gi} \]  

(11)

\[ \left| p_t^{gi} - p_{t-1}^{gi} \right| \leq \Delta p_{t, \text{max}}^{gi} \]  

(12)

where \( p_{t, \text{min}}^{gi} \) and \( p_{t, \text{max}}^{gi} \) represent the upper and lower limits of the thermal power unit output, respectively. \( \Delta p_{t, \text{max}}^{gi} \) refers to the maximum climbing power of the \( i \)th thermal power plant.

#### 2.2.3. Operational Constraints of Cascade Hydropower

- **Unit output constraints**

\[ p_{t, \text{min}}^{hj} \leq p_t^{hj} \leq p_{t, \text{max}}^{hj} \]  

(13)

where \( p_{t, \text{min}}^{hj} \) and \( p_{t, \text{max}}^{hj} \) represent the upper and lower limits of the output of the cascade hydropower station \( j \) in the time period \( t \), respectively, and the lower limit of the output is set to 0.

- **Hydropower output characteristic constraints**

\[ p_t^{hj} = C_1 j (V_t^{j})^2 + C_2 j (Q_t^{j})^2 + C_3 j V_t^{j} Q_t^{j} + C_4 j V_t^{j} + C_5 j Q_t^{j} + C_6 j \]  

(14)

where \( Q_t^{j} \) and \( V_t^{j} \), respectively, represent the water discharge and reservoir volume of hydropower station \( j \) during the time period \( t \). \( C_1 \sim C_6 \) is the corresponding power generation coefficient [41].

- **Water discharge and reservoir volume constraints**

\[ Q_{\text{min}}^{j} \leq Q_t^{j} \leq Q_{\text{max}}^{j} \]  

(15)

\[ V_{\text{min}}^{j} \leq V_t^{j} \leq V_{\text{max}}^{j} \]  

(16)

\[ V_0 = V_{\text{ini}}, V_T = V_{\text{end}} \]  

(17)

where \( Q_{\text{min}}^{j} \) and \( Q_{\text{max}}^{j} \) are the minimum and maximum water discharge of hydro unit \( h \), respectively. \( V_{\text{min}}^{j} \) and \( V_{\text{max}}^{j} \) are the minimum and maximum reservoir volume, respectively. \( V_{\text{ini}}^{j} \) and \( V_{\text{end}}^{j} \) are the initial and terminal reservoir volume.

- **Water balance constraints**
\[ V_j^t = V_{j-1}^t + \left[ I_j^t - Q_j^t - S_j^t + \sum_{k \in U} \left( Q_{k-j}^t - S_{k-j}^t \right) \right] \Delta t \]  

(18)

where \( I_j^t \) and \( S_j^t \), respectively, represent the inflow and abandoned flow of the \( j \)th hydropower station during the time period \( t \). \( U \) is the set of connected power stations upstream. \( \tau_i \) is the flow delay of upstream hydropower station \( k \), and \( \Delta t \) is the length of a single period in the dispatching period.

2.2.4. Renewable Energy Output Constraints

The on-grid power of wind power and photovoltaic is less than the maximum value of the predicted output.

\[ 0 \leq p_{WT}^t \leq p_{WT}^{t,f} \]  

(19)

\[ 0 \leq p_{PV}^t \leq p_{PV}^{t,f} \]  

(20)

where \( p_{WT}^{t,f} \) and \( p_{PV}^{t,f} \) represent the predicted output values of wind power and photovoltaic, respectively.

2.2.5. Operation Constraints of PSH

- Unit output constraints

\[ 0 \leq |P_{PG}^t| \leq P_{PG}^{max} \]  

(21)

where \( P_{PG}^{max} \) represents the upper limit of power generation and pumping power of the pumped storage power station, which is equal to its installed capacity.

- Unique operating condition constraints

The pumped storage units cannot pump water and generate electricity at the same time. By setting the sum of Boolean variables representing the pumping/power generation/shutdown state less than or equal to 1, the unit’s operating conditions within the same period are unique.

\[ y_p^t + y_g^t \leq 1 \]  

(22)

- Reservoir capacity and energy balance constraints

The real-time storage capacity is between a certain upper and lower limit, and the water level at the beginning and end of each dispatching cycle must be consistent, that is, the total energy in the reservoir in a single day must be balanced.

\[ E_{h,min} \leq E_{h,t} \leq E_{h,max} \]  

(23)

\[ E_{h,t+1} = E_{h,t} + \left( \eta_p p_{PG}^t \left| p_{PG}^t > 0 \right. + \eta_g \sum_{k=1}^{K} p_{PG}^t \left| p_{PG}^t < 0 \right. \right) \Delta t \]  

(24)

\[ E_{h,t_0} = E_{h,t_{end}} \]  

(25)

where \( E_{h,t} \) is the real-time storage capacity of the upper reservoir of the station during the \( t \) period, and \( E_{h,max} \) and \( E_{h,min} \) are the upper and lower limits of the upper reservoir storage capacity, respectively. \( E_{h,t_0} \) and \( E_{h,t_{end}} \) refer to the water level of the upper reservoir of the power station at the beginning and end of the dispatching cycle, respectively. \( \eta_p \) and \( \eta_g \), respectively, refer to the average water and electricity conversion coefficient during the pumping and generating of pumped storage units.

- Maximum start–stop times constraint of units

In the pumping or power generation state, frequent switching between the shutdown and operating conditions of the pumped storage units will bring a lot of start-up and
shutdown costs, and will not be conducive to the stable operation of PSH. Therefore, it is necessary to set constraints to limit the start-stop times of the pumped storage units.

\[
\sum_{t=2}^{T} |y^g_t - y^g_{t-1}| \leq n_g \tag{26}
\]

\[
\sum_{t=2}^{T} |y^p_t - y^p_{t-1}| \leq n_p \tag{27}
\]

where \( n_g \) and \( n_p \) are the maximum start-stop times of pumped storage units in one day, respectively.

3. Solution and Scheduling Strategy

3.1. Multi-Objective Optimization Method Based on NSGA-II Algorithm

As a nonlinear multi-objective optimization solution, NSGA-II algorithm, enhances the performance of the algorithm based on its elite selection strategy and fast non-dominated sorting. By introducing the crowding degree distance to screen the advantages and disadvantages of individuals at the same level, the independence of multiple optimization objectives is maintained to the maximum extent, and the convergence of the Pareto frontier is accelerated.

Since there is a spatial-temporal coupling relationship between the water discharge and the reservoir volume of cascade hydropower stations, the output characteristics of the hydropower station are determined by the water discharge \( Q_t \) and the reservoir volume \( V_t \). Therefore, in this paper, the water discharge of each cascade hydropower station is taken as the bottom decision variable, and the output of each power station is selected as the upper decision variable.

The program flow chart of solving the optimal scheduling model using the NSGA-II algorithm is shown in Figure 1.

The design of generating a feasible region in the optimization model and the specific implementation steps are as follows.

Step 1: The water discharge \( Q^j_t \) is selected as the underlying decision variable, which is randomly generated under the premise of satisfying the upper and lower limits.

Step 2: Combined with the above water discharge, based on the water balance constraint and the initial storage capacity of each reservoir, the reservoir volume of the \( j \)th hydropower station \( V^j_t \) is calculated, and whether the storage capacity of each period exceeds the upper limit is judged. If it exceeds the upper limit, it will produce abandoned water, and if it is lower than the lower limit, it will be limited to \( V^j_{\text{min}} \) and reduce the power generation flow.

Step 3: The water discharge required to meet the storage capacity constraints at the end of the dispatching period is calculated, and whether the flow during the termination period meets the upper and lower limits of the power station discharge constraints is judged. If not, return to Step 1.

Step 4: According to Equation (14), the corresponding output of the hydropower stations was calculated.

Step 5: Combined with the predicted output of wind power and photovoltaic, the output of thermal power units is obtained under the premise of meeting the power balance constraint by considering the pumping and storage operation strategy. And if the thermal power output is lower than the lower limit, it will be set as the minimum output and generate the corresponding abandonment of wind and photovoltaic.

Step 6: The feasibility domain of the model is generated by judging whether the output of the thermal power unit meets the upper limit constraints and climb constraints. If the judgment condition is not met, return to Step 1.
3.2. Operation Strategy of Hybrid Generation System

The dispatching strategy of a multi-energy hybrid generation system participating in the power grid is as follows: Based on the predicted value of the next day load, wind, and photovoltaic 24 h output, the renewable energy output should be accommodated as much as possible during the day ahead of dispatching. Combined with the output characteristics and constraints of each station, the output of the power stations is coordinated and scheduled to meet the load demand of the system with the lowest operation cost and minimum residual load fluctuation as the optimization objectives.

When the sum of the renewable energy predicts the output, the cascade hydropower regulation output and the lower limit of thermal power output in the hybrid system is greater than the predicted value of grid load, that is, the renewable energy output cannot be fully absorbed during the period. In order to ensure the stability of the system, the phenomenon of abandoning wind power and photovoltaic occurs.

In order to further improve the stability of the system operation and reduce the rate of wind and light abandonment, a pumped storage power station is configured in the system. The start and stop times of the pumping/generating conditions are set to two for the pumped storage power station in a day. Under certain load conditions, the pumped storage power station operates at a pumping condition during the low-load or wind and photovoltaic abandonment period to store the excess electric energy of the combined
operation system and participates in power generation high-load demand and during the thermal power output peak period to smooth the volatility of thermal power. The multi-energy hybrid generation system is shown in Figure 2.

![Figure 2](image_url)

**Figure 2.** Schematic diagram of the hybrid generation system. In Figure 2, different color block diagrams represent different power stations and load, and the specific meanings are marked in the figure. The solid green lines represent electrical energy and the dashed blue lines represent water flow of the PSH.

### 4. Case Study

#### 4.1. Basic Data

In this paper, a multi-energy combined system in a certain region is selected for the analysis of short-term optimal scheduling. The combined system includes two thermal power units with installed capacities of 1000 MW and 660 MW, respectively. The cascade hydropower system consists of four hydropower stations, whose hydraulic connection is shown in Figure 3. The installed capacity of hydropower stations $h_1$-$h_3$ is 120 MW, and that of hydropower station $h_4$ is 300 MW. The total installed capacity of wind farms and photovoltaic power plants is 200 MW and 120 MW, respectively. A pumped storage power station with an installed capacity of 200 MW is added to the system, which adopts the variable speed pumping storage units. The pollutant emission coefficient of thermal power plants and the operation parameters of cascade hydropower stations are derived from the literature [41]. The upper and lower limits of thermal power are set as (500, 1000) MW and (330, 660) MW, respectively.

![Figure 3](image_url)

**Figure 3.** Hydraulic connection of cascade hydropower stations. The green arrow line in the figure represents the inflow of each hydropower station, and the blue represents the discharge flow.
And the reservoir capacity limits, hourly water discharge constraints \((\times 10^4 \text{ m}^3)\), and delay time \((h)\) of hydropower stations are shown in Table 1.

### Table 1. Discharge and reservoir capacity constraints of cascade hydropower stations.

<table>
<thead>
<tr>
<th>Plant</th>
<th>(Q_{\text{min}})</th>
<th>(Q_{\text{max}})</th>
<th>(V_{\text{ini}})</th>
<th>(V_{\text{end}})</th>
<th>(V_{\text{min}})</th>
<th>(V_{\text{max}})</th>
<th>Time Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>(h_1)</td>
<td>5</td>
<td>15</td>
<td>100</td>
<td>120</td>
<td>80</td>
<td>150</td>
<td>2</td>
</tr>
<tr>
<td>(h_2)</td>
<td>6</td>
<td>15</td>
<td>80</td>
<td>70</td>
<td>60</td>
<td>120</td>
<td>3</td>
</tr>
<tr>
<td>(h_3)</td>
<td>10</td>
<td>30</td>
<td>170</td>
<td>170</td>
<td>100</td>
<td>240</td>
<td>4</td>
</tr>
<tr>
<td>(h_4)</td>
<td>6</td>
<td>20</td>
<td>120</td>
<td>140</td>
<td>70</td>
<td>180</td>
<td>0</td>
</tr>
</tbody>
</table>

Set the scheduling period \(T\) to 24 h and the interval to 1 h. In this paper, the NSGA-II algorithm is used to solve the optimization model, the number of populations is set as 100, the number of iterations is 1000, and the probability of crossover and mutation is set as 0.8 and 0.1, respectively.

Figure 4 shows the forecast curve of daily load and renewable energy output, and the corresponding data are obtained based on the literature [6,28]. The dotted lines in Figure 4a represent the installed capacity of wind power and photovoltaic, respectively.

![Figure 4. Daily load and renewable energy output prediction curve. (a) Renewable energy output. The green and orange dotted lines in Figure 4a represent the installed capacity of wind power and photovoltaic, respectively. (b) Daily load. The bars and curve in Figure 4b both represent the load power. This drawing method is used in this paper to make the image look more substantial.](image)

Photovoltaic power generation occurs during the day and stops at night, and its intra-day output fluctuates greatly, showing an arch bridge shape and having a certain positive peak-regulating effect [42,43]. The randomness of wind power generation is strong. Generally, wind power has a large output at night and in the early morning, and a small output at noon, which has a good intraday complementary characteristic with photovoltaic.

#### 4.2. Scheduling Scenarios

Four scheduling scenarios are selected to compare and verify the effectiveness of the proposed model. Scenario 1: Only renewable energy power generation is connected to the network, without considering hydropower and pumping storage, and two thermal power units are used for renewable energy consumption and system peak shaving. Scenario 2: Without considering the pumped storage power station, the 1000 MW thermal power unit assumes the base load, and the cascade hydropower station participates in the adjustment. And the wind and photovoltaic output are accommodated based on the scheduling strategy. Scenario 3: Based on scenario 2, the pumped storage power station is considered to participate in intra-day scheduling. Scenario 4: Applied to the scheduling model of scenario 3, in order to achieve the optimal optimization results of the combined system, the influence of the pumped storage power station capacity is studied.
5. Results and Discussion

5.1. Results

In scenario 1, although the renewable energy output has certain complementary characteristics on the intra-day scale, the net load of the system fluctuates greatly due to the large load peak-to-valley difference in this area, which makes the output adjustment of the second thermal power unit frequent. Simultaneously, the wind power output is large, and the system load demand is low in the early morning period. In order to meet the lower limit constraint of the thermal power units’ output, there will be a certain wind abandonment phenomenon during this period, resulting in an increase in system operation cost. Figure 5 shows the operating results of the system in scenario 1, where the abandoned power of the system is represented by the negative number.

Figure 5. Scheduling output of power stations in Scenario 1.

Figure 6 shows the Pareto optimal fronts obtained by the optimization model under scenario 2 and scenario 3, respectively. From the distribution of the solution sets, it can be seen that there is a certain contradiction between the two objectives, and the two objective function values of scenario 3 are better than those of scenario 2. It shows that the addition of the pumped storage power station can reduce the operation cost and further decrease the residual load fluctuation in the system, thus reducing the peak regulation pressure of thermal power units.

To determine the specific scheduling scheme of the next day, it is necessary to select the best compromise solution from the Pareto front. In this paper, the TOPSIS method based on the CRITIC weight method is used to select the optimal solution of the Pareto solution set. The CRITIC weight method comprehensively measures the objective weight of the two objective functions based on the comparison of evaluation indicators and the conflict between indicators and selects the scheme with the highest comprehensive score as a compromise solution. The intra-day scheduling scheme corresponding to the compromise solution of the Pareto front in scenario 2 is shown in Figure 7 below.
To determine the specific scheduling scheme of the next day, it is necessary to select the best compromise solution from the Pareto front. In this paper, the TOPSIS method based on the CRITIC weight method is used to select the optimal solution of the Pareto solution set. The CRITIC weight method comprehensively measures the objective weight of the two objective functions based on the comparison of evaluation indicators and the conflict between indicators and selects the scheme with the highest comprehensive score as a compromise solution. The intra-day scheduling scheme corresponding to the compromise solution of the Pareto front in scenario 2 is shown in Figure 7 below.

The output curves of four hydropower stations in this dispatching period are shown in Figure 8. From the optimization results, it can be seen that the output curves of $h_4$ with the largest installed capacity follow the daily load variation trend of the system and play a major role in peak regulation. The low output of $h_3$ in the early morning period and at the end of the dispatching period also plays a certain regulatory role. However, the inflow of $h_1$ and $h_2$ located upstream are all natural incoming water, and the output curves are relatively stable to ensure the reservoir dispatching plan within a day.

The output of a hydropower station is mainly affected by its water discharge and reservoir volume. This paper mainly analyzes the change curves of the discharge and reservoir volume of $h_4$ in this dispatching period, as shown in Figure 9.
The output of a hydropower station is mainly affected by its water discharge and reservoir volume. In this dispatching period, as shown in Figure 9, the variation trend of $h_4$ water discharge is roughly the same as that of its output curve and daily load curve, that is, the average water discharge is small in the load trough period and increases significantly in the load peak period. Due to the influence of flow delay, the discharge from the upstream $h_3$ cannot reach the reservoir in the early stage of dispatching, which makes the reservoir volume decrease first. After 4 h, the interval flow flows into the $h_4$, and the water discharge is small at that time, which leads to the rapid rise of the reservoir volume and tends to be flat. In general, the fluctuation in the $h_4$ reservoir volume is within the limit range, indicating that the water is not abandoned during the complementary operation of the system, and the water energy is efficiently utilized.

As the PSH is added to the combined system, the intra-day stations scheduling diagram corresponding to the compromise solution is as Figure 10.
Table 2 shows the changes in the residual load peak–valley difference, residual load variance, system operation cost, and renewable energy curtailment rate before and after the cascade hydropower participating in the regulation and pumped storage power station joining in the hybrid system.

Table 2. Comparison of optimization results in three scenarios.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Residual Load Variance (MW²)</th>
<th>Residual Load Peak–Valley Difference (MW)</th>
<th>Operation Cost (Thousand Dollars)</th>
<th>Renewable Energy Curtailment Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>20,681.67</td>
<td>487.04</td>
<td>540.17</td>
<td>6.16%</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>4487.80</td>
<td>226.26</td>
<td>347.10</td>
<td>2.60%</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>225.36</td>
<td>62.95</td>
<td>315.97</td>
<td>0%</td>
</tr>
</tbody>
</table>

Figure 11 shows the comparison diagram of the system residual load fluctuation and the output of hydropower stations and the pumped storage power station in different scenarios.

Table 2 shows that as only renewable energy enters the power grid, the variance of the system residual load is as high as 20,681.67 MW². If the output of thermal power units is relied on to achieve renewable energy accommodation only, the peak regulation pressure of the units will undoubtedly be increased, resulting in an obvious renewable energy abandonment phenomenon. When the cascade hydropower is involved in the system regulation, based on the stabilization control of the cascade hydropower, the fluctuation variance of the residual load is reduced to 4487.80 MW², which is reduced by nearly 80%. And the peak–valley difference in the residual load also decreased to 226.23 MW. As a clean energy source, hydropower can greatly reduce the operating cost of the combined system simultaneously. In the optimal scheduling scheme of Scenario 2, due to the large proportion of wind power output in the early morning, in order to meet the lower limit constraint of thermal power plant output, there is a certain amount of renewable energy abandonment during this period. The total amount of power abandonment per day is 91.83 MWh, and the renewable energy curtailment rate is about 2.60%, which is significantly lower than that of scenario 1.

The optimization results of Scenario 3 show that the residual load variance and peak–valley difference of the combined system are further reduced to 225.36 MW² and 62.95 MW after the addition of the pumped storage power station, and the renewable
energy curtailment rate is reduced to 0. In the initial period of dispatching, the wind power output is large during the low-load period at night, and the pumped storage units run in the pumped state to realize the full consumption of renewable energy. And the overall operation cost of the system is reduced by USD 30,926.84.

Figure 11. Comparison of system residual load fluctuation.

In Figure 12, the sum of the hydropower output in scenario 2 is roughly the same as the change trend of the intra-day load curve in the region, indicating that cascade hydropower has a significant effect on stabilizing the fluctuation in the system residual load. The hydropower output in scenario 3 is more stable than that in scenario 2 because the pumped storage power station stores the excess power generation of cascade hydropower stations in the low-load period by the virtue of its energy transfer characteristics and cooperates with the discharge of thermal power units in the peak load period to alleviate the peak regulation pressure of thermal power units.

Figure 12. Analysis of hydropower and PSH output. The black dotted line indicates that the PSH is in the shutdown state.

Pumped storage power plants with varying planning capacities have different optimal operating effects, and the costs of power plant development and maintenance are correlated
with the required capacity. Therefore, the ideal configuration of the pumped storage power station with the lowest capacity is investigated. Figure 13 shows the operation cost and residual load variances under the varying configuration capacity of the PSH connected to the hybrid system.

![Figure 13](image)

**Figure 13.** Effects of capacity changes in the pumped storage power station. (a) Impact on operation cost. (b) Impact on residual load variance. Green dots and red stars refer to the optimization results of operation cost and residual load variance under different PSH installed capacity, respectively. The lines represent the change curves as the installed capacity increases.

Figure 13 illustrates that the system operating cost and residual load variance gradually lower to stable with an increasing PSH capacity. The equilibrium point is identified at 200 MW. The PSH connected to the combined system could possess a capacity of 200 MW or fewer, which is in accordance with the minimal configuration capacity principle. Obviously, this paper focuses on the operation cost and residual load variance. The system’s actual requirements, the cost of construction planning, and the configuration scheme’s characteristics will be considered in future work.

### 5.2. Discussion

Based on the operation strategy of the multi-energy hybrid generation system proposed in this paper, Section 5.1 further studies the optimization results of the multi-objective optimal dispatching model under four different scheduling scenarios. The simulation results show that when only considering renewable energy, the residual load of the system fluctuates obviously, and the peak regulation pressure of thermal power units is large. Simultaneously, due to the large wind power output and low system load demand in the early morning period, there is an obvious wind abandonment phenomenon during this period, and the renewable energy curtailment rate within a day is as high as 6.16%. Cascade hydropower leads to a strong stabilizing effect on the renewable energy grid-connected system. The combined system’s operational costs can be significantly decreased by substituting clean energy for a portion of the thermal power generation. Some studies have obtained similar results, such as [22,23].

The experimental data show that when cascade hydropower is involved in system regulation, the fluctuation variance of the residual load is reduced from 20,681.67 MW² to 4487.80 MW², which is reduced by nearly 80%. And the peak–valley difference in the residual load also decreased by 54%. The joint output of the four cascade hydropower stations is roughly the same as the change trend of the intra-day load curve in the region, indicating that cascade hydropower has a significant effect on stabilizing the fluctuation in the system residual load. Most of the studies have not explored the reasons for the change in the hydropower station output from the perspective of water conservancy. But, in this paper, further research data reveal that the discharge of hydropower stations has roughly the
same trend as its output curve. And the water is not abandoned during the complementary operation of the system, which means that the water energy is efficiently utilized.

The PSH participates in power generation during the peak hours of thermal power output and works in pumping condition during low-load or photovoltaic and wind abandonment intervals. This successfully lowers the system’s rate of wind and solar curtailment. The simulation results show that the residual load variance and peak–valley difference in the combined system are further reduced to 225.36 MW and 62.95 MW after the addition of the pumped storage power station, and the renewable energy curtailment rate is reduced to 0. Simultaneously, the overall operation cost of the system is reduced by USD 30,926.84. In addition, the PSH cooperates with the operation of cascade hydropower stations to store the excess power generation of hydropower during the low-load period and cooperates with the discharge of thermal power units during the peak load period to alleviate the regulation pressure of thermal power units. Research is carried out to investigate the way the pumped storage power station’s configuration capacity affects the operational performance. Relatively enhancing the pumped storage power station’s configuration capacity can lower residual load variance and systematic operating costs. The optimal configuration capacity of PSH in the regional power grid studied in this paper is about 200 MW. But in terms of the planning phase, it is also important to take the system’s actual requirements, construction planning costs, and other factors into consideration.

In this paper, optimal scheduling is studied on the basis of the confirmed forecast data of wind power and photovoltaic, and the objective deviation between the predicted output and the actual output is not considered. In future, aiming at relieving the uncertainty of renewable energy output, scene clustering and robust optimization methods will be used to improve the richness of the model and the practical applicability of the research. In addition, market factors and the game between various stakeholders can also be considered to discuss the impact of system scheduling on the economic benefits.

6. Conclusions

Aiming to mitigate the impact of power fluctuation caused by large-scale renewable energy integration and increase the consumption of photovoltaic and wind power, a short-term optimal dispatching of a cascade hydro–wind–solar–thermal hybrid generation system with PSH is proposed in this paper. And this optimization issue is solved by the NSGA-II approach, which targets minimizing the system’s residual load variation and overall expenses. In the calculation model of the overall costs, the fuel and pollutant emission cost of thermal power units, the PSH’s operation cost, the penalty cost of power abandonment, and the maintenance cost of power stations are included. Considering the PSH’s flexibility and cascade hydropower’s complex constraints, the short-term optimal operation strategy of the hybrid generation system is proposed. Aiming to use the multi-energy hybrid generation system in a regional power grid, simulation is carried out under four different operating scenarios. The results show that the PSH can effectively reduce the operation cost of the hybrid generation system and decrease the rate of wind and photovoltaic abandonment. Furthermore, it can further stabilize the residual load fluctuation in the system and improve the stability of the thermal power supply.

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