Optimal Multi-Objective Scheduling for Peak Shaving of Hydropower Plants in Coordinated Hydro-Wind-Photovoltaic Hybrid Systems

Yongpei Li[1], Siyang Liao[1]*, Jian Xu[1], Youhan Deng[2,3], Hongfeng Xie[1], Jiahao Li[1], Haoyuan He[1]
1. School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China; 2. Laboratory of Hydro-Wind-Solar Multi-energy Control Coordination, Wuhan 430014, China; 3. Institute of Science and Technology, China Three Gorges Corporation, Beijing 100038, China

***Abstract*—Within the strategic framework of integrated hydro-wind-solar energy development in China, this paper addresses critical challenges arising from high-penetration renewable integration, including exacerbated net load "canyoning effects" and frequent hydropower unit cycling with deep regulation. A multi-objective peak-shaving dispatch model is proposed for hydropower unit scheduling, incorporating tri-dimensional constraints from power grid requirements, reservoir characteristics, and unit operational limits. The model simultaneously minimizes three objectives: output fluctuations, unit cycling frequency, and deep regulation volumes, enabling granular dispatch from system-level peak-shaving demands to unit-specific generation commands. Solved through multi-objective particle swarm optimization, the approach effectively avoids vibration zones and mitigates power oscillations, thereby enhancing operational stability and equipment longevity. Validation at the Wudongde Hydropower Station demonstrates the model's efficacy in addressing both amplified peak-valley differences and temporal load valley shifts, significantly strengthening hydropower's regulatory resilience and renewable accommodation capacity in hybrid systems. This research provides crucial technical support for leveraging hydropower as a cornerstone in clean energy infrastructure.**

Keywords—hydro-wind-solar hybrid system, multi-objective optimal dispatch, hydropower unit peak shaving, operational stability, unit-level dispatch

I. INTRODUCTION

For a long time, hydropower has served as a flexible regulating source to mitigate the fluctuations of wind and solar power and maintain grid stability, leveraging its advantages such as strong ramping capability and a wide output adjustment range[1-5]. With the deepening of the "Dual Carbon" strategy, the grid-connected capacity of wind and photovoltaic power has grown rapidly. However, their inherent anti-peak-shaving characteristics have intensified the peak-shaving pressure on the power grid. In this context, the state has proposed an integrated dispatch and operation strategy for hydropower, wind, and solar energy to address the challenge of renewable energy integration.

Thanks to its inherent strengths, hydropower has become a high-quality flexible peak-shaving resource in the power system. It can effectively perform peak-shaving dispatch in hydro-wind-solar hybrid energy systems to reduce the impact of wind and solar integration on the grid. Previous research on hybrid hydro-wind-solar power systems has primarily focused on the following aspects: first, the handling of uncertainties in load, wind, and photovoltaic power[6-7]; second, capacity configuration studies for hydropower, wind, and solar power within hybrid systems, aiming to determine the optimal installed capacity of wind and solar power by maximizing the utilization of hydropower[8-9]. Furthermore, research has also explored synergistic dispatch based on the complementarity of hydropower, wind, and solar power, focusing on the development of long-term and short-term multi-energy complementary dispatch models to solve problems such as generation scheduling, joint peak-shaving and frequency regulation, complementarity pattern analysis, and dispatch rule formulation[10-12].

However, the peak-shaving dispatch operation within hybrid hydro-wind-solar energy systems poses significant challenges to the operation of hydropower units. To meet the power generation demand corresponding to the peak load of the power system as much as possible, units are required to frequently start and stop, and switch between low and deep load conditions. This leads to unstable operation, a rapid increase in failure rates, and higher maintenance costs. To address this issue, the proposed model establishes constraints from three perspectives: the power grid, the hydropower plant, and the hydropower units themselves. It considers unit output fluctuations, the number of start-ups and shutdowns, and deep load adjustments, establishing a multi-objective peak-shaving dispatch model for hydropower unit output scheduling. This approach aims to ensure the units operate within an optimal engineering environment, enhance operational stability, and increase their service life.

II. METHODOLOGY

Leveraging its strong ramp-up capability and wide output adjustment range, hydropower has become the optimal regulating resource to mitigate the intermittency and volatility of wind and photovoltaic power generation. By integrating hydropower with wind and solar power as a unified dispatch unit for the grid, the coordinated utilization of hydro-wind-solar resources can be achieved. As shown in Figure 1, the integrated control center formulates a generation plan based on forecasted output information of hydropower, wind, and solar power, and submits it to the grid dispatch center. After coordinating with grid peak shaving and load demands, the modified generation plan is returned to the integrated control center. The control center then internally coordinates the specific output of hydropower, wind, and solar power to fulfill the generation plan. The hydropower plant further issues detailed generation schedules based on the actual operating conditions of the hydropower units, coordinating the output of each unit to ensure the safe and stable operation of the reservoir.

To construct a multi-objective peak-shaving dispatch model for hydropower unit output scheduling, the following steps were taken. First, a detailed analysis was conducted on reservoir constraints (Section 2.1), hydropower unit operational constraints (Section 2.2), and grid constraints (Section 2.3). Subsequently, a multi-objective peak-shaving dispatch model was developed (Section 2.4), which

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considers unit output fluctuations, the number of start-stop cycles, and the depth of output adjustments.

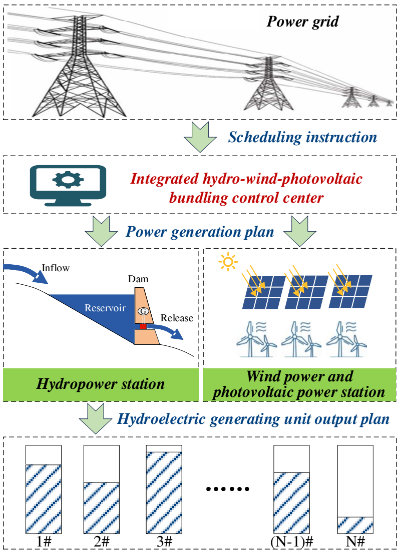


Fig. 1. Schematic diagram of bundled operation of hydro-wind-photovoltaic integration

This ensures that while mitigating the intermittency and volatility of wind and photovoltaic power generation, the hydropower units operate within an optimal engineering environment. Finally, the Wudongde Hydropower Station was used as an engineering case study to validate the superiority of the proposed peak-shaving dispatch model. Figure 2 shows the computational flowchart of the multi-objective peak-shaving dispatch model for hydropower unit output scheduling.

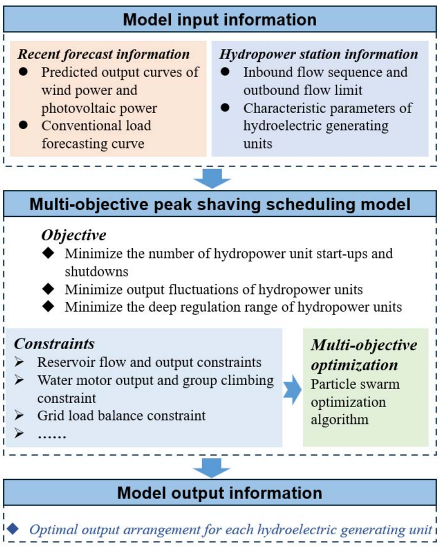


Fig. 2. Calculation flowchart of multi-objective peak shaving scheduling model

Figure 3 shows the change in load peak-valley difference before and after the grid integration of wind and photovoltaic power. The grid load exhibits a typical "double-hump" pattern, while the net load curve after wind and photovoltaic integration shows a significantly widened peak-valley difference, forming a "canyon-shaped" load profile. This will pose significant challenges to the operation of hydropower units.

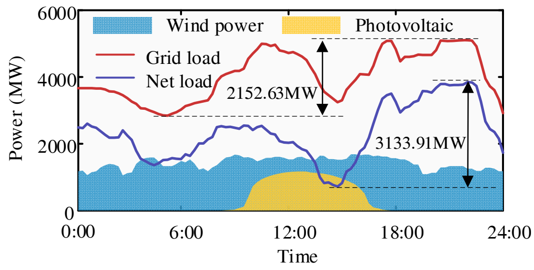


Fig. 3. The variation of load peak-valley difference before and after peak shaving

To formulate a detailed generation schedule for hydropower units that meets the "canyon-shaped" net load demand, constraints are defined from three perspectives: the power grid, the hydropower station, and the hydropower units themselves.

A. Hydropower Station Constraints

a) Water balance constraint

$$V_{i,t+1} = V_{i,t} + \left(Q_{i,t}^{\text{in}} - Q_{i,t}^{\text{out}}\right)\Delta t \times 900 \tag{1}$$

Where $V_{i,t+1}$ and $V_{i,t}$ are the reservoir storage capacities of hydropower station i at the beginning of time interval t+1 and t respectively; $Q_{i,t}^{\text{in}}$ and $Q_{i,t}^{\text{out}}$ are the inflow and outflow of hydropower station i during time interval t respectively; Δt is the number of hours per time unit; 900 represents the number of seconds corresponding to a 15-minute dispatch interval.

b) Hydraulic connection between cascade stations

$$Q_{i,t}^{\text{in}} = Q_{i,t}^{\text{area}} + \sum_{k\in\Phi} Q_{i-1,t-\tau_{i-1}}^{\text{out}} \tag{2}$$

Where $Q_{i,t}^{\text{area}}$ is the local inflow (interval flow) to hydropower station i during time interval t; $Q_{i-1,t-\tau_{i-1}}^{\text{out}}$ is the outflow from the direct upstream station i-1 of hydropower station i during time interval $t-\tau_{i-1}$, where τ_{i-1} denotes the water travel time (in number of time intervals) from upstream station i-1 to station i; Φ is the set of direct upstream stations of hydropower station i.

c) Reservoir flow relationship

$$Q_{i,t}^{\text{out}} = Q_{i,t}^{\text{P}} + Q_{i,t}^{\text{loss}} \tag{3}$$

Where $Q_{i,t}^{\text{P}}$ is the power generation flow of hydropower station i during time interval t; $Q_{i,t}^{\text{loss}}$ is the spillage flow of hydropower station i during time interval t.

d) Outflow constraint

$$\underline{Q}_{i,t}^{\text{out}} \le Q_{i,t}^{\text{out}} \le \overline{Q}_{i,t}^{\text{out}} \tag{4}$$

Where $\underline{Q}_{i,t}^{\text{out}}$ and $\overline{Q}_{i,t}^{\text{out}}$ are the minimum allowed outflow and the maximum allowed outflow of hydropower station i during time interval t respectively.

e) Power generation flow constraint

$$\underline{Q}_{i,t}^{\text{P}} \le Q_{i,t}^{\text{P}} \le \overline{Q}_{i,t}^{\text{P}} \tag{5}$$

Where $\underline{Q}_{i,t}^{\mathrm{P}}$ and $\overline{Q}_{i,t}^{\mathrm{P}}$ are the minimum allowed power generation flow and the maximum allowed power generation flow of hydropower station *i* during time interval *t* respectively.

f) Hydropower station output constraint

$$\underline{P}_{i,t}^{\mathrm{hyd}} \le P_{i,t}^{\mathrm{hyd}} \le \overline{P}_{i,t}^{\mathrm{hyd}} \tag{6}$$

Where $P_{i,t}^{\mathrm{hyd}}$ is the power output of hydropower station *i* during time interval *t*; $\underline{P}_{i,t}^{\mathrm{hyd}}$ and $\overline{P}_{i,t}^{\mathrm{hyd}}$ are the lower limit and upper limit of the power output for hydropower station *i* during time interval *t* respectively.

B. Hydropower Unit Constraints

a) Unit output constraint

$$\underline{P}_{i,n} \le P_{i,n,t} \le \overline{P}_{i,n} \tag{7}$$

Where $P_{i,n,t}$, $\overline{P}_{i,n}$ and $\underline{P}_{i,n}$ are the power output and its lower/upper limits for unit *n* of station *i* during time interval *t* respectively; consequently, the output of station *i* can be expressed as.

$$P_{i,t}^{\mathrm{hyd}} = \sum_{n=1}^{N_i} P_{i,n,t} \tag{8}$$

Where N_i is the number of units in hydropower station *i*.

b) Unit output peak-valley difference constraint

$$\varepsilon_{i,n}^{\min} \le P_{i,n}^{\max} - P_{i,n}^{\min} \le \varepsilon_{i,n}^{\max} \tag{9}$$

Where $P_{i,n}^{\max}$ and $P_{i,n}^{\min}$ are the maximum output and minimum output of unit *n* in station *i*, respectively; $\varepsilon_{i,n}^{\max}$ and $\varepsilon_{i,n}^{\min}$ are the lower and upper limits for the peak-valley output difference of unit *n* in station *i* respectively.

c) Unit ramping constraint

The power change between adjacent time intervals and the ramping constraints are:

$$P_{i,n,t} = P_{i,n,t-1} + \Delta P_{i,n,t} \tag{10}$$

$$\Delta\underline{P}_{i,n} \le \Delta P_{i,n,t} \le \Delta\overline{P}_{i,n} \tag{11}$$

Where $\Delta\overline{P}_{i,n}$ and $\Delta\underline{P}_{i,n}$ are the upward and downward ramping rates respectively. These rates depend on the specific turbine characteristics; The ramping rate is taken as 30% of the rated output.

d) Unit deep ramping constraint

The deep ramping constraint for a unit over multiple consecutive time intervals is:

$$\Delta\underline{P}_{i,n}^{\mathrm{deep}} \le \Delta P_{i,n}^{\mathrm{deep}} \le \Delta\overline{P}_{i,n}^{\mathrm{deep}} \tag{12}$$

Where $\Delta\overline{P}_{i,n}^{\mathrm{deep}}$ and $\Delta\underline{P}_{i,n}^{\mathrm{deep}}$ are the upward and downward deep ramping rates respectively. Here, the deep ramping rate is taken as 50% of the rated output.

e) Minimum up/down time constraints

$$\begin{cases} T_{i,n}^{\mathrm{on}} \le \alpha \\ T_{i,n}^{\mathrm{off}} \le \beta \end{cases} \tag{13}$$

Where $T_{i,n}^{\mathrm{on}}$ and $T_{i,n}^{\mathrm{off}}$ are the minimum up time and minimum down time for unit *n* of station *i* respectively; α and β are their respective maximum values.

f) Unit vibration zones constraint

$$(P_{i,n,t} - P_{i,n,k}^{\max})(P_{i,n,t} - P_{i,n,k}^{\min}) \ge 0 \tag{14}$$

Where $P_{i,n,k}^{\max}$ and $P_{i,n,k}^{\min}$ are the upper and lower output limits of the *k* vibration zone for unit *n* of station *i* respectively.

C. Grid Constraints

a) Power balance constraint

$$P_{\mathrm{G},t} = \sum_{i=1}^{I} P_{i,t}^{\mathrm{hyd}} + P_{\mathrm{PV},t} + P_{\mathrm{WP},t} \tag{15}$$

Where $P_{\mathrm{G},t}$ is the grid dispatch command for time interval *t*; $P_{\mathrm{WP},t}$ and $P_{\mathrm{PV},t}$ are the power outputs of wind power and photovoltaic power during time interval *t* respectively.

b) Transmission line constraint

$$0 \le P_t^{\mathrm{trans\_line}} \le P_{\max}^{\mathrm{trans\_line}} \tag{16}$$

Where $P_t^{\mathrm{trans\_line}}$ is the transmission power of the line during time interval *t*; $P_{\max}^{\mathrm{trans\_line}}$ is the maximum allowed transmission power capacity of the line.

D. Multi-Objective Peak-Shaving Dispatch Model

A multi-objective peak-shaving dispatch model, focusing on hydropower units, is established with the objectives of minimizing hydropower unit output fluctuation, minimizing the number of start-ups and shut-downs, and minimizing the depth of unit output adjustments. The objective functions are as follows:

$$F_1 = \min \sum_{t=1}^{T-1} (P_{i,n,t+1} - P_{i,n,t})^2 \tag{17}$$

$$F_2 = \min \sum_{t=1}^{T} (\delta_{i,n,t}^{\mathrm{on}} + \delta_{i,n,t}^{\mathrm{off}}) \tag{18}$$

$$F_3 = \begin{cases} \min \Delta P_{i,n}^{\mathrm{deep\_up}} \\ \max \Delta P_{i,n}^{\mathrm{deep\_down}} \end{cases} \tag{19}$$

Where $P_{i,n,t}$ is the power output of unit *n* in station *i* during time interval *t*; $\delta_{i,n,t}^{\mathrm{on}}$ and $\delta_{i,n,t}^{\mathrm{off}}$ are the start-up and shut-down decision variables (1 indicates start-up/shut-down operation) for unit *n* in station *i* during time interval *t*; $\Delta P_{i,n}^{\mathrm{deep\_up}}$ and $\Delta P_{i,n}^{\mathrm{deep\_down}}$ are the maximum continuous upward and downward deep ramping amounts for unit *n* in station *i* respectively, where $\Delta P_{i,n}^{\mathrm{deep\_up}}$ is positive and $\Delta P_{i,n}^{\mathrm{deep\_down}}$ is negative.

In summary, this model constitutes a multi-objective optimization problem. Therefore, a multi-objective particle swarm optimization algorithm is employed for its solution, aiming to balance unit output fluctuation, the number of start-ups/shut-downs, and the depth of output adjustments. This ensures the units operate within an optimal engineering environment, enhances their operational stability, and increases their service life.

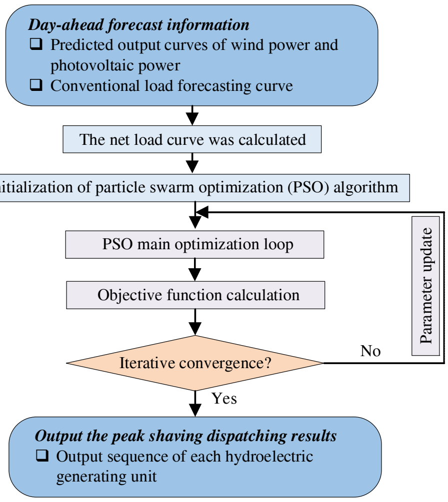


Fig. 4. Block diagram for solving the multi-objective peak shaving scheduling model

In Figure 4 presents the flowchart of the particle swarm optimization algorithm for solving this peak-shaving dispatch model. The process begins with calculating the net load curve based on grid load and renewable energy output data. Subsequently, multi-objective computation is performed using the particle swarm optimization algorithm. Through multiple iterative cycles, the specific output schedules for each unit are ultimately determined.

III. Case Analysis

A. *Engineering Background*

Taking the Wudongde Hydropower Station as an example, the plant has a total installed capacity of 10200MW. It has six 850MW hydropower units on each of its left and right banks, with an annual energy generation of 38.91TWh (billion kWh). The total reservoir storage capacity is 7.408 billion m³, and the flood control storage capacity is 2.44 billion m³.

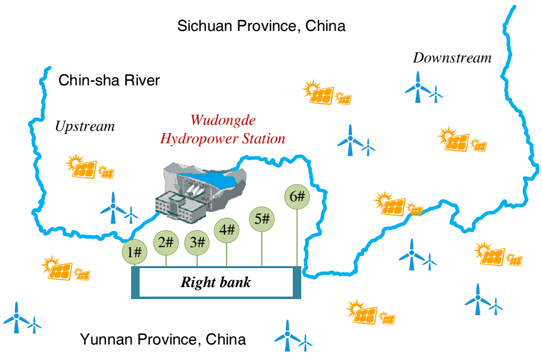


Fig. 5. Abundant wind and solar resources in the 70 km vicinity of Wudongde Hydropower Station

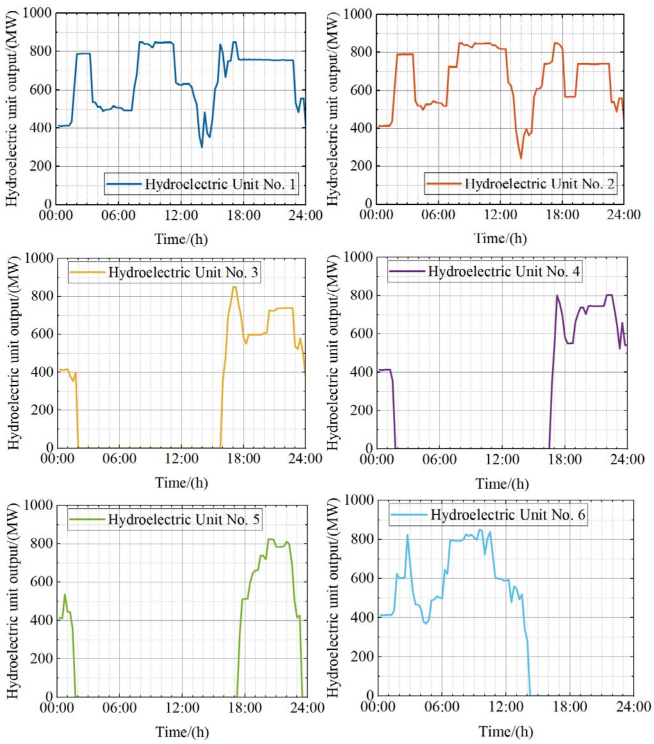
According to the "Study on Integration and Implementation Plan for the Comprehensive Renewable Energy Development Base Combining Hydropower, Wind and Solar Power in the Lower Reaches of the Jinsha River," the area within 70 km of the Wudongde Hydropower Station is rich in wind and solar resources. A total of 42 wind and solar projects on the right bank can be connected to the Yunnan side, forming a bundled capacity of 2853MW, comprising 1688MW of wind power and 1165MW of photovoltaic power.

B. *Analysis of Peak-Shaving Dispatch Results*

As shown in Figure 3, the grid's typical "double-peak" load demand for the right bank of Wudongde is illustrated. After integrating 1688MW of wind power and 1165MW of photovoltaic power, the peak-to-valley difference increases from 2152.63MW to 3133.91MW, representing a 45.59% year-on-year growth. Furthermore, the load valley shifts from 2716.80MW at 5:00 to 716.81MW at 14:30. This demonstrates that the integration of wind and photovoltaic power not only amplifies the peak-to-valley difference, making it challenging for hydropower to formulate matching generation schedules, but also causes a temporal displacement of the load valley.

The calculation results of the multi-objective peak-shaving dispatch model, with hydropower units as the core, are presented in Figure 6.

From the figures, it can be observed that the operation of the hydropower units successfully avoids vibration zones, with both startup and shutdown periods maintaining sufficient duration, and output fluctuations kept within a narrow range. Additionally, the deep regulation volume of the hydropower units is significantly reduced, devoid of large, sawtooth-shaped variations, which contributes to enhanced operational stability.



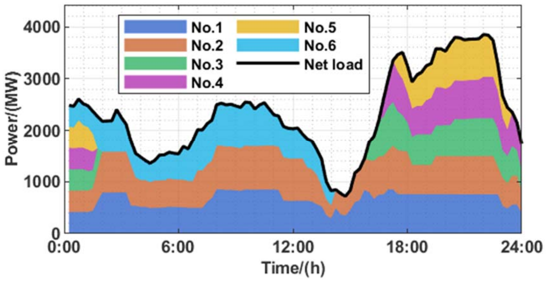


Fig. 6. Output information of hydroelectric generating units 1 to 6

During periods of increased photovoltaic output, when the net load exhibits substantial downward ramping requirements, selective shutdown of hydropower units is implemented. Conversely, during upward ramping periods, the hydropower units coordinate their output to collectively track the net load demand.

IV. Conclusion

Within the strategic context of integrated hydro-wind-solar operation in China, this paper addresses the severe challenges faced by hydropower units in providing peak-shaving services under high penetration of renewable energy. A multi-objective optimal dispatch model is developed to balance unit operational stability with system regulation requirements. Through systematic modeling and empirical analysis, the following conclusions are drawn:

1) A novel unit-level dispatch paradigm with multi-constraint coordination is proposed. The model transcends conventional plant-level scheduling by coupling three-dimensional constraints of grid demand, reservoir characteristics, and unit operation, achieving refined mapping from system peak-shaving requirements to unit-specific output commands.

2) Operational resilience of hydropower units is enhanced through optimized dispatch. By minimizing output fluctuations, cycling frequency, and deep regulation volumes, the model effectively avoids vibration zones and mitigates power oscillations, thereby reducing equipment fatigue from the control source and significantly improving operational stability and lifecycle.

3) The critical role of hydropower units as a stabilizing anchor in hybrid systems is empirically validated. In the case study of Wudongde hydro-wind-solar base, the model successfully handles extreme peak-shaving pressures caused by net load "canyonization" and load valley shift. Through coordinated unit cycling and power allocation, it ensures system power balance and secure operation under strong fluctuations.

This research not only provides an effective model and methodology for resolving operational difficulties of hydropower units in high-intensity peak-shaving services, but also offers crucial dispatch technical support and a practical paradigm from a systems engineering perspective for building a clean energy system with hydropower as its core pillar.

Future research will be deepened along three dimensions: at the objective level, explicitly incorporating economic indicators to develop a techno-economic integrated optimization framework; at the temporal scale, establishing a seasonal scenario library to achieve multi-period coordinated scheduling; and at the methodological level, adopting stochastic optimization theory to characterize uncertainties through probability distributions, thereby enhancing decision robustness.

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