

Article

Scheduling Strategies and Benefit Assessment of Pumped-Storage Retrofit for Cascade Hydropower Systems Under High Variable Renewable Energy Penetration

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Abstract

Adding an upper reservoir to conventional cascade hydropower stations to create pumped-storage systems is an effective strategy for enhancing hydropower regulation capacity and promoting high proportion of variable renewable energy consumption. To leverage the cross-seasonal energy and intra-day power regulation capabilities of such hybrid systems, this paper proposes a multi-scale nested dispatch and benefit assessment method. The coordination principles between pumped storage and cascade hydropower under high variable renewable energy penetration are first analyzed. Subsequently, a dynamic time-of-use electricity pricing mechanism is developed by capitalizing on the temporal characteristics of net load, and a multi-scale nested scheduling model that incorporates grid regulation demands is established. A techno-economic assessment framework is further developed to assess the comprehensive benefits of the pumped-storage retrofitting. The Wujiang Basin case study demonstrates significant benefits: a 4.5% improvement in peak–valley difference reduction, a decrease of 1039 GWh in annual variable renewable energy curtailment (8.8% of the system’s total), and a 30.8% rise in generation benefits. Under wet and dry hydrological years, generation benefits increase by 787 million and 645 million CNY, respectively. These results indicate that implementing pumped-storage retrofitting in cascade hydropower basins with abundant but seasonally uneven inflow can better align grid regulation requirements with project economic viability.

Keywords: reservoir scheduling; cascade hydropower; pumped storage; variable renewable energy consumption; added upper reservoir

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1. Introduction

China is promoting the construction of a new power system centered on wind and solar energy, under the framework of the global energy transition and “dual carbon” targets [1]. Between 2020 and 2025, the share of national installed capacity from wind and solar surged from 24% to 47%, and is projected to reach 78% by 2060, with the pace of expansion ranking first in the world [2]. Moreover, the fluctuating nature of wind and solar energy introduces substantial risks to grid security and operational stability, stemming from its unpredictable output and variable patterns [3,4]. Although hydropower provides indispensable regulation capabilities through its rapid response and multi-

timescale flexibility [5–7], the continued expansion of variable renewable energy (VRE) capacity has made it difficult for hydropower alone to simultaneously meet the dual demands of VRE consumption and system adequacy [8,9].

Against this backdrop, the integrated development of hydropower and energy storage has emerged as a key solution for integrating high shares of VRE [10–12]. Among storage options, pumped storage hydropower has become a major development direction owing to its high technological maturity, large regulation capacity, and low life-cycle costs [13,14]. Compared to constructing a new standalone pumped storage hydropower (PSH) plant, retrofitting existing conventional hydropower (CH) plants for pumped storage purposes enables full utilization of existing infrastructure such as reservoirs and transmission lines [15–17]. This approach has been widely recognized in both the literature and national energy planning as a key pathway for pumped storage development [18,19]. At present, common retrofitting methods include installing reversible units [20], configuring energy storage pump plants [21], and constructing upper reservoirs based on existing cascade hydropower plants to form pumped storage systems [22,23]. Among these, the upper reservoir method, which involves constructing an upper reservoir for a PSH in areas outside the main river channel to enhance the original hydropower system's water storage and bidirectional regulation capabilities has become a key focus of research on pumped storage retrofitting.

Research on retrofitting cascade hydropower stations into PSH systems by adding upper reservoirs has focused on two main areas. Studies in the first category do not account for high VRE penetration and examine medium- and long-term optimized operation following the addition of PSH, with an emphasis on pumped storage's contribution to water resource utilization and power generation enhancement [24]. Specifically, Hunt et al. [25] investigated the advantages associated with seasonal PSH development in Brazil and found that constructing a PSH with an upper reservoir can effectively regulate river flow and increase power generation of cascade hydropower stations. The second category of research targets VRE integration scenarios. It analyzes the short-term synergistic operation of cascade hydropower plants retrofitted with pumped storage, evaluating their capacity for smoothing wind and solar power fluctuations, reducing curtailment, and enhancing system flexibility. For instance, in the Brazilian context, Machado et al. [26] assessed the contribution of upper-reservoir PSH construction to mitigating wind power variability and enhancing the operational performance of cascade hydropower plants. Focusing on cost reduction, Li et al. [27] developed an optimization strategy for regional grids with PSH, exploring its benefits in terms of flexibility. These findings provide important references for retrofitting hydropower plants into pumped storage facilities. However, as VRE installed capacity continues to grow, the seasonal mismatch between VRE generation and load demand has become more pronounced, placing higher demands on the cross-cycle regulation capabilities of hydropower systems. Most existing studies focus on the single-scale optimized operation of PSHs [28–30], making it difficult to fully reflect the synergistic value of cascade hydropower and pumped storage across different time scales under a high-penetration VRE context. A multi-scale coordinated dispatch method, which strikes a balance between long-term and short-term objectives, is therefore crucial to implement, as well as water regulation and power response, in the context of high-penetration VRE grids. Furthermore, a techno-economic evaluation framework is needed to assess how retrofits influence the dispatch strategies and overall benefits of cascade hydropower systems.

To address these gaps, this paper investigates the retrofitting of cascade hydropower stations with pumped storage under high VRE penetration, proposing a multi-scale nested optimal scheduling and comprehensive benefit assessment method. To address the characteristics of cross-seasonal power imbalances and intra-day net load fluctuations

under VRE grid integration, a dynamic time-of-use electricity price mechanism guided by the time series change of net load is constructed, and a multi-scale nested optimal scheduling model considering inter-seasonal water allocation and intra-day pumping power regulation is established, and a set of techno-economic evaluation indicators is proposed. Finally, the hydropower system of the Wujiang River Basin serves as a case study to examine how pumped storage retrofitting alters dispatch patterns, generation revenue, the absorption of curtailed VRE, and spillage mitigation.

2. Retrofitting Approach and Dispatch Principles for New Upper Reservoirs in Cascaded Hydropower Systems

For existing cascade hydropower plants, constructing an upper reservoir outside the main river channel and installing reversible pump-turbine units enables the system to operate in both conventional hydropower and pumped storage modes (Figure 1). Compared to building a standalone PSH, this retrofitting approach leverages the existing cascade hydropower infrastructure and reduces construction costs for a new lower reservoir. For conventional hydropower, the retrofitted system can pump water for energy storage during periods of low load or surplus VRE generation and release water to generate electricity during peak load periods, thereby enhancing the plant's energy shifting capability and its capacity to accommodate VRE. Because the pumped storage system shares the lower reservoir with the cascade plants, its operation not only affects the output of the pumped storage facility itself but also alters the inflow patterns and generation sequences of the downstream cascade. Therefore, dispatch planning must fully account for the interplay between pumped storage operation and the hydraulic coupling within the cascade hydropower system.

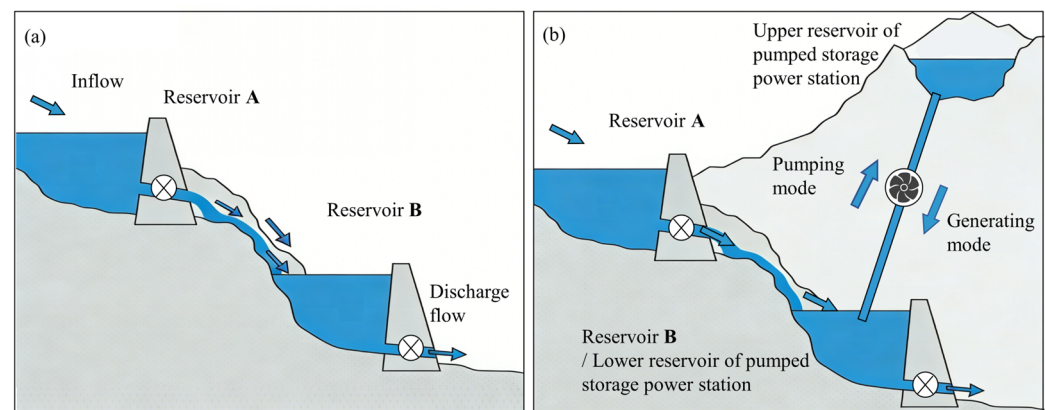


Figure 1. Schematic diagram of pumped storage retrofit for cascade hydropower by adding an upper reservoir: (a) conventional hydropower stations; (b) retrofitted pumped storage system.

The increasing penetration of wind and solar power imposes a dual challenge on the grid: the need to maintain seasonal energy balance while simultaneously ensuring real-time power stability. Taking the Guizhou power system's planning-year renewable integration scenario as a case study (Figure 2), VRE generation exhibits distinct seasonal fluctuations, resulting in a significant decrease in the grid's primary load regulation requirement (after deducting wind and solar generation) in spring and a marked increase in winter. This requires hydropower to shift its generation as much as possible from periods of abundant VRE to periods of insufficient VRE to meet the system's power demand. At an intra-day timescale, the pronounced variability and inverse coincidence with peak demand periods of renewable generation lead to a net load profile characterized by daytime surpluses and nighttime deficits. Power curtailment is common during midday periods

of high VRE generation, while supply gaps occur at night. The intra-day peak-valley difference widens significantly, making regulation considerably more difficult [31]. Therefore, the retrofitted cascade hydropower systems with newly constructed upper reservoir must not only coordinate water allocation among cascade plants but also adapt to the dual demands of long-term energy balancing and short-term flexible peak-shaving under high VRE penetration [32].

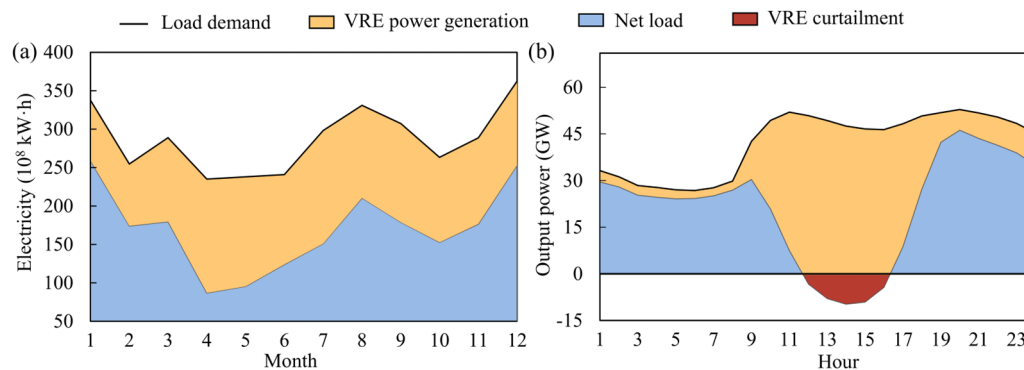


Figure 2. Load demand and VRE generation of the Guizhou power grid at different time scales: (a) annual scale; (b) daily scale. Daily net load profile (load minus VRE output). Negative values indicate surplus renewable generation; the red shaded area represents the resulting curtailment (calculated as the portion of wind and solar power that exceeds load demand).

Consequently, the retrofitted cascade hydropower systems with newly constructed upper reservoirs should fully leverage the energy time-shifting capabilities of pumped storage hydropower while ensuring the regulation of river flow and power generation efficiency. To this end, this paper establishes the following dispatch strategies for pumped storage and cascade hydropower:

- (1) On the long-term scale, adjust the reservoir storage water level by integrating the seasonal characteristics of inflow and VRE; on the short-term scale, leverage the regulating capabilities of PSH and CH to smooth out net load fluctuations. Through the control feedback of long-term and short-term scheduling results, the multi-scale coordinated scheduling of pumped storage and cascade hydropower is realized.
- (2) PSH operation follows an intra-day operation mode of pumping during off-peak hours and generating during peak hours. Pumped storage units engage in pumping to absorb surplus VRE during high-output periods or to capitalize on low electricity prices. The pumping load is met primarily with curtailed renewables, and secondarily with off-peak grid power; during periods with significant peak-shaving demands, the units are scheduled to release water for power generation, thereby reducing the net load peak-valley difference.
- (3) In terms of dispatch priority, PSH takes priority over CH plants. Since water released from pumped storage generation can be reused by CH plants at the lower reservoir, pumped storage units should be dispatched preferentially for power compensation during system shortages to enhance the hydropower energy utilization. When the lower reservoir of the PSH reaches its normal storage level, it can no longer store the discharge from the upper reservoir. In this case, the lower reservoir hydropower plant should be prioritized for power generation to free up storage capacity for pumped storage generation and reduce spillage in the lower reservoir.

3. A Multi-Scale Dispatch Model Considering Grid Regulation Requirements

In response to the complex regulatory demands arising from deep renewable integration across different time horizons, this study develops a dynamic time-of-use pricing mechanism directly linked to the system's net load. This profile drives a multi-scale dispatch model for PSH and cascade hydropower plants, aimed at maximizing system generation revenue. The model leverages the synergistic flexibility of these assets to reconcile power supply security with VRE consumption across diurnal and seasonal scales.

3.1. Dispatch Objectives

The dynamic TOU price is introduced as a simplified representation of the time-varying operational value of electricity under changing net-load conditions. Net load is used as a proxy for the instantaneous tightness of the supply–demand balance, with higher net-load periods assigned higher electricity prices. Compared with a conventional fixed-period TOU tariff, this formulation can adapt automatically to seasonal and intra-day variations in system conditions. In the present study, the annual maximum net load is used as the normalization reference to provide a consistent basis for comparison across the year. Accordingly, the dynamic TOU price signal is formed by scaling a benchmark price with the normalized net load curve:

$$P_{n,d,t} = \max(L_{net,d,t} / L_{net,max} \cdot P_{h,bench}, 0) \quad (1)$$

where $P_{n,d,t}$ is the composite electricity price for period t in day d (CNY/MW·h); $L_{net,d,t}$ and $L_{net,max}$ are the net load for period t in day d and the annual maximum net load, respectively (MW); $P_{h,bench}$ is the benchmark electricity price (CNY/MW·h).

Guided by the TOU electricity prices, a benefits-maximizing, multi-scale nested optimization dispatch model is proposed to schedule PSH and CH plants in a coordinated manner. On an annual basis, taking the whole year as the planning cycle and the single day as the dispatch interval, the cross-day dispatch process of PSH and CH plants is optimized by considering the system's average daily electricity demand, and a reservoir water level control plan is provided; on the short-term scale, with a daily and hourly scheduling period, the pumping and power generation processes are optimized using the water level profile derived from the long-term optimization as a control boundary. To this end, we define the objective function R_{max} as:

$$R_{max} = \text{Max} \sum_{d=1}^D \left(\sum_{t=1}^T \left(\sum_{k=1}^K N_{k,d,t}^{CH} + N_{g,d,t}^{PSH} - N_{pur,d,t}^{PSH} \right) \cdot \Delta t \cdot P_{n,d,t} \right) \quad (2)$$

where R_{max} is the total operating benefit (CNY); $d = 1, \dots, D$ indexes days; $t = 1, \dots, T$ indexes time periods within a day; $k = 1, \dots, K$ indexes CH plants; $N_{k,d,t}^{CH}$ is the power output of CH plant k during period t of day d (MW); $N_{g,d,t}^{PSH}$ and $N_{pur,d,t}^{PSH}$ are the generation power and the grid-purchased pumping power of the PSH plant during period t of day d , respectively (MW); Δt is the time step duration (h); $P_{n,d,t}$ is the composite electricity price as defined in Equation (1) (CNY/MW·h).

3.2. Constraints

3.2.1. Hydraulic Constraints

The hydraulic constraints of the pumped-storage and cascade hydropower system include water balance constraints, reservoir storage and water-level limits, and head limits.

(1) Water balance constraints

For each period, the water balance equation must be satisfied for both the upper reservoir of the PSH and the conventional reservoir that functions as its lower reservoir, as formulated as follows.

$$V_{up,t+1} = V_{up,t} + (mQ_{p,t}^{PSH} - (1-m)Q_{g,t}^{PSH}) \cdot \Delta t \quad (3)$$

$$V_{down,t+1} = V_{down,t} + (I_{down,t} - Q_{down,t}^{CH} - mQ_{p,t}^{PSH} + (1-m)Q_{g,t}^{PSH}) \cdot \Delta t \quad (4)$$

where $V_{up,t+1}$, $V_{up,t}$ denote the storage volumes in the newly constructed upper reservoir at the end of period $t+1$ and t (m^3); $Q_{p,t}^{PSH}$, $Q_{g,t}^{PSH}$ are the pumping flow rate and discharge flow rate of the PSH during period t , respectively (m^3/s); m is the operating status of the PSH, equal to 1 during pumping and 0 otherwise; For conventional reservoir serving as the lower reservoir of the PSH, $V_{down,t+1}$ and $V_{down,t}$ are its storages at the end of period $t+1$ and t (m^3); $I_{down,t}$ and $Q_{down,t}^{CH}$ are the inflow and outflow rates of the reservoir during period t , respectively (m^3/s).

(2) Reservoir storage and water-level limits

For both the upper reservoir of the PSH and each conventional cascade reservoir, the storage volume and water level must remain within permissible bounds:

$$V_{\min} \leq V_t \leq V_{\max} \quad (5)$$

$$Z_{\min} \leq Z_t \leq Z_{\max} \quad (6)$$

where V_t and Z_t are the storage volume and water level during period t , respectively; $V_{\min}$, $V_{\max}$ and $Z_{\min}$, $Z_{\max}$ denote the minimum (dead) and maximum (normal or flood-control) storage volume and level limits. For the upper reservoir of the PSH, the maximum water level is determined by the normal storage level of the newly constructed reservoir, and the minimum level corresponds to the dead level. For the lower reservoir (existing cascade reservoir), the maximum level is the normal storage level during non-flood seasons and the flood-control restriction level during flood seasons.

(3) Head limits

The operating head of the pumped-storage plant is determined by the difference between the upper and lower reservoir water levels and must satisfy the unit operating requirements:

$$H_{g,\min}^{PSH} \leq H_{g,t}^{PSH} \leq H_{g,\max}^{PSH} \quad (7)$$

$$H_{p,\min}^{PSH} \leq H_{p,t}^{PSH} \leq H_{p,\max}^{PSH} \quad (8)$$

where $H_{g,t}^{PSH}$ and $H_{p,t}^{PSH}$ denote the generating head and pumping head of the PSH during period t , respectively; $H_{g,\min}^{PSH}$ and $H_{g,\max}^{PSH}$ are the minimum and maximum

allowable heads in generating mode; $H_{p,\min}^{PSH}$ and $H_{p,\max}^{PSH}$ are the minimum and maximum allowable heads in pumping mode. In this study, the allowable generating head ranges from 440 to 484 m, and the allowable pumping head ranges from 444 to 484 m.

3.2.2. Pumping Operation Constraints

When the PSH is in pumping mode, the CH plant should operate at minimum output. The electrical energy consumed by the PSH during pumping comes from curtailed VRE that the grid cannot absorb, as well as electricity purchased from the grid.

$$N_{p,t}^{PSH} = N_{VRE,t}^{PSH} + N_{pur,t}^{PSH} \quad (9)$$

$$N_{p,\min}^{PSH} \leq N_{p,t}^{PSH} \leq N_{p,\max}^{PSH} \quad (10)$$

$$Q_{p,t,\min}^{PSH} \leq Q_{p,t}^{PSH} \leq Q_{p,t,\max}^{PSH} \quad (11)$$

$$Q_{p,t,\max}^{PSH} = \min(Q_{p,u,\max}^{PSH}, Q_{p,up,t,\max}^{PSH}, Q_{p,down,t,\max}^{PSH}) \quad (12)$$

$$Q_{p,up,t,\max}^{PSH} = (V_{up,\max} - V_{up,t}) / \Delta t \quad (13)$$

$$Q_{p,down,t,\max}^{PSH} = I_{down,t} - Q_{down,\min} + (V_{down,t} - V_{down,\min}) / \Delta t \quad (14)$$

where, $N_{p,t}^{PSH}$ is the total pumping power of the PSH during period t (MW), which consists of curtailed VRE power $N_{VRE,t}^{PSH}$ and grid purchases $N_{pur,t}^{PSH}$. Its lower and upper bounds are $N_{p,\min}^{PSH}$ and $N_{p,\max}^{PSH}$ (MW); $Q_{p,t}^{PSH}$ is the pumping flow rate, bounded by $Q_{p,t,\min}^{PSH}$ and $Q_{p,t,\max}^{PSH}$. The upper bound is determined by the minimum of the conveyance-system pumping capacity $Q_{p,u,\max}^{PSH}$, the maximum storable inflow of the upper reservoir $Q_{p,up,t,\max}^{PSH}$, and the maximum extractable flow from the lower reservoir $Q_{p,down,t,\max}^{PSH}$ (m^3/s); $V_{up,\max}$ and $V_{up,t}$ are the maximum storage volume and the storage volume during period t of the upper reservoir (m^3), respectively; $I_{down,t}$ is the inflow to the lower reservoir during period t (m^3/s); $Q_{down,\min}$ is the minimum discharge from the lower reservoir (m^3/s); $V_{down,t}$ and $V_{down,\min}$ are the storage volume during period t and the minimum storage capacity of the lower reservoir, respectively (m^3).

3.2.3. Power Generation Constraints

$$N_{g,\min}^{PSH} \leq N_{g,t}^{PSH} \leq N_{g,\max}^{PSH} \quad (15)$$

$$N_{k,\min}^{CH} \leq N_{k,t}^{CH} \leq N_{k,\max}^{CH} \quad (16)$$

$$Q_{g,t,\min}^{PSH} \leq Q_{g,t}^{PSH} \leq Q_{g,t,\max}^{PSH} \quad (17)$$

$$Q_{g,t,\max}^{PSH} = \min(Q_{g,u,\max}^{PSH}, Q_{g,up,t,\max}^{PSH}) \quad (18)$$

$$Q_{g,up,t,\max}^{PSH} = (V_{up,t} - V_{up,\min}) / \Delta t \quad (19)$$

where $N_{g,\max}^{PSH}$ and $N_{g,\min}^{PSH}$ denote the maximum and minimum power outputs of the PSH under power generation conditions (MW); $N_{k,\max}^{CH}$ and $N_{k,\min}^{CH}$ denote the maximum and minimum power outputs of CH plant k , (MW); $Q_{g,t,\min}^{PSH}$ and $Q_{g,t,\max}^{PSH}$ denote the minimum and maximum power generation flow rates of the PSH during period t (m^3/s); $Q_{g,u,\max}^{PSH}$ and $Q_{g,up,t,\max}^{PSH}$ represent the maximum allowable generation flow rate of the pumped storage unit and the maximum discharge capacity of the upper reservoir (m^3/s); $V_{up,t}$ and $V_{up,\min}$ represent the storage volume and minimum storage volume of the upper reservoir during period t (m^3).

3.2.4. Additional Modeling Assumptions

Several physical factors were simplified in the present model. Ramp-rate limits were not explicitly modeled because, at the hourly scheduling scale adopted here, both hydro-power and pumped-storage units can complete full output adjustment within one hour, so ramp-rate constraints do not materially affect the scheduling results. Evaporation losses were neglected because reservoir-specific evaporation data are unavailable; however, under the climatic conditions of the Wujiang basin, evaporation is small relative to reservoir inflow and storage variation and therefore has only a limited effect on the overall results. Cascade hydraulic delay was also neglected because accurate travel-time data between reservoirs are unavailable. In practice, the delay is expected to be about one hour, which may slightly shift the timing of downstream inflow but is unlikely to materially affect the overall cascade scheduling results. These simplifications preserve the dominant hydraulic and operational characteristics of the system while maintaining model tractability.

3.3. Solution Method

The joint optimization of PSH and CH involves high-dimensional decision variables. Given the high dimensionality of the problem, this study utilizes the progressive optimization algorithm (POA). Through the decomposition of the original multi-stage problem into tractable two-stage subproblems, POA achieves an iterative solution [33]. The solution procedure is as follows:

Step 1: Define the scheduling horizon T , the maximum number of iterations $K_{\max}$, and a storage convergence tolerance $\mathcal{E}$. Generate feasible initial storage trajectories for all reservoirs that satisfy the hydraulic and storage bound constraints. Set the iteration counter $k=1$ and compute the initial system revenue R^0 .

Step 2: At iteration k , for each time step t , fix the storage vectors of all reservoirs at $t-1$ and $t+1$, and jointly optimize the storage vector at t , along with the cascade generation discharges and pumped storage flow rates. The pumping and generation modes (each taking the value of pumping, generation, or idle) are treated as discrete variables. All feasible mode combinations that satisfy the operational constraints are enumerated. For each combination, the remaining continuous variables are optimized to maximize the two-interval revenue. The best combination is retained and the storage at t is updated.

Step 3: After completing a forward or backward sweep over all time steps, update the storage trajectories and the corresponding pumping–generation schedule. Compute the total system revenue R^k for the updated trajectories.

Step 4: Compute the maximum absolute storage change $\Delta V_{\max}$ between successive iterations across all reservoirs and periods. If $\Delta V_{\max} \leq \varepsilon$, or $k \geq k_{\max}$, terminate the algorithm. If the termination condition is not met, then increment k by 1 and revert to Step 2.

Step 5: Within the multi-scale nested framework, the long-term model is solved first to obtain the end-of-day storage trajectories for the reservoirs. These trajectories then act as initial boundary constraints for the short-term model. The short-term POA subsequently refines the intra-day pumping and generation schedules, operationalizing the seasonal energy shifting and short-term peak shaving strategy defined in Section 2. Output the optimal hourly generation schedules of all cascade plants, the pumping and generating flow rates, the reservoir water levels, and the total system revenue.

To assess the computational performance of the proposed POA, it was compared with dynamic programming with successive approximations (DPSA), a widely used DP-based decomposition approach in cascade hydropower scheduling. The comparison involves three conventional cascade reservoirs and one pumped-storage hydropower station for the full annual scheduling problem at hourly resolution (8760 time steps). Both methods were implemented under identical input data, objective function, and operational constraints, with a water-level discretization of 100 states per reservoir. The computations were performed on an Intel Core i7-9700 CPU (3.00 GHz, 16 GB RAM). Convergence was defined as the point at which successive iterations produced a relative change in annual benefit of less than 0.1%. POA required approximately 25 min and DPSA approximately 35 min, while the objective values differed by less than 1%. These results indicate that POA can achieve comparable solution quality with improved computational efficiency for the full annual scheduling problem.

4. Comprehensive Benefit Assessment Framework for Pumped Storage Retrofitting

To systematically assess the impact of pumped storage retrofitting of cascade hydropower plants on the operational modes and overall benefits of the original river basin hydropower system, this paper establishes a comprehensive assessment framework comprising technical, energy efficiency, and economic indicators.

(1) Technical indicators

① Reduction in peak-valley load difference

$$\beta = \frac{1}{D} \sum_{d=1}^D (\Delta L_{\text{net},d} - \Delta L_{\text{re},d}) / \Delta L_{\text{net},d} \cdot 100\% \quad (20)$$

$$\Delta L_{\text{net},d} = \max_{1 \leq t \leq T} (L_{\text{net},d,t}) - \min_{1 \leq t \leq T} (L_{\text{net},d,t}) \quad (21)$$

$$\Delta L_{\text{re},d} = \max_{1 \leq t \leq T} (L_{\text{re},d,t}) - \min_{1 \leq t \leq T} (L_{\text{re},d,t}) \quad (22)$$

where β is the average reduction rate of the peak-valley difference (%); $\Delta L_{\text{net},d}$ is the peak-valley difference of the net load (load minus VRE output) on day d (MW); $L_{\text{net},d,t}$ is the net load at hour t of day d (MW); $\Delta L_{\text{re},d}$ is the peak-valley difference of the residual load after CH and PSH operation on day d (MW); $L_{\text{re},d,t}$ is the residual load at hour t of day d (MW); D is the total number of days in the study period.

(2) Energy efficiency indicators

① Utilization of curtailed VRE

$$R_u = (\sum_{d=1}^D \sum_{t=1}^T E_{VRE,d,t}^{PSH}) / E_{curt} \cdot 100\% \quad (23)$$

$$E_{curt} = \sum_{d=1}^D \sum_{t=1}^T \max(N_{d,t}^{VRE} - L_{d,t}, 0) \cdot \Delta t \quad (24)$$

where R_u is the utilization rate of curtailed VRE (%); $E_{VRE,d,t}^{PSH}$ is the amount of curtailed VRE utilized by the PSH during period t of day d (MW·h); E_{curt} is the total amount of curtailed VRE of the grid over the study period (MW·h); $N_{d,t}^{VRE}$ is the total VRE power output, and $L_{d,t}$ is the load demand during period t of day d (MW).

② Water spillage volume

$$W_{sp} = \sum_{d=1}^D \sum_{t=1}^T W_{sp,d,t} \quad (25)$$

where W_{sp} denotes the cumulative water spillage volume (m³); $W_{sp,d,t}$ denotes the reservoir water spillage volume during period t of day d (m³).

③ System energy conversion efficiency

System energy conversion efficiency is quantified as the additional power generation divided by the electricity used for pumping.

$$R_{system} = \frac{\sum_{d=1}^D \sum_{t=1}^T (\Delta E_{d,t}^{CH} + \Delta E_{g,d,t}^{PSH})}{\sum_{d=1}^D \sum_{t=1}^T (E_{pur,d,t}^{PSH} + E_{VRE,d,t}^{PSH})} \quad (26)$$

where R_{system} is the system energy conversion efficiency; $\Delta E_{d,t}^{CH}$ and $\Delta E_{g,d,t}^{PSH}$ are the additional power generation from CH plants and PSH during period t of day d (MW·h); $E_{pur,d,t}^{PSH}$ and $E_{VRE,d,t}^{PSH}$ are the purchased electricity and the curtailed VRE used for PSH pumping during period t of day d , respectively (MW·h).

(3) Economic indicators

① Annual net revenue increment

$$\Delta B = B_{p,g} - B_{p,p} + \sum_{k=1}^K B_{h,k,af} - \sum_{k=1}^K B_{h,k,be} \quad (27)$$

where ΔB , $B_{p,g}$, and $B_{p,p}$ represent the system's annual net revenue increase, the power generation revenue of the PSH, and the power purchase cost, respectively, following the construction of the PSH (CNY); $B_{h,k,be}$ and $B_{h,k,af}$ are the annual revenue of CH plant k before and after retrofitting, respectively (CNY).

② Net present value (NPV) over the entire life cycle

$$NPV = \sum_{y=1}^Y \frac{\Delta B_y - C_y}{(1+r)^y} - C_{invest} \quad (28)$$

$$\Delta B_y = \Delta B \cdot (1+\theta)^{y-1} \quad (29)$$

where NPV denotes the life-cycle net present value for the PSH (CNY); Y is the operational lifespan of the PSH, in years; y represents the year of operation; r represents the social discount rate; ΔB_y represents the additional revenue generated by the PSH for the

system in year y (CNY); C_y is the operating cost of PSH in year y (CNY); C_{invest} is the initial investment cost (CNY); θ is the inflation rate.

③ Payback period

$$\sum_{y=0}^{P_y} (\Delta B_y - C_y) \cdot (1+r)^y - C_{invest} = 0 \quad (30)$$

where P_y represents the payback period of the PSH (year); r represents the benchmark rate of return, which here equals the social discount rate.

5. Case Study Analysis

5.1. Study Area and Data

Guizhou Province is a major clean energy base in China's southwestern region. By 2035, VRE is anticipated to reach 57% of the province's installed capacity, while hydro-power share will decline to 10%, intensifying the need for flexible grid regulation. Developing pumped storage is therefore a key measure to enhance renewable integration and support the low-carbon transition. This study focuses on the Wujiang River basin, the largest southern-bank tributary of the upper Yangtze and one of China's 13 major hydro-power bases. The Hongjiadu, Dongfeng, and Suofengying power plants constitute key components of the Wujiang River cascade. Together, they provide an installed capacity of 1895 MW and produce an average of 5897 million kWh annually. Table 1 details the main parameters of these hydropower plants.

Table 1. Basic parameters of hydropower plants.

Parameter	Hongjiadu	Dongfeng	Suofengying
Regulation performance	Multi-year regulation	Seasonal regulation	Daily regulation
Normal storage level (m)	1140	970	837
Flood control restriction level (m)	1138	970	837
Dead level (m)	1076	950	822
Total storage capacity (hm ³)	4947	1016	201
Regulating storage capacity (hm ³)	3361	491	67
Installed capacity (MW)	600	695	600
Transmission capacity (MW)	600	695	600

Note: The data of cascade hydropower stations comes from the basin hydropower development company.

As outlined in the Southern China region's long-range pumped storage development blueprint, a new upper reservoir will be added at the Dongfeng Reservoir to form a PSH plant. Designed with normal and dead water levels of 1434 m and 1410 m, respectively, the planned upper reservoir will offer an active storage capacity of 7.88 million m³. The installed capacity is 1200 MW, with a pumping-generation cycle efficiency of 80% [34]. This reservoir storage provides the daily regulation support for the pumping and generating operation. Moreover, when operated in coordination with the cascade hydropower reservoirs, the upper reservoir also has the potential to store part of the water and thereby contribute to longer-timescale regulation of the overall system. The operational lifespan is 40 years, the initial investment cost is 5990 CNY/kW, and annual operating costs are set at 1% of the investment cost. The inflation rate is assumed to be 3%, and the discount rate is 6.5%. According to the on-grid hydropower tariffs set by the Guizhou Provincial Development and Reform Commission, the benchmark electricity price is 294.9 CNY/MWh. The

study targets the 2035 VRE planning year. Runoff data span the measured series for the Hongjiadu–Dongfeng–Suofengying cascade from 1952 to 2024. The hourly grid load for 2035 is derived by scaling the 2024 hourly load profile according to the projected total electricity consumption for that year, while VRE output coefficient uses the 2024 series.

To verify the accuracy of the hydrological and energy-conversion calculations in the proposed model, the observed daily inflow series and end-of-day reservoir water levels of the cascade reservoirs for the full year 2023 were obtained from the basin hydropower development company and used as boundary conditions. The model was run with these inputs using the same turbine efficiency relationships and reservoir parameters as in the main model, and the simulated energy generation was compared with the historical operational records. The results show that the relative error of annual energy generation is less than 2%. A monthly comparison further confirms the model reliability, with relative errors remaining within 1% in most months. The largest deviations occur during the flood season (June–August), reflecting the increased operational complexity introduced by flood control constraints. This close agreement at both annual and monthly scales supports the reliability of the model in representing the water-energy conversion process and reservoir dynamics of the system.

Six comparative scenarios are defined, spanning three hydrological conditions (wet, average, and dry) and two system configurations: conventional hydropower (CH) and pumped storage integrated with conventional hydropower (PSH-CH).

5.2. Analysis of Dispatch

An average water year was selected as a typical hydrological scenario to analyze differences in system dispatch processes before and after pumped storage integration. The seasonal operation pattern of the PSH, characterized by energy storage in spring/summer and power generation in winter, is reflected in the annual water level fluctuations of its upper reservoir (Figure 3). Driven by the seasonal patterns of VRE output and load, net load is relatively low from April to August, when the pumped storage plant primarily operates in pumping mode; in winter, as VRE generation weakens and load increases, net load and the composite electricity price rise, causing the plant to switch to generation mode. These results indicate that adding the upper reservoir enables cross-seasonal water transfer on an annual scale, storing energy and water during low-value periods for release during high-value periods, thereby alleviating the regulation burden imposed by seasonal fluctuations in VRE. At the short-term scale, pumped storage operation is primarily driven by the intra-day net load curve. Under conditions of low wind and solar generation (Figure 4a), the plant employs a dual-mode strategy: pumping to absorb excess off-peak energy and generating to meet on-peak demand, which effectively flattens the net load curve. On a day with high wind and solar output and curtailment (Figure 4b), the pumping period shifts to midday when VRE generation is concentrated, converting otherwise curtailed energy into evening peak electricity. The pumped storage system simultaneously provides VRE curtailment utilization and peak-valley regulation, reducing annual VRE curtailment by 1039 GWh, accounting for approximately 8.8% of the grid's total curtailment, and increasing the peak-valley difference reduction rate by 4.5%.

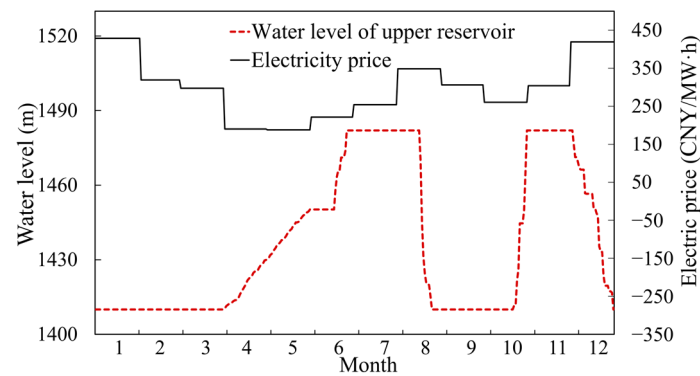


Figure 3. Annual water level variation process of the upper reservoir in the pumped storage plant.

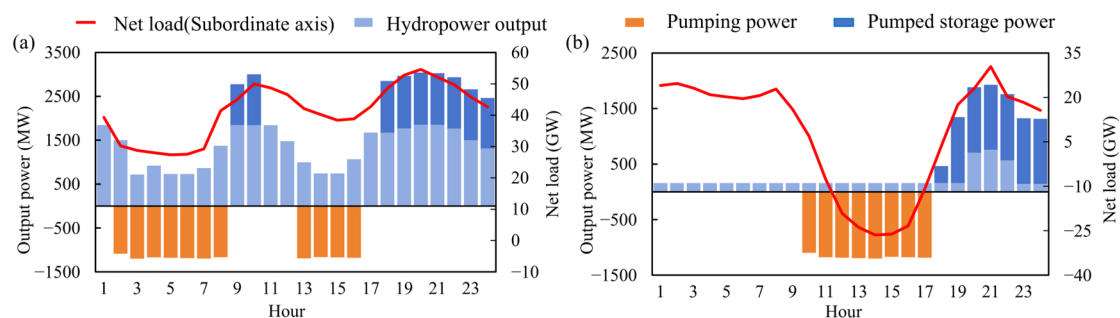


Figure 4. Typical daily output of the cascade hydropower system with the pumped-storage plant under (a) low VRE generation and (b) high VRE generation. The figures combine the outputs of cascade hydropower (CH) and pumped storage (PSH) for the retrofitted system.

The operation of the PSH plant affects the dispatch of the cascade reservoirs. Figure 5 illustrates the long-term water level variations of Hongjiadu and Dongfeng reservoirs before and after the retrofit, based on the multi-scale nested model of the pumped storage system. During high-price periods in winter (January–February), both plants operated primarily for power generation, irrespective of the retrofit. Consequently, Hongjiadu Reservoir’s water level declined, a trend mirrored at Dongfeng Reservoir. At the close of every day, the upper reservoir’s water level in the pumped storage plant reverts to its original state, indicating a predominantly daily regulation function. From April to June, as VRE output grows and displaces hydropower generation, outflow from Hongjiadu Reservoir decreases. The pumped storage plant pumps water into the upper reservoir for storage, leading to a reduction in storage volume of Dongfeng Reservoir and a lower water level compared to the scenario without pumped storage. During peak demand periods in summer and winter, the pumped storage plant releases stored water into the lower reservoir, resulting in a higher turbine discharge than in the without-pumped-storage case, effectively supplementing water for power generation when electricity prices are high. As a daily-regulation reservoir, the water level of Suofengying Reservoir remains constant over long-term operation.

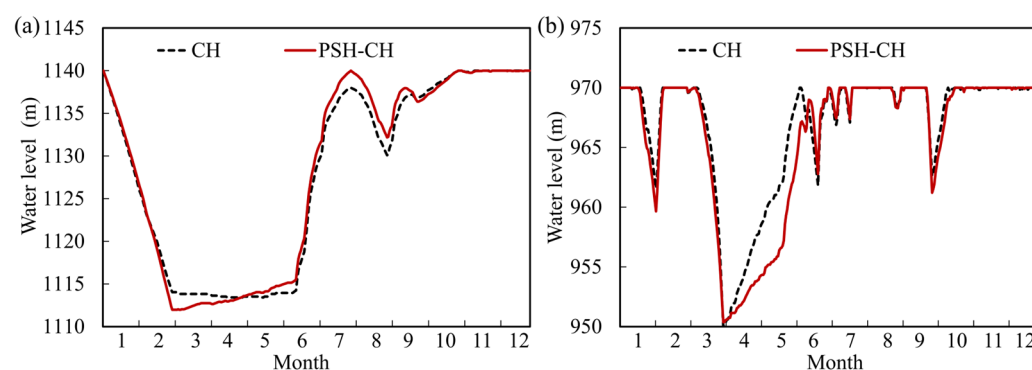


Figure 5. Annual water level variation process of cascaded reservoirs: (a) Hongjiadu reservoir; (b) Dongfeng reservoir. The water level curve depicted is the simulation result of the model proposed in a normal year.

Overall, the pumped storage plant modifies the storage and release patterns of the original cascade hydropower system, leading to a slight decrease of approximately 1.2% in the annual energy production of the conventional cascade plants. However, when including the additional electricity generated by the pumped storage plant, total system generation increases by 38.3% compared with the case without pumped storage; even after deducting pumping energy, net generation rises by 6.1%. These results indicate that despite incurring pumping losses, pumped storage delivers a substantial gain in system generation benefits through cross-seasonal water storage and intra-day regulation.

5.3. Comprehensive Benefit Analysis of Pumped Storage Retrofit

Table 2 shows the system dispatch results under an average water year. Compared with conventional cascade hydropower schemes, the addition of pumped storage hydropower significantly improves the system's peak-shaving capacity, VRE integration, and revenue. The plant's peak-shaving capability, achieved through pumping at low load and generating at high load, is evidenced by the increase in peak-valley difference reduction from 1.83% to 6.33%. For VRE consumption, the pumped storage plant absorbs curtailed VRE, primarily the midday solar surplus, for pumping and shifts it to the evening peak, reducing annual VRE curtailment by 1039 GWh, which accounts for 8.8% of the total curtailed VRE in the system. Regarding economic benefits, pumped storage performs temporal arbitrage through low-price pumping and high-price generation, raising the net generation revenue from 2265 million CNY to 2962 million CNY, an increase of 30.8%. Concerning water resource utilization, the upper reservoir stores water when VRE generation is high, thereby reducing the contemporaneous inflow to downstream cascade plants and smoothing the seasonal transfer of water between wet and dry seasons. The water spillage volume decreases from 205 million m³ to 196 million m³. The actual round-trip efficiency achieved by the PSH system reached 79.6%, slightly below the design value of 80%, owing to head variations caused by fluctuations in the lower reservoir water level during actual operation.

Table 2. Scheduling results of cascade hydropower with and without pumped storage plant.

Indicators	CH	PSH-CH
Reduction in peak-valley load difference (%)	1.83%	6.33%
Electricity generation (GW·h)	6474	8954
Electricity purchased (GW·h)	/	2078
Utilization of curtailed VRE (GW·h)	/	1039
Net power generation revenue (million CNY)	2265	2962
Water spillage (million m ³)	205	196
System energy conversion efficiency	/	79.6%

To further explore the influence of pumped storage capacity on comprehensive benefits, a sensitivity analysis was conducted for capacities ranging from 400 MW to 1400 MW under the average water year. As the installed capacity increases, the amount of curtailed VRE utilized rises from 202 GWh to 1164 GWh, the reduction in the peak-valley difference improves from 3.54% to 7.05%, the overall energy conversion efficiency remains around 79.7%, and the downstream water spillage continues to decline (Figure 6). Simultaneously, the annual net generation benefit and the full life-cycle net present value rise monotonically, reaching 3001 million CNY and 6535 million CNY, respectively, for the 1400 MW scheme. In summary, expanding pumped storage capacity can effectively enhance the system's overall benefits, but economic viability and scale-related constraints must be balanced.

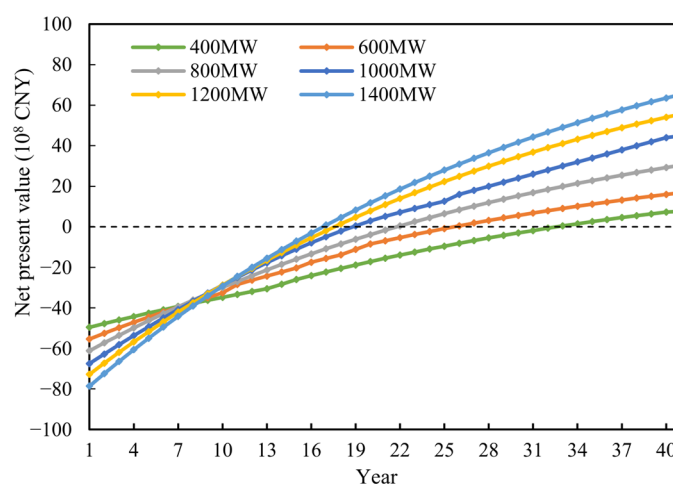


Figure 6. Comparison of net present value across different pumped storage capacities.

5.4. Benefit Comparison Under Different Inflow Scenarios

To verify the applicability of the PSH under different inflow conditions, the system's optimal operation was simulated for typical wet, average, and dry years. By comparing the configurations with and without pumped storage, the contribution of pumped storage to system generation revenue was quantified across these inflow conditions. Table 3 summarizes the detailed findings.

Table 3. Optimal system dispatch results under different inflow conditions.

Inflow Conditions	Scenario	Benefits (Million CNY)	Incremental Benefit (Million CNY)
Wet Year	CH	3024	/
	PSH-CH	3811	787
Average year	CH	2265	/
	PSH-CH	2962	697
Dry year	CH	1188	/
	PSH-CH	1833	645

The integration of pumped storage enhances generation revenue under all inflow conditions, but the absolute and relative gains display distinct patterns. In terms of absolute increments, the increase in power generation benefits is positively correlated with inflow abundance, with the largest increment occurring in wet years (787 million CNY) and the smallest in dry years (645 million CNY). This is primarily because the PSH increases the effective storage capacity of cascade reservoirs, allowing surplus inflow to be retained in the upper reservoir during wet periods and thereby improving water resource utilization. In terms of relative growth, the increase in power generation benefits is greatest during dry years, at approximately 54%. This is because the conventional cascade is highly inflow-constrained in dry years, yielding low baseline revenue; pumped storage, by contrast, can significantly lift system returns under such resource-limited conditions through flexible regulation that absorbs curtailed VRE and exploits low-price pumping and high-price generation. These findings suggest that in river basins with relatively abundant but seasonally uneven inflows and a strong demand for VRE consumption, retrofitting cascade hydropower systems with pumped storage is a promising strategy to reconcile grid regulation requirements with project economics.

Previous studies have also shown that reservoir management can be improved through operation rules and multi-objective/metaheuristic optimization under changing hydroclimatic conditions [35]. Extending such approaches to coordinated CH-PSH operation would be a useful direction for future research.

5.5. Sensitivity Analysis

To assess the robustness of the proposed pumped-storage retrofit under varying economic conditions, a systematic sensitivity analysis was conducted on three key economic factors, namely electricity price, discount rate, and investment cost, each varied by $\pm 50\%$ from its benchmark value. Under the benchmark on-grid tariff of 294.9 CNY/MWh, the lifecycle NPV is 6535 million CNY. Changes in electricity price led to a $\pm 118\%$ variation in NPV. A 50% price reduction lowers the NPV to −1215 million CNY, indicating a loss of economic viability. Over the tested discount-rate range, the NPV varies from +169.4% to −78.6% relative to the benchmark case but remains positive in all tested cases. Changes in investment cost led to an approximately $\pm 60\%$ variation in NPV. Overall, the economic performance is most sensitive to electricity price and discount rate, while the effect of investment cost is comparatively moderate.

It should also be noted that the present study has partially reflected VRE uncertainty through the variation in VRE energy penetration across different representative days in Section 5.2. However, different VRE installed-capacity scenarios may also affect the NPV and payback period of the proposed retrofit, and this effect warrants further investigation in future research.

6. Conclusions

Transforming conventional cascade hydropower stations by adding upper reservoirs to enable pumped storage operation represents a pivotal approach for augmenting the

energy storage potential of hydropower systems, as well as their grid-regulating flexibility. Using the Wujiang River basin as a case study, a multi-scale nested optimization dispatch framework is proposed to coordinate pumped storage and cascade hydropower, facilitating the integration of high-penetration VRE. By simulating system operation under wet, average, and dry inflow conditions both before and after the retrofit, the impacts on dispatch patterns and overall benefits were evaluated. Therefore, it can be concluded that:

- (1) A dynamic time-of-use pricing mechanism driven by the temporal characteristics of net load can effectively capture the differentiated system demands for cross-seasonal energy balancing and intra-day regulation under high VRE penetration. The multi-scale nested dispatch model built upon this pricing mechanism guides, on the long-term scale, the storage of water during periods of abundant VRE generation and the increase of hydropower output during VRE deficits, thereby alleviating cross-seasonal balancing pressure. On the short-term scale, it coordinates pumped storage and cascade hydropower by utilizing curtailed VRE and low-cost electricity for pumping, satisfying regulation requirements across multiple time scales.
- (2) Although pumped storage inevitably incurs energy losses in the pumping-generation cycle, the upper reservoir enables cross-seasonal water allocation and intra-day bidirectional regulation, converting otherwise curtailed VRE into generation revenue during high-price periods. The case study shows that retrofitting the cascade system into a pumped storage facility increases the reduction rate of the peak–valley load difference by 4.5 percentage points, reduces annual VRE curtailment by approximately 1039 GWh, accounting for about 8.8% of the system’s total curtailed VRE, raises net generation by 6.1%, and boosts net generation revenue by 30.8%.
- (3) The benefits of the pumped storage retrofit are significantly influenced by inflow, yet the system demonstrates strong adaptability across wet, average, and dry years. In wet years, water utilization is improved by storing surplus inflow for later use, yielding an incremental net generation revenue of 787 million CNY. In dry years, the incremental revenue decreases to 645 million CNY, but the relative increase reaches approximately 54% due to the low baseline revenue of the conventional cascade. Overall, in basins with abundant but seasonally uneven inflows and strong VRE consumption demand, pumped storage retrofits for cascade hydropower can effectively reconcile grid regulation requirements with project economics.

In addition, while the current study provides a comprehensive assessment under a fixed VRE planning scenario and deterministic inflow series, future research could extend the framework to incorporate probabilistic VRE and inflow scenarios, thereby enabling a more complete uncertainty quantification of economic indicators. It would also be valuable to examine how evolving electricity price structures and market mechanisms affect coordinated dispatch results. Furthermore, integrating water-supply reliability objectives (e.g., reliability, resilience, and vulnerability) into a multi-objective extension would broaden the applicability of the proposed dispatch model to multi-purpose reservoir systems.

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Data Availability Statement: This study used third party data made available under license that the author does not have permission to share.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

The following abbreviations are used in this manuscript:

VRE	Variable renewable energy
CH	Conventional Hydropower
PSH	Pumped storage hydropower
$P_{n,d,t}$	Composite electricity price for period t in day d
$L_{net,d,t}$	Net load for period t in day d
$L_{net,max}$	Annual maximum net load
$P_{h,bench}$	Benchmark electricity price
R_{max}	Total operating benefit
$N_{k,d,t}^{CH}$	Power output of CH plant k during period t of day d
$N_{g,d,t}^{PSH}$	Generation power of the PSH plant during period t of day d
$N_{pur,d,t}^{PSH}$	Grid-purchased pumping power of the PSH plant during period t of day d
Δt	Time step duration
$V_{up,t}$	Storage volume in the newly constructed upper reservoir at the end of period t
$Q_{p,t}^{PSH}$	Pumping flow rate of the PSH during period t
$Q_{g,t}^{PSH}$	Discharge flow rate of the PSH during period t
$V_{down,t}$	Storage of the PSH at the end of period t
$I_{down,t}$	Inflow rate of the reservoir during period t
$Q_{down,t}^{CH}$	Outflow rate of the reservoir during period t
V_t	Storage during period t
Z_t	Water level during period t
V_{min}	Minimum storage volume limit
V_{max}	Maximum storage volume limit
Z_{min}	Minimum level limit. For the upper reservoir of the PSH, the minimum level corresponds to the dead level Maximum level limit. For the upper reservoir of the PSH, the maximum water level is determined by the normal storage level of the newly constructed reservoir.
Z_{max}	For the lower reservoir (existing cascade reservoir), the maximum level is the normal storage level during non-flood seasons and the flood-control restriction level during flood seasons.

$H_{g,t}^{PSH}$	Generating head of the PSH during period t
$H_{p,t}^{PSH}$	Pumping head of the PSH during period t
$H_{g,min}^{PSH}$	Minimum allowable heads in generating mode
$H_{g,max}^{PSH}$	Maximum allowable heads in generating mode
$H_{p,min}^{PSH}$	Minimum allowable heads in pumping mode
$H_{p,max}^{PSH}$	Maximum allowable heads in pumping mode
$N_{p,t}^{PSH}$	Pumping power supplied by both curtailed VRE power and grid purchases
$N_{VRE,t}^{PSH}$	Pumping power supplied by curtailed VRE power
$N_{pur,t}^{PSH}$	Pumping power supplied by grid purchases
$N_{p,min}^{PSH}$	Lower limit of pumping power supplied by both curtailed VRE power and grid purchases
$N_{p,max}^{PSH}$	Upper limit of pumping power supplied by both curtailed VRE power and grid purchases
$Q_{p,t,min}^{PSH}$	Lower limit of pumping flow rate of the PSH during period t
$Q_{p,t,max}^{PSH}$	Upper limit of pumping flow rate of the PSH during period t
$Q_{p,u,max}^{PSH}$	Maximum pumping flow capacity of the water conveyance system
$Q_{p,up,t,max}^{PSH}$	Maximum storable flow in the upper reservoir
$Q_{p,down,t,max}^{PSH}$	Maximum extractable flow from the lower reservoir
$V_{up,t}$	Storage volume of the upper reservoir during period t
$V_{up,max}$	Maximum storage volume of the upper reservoir
$V_{up,min}$	Minimum storage volume of the upper reservoir
$I_{down,t}$	Inflow to the lower reservoir during period t
$Q_{down,min}$	Minimum discharge from the lower reservoir
$V_{down,t}$	Storage volume during period t of the lower reservoir
$V_{down,min}$	Minimum storage capacity of the lower reservoir
$N_{g,max}^{PSH}$	Maximum power outputs of the PSH under power generation conditions
$N_{g,min}^{PSH}$	Minimum power outputs of the PSH under power generation conditions
$N_{k,max}^{CH}$	Maximum power outputs of CH plant k

$N_{k,\min}^{CH}$	Minimum power outputs of CH plant k
$Q_{g,t,\min}^{PSH}$	Minimum power generation flow rates of the PSH during period t
$Q_{g,t,\max}^{PSH}$	Maximum power generation flow rates of the PSH during period t
$Q_{g,u,\max}^{PSH}$	Maximum allowable generation flow rate of the pumped storage unit
$Q_{g,up,t,\max}^{PSH}$	Maximum discharge capacity of the upper reservoir
β	Average reduction rate of the peak-valley difference
$\Delta L_{net,d}$	Peak-valley difference of the net load (load minus VRE output) on day d
$L_{net,d,t}$	Net load at hour t of day d
$\Delta L_{re,d}$	Peak-valley difference of the residual load after CH and PSH operation on day d
$L_{re,d,t}$	Residual load at hour t of day d
D	Total number of days in the study period
R_u	Utilization rate of curtailed VRE
$E_{VRE,d,t}$	Amount of curtailed VRE utilized by the PSH during period t of day d
E_{curt}	Total amount of curtailed VRE of the grid over the study period
$N_{d,t}^{VRE}$	Total VRE power output
$L_{d,t}$	Load demand during period t of day d
W_{sp}	Cumulative water spillage volume
$W_{sp,d,t}$	Reservoir water spillage volume during period t of day d
R_{system}	System energy conversion efficiency
$\Delta E_{d,t}^{CH}$	Additional power generation from CH plants during period t of day d
$\Delta E_{g,d,t}^{PSH}$	Additional power generation from PSH plants during period t of day d
$E_{pur,d,t}^{PSH}$	purchased electricity and the curtailed VRE used for PSH pumping during period t of day d
ΔB	System's annual net revenue increase
$B_{p,g}$	Power generation revenue of the PSH
$B_{p,p}$	Power purchase cost
$B_{h,k,be}$	Annual revenue of CH plant k before retrofitting
$B_{h,k,af}$	Annual revenue of CH plant k after retrofitting
NPV	Life-cycle net present value for the PSH
Y	Operational lifespan of the PSH
y	Year of operation

r	Benchmark rate of return, which equals social discount rate
ΔB_y	Additional revenue generated by the PSH for the system in year y
C_y	Operating cost of PSH in year y
C_{invest}	Initial investment cost
θ	Inflation rate
P_y	Payback period of the PSH
TOU	Time-of-use
POA	Progressive optimization algorithm

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