Energy Proceedings
Vol 66, 2026

ISSN 2004-2965

Optimization Scheduling Method for Enhancing Flexibility in Cascade Hydro-Wind-Solar Power System Utilizing Hybrid Pumped Storage

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ABSTRACT

To fully explore the potential of hybrid pumped storage in enhancing the power supply flexibility of the hydropower-wind-solar system in a river basin, the time-varying characteristics of water head under the joint operation of hybrid pumped storage and cascade hydropower, considering time delay, are analyzed. A model for cascade hydropower and hybrid pumped storage operations, considering hydrological coupling characteristics, is established. The active power scenarios of wind and photovoltaic are extracted through the improved SA-CGAN model. Then, a multi-scenario-based stochastic optimization dispatch method for the hybrid pumped storage-cascade hydropower-wind-solar joint generation system is proposed. The whale migration algorithm is used to improve the solution efficiency. Through simulation verification, the flexible complementarity of hybrid pumped storage and cascade hydropower can effectively improve the economic and reliable power supply of the hydropower-wind-solar renewable energy base in the river basin.

Keywords: Hydro-wind-solar energy base, Hybrid pumped storage, Stochastic optimization, Whale migration algorithm.

NONMENCLATURE

WMA	*Whale Migration Algorithm*
SA-CGAN	*Self-Attention Conditional Generative Adversarial Network*
F	*Cost in optimal scheduling*
V	*Storage capacity of reservoir*
Q	*Water-carrying capacity*
Z	*Water level*
H	*Water head*
P	*Power*

1. INTRODUCE

Basin-scale hydro-wind-solar power can achieve 100% clean energy generation. It represents a major form of global energy transition. To fully leverage hydropower in stabilizing the uncertainty of wind and solar power, hybrid pumped storage has gained significant attention in recent years. Its advantages include low investment costs and short construction periods.

Numerous studies have explored the coordinated optimal operation of hydro-wind-solar energy bases [1]. Reference [2] proposed a power system dispatch model considering hydro-photovoltaic-pumped storage complementarity and DC transmission. Reference [3] employed Copula functions to characterize the uncertainty and spatiotemporal correlation of wind and photovoltaic power output. It developed an optimization model to minimize the deviation between the combined wind-solar-pumped storage grid power and system load demand. Reference [4] introduced a novel system model integrating dual energy storage with hybrid pumped storage hydropower. Reference [5] established a hydro-wind-solar storage dispatch model to minimize system fluctuations, based on hydropower output characteristics across different periods. Reference [6] incorporated the complementary regulation of pumped storage and electrochemical storage. It built a stochastic day-ahead dispatch model with peak shaving demands, aiming to reduce wind/solar curtailment and grid reserve energy. Most existing studies address renewable energy integration with hydropower and pumped storage. However, they often overlook the wear from frequent adjustments of hydropower and pumped storage units due to wind/solar fluctuations. Water energy utilization efficiency is also insufficiently considered.

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[1] # This is a paper for the 17th International Conference on Applied Energy (ICAE2025), December 8-12, 2025, Bangkok, Thailand.

This paper develops a cascade reservoir model with hybrid pumped storage, incorporating hydrological time-delay effects. The model comprehensively accounts for the economics of frequent output adjustments, reserve costs, penalties for wind/solar/water curtailment, and load loss penalties. A joint operation method for hydro-wind-solar hybrid storage is proposed. To handle nonlinearities, an optimization algorithm based on the whale migration algorithm is designed. Case studies demonstrate that hybrid pumped storage significantly improves the power generation capacity of hydro-wind-solar energy bases.

2. JOINT OPERATION METHOD FOR HYDRO-WIND-SOLAR HYBRID STORAGE

2.1 Reservoir Modeling Method with Hybrid Pumped Storage

Cascade reservoirs are primarily arranged in series. Water flows between these reservoirs, and electricity is generated by converting potential energy into electrical energy. Hybrid pumped storage operates in different modes, such as power generation, shutdown, and pumping. Its integration complicates the hydraulic connections between cascade reservoirs. Water flow shifts from unidirectional to bidirectional. Therefore, refined modeling of the reservoirs is necessary.

Key parameters of cascade reservoirs include storage capacity, flow rate, and water level. Among these, storage capacity depends on natural inflow, upstream discharge, power generation flow, and spillage flow. With hybrid pumped storage, pumping flow must also be considered. Additionally, the time delay in water flow between reservoirs cannot be ignored. This effect is typically characterized by the flow time lag between cascade hydropower stations.

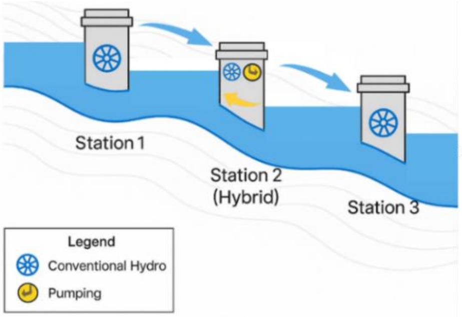

Figure 1Cascade hybrid pumped storage power station

The reservoir capacity can be calculated using Equation (1).

$$V_{c,t}=V_{c,t\text{-}1}+\left(Q^{F}_{c,t}+Q^{G}_{c-1,t-\tau_{c-1}}+Q^{S}_{c-1,t-\tau_{c-1}}+Q^{P}_{c,t-\tau'_{c}}-Q^{G}_{c,t}-Q^{S}_{c,t}-Q^{P}_{c-1,t}\right)\Delta t \quad (1)$$

Where $V_{c,t}$ and $V_{c,t\text{-}1}$ are the reservoir capacities of reservoir *c* at time *t* and *t-1*, respectively; $Q^{F}_{c,t}$ s the natural inflow to reservoir *c* at time *t*; Q^{G} is the total discharge flow, including both conventional units and pumped storage units; Q^{S} is the spillage flow; Q^{P} is the pumping flow of the pumped storage units; τ_{c-1} is the water flow time delay from reservoir *c-1* to reservoir *c*; τ'_{c} is the water flow time delay under pumping conditions

The head is usually calculated by subtracting the tailwater level and head loss from the upstream water level.

A nonlinear relationship exists between water level and capacity, as shown in Equation (2).

$$\left\{\begin{aligned} Z_{c,t} &= \mathbb{C}_{c}\left(V_{c,t}\right) \\ Z^{d}_{c,t} &= \mathbb{R}_{c}\left(Q^{G}_{c,t}+Q^{S}_{c,t}+Q^{P}_{c-1,t}\right) \end{aligned}\right\} \quad (2)$$

Where $Z_{c,t}$ and $Z^{d}_{c,t}$ are the water level and tailwater level of reservoir *c* at time *t*, respectively; $\mathbb{C}_{i}\left(\bullet\right)$ represents the nonlinear relationship between water level and reservoir capacity; $\mathbb{R}_{i}\left(\bullet\right)$ represents the nonlinear relationship between tailwater level and discharge flow.

In addition, reservoir operation must satisfy the following constraints:

$$\left\{\begin{aligned} Q_{c,\min} &\le Q_{c,t} \le Q_{c,\max} \\ V_{c,\min} &\le V_{c,t} \le V_{c,\max} \\ Z_{c,\min} &\le Z_{c,t} \le Z_{c,\max} \end{aligned}\right\} \quad (3)$$

Among, $Q_{c,\max}$ and $Q_{c,\min}$ are the upper and lower limits of flow for reservoir *c*, respectively; $V_{c,\max}$ and $V_{c,\min}$ are the upper and lower limits of storage capacity for reservoir *c*, respectively; $Z_{c,\max}$ and $Z_{c,\min}$ are the upper and lower limits of water level for reservoir *c*, respectively.

2.2 Water-wind-solar hybrid optimal scheduling model

Wind and solar power output have high uncertainty. Therefore, hydropower and pumped storage units are required for regulation. This ensures stable power supply capability. A cascaded hydro-wind-solar-storage complementary optimal scheduling model is proposed. It aims to achieve efficient coordinated utilization of hydro-wind-solar resources.

In hydro-wind-solar power system operation, economic efficiency, security, and resource utilization must be considered. Thus, a multi-objective optimization theory is used to establish a joint scheduling model. For computational convenience, each objective is converted into cost. The optimization objective is shown in Equation (4).

$$\min F = \alpha_1 f_1 + \alpha_2 f_2 + \alpha_3 f_3 + \alpha_4 f_4 \tag{4}$$

Where f_1 is represents the operating cost of hydropower and pumped storage units; f_2 represents the reserve cost for system security; f_3 is the penalty for water, wind, and solar curtailment losses; f_4 is the loss of load penalty.

Wind and solar active power exhibit strong fluctuations. This requires frequent adjustments to hydropower and pumped storage unit operations. Therefore, operating costs f_1 must include both start-stop costs and regulation costs. For computational convenience, this study uses the loss cost per MWh of regulation for hydropower and pumped storage units. Moreover, with hybrid pumped storage operation, system water abandonment must account for the pumping flow.

The optimization model must consider constraints such as unit operation and power balance. The active power output of units depends on head, discharge flow, and energy conversion efficiency. Efficiency is typically influenced by discharge flow and head. Specific constraints are as follows:

$$P_{c,h,t} = \rho g \eta H_{c,h,t} Q^G_{c,h,t} \tag{5}$$

$$H_{c,h,t} = \left(Z_{c,t-1} + Z_{c,t}\right)/2 - Z^d_{c,t} - H^{loss}_{c,h,t} \tag{6}$$

$$H^m_{c,h} \le H_{c,h,t} \le H^M_{c,h} \tag{7}$$

$$P^m_{c,h} \le P_{c,h,t} \le P^M_{c,h} \tag{8}$$

$$\sum_c \sum_h u_{c,h,t} \ge U_t \tag{9}$$

$$\begin{cases} y^U_{c,h,t} - y^D_{c,h,t} = u_{c,h,t} - u_{c,h,t-1} \\ y^U_{c,h,t} + y^D_{c,h,t} \le 1 \end{cases} \tag{10}$$

Where $P_{c,h,t}$ is the active power output of unit *h* in hydropower plant *c* at time *t*; $H_{c,h,t}$ is the net head of unit *h* in hydropower plant *c* at time *t*; $u_{c,h,t}$ is a 0-1 variable indicating the start-stop status of the unit.; $y^U_{c,h,t}$ and $y^U_{c,h,t}$ are 0-1 variables for start-up and shut-down operations, respectively; U_t is the minimum number of units online at time t.

For pumped storage units, the pumping mode must be further considered during operation. Specific constraints are as follows:

$$P^{Pm}_{c,h} \le P^P_{c,h,t} \le P^{PM}_{c,h} \tag{11}$$

$$P^P_{c,h,t} \times P_{c,h,t} = 0 \tag{12}$$

In the formula, $P^P_{c,h,t}$ is the pumping power of the pumped storage unit at time *t*. Minimum start-stop time constraints must be included. Shutdown constraints during mode changes between generation and pumping for pumped storage units are also needed.

Wind and solar active power outputs have strong uncertainty. Thus, the model becomes a stochastic optimization problem. This paper uses SA-CGAN to learn the probability distributions of random variables. The scenario method is applied to reduce uncertainty effects on model solving.

A conditional generative adversarial network (GAN) with self-attention mechanism is used. Conditional data and samples are concatenated based on data features. The basic structure and parameters of model components are designed. This enables effective dataset learning and scenario generation. Five typical scenarios are obtained through K-means clustering for the optimization scheduling model. Specific parameters are listed in the table below and are not repeated here.

Table I The structure and parameters of the generator

tier number	Type	Parameter Name	Parameter
1	Transposed convolution layer	Number of output channels	32
		dilation rate	1
		Activation Function	LeakyRelu(0.2)
2	Transposed convolution layer	Number of output channels	128
		dilation rate	2
		Activation Function	LeakyRelu(0.2)
3	Transposed convolution layer	Number of output channels	1
		dilation rate	3
		Activation Function	Relu

Table II The structure and parameters of the discriminator

tier number	Type	Parameter Name	Parameter
1	Self-attention	d_k	96
2	Convolutional Layer	Number of output channels	32
		dilation rate	1
		Activation Function	LeakyRelu(0.2)
3	Convolutional	Number of output channels	128

tier number	Type	Parameter Name	Parameter
	Layer	dilation rate	2
		Activation Function	LeakyRelu(0.2)
4	Convolutional Layer	Number of output channels	16
		dilation rate	3
		Activation Function	LeakyRelu(0.2)
5	Fully connected layer	Output dimension	1
		Activation Function	Sigmiod

The system constraints mainly include power balance constraints and reserve constraints, as follows:

$$\sum_{c}\sum_{h} P_{c,h,t} + \sum_{k} P^{W}_{k,t} + \sum_{j} P^{U}_{j,t} - \sum_{c}\sum_{h} P^{P}_{c,h,t} = L_t - \Delta L_t \tag{13}$$

$$\begin{cases} P^{M} \geq \sum_{c}\sum_{h} P_{c,h,t} - \sum_{c}\sum_{h} P^{P}_{c,h,t} + SR_{up,t} \\ P^{m} \leq \sum_{c}\sum_{h} P_{c,h,t} - \sum_{c}\sum_{h} P^{P}_{c,h,t} - SR_{down,t} \end{cases} \tag{14}$$

Where $P^{W}_{k,t}$ is the generation power of wind farm *k* at time *t*; $P^{U}_{j,t}$ is the generation power of photovoltaic station *j* at time *t*; P^{M} is the upper limit of generation power for the cascade hydropower group including pumped storage; P^{m} is the lower limit of generation power for the cascade hydropower group including pumped storage. This lower limit can be negative.

2.3 Solving algorithm

The cascade hydro-wind-solar-pumped storage complementary optimal scheduling model constructed in this paper encompasses multi-objective optimization and multiple constraint conditions. Due to the model's complex nonlinear characteristics and large-scale variable space, it is necessary to develop a solving algorithm tailored to the problem structure to ensure its practical application effectiveness.

The Whale Migration Algorithm (WMA) is an innovative bio-inspired metaheuristic optimization algorithm proposed in 2025, based on the collaborative migration behavior of humpback whales. WMA leverages the distinct features of humpback whale migration, emphasizing collective cooperation and leader-follower dynamics to enhance convergence and avoid local optima. It aims to improve performance in solving complex optimization problems by simulating team dynamics, leadership roles, and adaptive migration strategies.

The WMA algorithm is employed to solve the cascade hydro-wind-solar-pumped storage complementary optimal scheduling model. The output power processes of hydropower stations and hybrid pumped storage power stations are treated as optimization individuals. The upper and lower limits of the output from these stations are set as the movement range of the whale population, and the maximum number of iterations is designated as the model's termination condition. The variable correspondence between the cascade hydro-wind-solar-pumped storage complementary system and the WMA optimization algorithm is defined as follows: the output value of the *d-th* dimension in the *i-th* optimal scheduling scheme of the system is represented as $W_{i,d}$, which corresponds to the position of the *i-th* whale in the *d-th* dimension; $f(W_i)$ is the fitness value of the whale, which equates to the optimal scheduling objective value of the cascade hydro-wind-solar-pumped storage complementary system.

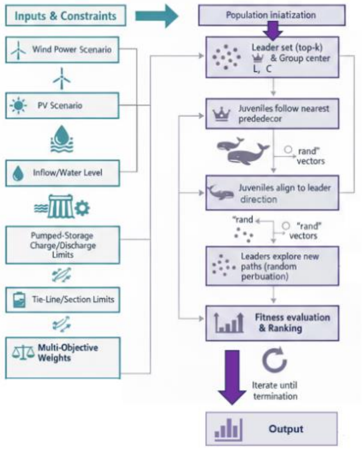

Figure 2 WMA Algorithm Flow Chart

3. EXAMPLE ANALYSIS

This paper takes a practical project in Southwest China as a case study, focusing on a complementary power generation system composed of an upstream hydropower station with an installed capacity of 3000 MW, a downstream hydropower station with 300 MW, a hybrid pumped storage power station with 1200 MW, a photovoltaic power station with a maximum output of 1000 MW, and a wind power station with a maximum output of 192 MW. The study optimizes the 24-hour power generation scheduling of this system.

The upstream hydropower station has 6 units, each with a capacity of 500 MW; the downstream hydropower station has 3 units, each with a capacity of 100 MW; the hybrid pumped storage power station has 4 reversible units, each with a capacity of 300 MW, sharing the same reservoir with the upstream hydropower station. Its pumping efficiency is 0.9, and its generation efficiency is

0.85. The maximum capacity of the upstream reservoir is 10,767 million cubic meters, and the downstream reservoir is 42.29 million cubic meters. The photovoltaic power station has a maximum output of 1000 MW, the wind power station has a maximum output of 192 MW, and both have a minimum output of 0.

To verify the effectiveness of the proposed cascade hydro-wind-solar-pumped storage optimal scheduling model, the Whale Migration Algorithm (WMA) is employed to solve the model. The whale population size is set to $N_{pop} = 200$, and the maximum number of iterations is 200. Given the data time resolution of 15 minutes, the scheduling period is divided into 96 intervals. The power balance diagram after system optimization is shown in Figure 3.

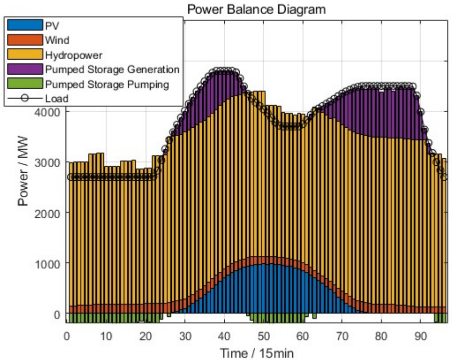

Figure 3 Power Balance Diagram

As shown in Figure 3, wind power maintains a high output level throughout the entire day, while photovoltaic power generation, constrained by sunlight conditions, primarily exhibits strong output during daytime hours. The time periods in the figure correspond to the following real-time intervals: Period 0-24 (night to early morning, 0:00-6:00): Wind power output is significant, hydropower serves as a stable base load, and the hybrid pumped storage power station operates mainly in pumping mode to store excess nighttime electricity. Period 24-48 (daytime, 6:00-12:00): Photovoltaic power output rapidly increases to its peak, wind power output declines, load demand rises to the daytime peak, and the hybrid pumped storage station switches to generation mode to compensate for the power gap. Period 48-72 (daytime, 12:00-18:00): Load demand slightly decreases, photovoltaic output gradually declines from its peak, and the hybrid pumped storage station transitions back to pumping mode. Period 72-96 (evening, 18:00-24:00): Photovoltaic output drops to zero, wind power output increases, load demand experiences a secondary peak, and hydropower combined with the hybrid pumped storage station collaboratively adjusts generation to meet the peak load requirements.

4. CONCLUSIONS

Hybrid pumped storage power stations can further enhance the system's peak shaving capacity and renewable energy integration capability beyond traditional hydro-wind-solar-pumped storage complementary operations, thereby improving the operational economy of hydro-wind-solar energy bases and reducing system operating costs. The Whale Migration Algorithm (WMA) is well-suited for solving this model, exhibiting fast convergence speed and strong optimization performance, making it applicable for addressing hydro-wind-solar-pumped storage complementary optimal scheduling problems.

ACKNOWLEDGEMENT

Science and technology projects of YALONG RIVER HYDROPOWER DEVELOPMENT COMPANY. LTD (000645-23ZB1422)

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