

STUDY ON SCHEDULING STRATEGIES BASED ON MULTI-RISK TRADE-OFF IN HYDROPOWER-WIND-SOLAR-STORAGE MULTI-ENERGY SYSTEM OPERATION

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Abstract

With the integration of high proportions of renewable energy in China, multi-energy complementary systems combining hydropower, wind power, solar power, and battery storage have become a critical approach to enhancing renewable energy integration capabilities and system operational stability. However, system operation faces coordinated challenges involving power curtailment, frequent start-stop cycles of hydroelectric units, operation within vibration zones, and battery storage capacity degradation. To address these issues, this paper establishes an optimal operation model for multi-risk balanced management in hydropower-wind-solar-storage systems and proposes a multi-objective weighting methodology based on the Analytic Hierarchy Process (AHP). By configuring various weight combinations, multiple operational strategies (S1 – S4) are developed. Under unified operational scenarios and constraints, a comparative analysis of these strategies systematically evaluates their impacts on system performance, hydroelectric unit behaviour, and battery storage degradation trajectories. Results demonstrate that multi-risk equilibrium strategies outperform single-objective approaches by reducing hydroelectric unit operating frequencies within vibration zones while effectively controlling battery storage degradation rates. In a typical case study, the equilibrium strategy significantly mitigates high-risk operational behaviours of units, suppresses battery storage degradation rates, and achieves a superior balance between economic efficiency and operational safety.

1 Introduction

In multi-energy complementary power generation systems, significant conflicts and trade-off relationships often exist among different operational risks. For example, improving renewable energy utilization generally requires enhanced system regulation capability; however, frequent power adjustments may increase the operational risk of hydropower units, while intensive operation of battery storage systems can further accelerate capacity degradation. Therefore, achieving a reasonable balance among renewable energy accommodation, equipment operational safety, and battery storage lifetime has become a critical issue in the optimal dispatch and operation of multi-energy complementary systems.

To address this issue, extensive research has been conducted both domestically and internationally. Yi et al.[1] proposed a risk-averse day-ahead scheduling model with constraints on curtailed power, shortages, and transmission stability,

focusing on balancing system revenue and operational risks. Fan et al.[2] incorporated generation and load uncertainties into a stochastic multi-objective framework, targeting net profit and residual load fluctuations, showing that both supply and demand uncertainties significantly affect optimal dispatch. Li et al.[3] quantified partial-load risks of hydropower units and developed a three-stage scheduling model based on “risk identification–assessment–control,” considering generation, grid, and wide-load operation risks. Xiong et al.[4] integrated hydropower vibration-avoidance strategies into the hydro–wind–solar optimization model, improving renewable utilization while ensuring unit safety and controlling equipment risks.

Tan et al.[5] proposed an optimal scheduling model for a hydro–wind–solar–storage multi-energy complementary system, considering coordinated operation of battery storage and combined heat and power systems, with the objective of minimizing operational cost and risk. Results show that multi-energy coordinated scheduling effectively mitigates

wind and solar fluctuations and enhances system stability. Zhao et al.[6] developed a short-term scheduling model for hydro–wind–solar systems, minimizing net load peak–valley difference while modelling wind and solar uncertainties through scenario generation and clustering; results indicate that hydropower regulation significantly improves renewable energy accommodation. Guo et al.[7] compared day-ahead scheduling of hydro–wind–solar and hydro–wind–solar–storage systems, quantifying the benefits of battery integration on complementarity, operational risk, peak shaving, and hydropower efficiency, showing that 10% storage capacity can improve system performance by 23.09%. Wang et al.[8] designed a short-term hydro–solar scheduling model balancing reliability and economy, highlighting trade-offs between profit and safety. Zhu et al.[9] proposed a risk-oriented SMAA-FOS model for large-scale hydro–solar systems to support robust long-term complementary operation. Feng et al.[10] addressed hydropower–solar joint peak regulation under PV forecast errors, reducing grid fluctuation via scenario-based optimization. Zhu et al.[11] applied stochastic programming to simultaneously handle wind–solar output and load uncertainties, enhancing peak shaving and scheduling robustness.

The above studies focus on the coordinated operation of multi-energy complementary systems. By employing multi-objective optimization, stochastic optimization, and risk-constrained approaches, they comprehensively consider renewable generation uncertainties, hydropower operational constraints, and battery storage regulation capabilities to achieve a coordinated optimization of system economy and security. Introducing risk assessment and coordinated scheduling mechanisms can effectively enhance system stability and renewable energy accommodation; however, the coupling relationships among different types of operational risks and the sensitivity of key parameters still require further investigation.

2. Methodology

2.1 Composition of Multiple Risks and Conflict Characteristics

As shown in Figure 1, the analysis begins with the entire system operation process, examining the coupling relationships and evolution characteristics among system power supply risks, hydropower unit operational risks, and battery storage capacity degradation risks. Based on this, a multi-objective optimization framework for coordinated multi-risk control is established. By integrating objectives such as system power supply reliability, hydropower unit operational safety, and sustainable use of battery storage into a unified optimization model, and considering different operational requirements and preferences, multiple trade-off coordination strategies are designed. By adjusting objective weights or constraint boundaries, various operating modes—such as economy-prioritized, hydropower safety-prioritized, and comprehensively balanced—can be characterized to reflect the diverse decision-making orientations encountered in practical engineering.

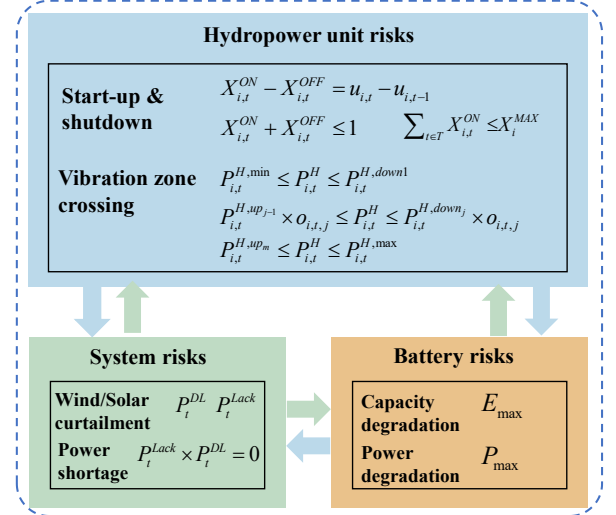


Fig. 1 Multidimensional risk interactions in the system

2.2 Construction of the Balanced Operation Strategy Model

To systematically characterize the operational characteristics under different objective priorities, a multi-objective operational trade-off mechanism is introduced. All trade-off strategies maintain consistency in system architecture, constraint conditions, and rolling optimization procedures. By modifying the objective function composition and its weight distribution, various operational strategies are developed and compared, enabling an analysis of risk evolution across the system, hydroelectric units, and electrochemical battery storage under varying operational objectives.

Multi-objective optimization operations typically employ a linear weighting method to transform multiple objective functions into a single objective function, with the weight coefficients of each objective function reflecting different operational preferences. By adjusting the weight combinations, operational schemes under various strategies can be derived, enabling the analysis of the system's operational characteristics under different objective orientations. The operational risks of multi-energy complementary systems can be categorized into system-level risks (e.g., power curtailment and power deficit), hydro power unit-level risks (e.g., crossing vibration zones and frequent start-stop cycles), and battery storage-level risks (e.g., frequent charging/discharging and capacity degradation). The multi-objective operational trade-off strategy focuses on the system's rolling optimization cycle, and the objective function of the system operation model can be expressed as:

$$\min J = \omega_1 J_{sys} + \omega_2 J_{hyd} + \omega_3 J_{bat} \quad (1)$$

$$\omega_1 + \omega_2 + \omega_3 = 1 \quad (2)$$

Where:

J_{sys} —Operational risk objectives at the system level;

J_{hyd} —Operational risk objectives for hydroelectric generating units;

J_{bat} —— Objectives related to the degradation of electrochemical battery storage capacity;

$\omega_1, \omega_2, \omega_3$ —— Corresponding weighting coefficients.

2.2.1 Objective function for operational risk at the multi-energy complementary system level: System-level operational risks are primarily quantified through curtailed power and power deficit. This objective aims to enhance overall system power supply reliability and the integration capacity of renewable energy. The objective function is defined as follows:

$$J_{sys} = \sum_{t \in T} (C_{cur} \cdot P_{cur}(t) + C_{loss} \cdot P_{loss}(t)) \quad (3)$$

Where:

$P_{cur}(t)$ —— Power curtailment at time slot t ;

$P_{loss}(t)$ —— Power deficit during time period t ;

C_{cur}, C_{loss} —— Corresponding to the penalty coefficient.

2.2.2 Risk objective function for hydroelectric power unit operation: The operational risks of hydroelectric units primarily manifest in unfavourable operating behaviours such as frequent start-stop cycles and crossing vibration zones. This study quantifies operational risks using the number of start-stop cycles and vibration zone crossings, with the objective function defined as:

$$J_{hyd} = \sum_{i \in H} \sum_{t \in T} (C_{su} \cdot u_i^{su}(t) + C_{sd} \cdot u_i^{sd}(t) + C_{vz} \cdot u_i^{vz}(t)) \quad (4)$$

Where:

$u_i^{su}(t), u_i^{sd}(t)$ —— The start/stop status variable of hydroelectric unit i during period t ;

$u_i^{vz}(t)$ —— The indicator variable for the unit crossing the vibration zone;

C_{su}, C_{sd}, C_{vz} —— Corresponding to the penalty coefficient.

2.2.3 Objective function related to battery storage capacity degradation: The degradation of electrochemical battery storage capacity is closely related to its charge-discharge behavior. To prevent rapid lifespan deterioration caused by excessive battery storage usage, an attenuation proxy objective function based on charge-discharge throughput has been introduced:

$$J_{bat} = \sum_{t \in T} C_{bat} \cdot |P_{bat}(t)| \quad (5)$$

where:

$P_{bat}(t)$ —— The charge/discharge power of electrochemical battery storage during period t ;

C_{bat} —— Battery degradation penalty coefficient.

2.3 Division of Operational Strategies Based on the Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method that decomposes complex decision-making problems into a multi-level structure for quantitative analysis. Its core principle involves organizing decision objectives, evaluation criteria, and alternative options into a hierarchical framework. By constructing pairwise comparison judgment matrices and applying scaling techniques to quantify the relative importance of each indicator, the method

calculates weight vectors for elements at each level. Subsequently, consistency checks are performed to validate the rationality of judgment results, enabling comprehensive evaluation and ranking under multi-factor and multi-objective conditions. AHP effectively addresses complex problems that are difficult to quantify directly and demonstrates strong applicability in multi-risk trade-offs and indicator weighting.

Within the multi-objective operational framework established by Equations (1)–(5), the AHP method is employed to adjust the weight coefficients of objective functions related to system-level operational risk, hydroelectric unit operational risk, and battery storage capacity degradation, thereby constructing operational modes with distinct objective priorities. This approach facilitates the analysis of different operational objective orientations. To analyse the operational characteristics of the hydro-wind-solar-storage multi-energy complementary system under different orientations, four typical operational strategies are defined, as detailed in Table 1:

2.3.1 System Economy-Oriented Strategy (S1): This strategy assigns no additional weight to hydropower unit operational risk or battery storage capacity degradation risk, focusing exclusively on the overall power supply capacity and renewable energy curtailment levels. The optimization objective is primarily composed of the system-level operational risk objective function:

$$\omega_1 > \omega_2 = \omega_3 \quad (6)$$

2.3.2 Hydropower Unit Safety-Oriented Strategy (S2): This mode emphasizes the operational safety of hydropower units. By increasing the weight of hydropower operational risk, it suppresses frequent unit start-stop cycles and crossings of the vibration zones:

$$\omega_2 > \omega_1 = \omega_3 \quad (7)$$

2.3.3 Battery storage Lifespan-Oriented Strategy (S3): This mode prioritizes the operational life of electrochemical battery storage. Based on the simulation results in Chapter 3, cycle degradation caused by frequent charging and discharging is the most significant factor affecting lifespan over a ten-year cycle. Consequently, this strategy imposes reasonable limits on battery storage throughput to inhibit frequent cycling.:

$$\omega_3 > \omega_1 = \omega_2 \quad (8)$$

2.3.4 Multi-risk Collaborative Balanced Mode (S4): To achieve a comprehensive coordination between system economy, equipment safety, and battery storage lifespan, a multi-risk collaborative balanced mode is introduced. This mode simultaneously accounts for system-level risk, hydropower unit risk, and battery storage degradation risk. To mitigate uncertainties inherent in subjective weighting, the AHP method is employed to determine the respective risk weights.

The weight determination process follows a two-step Analytic Hierarchy Process (AHP) approach. Initially, a hierarchical model is formulated with the minimization of integrated operational risk as the primary objective,

supported by a criterion layer comprising systemic, mechanical (hydropower), and electrochemical (storage) risks. Subsequently, a pairwise comparison matrix is generated using the Saaty 1-9 scale. The weight vector for these risk indicators is then extracted by calculating the principal eigenvalue and its associated eigenvector:

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} \\ 1/a_{12} & 1 & a_{23} \\ 1/a_{13} & 1/a_{23} & 1 \end{bmatrix} \quad (9)$$

$$\omega = [\omega_1, \omega_2, \omega_3] \quad (10)$$

$$\omega_i = \frac{\left(\prod_{j=1}^n a_{ij} \right)^{1/n}}{\sum_{i=1}^n \left(\prod_{j=1}^n a_{ij} \right)^{1/n}} \quad (11)$$

$$A\omega = \lambda_{\max} \omega \quad (12)$$

Where:

$\lambda_{\max}$ —the maximum eigenvalue of the judgment

matrix;

$a_{i,j}$ —the relative importance of objective i compared to objective j ;

ω_i —the weight of the i -th objective.

Finally, a consistency check is performed:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (13)$$

$$CR = \frac{CI}{RI} \quad (14)$$

Where:

CI —consistency index;

n —number of objectives;

CR —consistency ratio;

RI —random consistency index.

By constructing various weight combinations and operational scenarios, the trade-off relationships among the three operational objectives—system efficiency, equipment safety, and battery storage lifespan—are analysed for the multi-energy complementary system. The specific operational modes and their respective priorities are summarized as follows:

Table 1 Weight configuration for different scheduling strategies

Strategy	ω_1	ω_2	ω_3	Operational focus
S1	1	0	0	System economy
S2	0	1	0	Mechanical Reliability
S3	0	0	1	Battery Health
S4	0.11	0.63	0.26	Multi-objective equilibrium

3 Case Study

Table 2 presents the operational statistics under different strategies. The system consists of an 800 MW wind plant, a 1300 MW PV plant, and four hydropower units each with a capacity of 200 MW. Capacity of electrochemical energy storage system is set as 210 MW/420 MWh to satisfy local regulation. The output data of wind and photovoltaic power as well as load data are derived from the northwest region of China. In terms of total system power generation, strategy S2 achieves the highest value at 25,539.14 MW, followed by S1, while S3 and S4 are relatively lower. Regarding battery throughput, S1 and S2 recorded 2,181.38 MW and 2,202.32 MW, respectively, which are significantly higher than the approximately 1,188 MW observed for S3 and S4. This indicates more frequent regulation by the battery storage system (ESS) under the former two strategies.

Table 2 Comparison of system operational metrics under different scheduling strategies

	Total Generation (MW)	Battery Throughput (MW)	Power Deficit (MW)	Curtailed Energy (MW)
S1	25479.1973	2181.3750	37.3722	123.4822
S2	25539.1353	2202.3224	37.3722	123.4822
S3	25017.5018	1187.9614	37.3722	135.0080
S4	25017.5052	1187.9696	37.3722	135.0080

The power deficit remains constant at 37.37 MW across all four strategies, suggesting minimal differences in power supply reliability. For renewable energy integration, the curtailed energy in S1 and S2 (123.48 MW) is lower than that in S3 and S4 (135.01 MW), demonstrating that higher absorption levels are achieved when the regulation capacities of storage and hydropower units are fully utilized. Overall, S1 and S2 focus on enhancing economic efficiency and renewable energy consumption, whereas S3 and S4 balance storage lifespan and operational stability by reducing storage intensity.

As shown in Figure 2 and Figure 3, Strategy S1 has the highest operational stress, with 14 start-stops and 31 vibration zone crossings, indicating frequent hydropower adjustments to balance wind and solar fluctuations. Strategy S2 reduces fluctuations, lowering start-stops to 8 and crossings to 15, the lowest among all strategies, showing smoother output and improved safety. Under S3, start-stops remain at 8, but crossings increase to 25 due to limited battery storage regulation, requiring more hydropower adjustments. Strategy S4 achieves a balanced performance, with 8 start-stops and 17 crossings, effectively mitigating operational risks while meeting regulation demands.

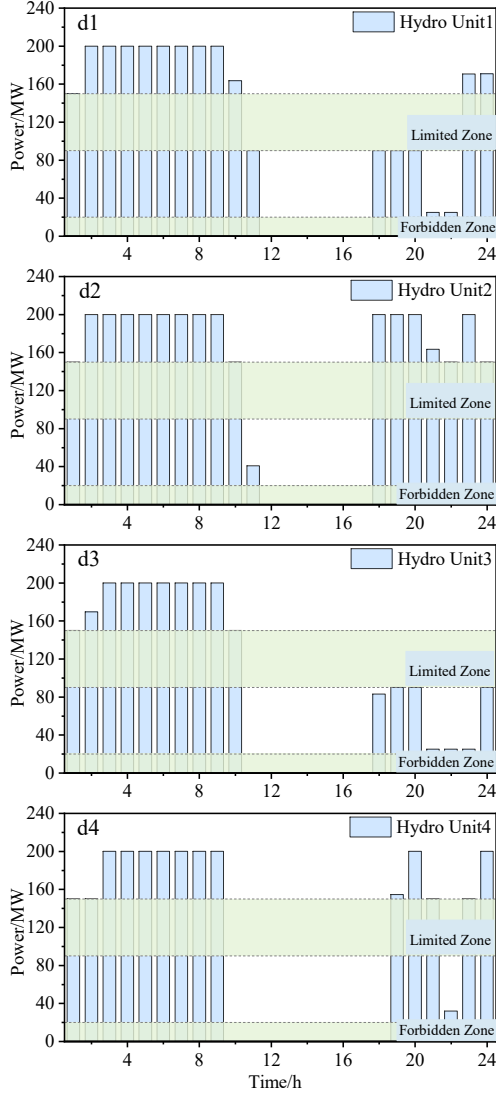


Fig. 2 Typical daily power allocation of the multi-energy complementary system under S4

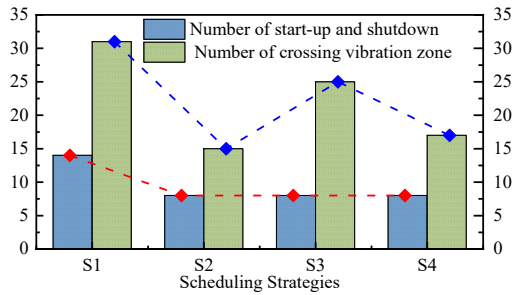


Fig. 3 Statistics of hydropower unit start-up and shutdown operations and vibration-zone crossings under different strategies

A statistical analysis of battery state of health (SOH) and system performance under different strategies is shown in Figure 4. Cycle degradation dominates battery life loss across all strategies, while calendar degradation remains minor. Under S1, cycle and calendar degradation account for 25.0% and 3.2%, with RUL at 71.8%; S2 further increases cycle degradation to 26.4%, reducing RUL to 70.4%, indicating the

greatest battery consumption. In contrast, S3 and S4 lower cycle degradation to about 20.8%, raising RUL to 74.2% and 74.4%, with S4 achieving the highest RUL. Slightly higher calendar degradation in S3 arises from longer high-SOC durations, which accelerate side reactions and aging. Overall, frequent regulation in S1 and S2 increases cycle aging, while S3 and S4 reduce operational intensity and better preserve battery life.

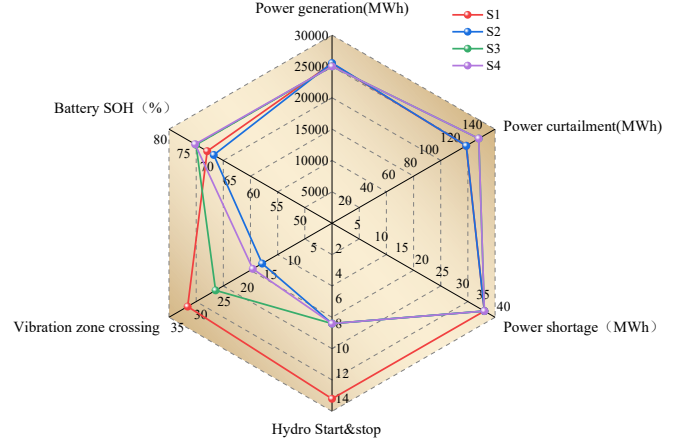


Fig. 4 Comparison of system performances under different scheduling strategies

4 Conclusion

This study develops a multi-objective trade-off operational model that considers system power supply risks, hydropower unit operational risks, and battery storage capacity degradation risks. By adjusting the weights of the objective function, four typical operational strategies are constructed: economy-prioritized, hydropower-safety-prioritized, storage-lifetime-prioritized, and multi-risk coordinated balance. The operational characteristics of these strategies are compared and analyzed at the system level, the hydropower unit level, and the electrochemical storage level. The main conclusions are as follows:

(1) Different strategies alter the division of regulation between hydropower units and battery storage, leading to distinct operational characteristics. Economy-prioritized mode increases total generation but raises unit risk; hydropower-safety-prioritized mode reduces vibration zone crossings and start-stop cycles; storage-lifetime-prioritized mode lowers battery cycling but reduces regulation capacity; multi-risk coordinated mode balances generation, unit safety, and storage life, with generation slightly below the economy-prioritized mode, significantly fewer vibration crossings, and moderate storage throughput.

(2) Increasing storage capacity enhances regulation capability, significantly reducing curtailed and unmet power while increasing total generation. However, storage throughput also rises, indicating greater participation. Insufficient capacity limits regulation, while excessive capacity may accelerate degradation, requiring a balance between system performance and storage lifespan.

(3) By adjusting objective weights, economy-prioritized, hydropower-safety-prioritized, storage-lifetime-prioritized, and multi-risk coordinated strategies can be constructed. Analysis at the system, unit, and storage levels reveals operational characteristics and risk distribution, providing guidance for multi-energy complementary system operation.

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6 References

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