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Comprehensive Evaluation of a Pumped Storage Operation Effect Considering Multidimensional Benefits of a New Power System

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Abstract: This paper focuses on the evaluation of the operational effect of a pumped storage plant in a new power system. An evaluation index system is established by selecting key indicators from the four benefit dimensions of system economy, low carbon, flexibility, and reliability. The evaluation criteria are based on the values of indexes for pumped storage plants that have already been put into operation. Using this method, the operational effect of pumped storage plants with different installed capacities, regulation durations, and conversion efficiencies are comprehensively evaluated and analyzed. The calculation results show that the operation effect of a pumped storage plant with high regulation performance and high comprehensive conversion efficiency is better, indicating that the established index system and evaluation method can comprehensively and truly reflect the positive benefits brought by a pumped storage plant to a new power system. This study can provide a practical reference for the early planning and decision making of pumped storage in a new power system.

Keywords: hydro-pumped storage technology; new energy-centric power system; operational benefit; assessment framework; holistic evaluation

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1. Introduction

With the new power system in wind power, photovoltaic power generation and other new energy accounting for a gradual increase in the volatility of new energy output caused by the abandonment of wind and light, other power limitation problems will become more serious [1], and typhoons, haze, and other extreme weather threats to the normal operation of the system will also be greater [2]. Hydrogen storage, pumped storage, compressed air, and other large capacity long-time energy storage technology to enhance the grid's acceptance of new energy and improve system resilience and reliability have an important role [3,4]. Among them, pumped storage is the most mature, economical, safe, and reliable energy storage technology, and it has the most favorable conditions for large-scale development. China plans to achieve a total installed capacity of pumped storage of around 120 gigawatts by 2030 [5]. However, due to the lack of a standard and unified evaluation system for the value and significance of pumped storage, the necessity and importance of building pumped storage power stations are often questioned. Under the planning requirement of the total capacity target, it is inevitable that a number of pumped storage power stations with insignificant contributions to carbon reduction targets and the construction of a new type of power system will emerge. It is necessary to study a set of pumped storage operation efficiency evaluation systems adapted to the new power system in order to guide the scientific and orderly investment and construction of pumped storage power stations.

Pumped hydro storage plays a versatile role in the power system, offering multiple operational benefits such as capacity substitution, coal consumption reduction, frequency regulation, and backup capabilities [6–8]. Pumped storage operation benefits were earlier divided into static and dynamic benefits for analysis; static benefits include the capacity benefits of replacing thermal power generation and energy conversion benefits generated by peak shaving and valley filling (or coal saving benefits), and dynamic benefits refer to the economic and reliability benefits generated by pumped storage to complete the system's dynamic tasks such as frequency regulation, phase regulation, accident standby, and load tracking [9]. In order to evaluate the performance and effectiveness of pumped storage power stations in a more systematic manner, current research efforts typically employ comprehensive evaluation methods to quantify their operational benefits. Liu et al. (2013) selected four evaluation indexes for evaluating the role of pumped storage power plants on the grid from two aspects of technology and economy and evaluated seven alternative pumped storage power plant access schemes to give the ranking of planning schemes [10]. Zhang and Cai (2014) conducted a comprehensive evaluation and analysis of each pumped storage capacity alternative through the thermal power capacity substitution coefficient, system coal consumption and coal saving, peaking capacity ratio, power shortage probability, and other indicators [11]. The indicators selected in references [10,11] are not comprehensive enough, focusing only on the impact of pumped storage on thermal power operation coal consumption and load peak-to-valley difference without considering the impact on new energy consumption. VO et al. (2017) explored the cost, efficiency, location flexibility, storage capacity/discharge time, energy carrier vectors, and environmental issues of pumped hydro energy storage (PHES) in terms of single-criteria and group multi-criteria analyses [3]. Silva (2024) developed a spatial probabilistic decision-making methodology to identify and rank the best PHES sites from the number of shortlisted sites identified by a previous technical environmental assessment, taking into account socio-economic factors [12]. References [3,12] lack detailed system operation simulations, making it impossible to accurately quantify the impact of pumped hydro storage on system operation.

Most of the indicators in the above studies apply only to the traditional power system dominated by thermal power and cannot reflect the benefits of pumped storage in serving the construction of a new type of power system. With the transformation of the energy structure, studies have proposed pumped storage to promote new energy consumption and reduce carbon emissions, as well as promote other benefit indicators. Ni et al. (2023) constructed an electricity power balance model considering the overall carbon emissions of the system and quantified the role of pumped storage in promoting new energy consumption in typical provincial power grids through an 8760 h time series production simulation [13]. Yagi and Takeuchi (2023) proposed an assessment method for pumped storage (PHS) systems to mitigate the intermittency of solar power generation [14]. References [13,14] only quantified the role of pumped storage as an energy storage system to reduce wind and light abandonment, without further analyzing the low-carbon economic performance of pumped storage. Li et al. (2023) proposed an operation model of priority regulation of pumped storage for a Wind–Photovoltaic (PV) Hydrothermal-Pumped storage hybrid energy system (HES WPHTP), and the annual simulation results show that compared with the operation mode of priority regulation of the general hydropower plant, both the annual average operating cost and carbon emission of the HES WPHTP are reduced by 0.84% and 0.70% [15]. Huang et al. (2023) scheduled pumped hydroelectric storage in the virtual power plant (VPP) for energy management to tackle uncertainties from PV outputs, which can effectively reduce system operating costs and regional carbon emissions in a distributed market framework [16]. References [15,16] analyzed the low-carbon economic performance (of pumped storage but did not consider the impact on the safe and stable operation of the system, which cannot fully reflect the value of pumped storage.

On the basis of the above indicators, relevant studies have further carried out a comprehensive evaluation of the operational benefits of pumped storage in a new type of power system. Xiao et al. (2014) constructed a comprehensive benefit evaluation model for the wind power-pumped storage joint system by considering the benefits of electricity generated by reducing wind abandonment, the benefits of tariff difference earned by "low storage and high generation", the benefits of in-depth peaking/starting and stopping peaking, and other indicators [17]. Xiao et al. analyzed the economic benefits of pumped storage from the point of view of the power station operator and did not reflect on the impact on the power system as a whole. Wang et al. (2022) established a comprehensive evaluation system for pumped storage power stations by taking into account three aspects, namely, peak shifting effectiveness, energy storage effectiveness, and dual-carbon effectiveness [18]. Wang et al. evaluated the effectiveness of peak shifting and energy storage based on the operation of the pumped storage plant itself, which did not visually show the impact on the system operation cost and reliable power supply capability. Peng et al. (2023) comprehensively quantified the value of pumped storage in the new system from the perspectives of reducing system asset investment, reducing power generation operating costs, improving flexible regulation capability, improving system resilience, reducing power outage losses, promoting renewable energy consumption, and emissions reduction [19]. But, the level of the evaluation system is too singular, the method of quantifying the benefits in terms of monetization is prone to neglecting the potential benefits of pumped storage, and the quantification results are easily affected by the selection of relevant economic indicators.

In this paper, a new power system operation simulation method proposed in reference [19] was adopted to compare the operation of the system with and without pumped storage. It also referred to the quantitative methods in references [17,18] for pumped storage energy to promote new energy consumption and reduce CO_2 emissions and constructed the operation evaluation indexes of pumped storage energy in the dimension of low carbon. Based on the method of quantifying the value of asset investment saved by pumped storage energy proposed in reference [19], the calculation method of the indicator of "replacing thermal power capacity" was proposed, and together with the indicator of "saving on power generation cost", the operation evaluation indexes in the dimension of the economy were constructed. Based on the value quantification method of pumped storage to improve flexible regulation capacity proposed in reference [19], the calculation methods of the "available frequency regulation capacity" and "available reactive energy" indicators were proposed to form the evaluation indicators of the flexibility dimension. Based on the value quantification method of pumped storage for improving system resilience and reducing the power outage losses proposed in reference [19], the "available rotational inertia" and "expected energy storage capacity" were proposed, forming the evaluation indicators of the reliability dimension. On the basis of the above research, this paper established a comprehensive evaluation index system of pumped storage operation effect by selecting key operation indexes based on the four benefit dimensions of economy, low carbon, flexibility, and reliability, which need to be considered for the operation of a new power system. Individual indicators were scored based on the actual performance of the commissioned and soon-to-be-commissioned pumped storage power stations. Compared with references [17,18], the indicator system proposed in this paper is more comprehensive and can reflect the operational benefits of pumped storage from the overall system level. Compared with reference [19], the classification of the index system proposed in this paper is more compatible with the construction and operation objectives of China's new power system. Finally, the Analytic Hierarchy Process (AHP) introduced in reference [20,21] was utilized to conduct pairwise comparisons of the importance of indicators at each level, resulting in the derivation of weights for each indicator and the achievement of a comprehensive evaluation. It can make an effective horizontal comparison of the operation effect of pumped storage power stations with different technical parameters, with a view to providing a reference for the reasonable selection and planning of pumped storage power stations and promoting the high-quality development of the industry.

2. Evaluation Index System Based on Multidimensional Benefits

As new energy gradually replaces conventional thermal power, the rotational inertia of the system and the flexible adjustment ability are reduced; the new power system puts forward new requirements for emergency support, new energy consumption, and balance adjustment, and the operation and control of pumped storage involves diversified objectives. Based on the principle of system value assessment [22], combined with the three core connotations of low carbon, security, and high efficiency of the new power system [23], four benefit dimensions of economy, low carbon, flexibility, and reliability are delineated to analyze the operational effects of the superimposed multiple roles of pumped storage.

(1) Economy mainly reflects the connotation of “high efficiency” of the new power system, which can be summarized as reducing the cost of power supply under the condition of meeting the safety, stability, and quality of power supply. Considering both fixed investment costs and daily operation costs, two indicators of economic operation effect are proposed, namely, “replacing thermal power capacity” and “saving on power generation costs”.

(2) Low carbon mainly reflects the important characteristics of a new type of power system that is “clean and low-carbon”, including the development of clean energy power and the reduction in coal consumption and carbon emissions in thermal power operation. Burning fossil fuels for power supply is the source of the low-carbon power system. Based on this fact, this paper put forward the “enhancement of new energy power” and “reduce carbon emissions” as two low-carbon operation effect indicators.

(3) Flexibility mainly reflects the important feature of the “flexible and nimble” new power system, which is able to maintain real-time supply and demand balance in the face of random source and load disturbances and ensure sufficient power supply. Power dispatching agencies mainly increase or decrease system active or reactive power to stabilize frequency and voltage and improve power quality. Based on this fact, this paper put forward the “available frequency regulation capacity” and “available reactive energy” as two flexibility operation effect indicators.

(4) Reliability mainly reflects the connotation of “security” of the new power system, which can withstand planned and unplanned shutdowns of components, as well as sudden disturbances, and uninterruptedly provide power and electricity to users in accordance with acceptable standards and required quantities. The inertia support can improve the ability of the system to cope with disturbances, and the long-time power generation can ensure the pumping and storage power supply after an accident; thus, the two reliability operation effect indicators of “available rotational inertia” and “expected energy storage capacity” are proposed.

Summarizing the results of the above dimension division and index selection, a set of comprehensive evaluation index systems of the pumped storage operation effect in the new power system is constructed, as shown in Figure 1.

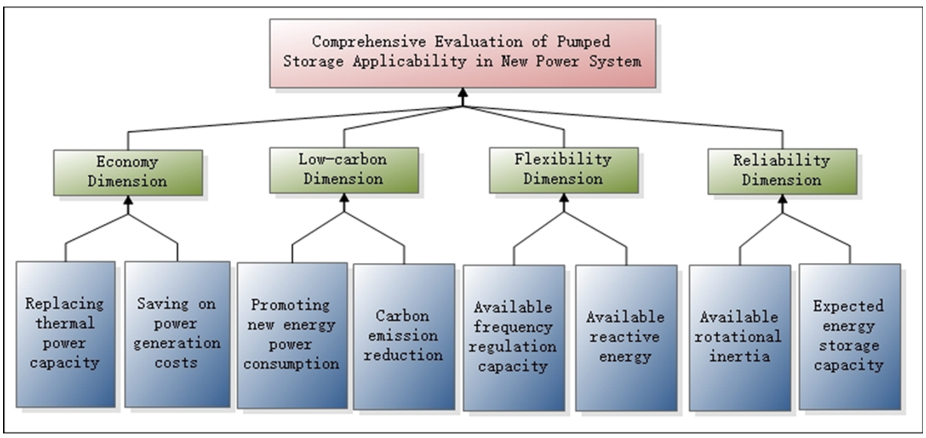

Figure 1. A comprehensive evaluation index system for the operational effect of pumped storage in the new power system.

3. Quantification Method of the Operation Effect Evaluation Index

Based on the principle of equivalent value substitution, the new power system operation simulation method proposed in reference [19] is adopted to compare the system operation when there are "with" and "without" pumped storage power stations in the system, and the annual evaluation cycle (a year is regarded as 365 days) is used to put forward the quantification method of evaluation indexes for each dimension. The evaluation cycle is yearly, and the quantification method of each dimension evaluation index is proposed.

3.1. Economy Dimension Indicators

(1) Replacing thermal power capacity. By comparing the operating capacity of thermal power units in the system with and without pumped storage, the peak shifting capacity C_{11} (MW) that can be replaced by pumped storage is quantified.

$$C_{11} = \frac{\sum_{d=1}^{365}\left(V_{0,d}^{\mathrm{op}} - V_{1,d}^{\mathrm{op}}\right)}{365} \tag{1}$$

$$V_{s,d}^{\mathrm{op}} = \max_{t} \sum_{g=1}^{\mathrm{N_G}}\left(S_{g,d,t,s}^{\mathrm{G}} P_{g,s}^{\mathrm{G,max}}\right) \tag{2}$$

where s refers to the scenario type, s = 0 denotes the operation scenario when the system has no pumped storage, and s = 1 denotes the operation scenario when the system has pumped storage; $V_{s,d}^{\mathrm{op}}$ denotes thermal power operation capacity of the power system in scenario s on day d, MW; $\mathrm{N_G}$ denotes the set of thermal power units in the system; $S_{g,d,t,s}^{\mathrm{G}}$ denotes the start–stop status of thermal power unit g in scenario s at time period t on day d, $S_{g,d,t,s}^{\mathrm{G}}$ = 1 denotes on operation, and $S_{g,d,t,s}^{\mathrm{G}}$ = 0 denotes off; and $P_{g,s}^{\mathrm{G,max}}$ denotes the installed capacity of thermal power unit g, MW.

(2) Saving on power generation costs. Quantify the savings on power generation costs C_{12} (CNY million) by comparing the operating costs of thermal units with and without pumped storage, including start-up costs and variable costs.

$$C_{12} = \sum_{d=1}^{d=365} \sum_{t=1}^{t=24}\left(Q_{d,t,0}^{\mathrm{tce}} - Q_{d,t,1}^{\mathrm{tce}}\right) \tag{3}$$

$$Q_{d,t,s}^{\mathrm{tce}} = \sum_{g=1}^{\mathrm{N_G}}\left[c_g^{\mathrm{S}} S_{g,d,t,s}^{\mathrm{G}}\left(1 - S_{g,d,t-1,s}^{\mathrm{G}}\right) + c_g^{\mathrm{P}}\left(P_{g,d,t,s}^{\mathrm{G}}\right) P_{g,d,t,s}^{\mathrm{G}}\right] \tag{4}$$

where $Q_{d,t,s}^{\mathrm{tce}}$ refers to the total system operating coal consumption at time period t on day d in scenario s, t; $P_{g,d,t,s}^{\mathrm{G}}$ denotes the active output of thermal unit g at time period t on day d in scenario s, MW; c_g^{S} denotes the single start-up cost of thermal unit g, CNY million; and $c_g^{\mathrm{P}}\left(P_{g,d,t,s}^{\mathrm{G}}\right)$ denotes the unit generation cost of thermal unit g, CNY million/MWh as a function of the unit's active output.

3.2. Low-Carbon Dimension Indicators

(1) Promoting new energy power consumption. Quantify the amount of new energy power C_{21} (MWh) that can be boosted by pumped storage by comparing the amount of wind power and PV power generated in the system with and without the pumped storage plant.

$$C_{21} = \sum_{d=1}^{d=365} \sum_{t=1}^{t=24}\left(Q_{d,t,1}^{\mathrm{vre}} - Q_{d,t,0}^{\mathrm{vre}}\right) \tag{5}$$

$$Q^{\mathrm{vre}}_{d,t,s} = \sum_{w=1}^{\mathrm{N_w}} P^{\mathrm{W}}_{w,d,t,s} + \sum_{p=1}^{\mathrm{N_P}} P^{\mathrm{P}}_{p,d,t,s} \quad (6)$$

where $Q^{\mathrm{vre}}_{d,t,s}$ refers to the wind and solar renewable energy generation in scenario s at time period t on day d, MWh; $\mathrm{N_w}$ denotes wind farm pool in the system; $\mathrm{N_P}$ denotes photovoltaic power plant pool in the system; $P^{\mathrm{W}}_{w,d,t,s}$ denotes the actual output of wind farm w in scenario s at time period d day t, MW; and $P^{\mathrm{P}}_{p,d,t,s}$ denotes the actual output of photovoltaic power plant p in scenario s at time period d day t, MW.

(2) Carbon emission reduction. Quantify the reduction in carbon emissions from pumped storage C_{22} (tCO_2) by comparing the carbon dioxide produced by the system's power generation fuel consumption with and without pumped storage.

$$C_{22} = \sum_{d=1}^{d=365} \sum_{t=1}^{t=24} \left(Q^{\mathrm{co2}}_{d,t,1} - Q^{\mathrm{co2}}_{d,t,0} \right) \quad (7)$$

$$Q^{\mathrm{co2}}_{d,t,s} = \sum_{g=1}^{\mathrm{N_G}} \left[\alpha^{\mathrm{S}}_{g} U^{\mathrm{G}}_{g,d,t,s} \left(1 - U^{\mathrm{G}}_{g,t-1,s} \right) + \alpha^{\mathrm{G}}_{g} \left(P^{\mathrm{G}}_{g,d,t,s} \right) P^{\mathrm{G}}_{g,d,t,s} \right] \quad (8)$$

where $Q^{\mathrm{co2}}_{d,t,s}$ refers to the system CO_2 emissions for time period t on day d in scenario s, t; α^{S}_{g} denotes single start-up CO_2 emissions for thermal unit g, t; and $\alpha^{\mathrm{G}}_{g}\left(P^{\mathrm{G}}_{g,d,t,s}\right)$ denotes thermal unit g's CO_2 emission factor, t/MWh, which is a function related to the active output of the unit.

3.3. Flexibility Dimension Indicators

(1) Available frequency regulation capacity. Quantify the available frequency regulation capacity C_{31} (MWh) of the pumped storage power plant to be evaluated according to its operation in the new power system.

$$Q^{\mathrm{co2}}_{d,t,s} = \sum_{g=1}^{\mathrm{N_G}} \left[\alpha^{\mathrm{S}}_{g} U^{\mathrm{G}}_{g,d,t,s} \left(1 - U^{\mathrm{G}}_{g,t-1,s} \right) + \alpha^{\mathrm{G}}_{g} \left(P^{\mathrm{G}}_{g,d,t,s} \right) P^{\mathrm{G}}_{g,d,t,s} \right] \quad (9)$$

where $\mathrm{n_g}$ refers to the set of units of the pumped storage plant to be evaluated and $P^{\max}_{i,d,t}$ and $P^{\min}_{i,d,t}$ denote the upper and lower limits of the active output/load of pumped storage unit i at time period t on day d, MW.

(2) Available reactive energy. The pumped storage generator only delivers inductive reactive energy to the grid in the phase-regulating condition of power generation, and the amount of reactive energy that can be supplied by pumped storage is quantified according to the operation of the pumped storage power station to be evaluated in the new type of power system C_{32}(MVArh).

$$C_{32} = \sum_{d=1}^{d=365} \sum_{t \epsilon t_p} P^{\max} \quad (10)$$

where t_p refers to the time period during which the pumped storage power station can be converted to the power generation phasing condition, according to the pumped storage condition conversion diagram [24], and the time period in power generation condition is selected, and $P^{\max}$ denotes the installed capacity of the pumped storage power station to be evaluated, MW.

3.4. Reliability Dimension Indicators

(1) Available rotational inertia. Kinetic energy is one of the commonly used metrics to describe the level of system inertia, which mainly depends on the inertia constant and rated capacity of the unit [25]. The available rotational inertia C_{41} (MWs) for pumped

storage is quantified based on the average kinetic energy of the pumped storage unit during operation.

$$C_{41} = \frac{\sum_{d=1}^{d=365}\sum_{t=1}^{t=24}\sum_{i=1}^{n_g} H_i S_i u_{i,d,t}}{8760} \quad (11)$$

where H_i refers to the inertia constant of the pumping and storage unit i, s; S_i denotes the rated capacity of the pumping and storage unit i, MW; and $u_{i,d,t}$ denotes the start–stop state of the pumping and storage unit i at the time period t on day d (1 means running, 0 means out of operation).

(2) Expected energy storage capacity. According to the operation of the pumped storage power station to be evaluated in the new type of power system, quantify the expected energy storage capacity of pumped storage C_{42} (MWh).

$$C_{42} = \frac{\sum_{d=1}^{d=365}\sum_{t=1}^{t=24} E_{d,t}^{SOC}}{365} \quad (12)$$

where $E_{d,t}^{SOC}$ refers to the energy storage capacity of the pumped storage plant at time period t on day d, MWh.

4. Comprehensive Evaluation Methodology for Pumped Storage Operational Benefit

Comprehensive evaluation of the pumped storage operation effect refers to the use of multiple indicators to evaluate the operation effect of various aspects of a pumped storage power station, which can transform into a comprehensive indicator that can reflect the good or bad operation effect. There are several common comprehensive evaluation methods, such as principal component analysis, hierarchical analysis, the fuzzy comprehensive evaluation method, the TOPSIS method, the neural network evaluation method, etc. [20]. Combined with the needs of the problem, this paper constructs the pumped storage operation effect comprehensive evaluation method specific process shown in Figure 2.

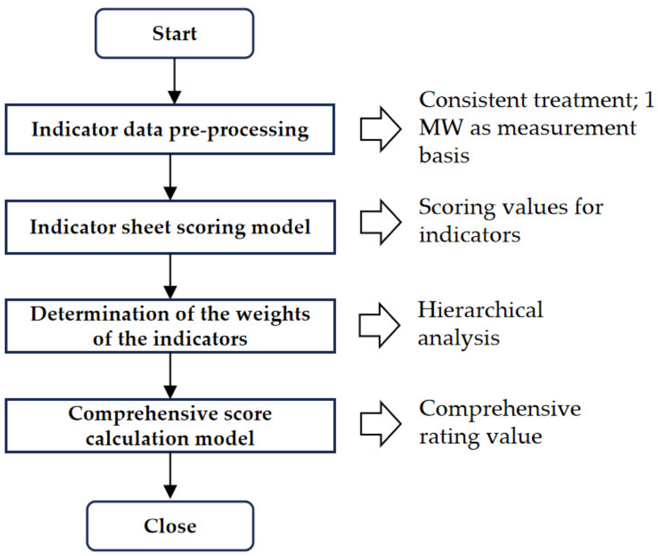

Figure 2. Comprehensive evaluation process of the pumped storage operation effect.

(1) Indicator data pre-processing. The operation effect indicators selected in this paper are positive indicators, i.e., the larger the value of the indicators, the better, without the need for consistent processing. In order to eliminate the influence of the installed scale of the pumping and storage power station on the indicator data, the installed capacity is selected as the measurement benchmark of the indicators, and each indicator after processing represents the operating effect brought by 1MW of pumping installed capacity.

(2) Indicator single scoring. This paper adopts the percentage system to score each indicator and transforms the value of each indicator into a unified evaluation scale system to eliminate the differences in the scale and order of magnitude between indicators [26]. Currently, there are more pumped storage power stations in operation and under construction, with a certain sample size. Considering that the index scores of pumped storage power stations in operation and under construction are at least 60 and at most 90, the evaluation indexes of commissioned and quasi-commissioned power stations are taken as the benchmark, and the values of the indexes are transformed into the interval [60, 90] through intervalization. If the actual value of indicator i of the pumped storage power station to be evaluated is x_i, then the scoring result of indicator S_i is calculated as follows.

$$\mathrm{X}_{i,\max} = \mathrm{a}_{i,\max} + \frac{\mathrm{a}_{i,\max} - \mathrm{a}_{i,\min}}{3} \tag{13}$$

$$\mathrm{X}_{i,\min} = \mathrm{a}_{i,\min} - 6 \times \frac{\mathrm{a}_{i,\max} - \mathrm{a}_{i,\min}}{3} \tag{14}$$

$$S_i = \frac{x_i - \mathrm{X}_{i,\min}}{\mathrm{X}_{i,\max} - \mathrm{X}_{i,\min}} \times 100 \tag{15}$$

where $\mathrm{a}_{i,\max}$ and $\mathrm{a}_{i,\min}$ refer to the maximum and minimum values of indicator i for pumped storage power stations already in operation and $\mathrm{X}_{i,\max}$ and $\mathrm{X}_{i,\min}$ are, respectively, the values when the score of indicator i is 100 and 0.

(3) Determine the weight of each indicator. A comprehensive evaluation of the pumped storage operation effect involves more indicators and has a certain hierarchical nature. This paper adopts the hierarchical analysis method [21] to determine the weight size of each indicator. The evaluation index includes three layers of structure: the target layer, the criterion layer, and the indicator layer. The target layer is a "comprehensive evaluation of pumped storage operation effect in new power systems". The target layer is divided into four criteria indicators, corresponding to the "economy dimension indicator", the "low-carbon dimension indicator", the "flexibility dimension indicator", and the "reliability dimension indicator"; furthermore, the four criteria layers are split into eight factor layer indicators, as shown in Table 1.

Table 1. Comprehensive evaluation index table of the pumped storage operation effect in new power systems.

Target Layer A	Guideline Layer B	Factor Layer C
Comprehensive evaluation of the operational effect of pumped storage	Economy dimension benefits B_1	Replacing thermal power capacity C_{11}
		Saving on power generation costs C_{12}
	Low-carbon dimension benefits B_2	Promoting new energy power consumption C_{21}
		Carbon emissions reduction C_{22}
	Flexibility dimension benefits B_3	Available frequency regulation capacity C_{31}
		Available reactive energy C_{32}
	Reliability dimension benefits B_4	Available rotational inertia C_{41}
		Expected energy storage capacity C_{42}

The specific implementation process is shown in Figure 3. First of all, the indicators in each level of the pairwise comparison are important, according to the nine-level scaling method [27], which is used to construct a judgment matrix. Second, the the root-of-eigen method is used to determine the hierarchical order of the indicators, that is, the indicators of a level of the previous level of the relative importance of a certain indicator of the weights, which is later referred to as the "single weight". A consistency test is used to ensure that the judgment matrix is logically reasonable. Finally, the total hierarchical ranking of each indicator is calculated from top to bottom, i.e., the weights of all the indicators at a certain level for the importance of the target level, which is later referred to as the "comprehensive weight", and a consistency test is carried out. The combined weight of each criterion level indicator is equal to its individual weight. The combined weights of the indicators at the factor level are calculated as follows.

$$w_{ij} = w_i^A w_j^{B_i} \tag{16}$$

where w_{ij} refers to the composite weight of indicator C_{ij}. w_i^A denotes the single weight of indicator B_i, which is also its composite weight. $w_j^{B_i}$ denotes the single weight of indicator C_{ij}.

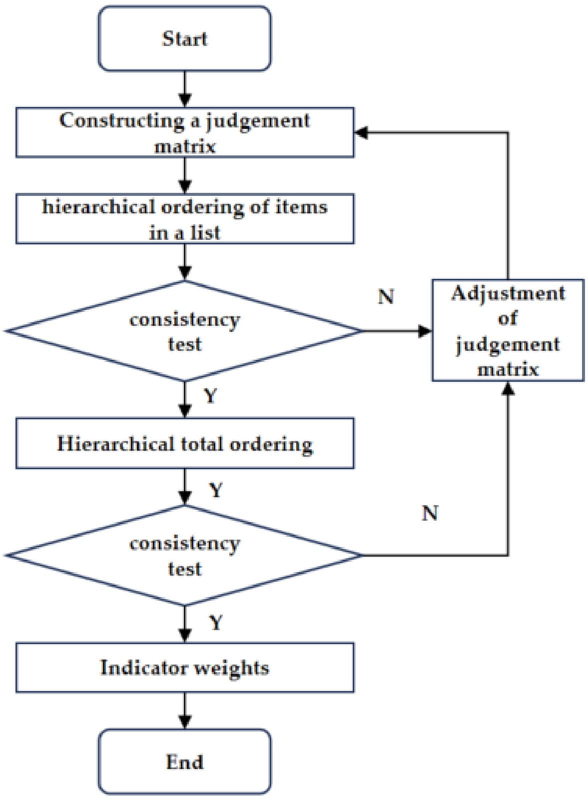

Figure 3. Evaluation index of the weight determination process.

(4) Calculate the comprehensive score value. Based on the scoring results and weighting values of each index of the pumped storage power station to be evaluated, calculate the comprehensive score of its operating effect in the new type of power system C.

$$C = \sum_{i=1}^{N} w_i S_i \tag{17}$$

where w_i refers to the composite weight of indicator i and S_i is the scoring result of indicator i.

5. Case Analysis

In this paper, Province A, which has a large number of pumped storage power stations, is selected as the example system, and the year 2030, the target year for peaking carbon emissions, is chosen as the evaluation year. Province A is a typical thermal power-dominated power system, and according to the new type of power system plan, by 2030, the proportion of coal-fired and gas-fired thermal power installations will be reduced to about 50%, down from about 70% in 2020, the proportion of new energy will be increased to about 30%, up from about 10% in 2020 and down to about 50%, and the share of new energy will increase from about 10% in 2020 to about 30%. In order to provide a reference for the future planning and selection of pumped storage power plants, the installed capacity, regulation duration, conversion efficiency, number of variable speed units, and new energy proportion of the power grid are selected as sensitive parameters, and an arithmetic analysis is carried out for the comprehensive evaluation of the operation effect of pumped storage power plants with different parameters in the new type of power system.

(1) Obtaining evaluation index data

In this paper, three dimensions of installed capacity, regulation duration, and conversion efficiency are selected to compare the operation effect of pumped storage power stations with different technical parameters in the new power system. An actual pumped storage power plant in Province A is used as the benchmark power plant, with an installed capacity of 1200 MW, a regulation duration of 10 h, and a conversion efficiency of 80%. Another six comparison power plants are set up and the parameter situation of the three dimensions of each power plant is shown in Figure 4, and other technical parameters are the same as those of the benchmark power plant.

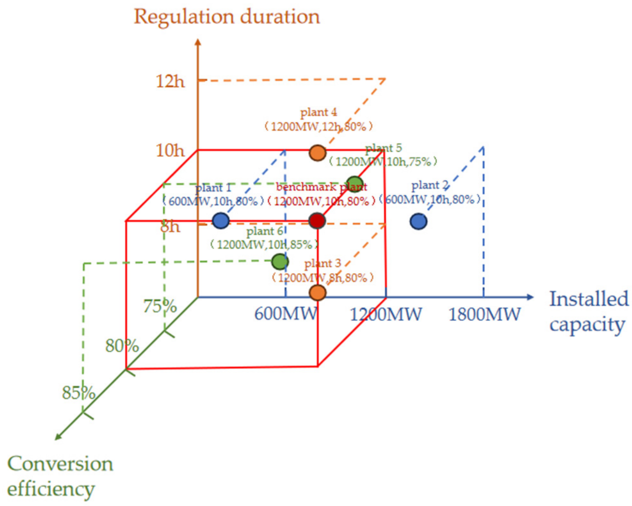

Figure 4. Parameters of pumped storage plants to be evaluated.

Substitute the above pumped storage power stations into the new power system in Province A in 2030, carry out the system operation simulation of "with" and "without" pumped storage scenarios, calculate the operation index data of each pumped storage power station in different dimensions according to Section 2 of this paper, and pre-process the data according to the installed capacity. Pre-processing is carried out, and the data of each index are shown in Table 2.

Table 2. Operation effect index data of pumped storage plants to be evaluated.

Index Name	Benchmark Plant	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6
Replacing thermal power capacity/MW	0.76	1.00	0.97	0.90	1.00	0.76	1.00
Saving on power generation costs/CNY million	1.06	1.08	1.01	1.00	1.11	1.01	1.11
Promoting new energy power consumption /MWh	470	490	502	394	536	472	455
Carbon emission reduction/t	3313	3359	3189	3138	3487	3217	3454
Available frequency regulation capacity/MWh	1274	1506	1331	1264	1405	1266	1413
Available reactive energy/MVArh	2547	2510	2661	2527	2809	2531	2825
Available rotational inertia/MWs	3.12	2.45	3.41	2.96	3.38	3.09	3.39
Expected energy storage capacity/MWh	7.91	7.80	7.76	6.20	9.38	7.94	7.66

(2) Indicator scoring results. Based on the construction of a new type of power system in Province A in 2030, for the pumped storage power stations in operation and under construction, the system operation simulation of "with" and "without" pumped storage scenarios will be carried out, respectively, and the actual distribution of each indicator of the commissioned and quasi-commissioned pumped storage power stations will be calculated. The actual distribution of each index of the commissioned and quasi-commissioned pumped storage power stations is calculated, and then the single scoring results of each index to be evaluated are obtained according to Equations (13) and (14), as shown in Figure 5. Only the two indicators of "available rotational inertia" and "available reactive energy" will increase with the increase in installed capacity; except for the indicator of "replacing thermal power capacity", all other indicators can increase with the increase in regulation duration. Except for the indicators of "promoting new energy power consumption" and "expected energy storage capacity", all other indicators can increase with the increase in conversion efficiency.

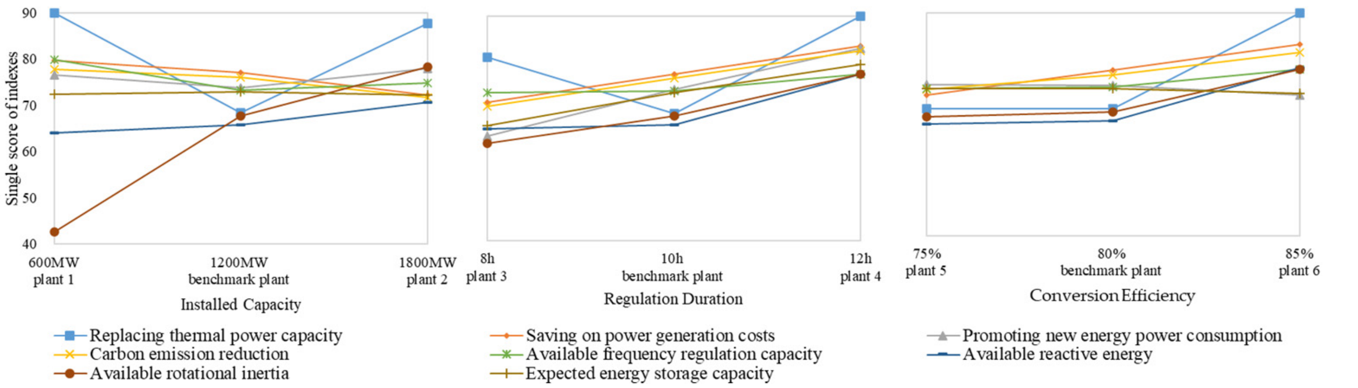

Figure 5. Single scoring results of indexes of pumped storage plants to be evaluated with different installed capacities, regulation durations, and conversion efficiencies.

(3) Indicator weighting coefficients

This paper considers that pumped storage, as a large-scale energy storage resource, in the new power system mainly plays a flexible regulation and stability support role, so the indicators of the flexibility dimension and reliability dimension are considered to be slightly more important compared to the other indicators. In the economy dimension, considering that the system power supply capacity is redundant most of the time, this paper considers that the indicator of "saving on power generation cost" is slightly more important than the indicator of "replacing thermal power capacity". In the low-carbon dimension, considering that the new power system will face severe power abandonment problems when new energy is put into operation on a large scale, this paper considers that the indicator of "promoting new energy consumption" is slightly more important than the indicator of "carbon emission reduction". In the flexibility dimension, both active and reactive power regulation are crucial in the new power system, and this paper considers that "available frequency regulation capacity" and "available reactive energy" are equally important. In the dimension of reliability, considering that the high proportion of new energy access leads to the outstanding low inertia characteristics of the new power system, this paper considers that "the available rotational inertia index" is slightly more important than the "expected energy storage capacity" index. Using the subjective method to pairwise compare the importance of each indicator and employing a nine-level scale to construct a judgment matrix as follows, the weights (single and comprehensive) of each indicator were calculated using the Analytic Hierarchy Process (AHP), as presented in Table 3.

$$\mathbf{A} = \begin{bmatrix} 1 & 1/2 & 1/2 & 1/2 \\ 2 & 1 & 1/2 & 1/2 \\ 2 & 2 & 1 & 2 \\ 2 & 2 & 1/2 & 1 \end{bmatrix}$$

$$\mathbf{B}_1 = \begin{bmatrix} 1 & 1/2 \\ 2 & 1 \end{bmatrix}$$

$$\mathbf{B}_2 = \begin{bmatrix} 1 & 2 \\ 1/2 & 1 \end{bmatrix}$$

$$\mathbf{B}_3 = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$$

$$\mathbf{B}_4 = \begin{bmatrix} 1 & 2 \\ 1/2 & 1 \end{bmatrix}$$

Table 3. Weight coefficient of comprehensive evaluation indexes for the pumped storage operation effect.

Objective Layer A	Criterion Layer B	Weight	Factor Layer C	Single Weight	Comprehensive Weight
Comprehensive evaluation of the operational effect of pumped storage	Economy dimension benefits B_1	0.138	Replacing thermal power capacity C_{11}	0.333	0.046
			Saving on power generation costs C_{12}	0.667	0.092
	Low-carbon dimension benefits B_2	0.195	Promoting new energy power consumption C_{21}	0.333	0.130
			Carbon emission reduction C_{22}	0.667	0.065
	Flexibility dimension benefits B_3	0.391	Available frequency regulation capacity C_{31}	0.5	0.195
			Available reactive energy C_{32}	0.5	0.195
	Reliability dimension benefits B_4	0.276	Available rotational inertia C_{41}	0.667	0.184
			Expected energy storage capacity C_{42}	0.333	0.092

(4) Comprehensive evaluation results

Based on the single scoring results and comprehensive weights of each indicator, the scoring results of various pumped storage power plants across different benefit dimensions are presented in Figure 6. This figure visually demonstrates the extent to which various technical parameters impact the operational benefit of pumped storage in distinct dimensions. Among them, the larger the installed capacity of pumped storage power stations in the reliability dimension of the score growth is more obvious, the longer the regulation duration of pumped storage power stations in the different dimensions of the score has obvious growth, and a higher the conversion efficiency of pumped storage power stations in the economy, flexibility, and reliability dimensions of the score is more advantageous.

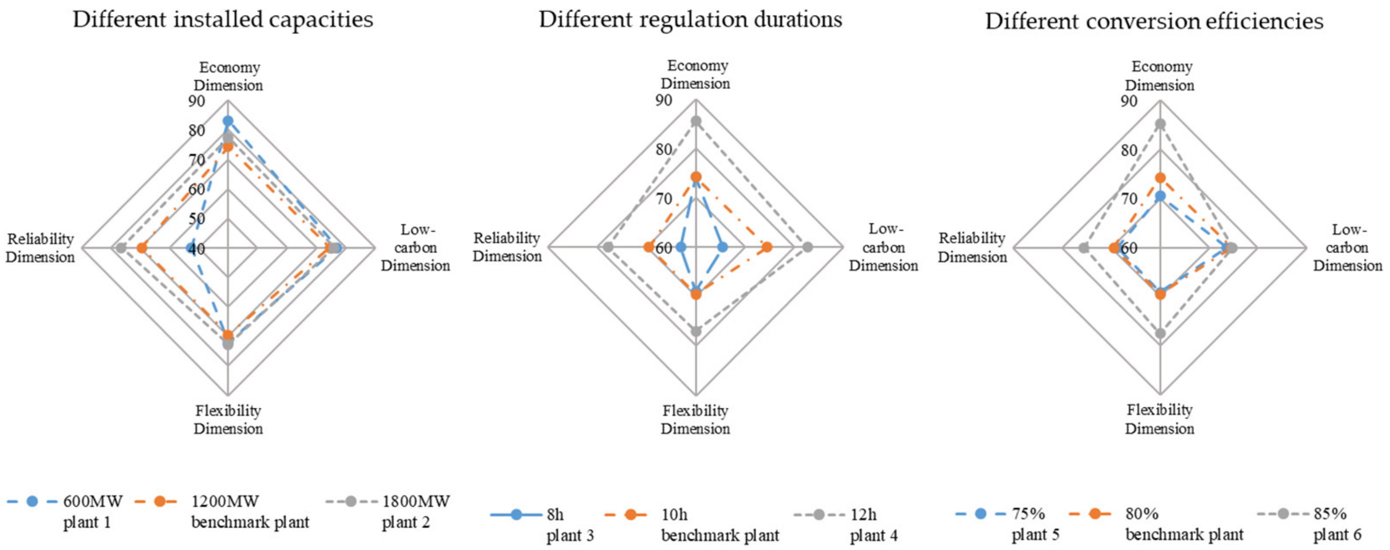

Figure 6. Scoring results for different dimensions of pumped storage plants to be evaluated.

According to the single scoring results and comprehensive weights of each index, the comprehensive scoring results of pumped storage power plants with different technical parameters are calculated according to Equation (15), as shown in Figure 7. It can be observed that as the installed capacity, regulation duration, and conversion efficiency increase, the comprehensive score results for the operational benefit of pumped storage in the new power system also increase. Notably, the regulation duration and conversion efficiency have a more pronounced impact on the results.

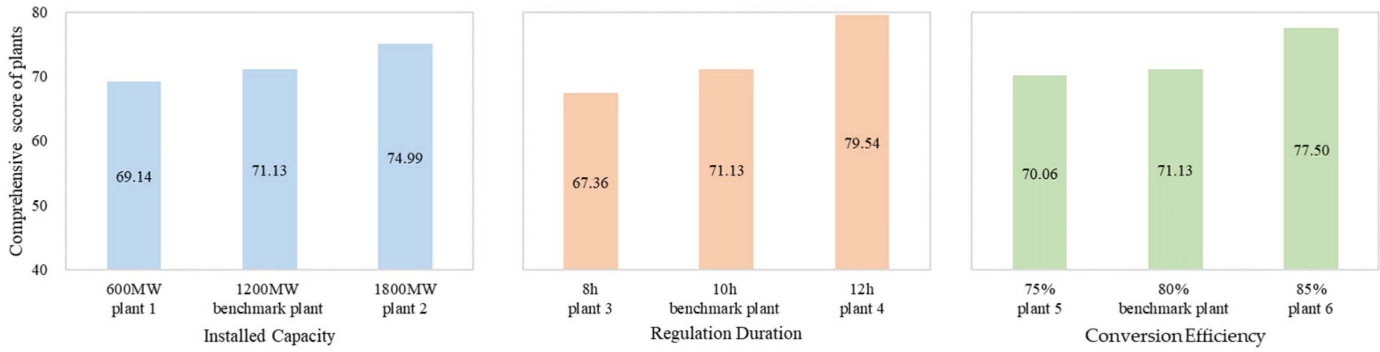

Figure 7. Comprehensive evaluation results of pumped storage plants to be evaluated with different installed capacities, regulation durations, and conversion efficiencies.

6. Discussion

In this paper, four dimensional evaluation indexes were selected to analyze the multidimensional evaluation of the operational effectiveness of pumped storage power plants with seven different technical parameters in a new type of power system. The results of this paper are basically consistent with the results of previous studies by other researchers, which all indicate that pumped storage is beneficial to the economic, low-carbon, flexible, and reliable operation of power systems. However, the calculation results of specific indicators in this study are different from those of other researchers, mainly stemming from the use of different case samples or analysis methods. The following is a comparison of the results of the operational efficiency evaluation of the benchmark power plant in this study with those of previous studies and the reasons for the differences.

(1) In the economy dimension, the thermal power capacity that can be replaced by the benchmark power plant in this paper is 0.76 MW per MW of installed capacity, which saves CNY 1.06 million per year in power generation costs. Similarly, Zhang and Cai proposed pumped storage "equivalent thermal capacity replacement factor" and "annual coal savings" indicators [11]. Taking a 1200 MW pumped storage power plant as an example, Zhang and Cai calculated that each MW of installed capacity can replace 1.06 MW of thermal power capacity, which can save CNY 0.50 million per year in power generation costs (according to the coal price used in this paper, the 405 tons of coal consumption per year in the original article can be converted into power generation cost savings). Both this paper and Zhang and Cai's verified that pumped storage could improve the economics of the operation of the new power system. As Zhang and Cai only considered one typical operation scenario, while this paper considered six operation scenarios (including two extreme scenarios), the results of this paper's evaluation of the economic operation benefits of pumped storage are more obvious.

(2) In the low-carbon dimension, each MW of installed capacity of the baseline plant in this paper can promote new energy consumption of 470 MWh per year and reduce carbon emissions by 3313 tCO_2 per year. Ni et al. have also analyzed the role of pumped storage in promoting new energy and carbon emission reduction [13]. Taking the performance of a 1200 MW pumped storage power plant in a typical provincial receiving grid in 2030 as an example, Ni et al. calculated that each MW of installed capacity can promote new energy consumption of 2317 MWh per year and reduce carbon emissions of 1417 tCO_2 per year.

Both this paper and Ni et al. verified that pumped storage could improve the low-carbon nature of new power system operation. Since the proportion of new energy installed in the example system in reference [13] is as high as 50% (30% in this paper), the operational effect of pumped storage in promoting new energy consumption is more obvious. This paper not only considers the carbon emission reduction generated by pumped storage to promote the substitution of new energy to thermal power but also considers the carbon emission reduction generated by optimizing the thermal power operation conditions (improving the thermal power load rate) and evaluates the carbon emission reduction benefits more obviously.

(3) In the flexibility dimension and reliability dimension, the benchmark power plant in this paper has an available frequency regulation capacity of 1247 MWh per MW of installed capacity per year, an average available rotational inertia of 3.12 MWs, and an average annual expected energy storage capacity of 7.91 MWh. Peng et al. have also measured the same indicators [19]. Taking the Shenzhen pumped storage power plant as an example, Peng et al. calculated that the annual available frequency regulation capacity per MW of installed capacity is 48 MWh, the average available rotational inertia is 0.78 MWs, and the average energy storage capacity is 8.73 MWh. Peng et al. considered that the frequency regulation is available only when the active power is zero. In this paper, considering different working conditions, pumped storage can provide frequency regulation auxiliary service only when it is in generator mode or pump mode, which leads to a large difference in the calculation results of the available frequency regulation capacity. Peng et al. combined the inertia compensation rules in the region where pumped storage is located and set the inertia compensation coefficient (the inertia compensation coefficient is 0 when the load rate of the pumped storage power plant is more than 15%) [19]. In contrast, this paper ignored the artificial rules and calculated a higher actual average available rotational inertia for pumped storage than Peng et al.

The difference between the results of this paper's study and those of previous studies reflects the complexity of the operational benefits of pumped storage under different power systems, and together they construct a more comprehensive evaluation framework. It also points out the necessity for future studies to explore more deeply the evaluation criteria of pumped storage operational benefits.

7. Conclusions

Pumped hydro storage stands as a crucial supporting technology in building a new power system. Establishing a comprehensive, standardized, and practical evaluation methodology is significant. It aids in the rational planning and selection of pumped hydro stations. This approach ensures sustainable and healthy development of pumped hydro storage. This paper closely combines the connotation characteristics of the new power system and establishes a comprehensive evaluation index system of the pumped storage operation effect from four benefit dimensions: economy, low carbon, flexibility, and reliability. Single scoring models were constructed for each index, and these were then combined with the AHP to build a comprehensive evaluation model. Sample pumped storage power plants with different technical parameters in terms of installed capacity, regulation duration, and conversion efficiency were selected to carry out case analysis. Furthermore, comparing these results with previous research findings, the following conclusions have been drawn.

(1) The larger the installed capacity of the pumped storage power plant, the higher the available rotational inertia per unit capacity and the lower the saving on power generation costs. In the example, the installed capacity of 600 MW, 1200 MW, and 1800 MW in pumped storage plants are rated as 43, 68, and 78, respectively, for the "available rotational inertia" index, and 80, 77, and 72, respectively, for the "saving on power generation cost" index. This results in higher scores for the reliability dimension and lower scores for the economy dimension for pumped storage plants with a larger installed capacity. Therefore, a balanced consideration of the economic and reliability requirements of the system is needed for

planning decisions on installed pumped storage capacity. For power systems with a surplus of supply capacity, the focus should be on economics. For power systems with tighter supply capacity, the focus should be on reliability.

(2) Pumped storage plants with a longer regulation duration and higher conversion efficiency have higher scores on different value dimensions, and, therefore, higher overall scores. Among them, the regulation duration has a more obvious impact on the operational efficiency of pumped storage. In the example, pumped storage plants with regulation durations of 8 h, 10 h, and 12 h have comprehensive scores of 67, 71, and 80, respectively. Therefore, increasing the regulation duration and conversion efficiency will have a better effect on the operational efficiency of pumped storage power plants in the new power system. This is suggested that in the future, by developing hybrid pumped storage according to local conditions and using natural runoff to improve the regulation performance and comprehensive conversion efficiency of pumped storage power plants, they can better support the efficient, low-carbon, and flexible operation of the new power system.

(3) The results of previous studies have shown the operational benefits of pumped storage in different dimensions, but this paper constructs a relatively more comprehensive multidimensional evaluation index system, which is more applicable to the evaluation of the operational effects of pumped storage in the new power system. The results of the previous studies and the results of this paper, despite the differences in specific values, jointly reveal the multidimensional operational benefits of pumped storage in new power systems in terms of economy, low carbon, flexibility, and reliability.

Although the comprehensive evaluation method proposed in this paper can comprehensively demonstrate and quantify the operational benefits of pumped storage in new power systems and has strong practical significance, it still has certain limitations.

(1) The characteristics of the power grid where pumped storage is located were not considered. Different grid supply and demand characteristics will affect the decision makers to set the weight of each evaluation index. Pumped storage plants with the same technical parameters operate differently in different grids. How to eliminate the differences in the power grids where they are located and how to compare and evaluate the operational benefits of pumped storage across power grids is the direction of the follow-up efforts of this research topic.

(2) The calculation method for dynamic benefit evaluation indicators under the dimensions of flexibility and reliability is relatively simple. This study mainly quantifies the relevant indicators from the supply of auxiliary services, such as frequency regulation and rotational inertia, which can be provided by the pumped storage power plant itself. By constructing a grid transient instability scenario to simulate the stability control behavior of pumped storage, it is possible to more accurately quantify the dynamic operational efficiency indicators of pumped storage.

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