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Comprehensive Benefit Evaluation of Hybrid Pumped-Storage Power Stations Based on Improved Rank Correlation-Entropy Weight Method

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Abstract: Over the past decade, the growth of new power plants has become a trend, with new energy stations growing particularly fast. In order to solve the problem of electricity consumption, the development of hybrid pumped storage based on hydropower stations has become a focus, so it is necessary to evaluate and analyze its technical and economic characteristics. Based on the characteristics of pumped-storage power stations, this paper proposes a comprehensive benefit evaluation model for the functional, financial, and environmental benefits. The model uses the fuzzy Delphi method to improve the rank correlation analysis method and introduces the entropy weighting method, calculating the comprehensive weight of indicators by the subjective and objective combination weighting method. The fuzzy comprehensive evaluation method is used to establish a comprehensive evaluation model and calculate the comprehensive benefit evaluation grade of hybrid pumped-storage power plants. Finally, the practicality and validity of the evaluation model are verified through case studies, and the technical and economic characteristics and superiority of the hybrid pumped-storage power plants are analyzed based on the evaluation results.

Keywords: hybrid pumped-storage power station; comprehensive benefit evaluation; rank correlation analysis method; entropy weight method; fuzzy Delphi method

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1. Introduction

In the last decade, the rapid growth of power stations has become a trend as people's living needs have increased, which is particularly evident in China, the world's largest developing country. In order to actively address climate change, China proposed carbon peaking and carbon-neutral targets in September 2020, committing to peak CO_2 emissions by 2030 and working towards carbon neutrality by 2060 [1]. To reduce fossil energy use, China planned to build a new power system dominated by new energy sources and vigorously develop clean and renewable energy sources. Currently, China leads the world in installed wind power of over 290 GW and solar PV power of 270 GW. By 2030, China's non-fossil energy will account for about 25% of primary energy consumption, and the total installed capacity of wind and solar power will reach more than 1.2 billion kW [2]. To adapt to the low-carbon development needs of the power system, the capacity of new energy sources on the grid has increased significantly, and the problem of the grid-connected consumption of new energy has become increasingly significant [3,4]. With this background, large-capacity power storage technology has become an important technical means of ensuring a power supply and promoting the consumption of new energy.

As the most mature large-scale energy storage technology, pumped storage has the technical advantages of large rated power and a long continuous discharge time and is safe and environmentally friendly, which makes pumped-storage power stations the most widely used energy storage facilities today [5]. China expects pumped storage to reach a total capacity of over 62 million kW by 2025 and 120 million kW by 2030 [6].However, conventional pumped storage has been slow to develop due to the scarcity of station resources and stringent site selection requirements [7,8]. To alleviate the difficulties of building pumped-storage power stations, existing hydropower plants can be modified to have pumping and storage functions by building additional reversible units or pumping pumps, which are called hybrid pumped-storage power stations [9]. The development of hybrid pumped-storage power stations can provide more resources for energy storage sites, which to some extent alleviates the problems of the difficult site selection and slow development of pumped-storage power stations [10]. Therefore, for provinces with abundant hydro resources, the development of hybrid pumped-storage technology by tapping into resource endowments can effectively alleviate the problems of new energy consumption and the lack of grid flexibility caused by the rapid development of new energy [11,12].

Therefore, the transformation of hybrid pumped-storage power plants will produce rich operational benefit enhancements. In order to concretely reflect the development value of hybrid pumped storage and study its technical and economic characteristics, a comprehensive evaluation of its overall benefits is needed, and in addition, the comprehensive benefit evaluation of hybrid pumped-storage power plants has research value and practical significance [13]. According to the existing literature, some studies have focused on hybrid pumped-storage power stations. Tang Haihua et al. [14] developed a general model for the joint optimal dispatching of a reservoir group including a hybrid pumped-storage power station. LI Wen-wu et al. [15] established a mid- to long-term reservoir operation stochastic optimization model for a hybrid pumped-storage power station based on describing the stochastic process of runoff. Cheng Xiong et al. [16] proposed a valid long-term dispatch rule modeling method for a cascade hydropower station group and built a long-term scheduling rule optimization model based on the typical daily load. From the above literature review, it can be seen that most studies focus on the optimal dispatch of hybrid pumped-storage power stations. However, the comprehensive benefit assessment of hybrid pumped-storage power plants lacks in-depth studies. Therefore, in order to meet the current development needs, this paper studies a comprehensive benefit evaluation method for hybrid pumped-storage power stations.

There are many studies on the benefit evaluation of power systems and relevant experience can be drawn. Ji, HZ et al. [17] constructed a comprehensive benefit evaluation model of the TOPSIS method, combining the projection pursuit method and relative entropy model, for wind-PV-ES and transmission hybrid power systems. Yang, XL et al. [18] evaluated the economic benefits of combined heat and power (CHP) technical renovation projects based on the improved factor analysis and incremental methods. Yang, HJ et al. [19] established the comprehensive benefit evaluation model of grid-side commercial storage projects based on a fuzzy analytic network process (ANP) approach for four dimensions: energy efficiency, economic, social, and environmental. On the basis of existing research, this paper establishes a comprehensive benefit evaluation system for hybrid pumped-storage power stations by selecting evaluation indicators and methods from three dimensions: functional, financial, and environmental. Due to the diversity and complexity of the evaluation indicators, an improved rank correlation analysis method combined with the fuzzy Delphi method is proposed in this paper, and the indicator weights are calculated using this method in combination with the entropy weighting method. Finally, the evaluation results are obtained using the fuzzy comprehensive evaluation method, which can provide a comprehensive and objective analysis of the comprehensive benefits of the power station.

2. Comprehensive Evaluation Indicator System of Hybrid Pumped-Storage Power Station

To conduct a comprehensive evaluation of hybrid pumped-storage power stations, it is first necessary to establish a reasonable comprehensive evaluation indicator system by selecting suitable indicators that can reflect the benefits of the power station and serve as the basis for the subsequent evaluation.

2.1. Construction Principles of Comprehensive Evaluation Indicator System

The purpose of constructing an evaluation indicator system is to reflect the main characteristics of the evaluation object through the selected indicators in order to make a comprehensive and objective evaluation. In the case of hybrid pumped-storage power stations, the evaluation indicators cannot be limited to economics but must be considered in conjunction with the specific functions of the power station. Therefore, under a comprehensive consideration of the benefits of hybrid pumped-storage power stations, the indicators are selected from three main components: operational function, economic capacity, and environmental protection [20,21]. The comprehensive benefit evaluation indicator system for hybrid pumped-storage power stations is shown in Table 1.

Table 1. Power station comprehensive benefit evaluation indicator system.

Overall Indicator A	Primary Indicator B	Secondary Indicator C
Comprehensive Benefit Evaluation of Hybrid Pumped-Storage Power Station A	Functional benefit B_1	Equivalent Availability Factor C_1
		Annual Pumping Utilization Hours of Pumped-Storage Units C_2
		Start-up Success Rate of Pumped-Storage Units C_3
		Power Station Energy Conversion Efficiency C_4
	Financial benefit B_2	Financial Internal Rate of Return C_5
		Payback Period C_6
		Unit Investment C_7
	Environmental benefit B_3	Renewable Energy Consumption Ratio C_8
		Equivalent Coal-Saving Weight C_9
		Environmental Governance Benefit C_{10}

2.2. Connotation of Comprehensive Evaluation Indicators

The evaluation indicator system established in this paper adopts a two-tier structure; the primary indicators include the functional, financial, and environmental benefits, and then ten representative secondary indicators are selected according to the characteristics of each primary indicator.

2.2.1. Functional Benefit Indicator

The functional benefits refer to the benefits brought by a hybrid pumped-storage power station in the grid through energy storage and power generation, regulating the system's power and playing its own special function. The secondary indicators are as follows [17].

(1) Equivalent Availability Factor (*EAF*)

The equivalent availability factor of the unit reflects the operating stability of the power station. Its calculation formula is as follows:

$$EAF = \frac{T_a}{T} \tag{1}$$

where T is the number of hours that need to be selected for the statistical evaluation and T_a is the available hours and refers to the number of hours when the pumped-storage unit is in the available and standby states.

(2) Annual Pumping Utilization Hours of Pumped-Storage Units ($APUH_p$)

The annual pumping utilization hours of the units refer to the operating hours of the average pumping equipment capacity under full-load operating conditions in a certain period of time, which can reflect the power grid adjustment benefit of the power station. Its calculation formula is as follows:

$$APUH_P = \frac{W_{ch}}{S_p} \quad (2)$$

where W_{ch} is the pumped power consumption of the pumped-storage units in one year and S_p is the rated installed capacity of pumped-storage units.

(3) Start-up Success Rate of Pumped-Storage Units

Pumped-storage units will change their start-stop status in response to demand in order to complete tasks on the grid. The unit's start-up success rate is the probability that the unit will start up successfully as specified within the investigation time, which reflects the reliability of the pumped-storage unit's regulation and standby functions.

(4) Power Station Energy Conversion Efficiency

Pumped-storage power plants inevitably produce energy losses when storing and generating energy. The energy conversion efficiency of pumped-storage power stations is the ratio of annual power consumption to annual power generation, which represents the efficiency of the station's operation.

2.2.2. Financial Benefit Indicators

The economic benefit indicator of a hybrid pumped-storage plant includes an assessment of the impact of various aspects such as human resources, infrastructure, etc., whereas the financial benefit is a measure of the cost, expense, and income of the power station itself, and is the most direct indicator of economic efficiency. Secondary indicators were chosen to reflect the financial position of the plant in terms of profitability as well as costs [19,22].

(1) Financial Internal Rate of Return (*FIRR*)

The financial internal rate of return is the main dynamic indicator for judging the financial feasibility of a power station. It is the discount rate when the financial net present value is equal to zero during the operation period. Its calculation formula is as follows:

$$\sum_{t=1}^{n} (CI - CO)_t (1 + FIRR)^{-t} = 0 \quad (3)$$

where *CI* is the cash inflow (including sales revenue, recovery of residual value of fixed assets, recovery of working capital, etc.); *CO* is the cash outflow (including investment in fixed assets, working capital, operating costs, sales tax surcharge, etc.); $(CI - CO)_t$ is the yearly net cash flow of all investments; and n is the calculation period.

(2) Payback Period (P_t)

The payback period refers to the time required for the annual net income of the power station to repay the total investment. It is the main static indicator for examining the financial feasibility of the power station. The payback period is calculated as follows:

$$\sum_{t=1}^{P_t} (CI - CO)_t = 0 \quad (4)$$

(3) Unit Investment (I_u)

The unit investment refers to the investment amount required by a hybrid pumped-storage power station on average per kilowatt of installed capacity, which is used to measure the investment cost of the power station. The unit investment is calculated as follows:

$$I_u = \frac{I}{S_p} \tag{5}$$

where I is the total investment of the power station in a hybrid pumped-storage renovation project and S_p is the rated installed capacity of newly built pumped-storage units.

2.2.3. Environmental Benefit Indicators

The construction of hybrid pumped-storage power stations has a positive impact on environmental protection and resource development and can reduce the use of fossil fuels and carbon emissions while consuming renewable energy. The following secondary indicators were selected [23].

(1) Renewable Energy Consumption Ratio

The decarbonization of a power system will result in a large increase in renewable energy generation, whereas its anti-peaking characteristics will exacerbate the increase in power abandonment. Pumped-storage power stations will consume excess renewable energy with thermal power during grid load troughs, and the renewable energy consumption ratio represents the environmental benefits of the power station and the contribution to the utilization of clean energy.

(2) Equivalent Coal-Saving Weight

This indicator refers to the weight of coal savings generated by hybrid pumped-storage power stations in the process of power system peaking by consuming surplus new energy power and optimizing the operation of thermal units to equivalently reduce the use of coal fuel in the system. The power station reduces carbon emissions and protects the environment by reducing the use of fossil fuels, and its ability to reduce fossil energy use is represented by the equivalent coal-saving weight generated per unit of unit capacity. Its calculation formula is as follows:

$$B = \frac{W_f b_f - W_{ch}(1 - \alpha_R) b_{ch}}{S_p} \tag{6}$$

where b_f is the unit coal consumption of the thermal power unit replaced by the power station when generating electricity; b_{ch} is the unit coal consumption of the thermal power unit that provides the pumped power consumption; W_{ch} is the annual pumped power consumption of the pumped-storage unit; W_f is the annual power generation of the power station; and S_p is the total installed capacity of a pumped-storage power station.

(3) Environmental Governance Benefits

Environmental governance benefits refer to the benefits that the hybrid pumped-storage power station will bring to the watershed and surrounding environment after the completion of construction, which will bring about environmental optimization and disaster prevention and control.

3. Comprehensive Evaluation Model of Hybrid Pumped-Storage Power Station

Once the evaluation indicator system is established, the next step is to evaluate the overall effectiveness of the pumped-storage power station using the selected indicators. To derive an overall final evaluation value based on the existing multi-indicator system, it is necessary first to determine the weights of each indicator and second to select a suitable comprehensive evaluation method. After these steps, the establishment of a comprehensive evaluation model for hybrid pumped-storage power stations is completed [24,25].

3.1. Determining the Weights of Comprehensive Evaluation Indicators Using the Subjective and Objective Combination Weighting Method

Generally, the weights of multiple indicators need to be evaluated with reference to expert experience, and therefore subjective assignment methods are often used. However, with a single assignment method, the weighting results are likely to be influenced by the expert supervisor's preferences so this paper introduces an objective assignment method to assist in determining the weights of the comprehensive evaluation indicators using the subjective and objective combination weighting method.

3.1.1. The Process of Determining the Weights of Indicators Using Improved Rank Correlation Analysis Method

Considering the large number of indicators in the comprehensive benefit evaluation of hybrid pumped-storage power stations, the rank correlation analysis method can be used to assign weights, which is also known as the G1 method [26,27]. The steps are as follows:

Step 1: Indicator rank relationship establishment.

If the importance of the evaluation indicator x_i is greater than x_j, it is recorded as $x_i \succ x_j$; for the evaluation indicator set $\{x_1, x_2, \cdots, x_m\}$, the experts need to rank the importance of each indicator according to the actual situation to determine the rank relationship of the evaluation indicators as $x_1^* \succ x_2^* \succ \cdots \succ x_m^*$. x_i^* represents the evaluation indicators whose importance order is i after the rank relationship is sorted.

Step 2: Determine the relative importance of adjacent indicators.

The importance ratio r_k between adjacent indicators needs to be determined by the experts based on experience and technical factors. The ratio of the importance degrees of the adjacent indicators x_k^* and x_{k-1}^* can be expressed as

$$r_k = \frac{w_{k-1}}{w_k}, k = m, m-1, \cdots, 3, 2 \tag{7}$$

where w_k represents the indicator weight of x_k^*.

Step 3: Calculate the indicator weights.

According to r_k confirmed by the experts, the formula for calculating the weight of an evaluation indicator is

$$w_m = \left(1 + \sum_{k=2}^{m} \prod_{i=k}^{m} r_i\right)^{-1} \tag{8}$$

Although the G1 method is convenient, it has its limitations. The main problem is that it is difficult to synthesize the opinions of all members for the importance evaluation results of the adjacent indicators, and when experts have different opinions on r_k, conflicts will arise and it is difficult to obtain unified evaluation results. Therefore, the fuzzy Delphi method was introduced to improve it. The fuzzy Delphi method combines fuzzy theory and the traditional Delphi method, and the experts need to use triangular fuzzy numbers to make a three-point evaluation of the indicators [28,29]. The membership function can use the information provided by the expert judgments to the greatest extent so the judgment results of the experts can be verified by the membership function. Then, an improved rank correlation analysis method was proposed to improve the step of determining the relative importance among the adjacent indicators:

Step 1: Determine the importance interval.

When determining the relative importance of the adjacent indicators, the expert needs to give a relative importance interval, where the lower bound of the interval represents the conservative value C^k and the upper bound represents the optimistic value O^k:

$$\begin{gathered} C^k < O^k \\ C^k \in [0, 10], O^k \in [0, 10] \end{gathered} \tag{9}$$

Step 2: Calculate triangular fuzzy numbers.

Based on the conservative and optimistic values of each indicator obtained in the previous step, the conservative triangular fuzzy number $A(C_L^k, C_M^k, C_U^k)$ and the optimistic triangular fuzzy number $A(O_L^k, O_M^k, O_U^k)$ of the relative importance ratio r_k can be calculated, and the r_k between each indicator can be represented and judged intuitively by the two types of triangular fuzzy numbers The specific calculation formula is as follows:

$$\begin{cases} C_L^k = \min(C_1^k, C_2^k, \cdots, C_n^k), O_L^k = \min(O_1^k, O_2^k, \cdots, O_n^k) \\ C_U^k = \max(C_1^k, C_2^k, \cdots, C_n^k), O_U^k = \max(O_1^k, O_2^k, \cdots, O_n^k) \\ C_M^k = \sqrt[n]{C_1^k C_2^k \cdots C_n^k},\ O_M^k = \sqrt[n]{O_1^k O_2^k \cdots O_n^k} \end{cases} \tag{10}$$

where n represents the number of experts who evaluated the indicator and C_x^k and O_x^k represent the evaluations of the conservative and optimistic values of the relative importance ratio r_k by the expert whose bit sequence number is x.

Step 3: Calculate of importance consistency value.

Based on the conservative triangular fuzzy number and the optimistic triangular fuzzy number calculated in step 2, the consistency of the expert evaluation results is verified, the importance agreement value D_k of the relative importance ratio r_k according to the judgment situation can be calculated, and the value of D_k represents the result of r_k.

(1) $C_U^k \leq O_L^k$

In this case, the experts' judgments on the relative importance ratio r_k are consistent. At this time, the importance consistency value D_k can be calculated as

$$D_k = \frac{C_M^k + O_M^k}{2} \tag{11}$$

(2) $C_U^k > O_L^k$

In this case, it is necessary to further judge the consistency of the expert evaluation results and calculate the relationship between the gray range values Z_k and M_k:

$$Z^k = C_U^k - O_L^k,\ M^k = O_U^k - C_M^k \tag{12}$$

If $Z^k \leq M^k$, the experts' judgments on r_k are still valid at this time and the consistency value D_k of importance can be calculated as

$$D_k = \frac{C_U^k O_M^k - O_L^k C_M^k}{C_U^k + O_M^k - O_L^k - C_M^k} \tag{13}$$

If $Z^k > M^k$, it proves that there is a big difference between the judgments of the relative importance ratio r_k by the experts at this time and the evaluation result is invalid so it is necessary to re-consult the experts until the judgments of r_k are consistent. Finally, using the evaluation value of r_k, the subjective weights of each indicator can be calculated.

3.1.2. Entropy Weight Method

The entropy weight method is an objective assignment method. For m samples and n evaluation indicators, there is a data matrix $X = (x_{ij})_{m\times n}$. For a certain indicator j, if the difference between the indicator values x_{ij} of each object to be evaluated is greater, the indicator plays a greater role in the comprehensive evaluation. The greater the role played by the indicator in the comprehensive evaluation, the smaller the role [30]. The steps are as follows:

Step 1: Dimensionless processing of data for each indicator.

Since the value ranges of the values in the matrix are inconsistent, dimensionless processing of the raw data is required. For the positive and negative indicators in the evaluation system, the processing formula is

$$x_{ij}^{-} = \frac{x_{ij.U}^{r} - x_{ij}^{r}}{x_{ij.U}^{r} - x_{ij.L}^{r}} \tag{14}$$

$$x_{ij}^{+} = \frac{x_{ij}^{r} - x_{ij.L}^{r}}{x_{ij.U}^{r} - x_{ij.L}^{r}} \tag{15}$$

where x_{ij}^{-} is the processing result of the negative indicator, x_{ij}^{+} is the processing result of the positive indicator and $x_{ij.U}^{r}$ and $x_{ij.L}^{r}$ are the upper and lower bounds of the raw indicator data.

Step 2: Feature-specific gravity calculation.

Create the standardized data matrix D. Let D = $\{d_{ij}\}_{m\times n}$ and d_{ij} is the specific gravity, and for the positive and negative indicators, the calculation formula is

$$d_{ij} = x_{ij} / \sum_{i=1}^{m} x_{ij}, 0 \leq d_{ij} \leq 1 \tag{16}$$

Step 3: Entropy calculation.

Calculate the entropy value $e(d_j)$ of the j-th indicator:

$$e(d_j) = -\frac{1}{\ln m}\sum_{i=1}^{m} d_{ij} \ln d_{ij}, 0 < e(d_j) \leq 1 \tag{17}$$

Step 4: Entropy weighting calculation.

Calculate the entropy weights W_{Sj} of the j-th evaluation indicator:

$$W_{Sj} = [1 - e(d_j)]/(n - E),\ E = \sum_{j=1}^{n} e(d_j) \tag{18}$$

3.1.3. Comprehensive Weighting Calculation

Based on the results of the G1 method and entropy weight method, the comprehensive subjective and objective weights can be calculated:

$$w_j = \frac{w_j^s w_j^o}{\sum\limits_{j=1}^{n} w_j^s w_j^o} \tag{19}$$

where w_j^s represents the subjective assigned weight value, w_j^o represents the objective assigned weight value, and w_j^s is the combined weight of the j-th evaluation indicator. The method flow is shown in Figure 1.

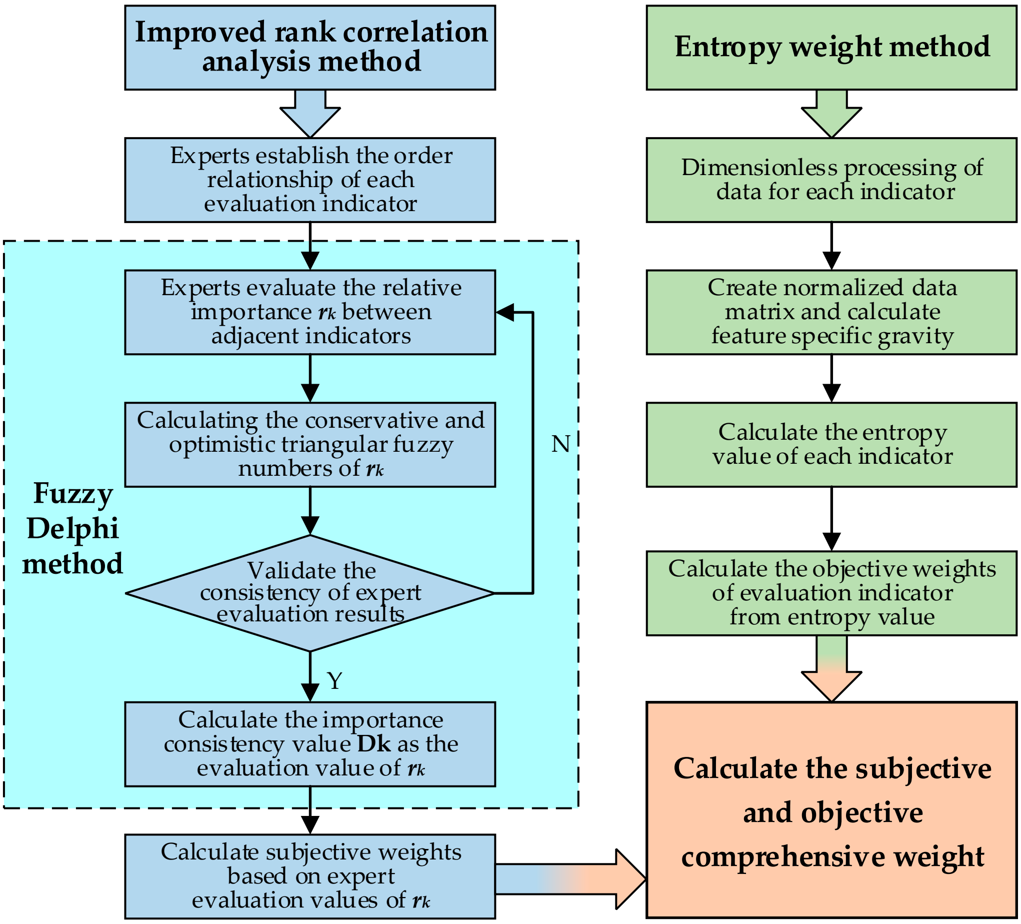

Figure 1. Subjective and objective combination weighting method flow.

3.2. Fuzzy Comprehensive Evaluation Method for Comprehensive Benefit Evaluation

The fuzzy comprehensive evaluation method is based on a fuzzy mathematical concept and uses the principle of fuzzy relationship synthesis to quantify some factors that cannot be quantified, which makes it one of the most widely used comprehensive evaluation methods at present. Since there are many indicators for the comprehensive evaluation of pumped-storage power station efficiency, the quantitative and qualitative indicators are intersected and the content is complex so this paper chooses the fuzzy comprehensive evaluation method to carry out the evaluation work [31,32].

The fuzzy comprehensive evaluation method needs to determine a judgment level set; each indicator has a membership degree u for each determination level and the closed interval [0, 1] is the value of u. The value of u reflects the membership degree of each indicator to the judgment level set. Therefore, the key to the fuzzy comprehensive evaluation method is how to obtain the membership degrees of indicators relative to the evaluation level system. The specific steps are as follows:

Step 1: Determine the evaluation indicators and levels.

In a comprehensive evaluation of a selected evaluation object, the first step is to determine the evaluation indicator set of the evaluation object. If there are n indicators, they can be expressed as

$$U = (u_1, u_2, \cdots, u_n) \tag{20}$$

In order to measure the degree of merit of an indicator, it is necessary to determine the comment level of the indicator, and we use v to denote the comment level domain of the indicator:

$$v = (v_1, v_2, v_3, v_4, v_5) \tag{21}$$

where v_1 represents excellent, v_2 represents relatively good, v_3 represents average, v_4 represents poor, and v_5 represents terrible.

For indicator u_i, we denote its membership degree for each evaluation level with $r = (r_1, r_2, r_3, r_4, r_5)$, and call r the membership degree vector of u_i. The value range of each element r_i is [0, 1], and $\sum_{i=1}^{5} r_i = 1$.

Step 2: Determine the membership function and fuzzy relationship matrix R.

The membership function is the key to processing each indicator value belonging to five grades. By selecting the appropriate membership function, the membership vector of each indicator is obtained, that is, the specific degree of membership of each indicator to the five levels. The membership vectors of all indicators together form the total evaluation object's membership matrix, which is the evaluation object's fuzzy relationship matrix R:

$$R = \begin{bmatrix} R|u_1 \\ R|u_2 \\ \vdots \\ R|u_n \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1j} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2j} & \cdots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nj} & \cdots & r_{nm} \end{bmatrix} \tag{22}$$

The element r_{ij} represents the membership degree of the indicator u_i of the evaluation object to the fuzzy subset of the v_j level. The performance of an evaluation object in the factor domain U is characterized by a fuzzy relationship matrix R. The scientific nature of the membership function will affect the accuracy of the comprehensive evaluation conclusion, so it is necessary to accurately confirm the membership function. Generally, when confirming the membership function, the fuzzy distribution method is often used for quantitative indicators and the fuzzy statistical method is often used for qualitative indicators [31,32].

Based on the data of the affiliation vector, the weighted score S is introduced to characterize the overall evaluation of each indicator, which can be expressed as

$$S = \sum_{i=1}^{5} r_i (5 - i) \tag{23}$$

Step 3: Use the weighted average method to confirm the comprehensive evaluation results.

In the previous article, the weight W of the indicator system was determined by the improved G1 method and entropy weight method, and the fuzzy relationship matrix R was determined by the fuzzy comprehensive evaluation method. When B_i is used to represent the comprehensive evaluation of pumped-storage power stations in terms of indicator i, it can be expressed as

$$\begin{aligned} B_i &= (w_1, w_2, \cdots w_n) \circ \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \\ &= (b_{i1}, b_{i2}, \cdots b_{in}) \end{aligned} \tag{24}$$

Among them, $\circ$ represents the fuzzy synthesis operator, through the comparison of different fuzzy operators, $M(\bullet, \oplus)$ can make full use of the information of R, and the comprehensive degree is high so this operator is selected for fuzzy synthesis.

4. Empirical Research

4.1. Project Introduction

In this section, four power stations are selected for the project as the evaluation objects, the benefits of each power station are evaluated through the comprehensive benefit evaluation indicators and methods, and the technical and economic characteristics of the power stations are compared and analyzed according to the results [33,34].

Power station P_1 uses two adjacent reservoirs of the original step hydropower station as the upper and lower reservoirs of the hybrid pumped-storage power station and carries out pumped-storage transformation by adding reversible hydropower units; its reservoir management authority is unified. The installed capacity of the reversible unit of the power station is 300 MW, with an annual pumping power consumption of 624 million kWh and a total investment of USD 111.07 million for the pumped-storage renovation project.

Hybrid pumped-storage power station P_2 is a conventional hydropower station reservoir with a pumped-storage upper reservoir, new lower reservoir, and installation of reversible hydropower units for transformation; its upper and lower reservoirs are managed by different departments. The installed capacity of the reversible unit of the power station is 270 MW, with an annual pumping power consumption of 265 million kWh and a total investment of USD 119.12 million for the pumped-storage renovation project.

In order to explore the technical and economic characteristics of hybrid pumped storage and considering that the majority of those currently operating are conventional pumped-storage power stations, two conventional pumped-storage power stations, P_3 and P_4, were selected for comparative research in the example. The installed capacity of power plant P_3 is 1200 MW, with a total investment of USD 720.48 million. Power station P_4 has an installed capacity of 1800 MW, with a total investment of USD 1024.56 million. According to the method and indicators proposed above, based on the data collection of the relevant indicators of each power station, a comprehensive evaluation model was established.

4.2. Determination of Indicator Weights

According to the steps of the subjective and objective combination weighting method proposed in this paper, the comprehensive weight value of the indicator was calculated. The weights of each secondary indicator were obtained based on the results of the improved rank correlation analysis method and entropy weighting method (the indicator C_{10} is a qualitative indicator, so its objective weight was calculated based on the values of the elements in the fuzzy relationship matrix). Since the evaluation results of the primary indicators were weighted by the evaluation values of the secondary indicators, their data were influenced by many factors, and the use of the entropy weighting method may easily lead to distortion of the weights, so the primary indicators did not consider the objective weights; their weights were obtained using the improved sequential relationship analysis method. The results are shown in Table 2.

Table 2. Evaluation indicator weights.

Primary Indicator	Weight	Secondary Indicator	Subjective Weights	Objective Weights	Weight
B_1	0.4358	C_1	0.1899	0.1746	0.1453
		C_2	0.1486	0.4262	0.2776
		C_3	0.3657	0.1946	0.3119
		C_4	0.2958	0.2046	0.2652
B_2	0.2521	C_5	0.5041	0.3133	0.4947
		C_6	0.3079	0.2686	0.2591
		C_7	0.1880	0.4181	0.2462
B_3	0.3121	C_8	0.2963	0.2773	0.2370
		C_9	0.4790	0.4013	0.5546
		C_{10}	0.2247	0.3214	0.2084

From the weights of each evaluation indicator in Table 2, it can be seen that among the three primary indicators, the functional benefits had the highest weight of 43.58%, which was 18.37% higher than the financial benefits and 12.37% higher than the environmental benefits. Since the main function of a hybrid pumped-storage power station is to provide the power supply and auxiliary regulation function for the power grid, the comprehensive benefit evaluation mainly examines their functions, and the weight calculation results are consistent with its benefit positioning.

Among the functional efficiency secondary indicators, C_3 had the highest weighting because the pumped-storage unit start-up success rate reflects the reliability of the plant's regulation and standby capacity, which is the most stringent and important indicator; in the financial efficiency secondary indicators, C_5 had a weight of 49.97%, which was more than 20% higher than the other two indicators, indicating that the financial profitability of power stations is the focus of efficiency inspection. Since reducing fossil energy consumption is the main way to generate environmental benefits and one of the main goals of power system development, notably, the weight of C_9 was 31.76% higher than C_8 and 34.62% higher than C_{10}.

4.3. Comprehensive Benefit Evaluation

First, the respective values of quantitative indicators C_1 to C_9 were obtained from the power station operation data. The results are shown in Table 3.

Table 3. Values of the quantitative indicators.

Indicator	C_1/%	C_2/h	C_3/%	C_4/%	C_5/%	C_6/year	C_7/$	C_8/%	C_9/t
P_1	90.49	2080.1	98.66	77.08	19.35	9.88	370.2	89.2	441,476.3
P_2	91.17	1232.1	98.84	77.55	12.62	15.52	441.2	95.3	284,592.4
P_3	89.23	1571.4	98.09	75.76	15.8	11.24	600.4	93.1	344,320.4
P_4	88.3	1618.8	97.68	75.24	16.36	11.03	569.2	92.7	350,222.5

Then, according to the steps of the fuzzy comprehensive evaluation method, the fuzzy relationship matrix of the secondary indicators (R_{B1}, R_{B2}, and R_{B3}) for power stations P_1 to P_4 was calculated and the weighted average method was used to obtain the fuzzy relationship matrix of the primary indicators (R_A). When calculating the results of the matrix, the membership degree vectors of the qualitative indicator C_{10}were determined using the fuzzy statistics method. The results are shown in Table 4.

Table 4. Fuzzy relationship matrix of the quantitative indicators.

	R_{B1}	R_{B2}	R_{B3}	R_A
P_1	$\begin{bmatrix} 0 & 0 & 0.746 & 0.254 & 0 \\ 0.457 & 0.543 & 0 & 0 & 0 \\ 0.407 & 0.593 & 0 & 0 & 0 \\ 0 & 0.332 & 0.668 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0.12 & 0.88 & 0 \\ 0.22 & 0.78 & 0 & 0 & 0 \\ 0.1 & 0.6 & 0.3 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0.254 & 0.532 & 0.214 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.143 & 0.558 & 0.091 & 0.208 & 0 \end{bmatrix}$
P_2	$\begin{bmatrix} 0.115 & 0.885 & 0 & 0 & 0 \\ 0 & 0 & 0.034 & 0.966 & 0 \\ 0.704 & 0.296 & 0 & 0 & 0 \\ 0 & 0.6 & 0.4 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0.791 & 0.209 & 0 \\ 0 & 0 & 0.792 & 0.208 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0.747 & 0.253 & 0 & 0 \\ 0 & 0 & 0.128 & 0.872 & 0 \\ 0.3 & 0.6 & 0.1 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0.236 & 0.38 & 0.116 & 0.268 & 0 \\ 0.246 & 0 & 0.596 & 0.158 & 0 \\ 0.062 & 0.302 & 0.152 & 0.484 & 0 \end{bmatrix}$
P_3	$\begin{bmatrix} 0 & 0.062 & 0.938 & 0 & 0 \\ 0 & 0.004 & 0.996 & 0 & 0 \\ 0 & 0.469 & 0.531 & 0 & 0 \\ 0 & 0 & 0.577 & 0.423 & 0 \end{bmatrix}$	$\begin{bmatrix} 0.023 & 0.977 & 0 & 0 & 0 \\ 0.504 & 0.496 & 0 & 0 & 0 \\ 0 & 0.353 & 0.647 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0.16 & 0.84 & 0 & 0 \\ 0 & 0 & 0.924 & 0.076 & 0 \\ 0.1 & 0.7 & 0.2 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0.156 & 0.732 & 0.112 & 0 \\ 0.142 & 0.699 & 0.159 & 0 & 0 \\ 0.021 & 0.184 & 0.753 & 0.042 & 0 \end{bmatrix}$
P_4	$\begin{bmatrix} 0 & 0 & 0.558 & 0.442 & 0 \\ 0 & 0.139 & 0.861 & 0 & 0 \\ 0 & 0 & 0.794 & 0.206 & 0 \\ 0 & 0 & 0.28 & 0.72 & 0 \end{bmatrix}$	$\begin{bmatrix} 0.24 & 0.76 & 0 & 0 & 0 \\ 0.588 & 0.412 & 0 & 0 & 0 \\ 0 & 0.803 & 0.197 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0.053 & 0.947 & 0 & 0 \\ 0 & 0.003 & 0.997 & 0 & 0 \\ 0.1 & 0.7 & 0.2 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0.039 & 0.642 & 0.319 & 0 \\ 0.271 & 0.68 & 0.049 & 0 & 0 \\ 0.021 & 0.16 & 0.819 & 0 & 0 \end{bmatrix}$

Finally, the comprehensive evaluation vector of each power station wasobtained by the weighted calculation of the first-level indicator fuzzy relationship matrix:

$$
\begin{aligned}
A_{P1} &= \begin{bmatrix} 0.407 & 0.406 & 0.122 & 0.065 & 0 \end{bmatrix} \\
A_{P2} &= \begin{bmatrix} 0.184 & 0.261 & 0.248 & 0.307 & 0 \end{bmatrix} \\
A_{P3} &= \begin{bmatrix} 0.042 & 0.289 & 0.620 & 0.049 & 0 \end{bmatrix} \\
A_{P4} &= \begin{bmatrix} 0.075 & 0.238 & 0.548 & 0.139 & 0 \end{bmatrix}
\end{aligned}
$$

4.4. Evaluation Results Analysis

Based on the membership degree of each level in the comprehensive evaluation vector of the P_1-P_4 power stations, the weighted score of each indicator was calculated and the comparative analysis of the technical and economic characteristics of each power station was performed. The weighted scores of all indicators are shown in Figure 2. According to the results, power station P_1 was overall better than P_3 and P_4. The functional, financial, and environmental benefits of P_1 were 49%, 34%, and 20% higher than those of P_3, whereas the evaluation results for P_3 and P_4 were similar.

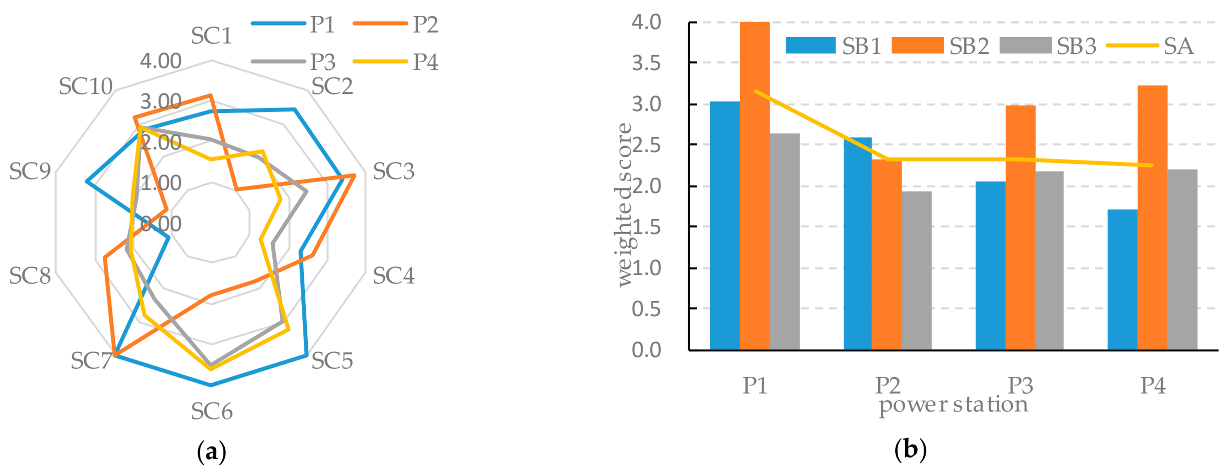

Figure 2. Weighted scores of all indicators. (**a**) Weighted scores of secondary indicators. (**b**) Weighted scores of primary and overall indicators.

In terms of functional benefits, the upper reservoir of a hybrid pumped-storage power station has natural water from upstream while pumping water from downstream, which raises the power head and improves the operational efficiency of the power station; therefore, the operating efficiency of power plant P_1 was 1.32% higher than that of P3, and the weighted score of C_4 was 47% more. In addition, a hybrid pumped-storage power station can use the conventional units of the original hydropower station for power generation, so it can undertake more pumping tasks than a normal pumped-storage plant of the same size. Therefore, the pumping and storage unit of power plant P_1 had about 500 more pumping hours than P_3, and the weighted score of C_2 was 73% higher.

In terms of financial benefits, since a hybrid pumped-storage power station renovation has a greater economic advantage in terms of initial construction inputs, such as reservoirs and a powerhouse, the evaluation results of the unit investment volume of power plant P_1 had a greater advantage compared to P_3, with a weighted score of C_7 that was 70% higher; moreover, due to the greater efficiency and pumping utilization hours of hybrid pumped-storage power stations, the power station gains higher revenue through power generation. The internal rate of return of plant P_1 was 3.55% greater than that of P_3, and the weighted score of C_5 was 32% higher.

In terms of environmental benefits, most of the electricity consumed by pumped-storage power stations during the low-load hours of the power system is surplus wind power as well as PV power. As for the coal-saving benefits, because more electricity is consumed overall, the equivalent coal-saving weight of power station P_1 was the largest, and its weighted score of indicator C_9 was 68% higher than that of power station P_3.

In spite of the differences between the comprehensive benefits of conventional and hybrid pumped-storage power stations, different hybrid pumped-storage power stations may also have significant differences in their benefits due to different retrofitting methods and operating models. According to Figure 2, the functional, financial, and environmental benefits of power station P_2 were lower than those of P_1, which had a 36% higher overall indicator score than P_2. Both the upper and lower reservoirs of power station P_1 utilize the existing reservoirs of the terraced hydropower station, whereas power station P_2 required a new lower reservoir during the renovation so the unit investment volume of power station P_2 was 119% higher than that of P_1. Moreover, the upper and lower reservoirs of power station P_2 are operated by the water resources department and the power grid company, respectively, whereas the whole of power station P_1 is under the jurisdiction of the power grid company. As a result, due to the difference in the operation objectives between the departments, the operation of power station P_2 cannot be fully coordinated and optimized and it does not fully take advantage of the operational capacity of a hybrid pumped-storage power station. As a result, the pumping utilization hours, internal rate of return, and equivalent coal-saving weight are greatly affected, and the weighted scores of indicators C_2, $C_{5,}$ and C_9 of power station P_2 were only 30%, 45%, and 35% of those of P_1.

In summary, according to the evaluation results, power station P_1 had the highest total indicator weighting score, reaching 3.16, whereas the rest of the power plants had weighting scores below 2.4. On the one hand, it shows that hybrid pumped-storage power stations are superior to conventional pumped-storage power station in terms of technical and economic performance and have practical value and development potential; on the other hand, it also proves that the transformation mode of hybrid pumped-storage power plants will have a great impact on their benefits.

4.5. Method Comparative Analysis

In the comprehensive benefit evaluation model established in this paper, an improved rank correlation-entropy weight method was used to calculate the weight of each indicator. On the one hand, this method improves the G1 method and to a certain extent, solves its problems and retains its advantages. On the other hand, it combines both subjective and objective assignment methods, forming an optimization based on the evaluation results of both methods and breaking the limitations of the single assignment method. Therefore, it is necessary to analyze its advantages using method comparison.

Table 5 shows the calculation volume comparison of the AHP method and the improved G1 method. The determination of the subjective weights is widely performed using the analytic hierarchy process (AHP) method, which requires the comparison of the importance of each factor and is complicated to calculate. It would require 15 comparisons of elements to build the judgment matrix alone if the index system in this paper was assigned, whereas the improved G1 method only needs 9 comparisons, reducing the computational effort by 40%, and this gap increases as the number of indicators becomes larger. Moreover, it is difficult to pass the consistency test. In contrast, the G1 method does not have the computational complexity of the AHP method and does not require consistency testing, which greatly simplifies the process of calculating the indicator weights. On this basis, the fuzzy Delphi method was introduced to improve the G1 method, which solves the problem of the difficulty in unifying the opinions of different experts and further enhances the effectiveness and practicality of the subjective weighting method.

Table 5. Calculation volumes of AHP method and improved G1 method.

Method	Comparison Times				Total
	C_1–C_4	C_5–C_7	C_8–C_{10}	B_1–B_3	
AHP	6	3	3	3	15
I-G1	3	2	2	2	9

Figure 3 shows the evaluation results of different power stations based on the improved G1 and entropy weight methods. Compared with Figure 2, when the subjective and objective weighting method was used separately for the secondary indicators, the overall scoring results showed that P_2 scored second, P_3 ranked in third, and the other two power stations originally scored the same. The ranking of the other stations remained unchanged, but the weighted scores of the indicators had differences. The most significant change was in the functional and financial indicator evaluation results for power station P_2; it was found that S_{B1} scored 30% higher than S_{B2} when using the improved G1 method but 21% lower when using the entropy weighting method. The situation with using the subjective and objective combination weighting method was in between the two. This also shows that a single evaluation method has certain limitations. So, the improved rank correlation-entropy weight method is more comprehensive and explanatory.

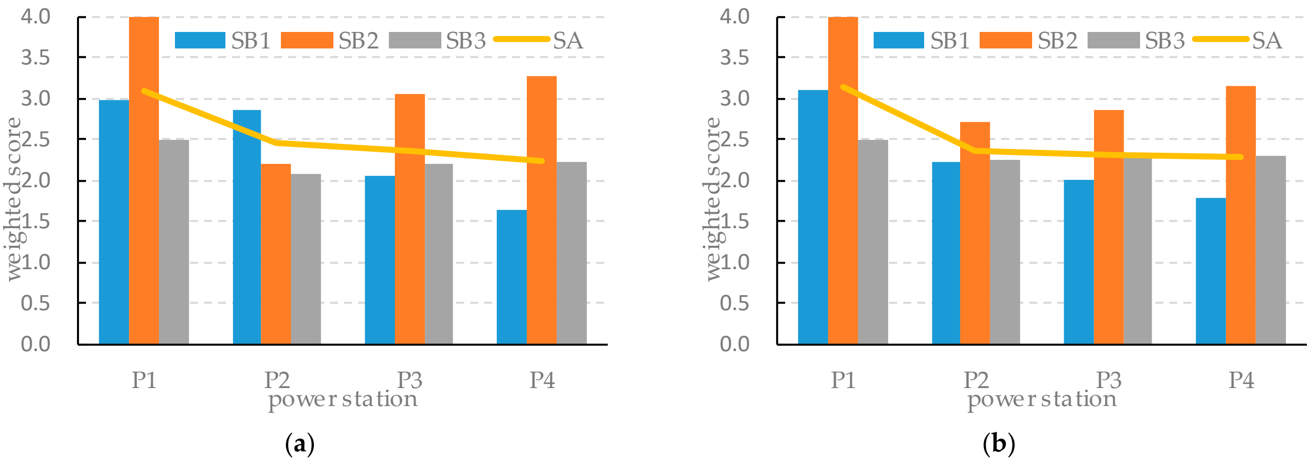

Figure 3. Weighted scores of primary and overall indicators based on different methods. (**a**) Evaluate results based on improved G1 Method. (**b**) Evaluate results based on entropy weight method.

5. Conclusions

In recent years, new energy sources such as wind power and photovoltaics have developed rapidly. The main reason for this is the lack of grid regulation capacity, resulting in the power system being unable to carry the new energy brought by the power volatility, and the power system is also facing the problem of electric energy consumption. The construction of hybrid pumped-storage power plants can help to solve the problem of insufficient pumped-storage selection points, which can both consume new energy sources and produce excellent comprehensive benefits. In order to study the technical and economic characteristics, this paper proposes a comprehensive system benefit evaluation model method and presents an example to verify it and analyze the advantages of hybrid pumped-storage power plants. The evaluation model established in this paper can effectively characterize the comprehensive benefits of pumped storage power stations and provide a reference for system planning and construction work. The main research contents are as follows:

(a) Through method comparative analysis, the model proposed in this paper uses the subjective and objective combination weighting method, which is based on the improved rank correlation analysis method and entropy weight method, to make the index assignment results more reasonable and effective. Compared to traditional AHP methods, the improved G1 method solves the problem of the difficulty in unifying expert evaluation opinions through the fuzzy Delphi method and further enhances the practicality of the subjective assignment method.

(b) In this paper, several power stations are selected for comprehensive benefit evaluation and empirical research is conducted. The evaluation results show that the comprehensive efficiency of the hybrid pumped-storage power stations is excellent, which is consistent with the theoretical perception of hybrid pumped storage and proves the effectiveness of the evaluation model.

(c) Based on the in-depth study and analysis of the evaluated score results, it is proved that the technical and economic performance of hybrid pumped-storage power stations is better than that of traditional pumped-storage power stations and the construction of hybrid pumped-storage power stations can meet the current needs of power system development, which has good practicality and application prospects. However, at the same time, depending on the specific situation, the comprehensive benefits of different hybrid pumped-storage power stations may differ significantly, and it is necessary to pay attention to the transformation method and operation mode of the power station when designing it to avoid negative impacts on the power station benefits.

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