A Hybrid Novel Fuzzy MCDM Method for Comprehensive Performance Evaluation of Pumped Storage Power Station in China

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Abstract: Considering the goals of carbon peaking and carbon neutrality, along with their related policies, pumped storage power stations are set to develop quickly in China. The comprehensive performance of pumped storage power stations must urgently be evaluated, which can help investors in decision making and provide a reference for policymakers. In this paper, a hybrid novel fuzzy multicriteria decision-making (MCDM) method combining the fuzzy best worst method (BWM) and fuzzy TOPSIS was proposed for the comprehensive performance evaluation of pumped storage power stations in China. The fuzzy BWM was utilized to determine the criteria weights describing the comprehensive performance of pumped storage power stations, while the fuzzy TOPSIS was used to rank the comprehensive performance of pumped storage power stations. The index system for the comprehensive performance evaluation of pumped storage power stations in China incorporated economic, social, and environmental aspects. The comprehensive performance of four pumped storage power stations in China was empirically evaluated using the proposed hybrid novel fuzzy MCDM method, and the results indicate that pumped storage power station PSPS2 exhibited the best comprehensive performance, followed by pumped storage power stations PSPS1 and PSPS4, whereas pumped storage power station PSPS3 had the worst comprehensive performance. A sensitivity analysis and comparative analysis were also conducted. The results indicate that the proposed hybrid novel fuzzy MCDM method, combining the fuzzy BWM and fuzzy TOPSIS for comprehensive performance evaluation of pumped storage power stations, is robust and effective.

Keywords: pumped storage power station; comprehensive performance evaluation; hybrid fuzzy MCDM; fuzzy best worst method; fuzzy TOPSIS

1. Introduction

Currently, many countries have proposed the development goal of carbon neutrality. To actively address climate change, China proposed the goals of carbon peaking and carbon neutrality in October 2020, with the aim of peaking CO₂ emissions before 2030 and neutralizing CO₂ emissions before 2060 [1]. In March 2021, China also proposed to build a new type of energy-centered electric power system. In the past few years, new and renewable energy types have developed rapidly [2]. Currently, the installed capacities of wind power and solar PV power in China exceed 290 GW and 270 GW, respectively, which rank first in the world. With the goals of carbon peaking and carbon neutrality and the construction of the new type of energy-centered electric power system in China, new and renewable energies such as wind power and solar PV power will develop quickly. However, the power output of renewable energy holds the characteristics of randomness, intermittency, and uncertainty [3,4]. With the high penetration of renewable energy, risk will be introduced to the safe and stable operation of the electric power system [5,6]. Therefore, energy storage devices in the new energy-centered electric power system will...
need to be configured to maintain its safety and stability [7,8]. Currently, there are several kinds of energy storage devices, such as pumped storage power stations, electrochemical energy storage, and flywheel energy storage [9,10]. As a mature energy storage device, pumped storage power stations have a long development history, with an installed capacity exceeding 31 GW in China. In September 2021, the National Energy Administration of China issued the “medium- and long-term development plan for pumped storage power stations (2021–2035)”, which proposes that the installed capacity of pumped storage power station will reach 62 GW in 2025 and 120 GW in 2030. Therefore, pumped storage power stations will develop rapidly in the upcoming years in China. With this booming development, it is necessary to evaluate the comprehensive performance of pumped storage power stations, which can help investors in decision making and provide a reference for policymakers. Furthermore, an evaluation of the comprehensive performance of pumped storage power stations will allow an accurate characterization of their parameters, which will be conducive to reasonable pricing and promote sustainable development.

In this paper, an evaluation of the comprehensive performance of pumped storage power stations in China is conducted by employing a hybrid novel fuzzy MCDM method. Compared with existing studies (please see details in Section 2), there are two main contributions of this paper. One contribution of this paper is its proposal of a hybrid novel fuzzy MCDM method for the comprehensive performance evaluation of pumped storage power stations, which combines the fuzzy best worst method (BWM) and the fuzzy technique for order preference by similarity to an ideal solution (TOPSIS). The former is used to determine the weights of the comprehensive performance evaluation criteria of pumped storage power stations, which allows the ambiguity and intangibility of decision makers to be considered, whereas the latter is employed to rank the comprehensive performance of pumped storage power stations. Another contribution of this paper is its provision of a novel method for the comprehensive performance evaluation of pumped storage power stations, which includes economic, social, and environmental aspects. The current studies related to the performance of pumped storage power stations mainly focused on the economic aspect; hence, it can be said this paper extends the scope of pumped storage power station performance by also considering social and environmental aspects. Moreover, the fuzzy BWM and fuzzy TOPSIS are employed for the first time to evaluate the performance of pumped storage power stations, thereby extending their application domains.

The remainder of this paper is structured as follows: Section 2 presents the literature review; Section 3 builds the comprehensive performance evaluation index system of pumped storage power stations; Section 4 introduces the proposed hybrid novel fuzzy MCDM method for the comprehensive performance evaluation of pumped storage power stations, which includes fuzzy BWM and fuzzy TOPSIS; Section 5 conducts an empirical analysis of four pumped storage power stations in China; Section 6 discusses the results; Section 7 concludes the paper.

2. Literature Review

Currently, some studies have focused on on pumped storage power station. Kong YG et al. conducted a review on the development of pumped storage power stations in China and stated that many sites suitable for the construction of pumped storage power stations have been planned, but there are challenges existing in the exploitation course [11]. Li JY et al. reviewed a new type of pumped storage power station with better stability, faster response speeds and wider regulation ranges [12]. Ji LY et al. proposed a method for the site selection of pumped storage power stations considering power structure optimization based on Kendall’s concordance coefficient, the analytic hierarchy process (AHP), and TOPSIS models [13]. He YX et al. proposed a “three-stage” competitive model of pumped storage power plants participating in the electricity spot market by using a quadratic programming algorithm with two consecutive iterations and a reinforcement learning algorithm, and the result indicates that the proposed model can bring better benefits to the pumped storage power station [14]. Hu SH et al. proposed a three-dimensional nonlinear seepage in a
pumped storage power station by using Forchheimer nonlinear flow theory, the discrete variational inequality formulation of Signorini’s type, and an adaptive penalized Heaviside function, which verified that this proposed method is more remarkable [15]. Papaefthymiou SV et al. studied the optimum sizing of a pumped storage power station with a wind farm operating in an island system by using a genetic algorithm with the objective of maximizing the return on the pumped storage power station investment [16]. Anagnostopoulos JS et al. investigated the performance of a pumped storage unit introduced in a conventional hydroelectric power plant in Greece with the consideration of various scenarios concerning the pumping station power rate and feeding program, and the economic viability of the pumping station investment was also studied [17]. Lin SJ et al. studied the stochastic economic dispatch of a power system with multiple wind farms and pumped-storage hydro stations by using a stochastic dynamic programming (DP) model, and the actual provincial power system and the modified IEEE 39-bus system were selected to verify the feasibility and efficiency of the proposed model and algorithm [18]. Kocaman AS and Modi V proposed a two-stage stochastic mixed-integer programming model for use in sizing an integrated hybrid energy system with pumped hydro storage and solar generation and concluded that the benefit of pumped hydro is more significant in isolated systems [19]. Wu YN et al. proposed a risk assessment method of a seawater pumped hydro storage project in China under three typical public–private partnership management modes by using a linguistic hesitant fuzzy-set-based cloud model [20]. Smallbone A et al. conducted the economic analysis of a pumped heat energy storage system by using the Levelised Cost of Storage method, and the result shows the cost of stored electricity of a demonstration plant proved to be between 2.7 and 5.0 EUR ct/kWh [21].

From the above literature review, it can be seen that most studies focus on the development situation, site location selection, market behavior, economic dispatch, risk evaluation, and economy of pumped storage power stations. However, the studies related to the comprehensive performance of pumped storage power stations including economic, social, and environmental performances are rare and inadequate. Therefore, this paper conducts a comprehensive performance evaluation on pumped storage power stations considering economic, social, and environmental performances. The comprehensive performance evaluation index system for a pumped storage power station is built using multiple criteria. Meanwhile, considering these multiple criteria, a hybrid novel fuzzy multi-criteria decision-making (MCDM) method is proposed for the comprehensive performance evaluation of pumped storage power stations.

3. Comprehensive Performance Evaluation Index System for Pumped Storage Power Station

A pumped storage power station is a kind of energy storage device which can store energy in the form of gravitational potential energy of water and use it to generate electrical energy during peak periods [22]. A pumped storage power station can obtain economic benefit through this action of peak-load shifting [23]. Meanwhile, pumped storage power stations have the merits of rapid start, flexible operation, and quick response to power load fluctuation, which can also be suitable for the tasks of frequency modulation, phase modulation, and emergency reserve for the electric power system [10,24]. Therefore, a pumped storage power station can improve the flexibility of an electric power system and ensure the safe and stable operation of an electric power system, especially electric power systems with high penetrations of renewable energy. Moreover, a pumped storage power station can reduce the renewable energy curtailment rate and improve the renewable energy consumption in a new-type electric power system with high penetration of renewable energy, which can help the development of renewable energy and reduce CO₂ emission rates. So, it can be said that a pumped storage power station configured in a new-type electric power system with high penetration of renewable energy has multiple performances, which not only include economic performance, but also include social and environmental performances.
A proper index system is very important for the comprehensive performance evaluation of pumped storage power stations. Representative and important performance criteria need to be included in the comprehensive performance evaluation of pumped storage power stations, which can reflect the main characteristics of pumped storage power station performance. In this paper, the comprehensive performance evaluation index system of pumped storage power stations is built from the perspective of sustainability, including economic, social, and environmental criteria. Moreover, these three criteria include several sub-criteria. The detailed determination process for a comprehensive performance evaluation index system of pumped storage power stations is as follows:

Firstly, the expert panel including six experts in the field of electric power industry management was set up. Of these, three experts were power grid enterprise practitioners and three experts were academic professors. Secondly, according to the functions of pumped storage power stations in electric power systems and related feasibility study reports of pumped storage power stations, after expert panel discussion, the criteria for the comprehensive performance evaluation of pumped storage power stations were determined, which include economic, social, and environmental performance criteria, and then, the initial sub-criteria for economic, social, and environmental performance criteria were also determined. Thirdly, the expert panel was invited again to review the initial sub-criteria and then select more important sub-criteria related to economic criterion, social criterion, and environmental criterion based on their practical experience and professional knowledge. Finally, according to the comments of the invited expert panel, the final sub-criteria were determined for the comprehensive performance evaluation of pumped storage power stations.

The comprehensive performance evaluation index system of pumped storage power stations is shown in Figure 1, which includes three criteria and nine sub-criteria. The three criteria include economic performance criterion, social performance criterion, and environmental performance criterion.

![Figure 1. Comprehensive performance evaluation index system for pumped storage power stations.](image-url)
For economic performance criterion, this includes the internal rate of return sub-criterion \((C_1)\), the asset–liability ratio sub-criterion \((C_2)\), and the pay back period sub-criterion \((C_3)\).

For social performance criterion, this includes the improvement of safe and stable operation of electric power system sub-criterion \((C_4)\), the improvement of power quality sub-criterion \((C_5)\), and the promotion of regional employment sub-criterion \((C_6)\).

For environmental performance criterion, this includes the renewable energy curtailment reduction sub-criterion \((C_7)\), the \(\text{CO}_2\) emission reduction sub-criterion \((C_8)\), and the ecological influence sub-criterion \((C_9)\).

For the comprehensive performance evaluation index system of pumped storage power stations in this paper, the internal rate of return sub-criterion \((C_1)\), the asset–liability ratio sub-criterion \((C_2)\), the pay back period sub-criterion \((C_3)\), and the \(\text{CO}_2\) emission reduction sub-criterion \((C_8)\) are quantitative criteria, and the remaining sub-criteria are qualitative criteria.

4. The Proposed Hybrid Novel Fuzzy MCDM Methodology for Comprehensive Performance Evaluation of Pumped Storage Power Stations

In this paper, the comprehensive performance of pumped storage power stations was evaluated with the consideration of three performance criteria, including economic performance, social performance, and environmental performance, and nine performance sub-criteria. In most cases, some criteria and sub-criteria of a pumped storage power station show good performances, but some criteria and sub-criteria of this pumped storage power station may show bad performances. Therefore, the multiple performance criteria and sub-criteria of a pumped storage power station may be conflicting, which need to be simultaneously considered for the comprehensive performance evaluation of pumped storage power stations. The MCDM method is a frequently used decision-making method which can consider multiple conflicting criteria to make a proper decision, which has been employed in many practical scenarios, such as battery energy storage system evaluation [25], the comprehensive benefit evaluation of eco-industrial parks [26,27], and the business risk evaluation of an electricity retail company [28]. Moreover, as the extension of the MCDM method, the fuzzy MCDM method can consider the ambiguity and intangibility of a decision maker, and it can also consider the vagueness frequently present in decision data due to the lack of complete information [29,30]. The fuzzy MCDM method has been developed and is used to tackle many issues under fuzzy and uncertain environments [31,32]. Therefore, in this paper, the fuzzy MCDM method was employed to evaluate the comprehensive performance of pumped storage power stations, which is composed of the fuzzy BWM and fuzzy TOPSIS methods. Of these, the fuzzy BWM was used to weight performance sub-criteria of pumped storage power stations, and the fuzzy TOPSIS was employed to rank the comprehensive performance of different pumped storage power stations. The detailed theories of the proposed hybrid novel fuzzy MCDM method are introduced in the sections that follow.

4.1. The Fuzzy BWM for Weight Determination of Performance Criteria

The fuzzy best worst method was first proposed in 2017 [29], which is an extension of the BWM, proposed in 2015 [33,34]. Compared with the BWM, the fuzzy BWM can obtain more highly reliable weights for criteria and help the decision maker make reference comparisons more accurately and easily [29]. The detailed theory of fuzzy BWM for the weight determination of comprehensive performance evaluation of pumped storage power station is as follows:

In this paper, three performance criteria and nine sub-criteria were used for the comprehensive performance evaluation of pumped storage power stations. The nine sub-criteria were weighted by using the fuzzy BWM.

Step 1. Build the Decision Criteria System
The decision criteria system is the comprehensive performance evaluation index system of pumped storage power stations, which includes nine sub-criteria, namely \( \{C_1, C_2, ..., C_9\} \).

Step 2. Determine the Best Criterion and the Worst Criterion

Based on the built comprehensive performance evaluation index system of pumped storage power stations, the best (most important) criterion and the worst (least important) criterion are determined by the expert panel. The best criterion for the comprehensive performance evaluation of pumped storage power stations is represented as \( C_B \), and the worst criterion is labeled as \( C_W \).

Step 3. Execute the Fuzzy Reference Comparisons for the Best Criterion

The fuzzy reference comparison is the fuzzy comparison between reference criterion and other criteria, which can be executed based on the linguistic variables of the expert panel. The linguistic variables given by the expert panel can then be transformed to fuzzy ratings represented by triangular fuzzy number (TFN), and the transformation rule is listed in Table 1 \([35,36]\).

<table>
<thead>
<tr>
<th>Linguistic Terms</th>
<th>Membership Function</th>
</tr>
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<tbody>
<tr>
<td>Equally importance (EI)</td>
<td>(1, 1, 1)</td>
</tr>
<tr>
<td>Weakly important (WI)</td>
<td>(2/3, 1, 3/2)</td>
</tr>
<tr>
<td>Fairly Important (FI)</td>
<td>(3/2, 2, 5/2)</td>
</tr>
<tr>
<td>Very important (VI)</td>
<td>(5/2, 3, 7/2)</td>
</tr>
<tr>
<td>Absolutely important (AI)</td>
<td>(7/2, 4, 9/2)</td>
</tr>
</tbody>
</table>

Then, the fuzzy comparison matrix can be obtained as follows:

\[
\hat{A} = \begin{bmatrix}
    C_1 & C_2 & \cdots & C_n \\
    \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\
    \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{nn}
\end{bmatrix}
\]  

(1)

where \( \tilde{a}_{ij} \) represents the relative fuzzy preference of criterion \( i \) to criterion \( j \), which is a TFN.

For the fuzzy BWM, the fuzzy reference comparison includes the fuzzy pairwise comparison between the best criterion and other criteria, and the fuzzy pairwise comparison between the worst criterion and other criteria. In this step, the fuzzy pairwise between the best criterion and other criteria is conducted first.

The fuzzy preferences of the best criterion for the comprehensive performance evaluation of pumped storage power stations over all the criteria can be determined by using linguistic terms listed in Table 1. Then, they are transformed to TFNs according to the transformation rules listed in Table 1. Finally, the fuzzy Best-to-Others vector for the comprehensive performance evaluation of pumped storage power stations can be obtained as:

\[
\hat{A}_B = (\tilde{a}_{B1}, \tilde{a}_{B2}, \cdots, \tilde{a}_{Bn})
\]  

(2)

where \( \hat{A}_B \) represents the fuzzy Best-to-Others vector; \( \tilde{a}_{Bj} \) represents the fuzzy preference of the best criterion \( C_B \) over criterion \( j \), \( j = 1, 2, \cdots, n \).

Step 4. Execute the Fuzzy Reference Comparisons for the Worst Criterion

In this step, the fuzzy pairwise comparison between the worst criterion and other criteria for the comprehensive performance evaluation of pumped storage power stations is executed. Using the decisions made by the expert panel according to Table 1, the fuzzy preferences of all the criteria over the worst criterion for the comprehensive performance evaluation of pumped storage power stations can be determined, which can then be transformed to TFNs according to the transformation rules listed in Table 1. The fuzzy
Others-to-Worst vector for the comprehensive performance evaluation of pumped storage power stations can be obtained as:

$$\tilde{A}_W = (\tilde{a}_{1W}, \tilde{a}_{2W}, \cdots, \tilde{a}_{nW})$$  \hspace{1cm} (3)

where $\tilde{A}_W$ represents the fuzzy Others-to-Worst vector; $\tilde{a}_{iW}$ represents the fuzzy preference of criterion $i$ over the worst criterion $C_{iW}$, $i = 1, 2, \cdots, n$.

Step 5. Determine the Optimal Fuzzy Weights

To determine the fuzzy weights in the fuzzy BWM, the following constrained optimization problem is constructed as:

$$\begin{aligned}
\min & \quad \max_j \left\{ \left[ \frac{\tilde{w}_B}{w_j} - \tilde{a}_{Bj} \right], \left[ \frac{\tilde{w}_W}{w_j} - \tilde{a}_{jW} \right] \right\} \\
\text{s.t.} & \quad \sum_{j=1}^{n} R(\tilde{w}_j) = 1 \\
& \quad l^w_j \leq m^w_j \leq u^w_j \\
& \quad l^w_j \geq 0 \\
& \quad j = 1, 2, \cdots, n
\end{aligned}$$  \hspace{1cm} (4)

where $\tilde{w}_B = (l^w_B, m^w_B, u^w_B)$, $\tilde{a}_j = (l^w_j, m^w_j, u^w_j)$, $\tilde{w}_W = (l^w_W, m^w_W, u^w_W)$, $\tilde{a}_{Bj} = (l_{Bj}, m_{Bj}, u_{Bj})$, $\tilde{a}_{jW} = (l_{jW}, m_{jW}, u_{jW})$.

To generate the optimal solution, Equation (4) needs to be transferred to the following nonlinearly constrained optimization problem.

$$\begin{aligned}
\min & \quad \tilde{\xi} \\
\text{s.t.} & \quad \sum_{j=1}^{n} R(\tilde{w}_j) = 1 \\
& \quad l^w_j \leq m^w_j \leq u^w_j \\
& \quad l^w_j \geq 0 \\
& \quad j = 1, 2, \cdots, n
\end{aligned}$$  \hspace{1cm} (5)

where $\tilde{\xi} = (l^s, m^s, u^s)$.

Considering $l^s \leq m^s \leq u^s$, it supposes $\tilde{\xi}^* = (k^*, k^*, k^*)$, $k^* \leq l^s$, then Equation (5) can be transferred as:

$$\begin{aligned}
\min & \quad \tilde{\xi}^* \\
\text{s.t.} & \quad \sum_{j=1}^{n} R(\tilde{w}_j) = 1 \\
& \quad l^w_j \leq m^w_j \leq u^w_j \\
& \quad l^w_j \geq 0 \\
& \quad j = 1, 2, \cdots, n
\end{aligned}$$  \hspace{1cm} (6)

By solving Equation (6), the optimal fuzzy weights $(\tilde{w}^*_1, \tilde{w}^*_2, \cdots, \tilde{w}^*_n)$ for the comprehensive performance evaluation of pumped storage power stations can be obtained.

The detailed steps of fuzzy BWM are shown in Figure 2.
Figure 2. The detailed steps of the BWM.

To verify the validity of the obtained optimal fuzzy weights, the Consistency Ratio (CR) is developed in the fuzzy BWM, which is an important indicator to check the consistency degree of pairwise comparison. When the CR is less than 0.1, it can be said that the pairwise comparison is consistent, and the fuzzy weights obtained are acceptable.

4.2. The Fuzzy TOPSIS for Comprehensive Performance Ranking of Pumped Storage Power Stations

As the extension of the traditional TOPSIS method, the fuzzy TOPSIS can deal with the decision-making issues under fuzzy environments [31]. Different from the traditional TOPSIS method, the entry in the decision matrix of fuzzy TOPSIS is represented by TFNs. The detailed theory of fuzzy TOPSIS for the comprehensive performance ranking of pumped storage power stations is illustrated as follows.

Step 1: Calculate the Fuzzy Linguistic Ratings for Qualitative Criteria Performance of Alternatives

Suppose that there are m alternatives $A = \{A_1, A_2, \cdots, A_m\}$ to be ranked, namely m pumped storage power stations. For nine comprehensive performance evaluation sub-criteria of pumped storage power stations in this paper, the quantitative sub-criteria include the internal rate of return ($C_1$), asset-liability ratio ($C_2$), pay back period ($C_3$), and CO$_2$ emission reduction ($C_8$). The performance data of these four quantitative sub-criteria are taken from project feasibility study reports and field research. For the qualitative sub-criteria including the improvement of the safe and stable operation of electric power system ($C_4$), the improvement of power quality ($C_5$), the promotion of regional employment ($C_6$), renewable energy curtailment reduction ($C_7$), and ecological influence ($C_9$), the performance data are taken from the fuzzy linguistic ratings of the expert panel, which are TFNs.

To obtain the fuzzy linguistic ratings for the qualitative sub-criteria performance of pumped storage power stations, the expert panel firstly gives the linguistic terms for every qualitative sub-criterion of each pumped storage power station according to Table 2, and then the linguistic terms are transformed to TFNs according to Table 2.
Let \( \tilde{a}_{ik} = (a_{ik}^{L}, a_{ik}^{M}, a_{ik}^{R}) \), \( 0 \leq a_{ik}^{L} \leq a_{ik}^{M} \leq a_{ik}^{R} \leq 1 \), \( i = 1, 2, \ldots, m \), \( k = 1, 2, \ldots, n \) be the superiority linguistic rating on performance assigned to pumped storage power station \( A_i \) for qualitative sub-criteria \( C_k \).

Step 2: Determine the Fuzzy Weights of Criteria

In this paper, the fuzzy weights of criteria are determined by using the fuzzy BWM. Let \( s_k = (s_{k}^{L}, s_{k}^{M}, s_{k}^{R}) \), \( 0 \leq s_{k}^{L} \leq s_{k}^{M} \leq s_{k}^{R} \leq 1 \), \( k = 1, 2, \ldots, 9 \) be the fuzzy weights of nine sub-criteria for the comprehensive performance evaluation of pumped storage power stations.

Step 3: Build the Initial Fuzzy Decision Matrix

The initial fuzzy decision matrix \( A \) can be obtained based on the performance values of nine sub-criteria. The crisp performance values of four quantitative sub-criteria for the comprehensive performance evaluation of pumped storage power stations can also be transformed to TFNs, and the lower, middle, and upper bounds of TFNs are all the crisp performance values of the quantitative sub-criteria. The TFNs of five qualitative sub-criteria for the comprehensive performance evaluation of pumped storage power stations can be obtained according to Step 1.

Then, the entries of matrix \( A \) are given in the form of TFNs, namely:

\[
A = (\tilde{a}_{ik})_{m \times n} = \begin{bmatrix}
\tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\
\tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{a}_{m1} & \tilde{a}_{m2} & \cdots & \tilde{a}_{mn}
\end{bmatrix} = \begin{bmatrix}
(a_{11}^{L}, a_{11}^{M}, a_{11}^{R}) & (a_{12}^{L}, a_{12}^{M}, a_{12}^{R}) & \cdots & (a_{1n}^{L}, a_{1n}^{M}, a_{1n}^{R}) \\
(a_{21}^{L}, a_{21}^{M}, a_{21}^{R}) & (a_{22}^{L}, a_{22}^{M}, a_{22}^{R}) & \cdots & (a_{2n}^{L}, a_{2n}^{M}, a_{2n}^{R}) \\
\vdots & \vdots & \ddots & \vdots \\
(a_{m1}^{L}, a_{m1}^{M}, a_{m1}^{R}) & (a_{m2}^{L}, a_{m2}^{M}, a_{m2}^{R}) & \cdots & (a_{mn}^{L}, a_{mn}^{M}, a_{mn}^{R})
\end{bmatrix}
\] (7)

Step 4: Normalize the Initial Fuzzy Decision Matrix

Generally, different sub-criteria for the comprehensive performance evaluation of pumped storage power stations may hold different attributes. Some comprehensive performance evaluation sub-criteria hold the benefit-type attribute, namely the larger the better, while some comprehensive performance evaluation sub-criteria may hold the cost-type attribute, namely the smaller the better. Therefore, the normalization processing on all comprehensive performance evaluation sub-criteria of pumped storage power station needs to be performed first.

For benefit-type comprehensive performance evaluation sub-criteria of pumped storage power stations, the normalization processing can be conducted according to Equation (8):

\[
\tilde{b}_{ik} = \left( a_{ik}^{L}/t_k, a_{ik}^{M}/t_k, a_{ik}^{R}/t_k \right)
\] (8)

where

\[
t_k = \max_i \{ a_{ik}^{R} \}
\] (9)

For cost-type comprehensive performance evaluation sub-criteria of pumped storage power stations, the normalization processing can be conducted according to Equation (10):

\[
\tilde{b}_{ik} = \left( t_k/a_{ik}^{L}, t_k/a_{ik}^{M}, t_k/a_{ik}^{R} \right)
\] (10)
where

$$t_k = \min_i \left\{ a_{ik}^j \right\}$$  \hspace{1cm} (11)

Then, the normalized fuzzy decision matrix $B$ can be obtained as:

$$B = \left( \tilde{b}_{ik} \right)_{m \times n} = \begin{bmatrix}
\tilde{b}_{11} & \tilde{b}_{12} & \cdots & \tilde{b}_{1n} \\
\tilde{b}_{21} & \tilde{b}_{22} & \cdots & \tilde{b}_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{b}_{m1} & \tilde{b}_{m2} & \cdots & \tilde{b}_{mn}
\end{bmatrix}
= \begin{bmatrix}
(b_{11}^L, b_{11}^M, b_{11}^R) & (b_{12}^L, b_{12}^M, b_{12}^R) & \cdots & (b_{1n}^L, b_{1n}^M, b_{1n}^R) \\
(b_{21}^L, b_{21}^M, b_{21}^R) & (b_{22}^L, b_{22}^M, b_{22}^R) & \cdots & (b_{2n}^L, b_{2n}^M, b_{2n}^R) \\
\vdots & \vdots & \ddots & \vdots \\
(b_{m1}^L, b_{m1}^M, b_{m1}^R) & (b_{m2}^L, b_{m2}^M, b_{m2}^R) & \cdots & (b_{mn}^L, b_{mn}^M, b_{mn}^R)
\end{bmatrix}$$ \hspace{1cm} (12)

Step 5: Construct the Weighted Normalized Fuzzy Decision Matrix

The weighted normalized fuzzy decision matrix $C$ can be obtained by the calculation of the normalized fuzzy decision matrix $B$ multiplied by the fuzzy criteria weights $(\tilde{c}_k)$, namely:

$$C = (c_{ik})_{m \times n} = \begin{bmatrix}
\tilde{c}_1 \odot \tilde{b}_{11} & \tilde{c}_2 \odot \tilde{b}_{12} & \cdots & \tilde{c}_n \odot \tilde{b}_{1n} \\
\tilde{c}_1 \odot \tilde{b}_{21} & \tilde{c}_2 \odot \tilde{b}_{22} & \cdots & \tilde{c}_n \odot \tilde{b}_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{c}_1 \odot \tilde{b}_{m1} & \tilde{c}_2 \odot \tilde{b}_{m2} & \cdots & \tilde{c}_n \odot \tilde{b}_{mn}
\end{bmatrix}
= \begin{bmatrix}
(s_{11}^L, s_{11}^M, s_{11}^R) & (s_{12}^L, s_{12}^M, s_{12}^R) & \cdots & (s_{1n}^L, s_{1n}^M, s_{1n}^R) \\
(s_{21}^L, s_{21}^M, s_{21}^R) & (s_{22}^L, s_{22}^M, s_{22}^R) & \cdots & (s_{2n}^L, s_{2n}^M, s_{2n}^R) \\
\vdots & \vdots & \ddots & \vdots \\
(s_{m1}^L, s_{m1}^M, s_{m1}^R) & (s_{m2}^L, s_{m2}^M, s_{m2}^R) & \cdots & (s_{mn}^L, s_{mn}^M, s_{mn}^R)
\end{bmatrix}$$ \hspace{1cm} (13)

Step 6: Determine the Fuzzy Positive and Negative Ideal Solution

Let $C^+$ and $C^-$ represent the fuzzy positive ideal solution and fuzzy negative ideal solution, respectively, for the comprehensive performance evaluation of pumped storage power stations, which can be computed by

$$C^+ = (\tilde{c}^+_k) = \left\{ \left( \max_i \tilde{c}_{ik}^+ | j \in J_1 \right), \left( \min_i \tilde{c}_{ik}^- | j \in J_2 \right) \right\}$$

$$C^- = (\tilde{c}^-_k) = \left\{ \left( \min_i \tilde{c}_{ik}^- | j \in J_1 \right), \left( \max_i \tilde{c}_{ik}^+ | j \in J_2 \right) \right\}$$ \hspace{1cm} (14)

where

$$\max_i \tilde{c}_{ik}^+ = \left\{ \max_i \{ b_{ik}^L, \max_k s_{ik}^M, \min_k s_{ik}^R \} \right\}$$

$$\min_i \tilde{c}_{ik}^- = \left\{ \min_i \{ b_{ik}^L, s_{ik}^M \} \right\}$$

$$\tilde{c}^+_k = \left( c^+_k, c^+_k, c^+_k \right)$$

$$\tilde{c}^-_k = \left( c^-_k, c^-_k, c^-_k \right)$$

$$i = 1, 2, \cdots, m; k = 1, 2, \cdots, n$$

where $J_1$ and $J_2$ represent the benefit-type criteria set and cost-type criteria set, respectively.

Step 7: Calculate the Distance of Each Pumped Storage Power Station from Fuzzy Positive and Negative Ideal Solution

According to related references [31,37], a modified geometrical distance method is adopted in this paper, which has the merits of being a powerful concept and being easy to implement. The distance $d(\tilde{a}_i, \tilde{a}_j)$ between two TFNs $\tilde{a}_i$ and $\tilde{a}_j$ can be computed by:

$$d(\tilde{a}_i, \tilde{a}_j) = \left\{ \left[ (a^+_i - a^+_j)^2 + 2(a^M_i - a^M_j)^2 + (a^R_i - a^R_j)^2 \right] / 4 \right\}^{1/2}$$ \hspace{1cm} (15)
Therefore, the distance \((d^+_i, d^-_i)\) of pumped storage power station \(i\) from the fuzzy positive and negative ideal solution can be calculated as follows:

\[
d^+_i = \left\{ \sum_{k=1}^{n} \left\{ \left[ \left( c_{ik}^L - c_{ik}^{+L} \right)^2 + 2 \left( c_{ik}^M - c_{ik}^{+M} \right)^2 + \left( c_{ik}^R - c_{ik}^{+R} \right)^2 \right] / 4 \right\}^{1/2} \right\}^{1/2}
\]

\[
d^-_i = \left\{ \sum_{k=1}^{n} \left\{ \left[ \left( c_{ik}^L - c_{ik}^{-L} \right)^2 + 2 \left( c_{ik}^M - c_{ik}^{-M} \right)^2 + \left( c_{ik}^R - c_{ik}^{-R} \right)^2 \right] / 4 \right\}^{1/2} \right\}^{1/2}
\]

\[(16) \quad (17)\]

Step 8: Compute the Closeness Coefficient of Each Pumped Storage Power Station

The closeness coefficient of a pumped storage power station represents the distance closest to the fuzzy positive ideal solution \(C^+\) and furthest from the fuzzy negative ideal solution \(C^-\) simultaneously, namely:

\[
CC_i = \frac{d^-_i}{d^+_i + d^-_i}, 0 \leq CC_i \leq 1
\]

\[(18)\]

Step 9: Rank the Comprehensive Performance of Pumped Storage Power Station

According to the calculation result, the pumped storage power station with the maximum comprehensive performance \(CC_i\) value has the highest ranking score, which indicates this pumped storage power station has the best comprehensive performance.

4.3. The Framework and Applicability of Proposed Hybrid MCDM Model

In this paper, the hybrid novel fuzzy MCDM method for comprehensive performance evaluation of pumped storage power station is proposed, which combines the fuzzy BWM and fuzzy TOPSIS methods. The fuzzy BWM is employed to determine nine performance sub-criteria weights which can consider the fuzziness, ambiguity, and intangibility of decision making, and the determination for nine performance sub-criteria weights of a pumped storage power station is more practical and credible. The fuzzy TOPSIS model is applied to rank the comprehensive performance of a pumped storage power station, which can consider the vagueness frequently present in decision data due to the lack of complete information. Therefore, the comprehensive performance evaluation result for a pumped storage power station by using the proposed hybrid novel fuzzy MCDM method including the fuzzy BWM and fuzzy TOPSIS is effective and appropriate.

The detailed procedure of the hybrid novel fuzzy MCDM method for the comprehensive performance evaluation of pumped storage power stations in this paper is elaborated on in Figure 3.

Regarding the MCDM, the weighting method of criteria has an important impact on the MCDM results. In this paper, considering that there are some qualitative criteria in the constructed evaluation index system, a subjective weighting method is employed. The commonly used subjective weighting method is mainly based on the relative judgment of experts on the importance of criteria, such as the AHP, the Analytic Network Process (ANP), Step-wise Weight Assessment Ratio Analysis (SWARA), the Full Consistency Method (FUCOM), Defining Interrelationships Between Ranked criteria (DIBR), Level-Based Weight Assessment (LBWA), and the BWM.
Figure 3. The procedure of the hybrid novel fuzzy MCDM method for comprehensive performance evaluation of pumped storage power stations.

The AHP and ANP methods need to make pairwise judgment on all criteria, which is prone to inconsistency, and the judgment process is complex [38,39]. SWARA determines the importance of criteria level by level and then solves the criteria weights. The calculation process is relatively simple. However, when sorting the importance of all criteria level by level before judgment, there may be sorting errors when the number of criteria is large [40,41]. The FUCOM determines the weight of criteria by solving the optimization model by sorting the importance of all criteria, combined with the judgment results of criteria, so that the results have high consistency. However, similar to SWARA, there may be errors in the ranking process of criteria importance, especially when there are a large number of criteria [42,43]. DIBR firstly selects the optimal criterion and sorts the importance of all criteria, then considers the correlation between adjacent criteria, defines the mutual importance between adjacent criteria through continuous real numbers in the [0,1] interval, and calculates the weight of all criteria. This method takes the importance judgment of adjacent criteria as the core point, breaks through the limitations of the traditional expert judgment method applicable to the fixed importance scale, and ensures the consistency and accuracy of the weight results. However, when the number of criteria increases, the computational complexity of the model increases significantly, and there is great subjectivity in the importance ranking of all criteria [44]. LBWA firstly determines the most important criterion, layers other criteria according to their importance with the most important criterion, and sorts the importance of criteria within each level. Next, the
elasticity coefficient is determined according to the number of criteria in different levels, and the influence function and weight of each criterion are determined combined with the elasticity coefficient. The calculation of this method is relatively simple and it can ensure the consistency of the results, but the process of criteria stratification and criteria importance ranking within the layer is subjective, and the determination of the elastic coefficient lacks sufficient mathematical basis [45,46].

The BWM is also a subjective weighting method based on criteria importance judgment. Different from the above methods, the BWM does not need to rank the importance of all criteria in advance, but only needs to determine the most important criterion and the least important criterion (namely, the best and worst criteria), then compare the other criteria with the best and worst criteria, and finally obtain the criteria weight by solving the optimization problem. Therefore, on the one hand, this method avoids subjectivity in the importance ranking process of all criteria; on the other hand, it simplifies the number of pairwise comparisons of criteria because it only needs to be compared with the best and worst criteria [33,34]. Meanwhile, due to the ambiguity and intangibility of the problem studied in this paper, fuzzy numbers are introduced into the traditional BWM, and a fuzzy BWM method [29] is employed. Furthermore, the sensitivity analysis results show that the proposed weighting method has good robustness and consistency.

What is more, a variety of common MCDM methods have important application value in alternative ranking, such as Multi-Attributive Border Approximation area Comparison (MABAC), Measurement Alternatives and Ranking according to the Compromise Solution (MARCOS), Complex Proportional Assessment (COPRAS), Multi-Attributive Ideal–Real Comparative Analysis (MAIRCA) and Ranking of Alternatives through Functional mapping of criterion sub-intervals into a Single Interval (RAFSI), and different methods have their own advantages and disadvantages.

The evaluation results of the MABAC are highly robust, but the evaluation results are less affected by the criteria weight. Therefore, the impact of the importance of criteria is ignored to a certain extent [47,48]. The MARCOS considers both ideal solutions and anti-ideal solutions and calculates the utility functions of alternatives to rank them. The results have good robustness and accuracy, but the computational complexity is high [49]. The COPRAS mainly considers the distance between the alternative and the best scheme to calculate the utility degree of the alternative, so as to rank the schemes. The results are vulnerable to extreme criteria values, that is, it may pay too much attention to the difference between the criterion value with large weight and the optimal value, thus ignoring the performance of other criteria [50,51]. Based on the concepts of ideal solution and anti-ideal solution, the MAIRCA calculates and adds the “distance” between the actual judgment and ideal judgment of all criteria of the alternative scheme and finally ranks the alternatives according to the ascending order of the total distance. This method determines the ideal evaluation matrix through expert evaluation, which can make the results robust, but may cause more subjectivity [52,53]. The RAFSI uses a new data normalization technology, which can effectively deal with complex MCDM problems, and the results have good robustness, but the calculation process of data normalization technology is cumbersome [54].

Compared with the above methods, the TOPSIS method is also an alternative ranking method based on ideal solutions. This method considers the attribute value and importance of the criteria more evenly, the selection of ideal/anti-ideal solutions is not subjective, and the computational complexity of the model is low. Meanwhile, due to the ambiguity and intangibility of the problem examined in this paper, the fuzzy numbers are introduced into the traditional TOPSIS method, and a fuzzy TOPSIS method is employed. Furthermore, sensitivity analysis and model comparison analysis are performed to verify the robustness and effectiveness of the proposed method in this paper.
5. Empirical Analysis

In China, pumped storage power stations have developed in recent years, and the installed capacity has exceeded 31 GW. Currently, under the backgrounds of the goal of carbon peaking and carbon neutrality, the construction of new-type new energy-centered electric power systems, and the “Medium- and Long-term development plan for pumped storage power station (2021–2035)” released by the National Energy Administration of China, the pumped storage power station will experience rapid expansion in the near future. In this paper, four pumped storage power stations in China were selected for use in empirical analysis. The comprehensive performances of four pumped storage power stations labeled as PSPS1, PSPS2, PSPS3, and PSPS4 in China are evaluated in this section by using the hybrid novel fuzzy MCDM method including the fuzzy BWM and fuzzy TOPSIS. The detailed steps are as follows.

5.1. Calculate the Fuzzy Linguistic Ratings for Qualitative Criteria Performance of Alternatives

For the qualitative sub-criteria of the comprehensive performance of four pumped storage power stations, including the improvement of safe and stable operation of electric power systems ($C_4$), the improvement of power quality ($C_5$), the promotion of regional employment ($C_6$), renewable energy curtailment reduction ($C_7$), and ecological influence ($C_9$), the expert panel was asked to give the linguistic terms for every qualitative sub-criterion of four pumped storage power stations according to Table 2, and the results are listed in Table 3. Then, the TFNs for every qualitative sub-criterion of four pumped storage power stations can be obtained according to Table 2.

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>$C_4$</th>
<th>$C_5$</th>
<th>$C_6$</th>
<th>$C_7$</th>
<th>$C_9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSPS1</td>
<td>G</td>
<td>G</td>
<td>H</td>
<td>H</td>
<td>G</td>
</tr>
<tr>
<td>PSPS2</td>
<td>H</td>
<td>G</td>
<td>G</td>
<td>H</td>
<td>G</td>
</tr>
<tr>
<td>PSPS3</td>
<td>G</td>
<td>H</td>
<td>G</td>
<td>G</td>
<td>H</td>
</tr>
<tr>
<td>PSPS4</td>
<td>H</td>
<td>G</td>
<td>H</td>
<td>G</td>
<td>G</td>
</tr>
</tbody>
</table>

5.2. Determine the Fuzzy Weights of Criteria

The fuzzy weights of nine sub-criteria for comprehensive performance evaluation of four pumped storage power stations are determined by the fuzzy BWM in this paper. Firstly, the best sub-criterion and the worst sub-criterion were determined by the expert panel, which are $C_1$ and $C_2$, respectively.

Secondly, the fuzzy reference comparisons for the best sub-criterion $C_1$ were executed according to Table 1, and the results are listed in Table 4. According to Table 1, the fuzzy Best-to-Others vector can be obtained as:

$$\tilde{A}_B = \left( \begin{array}{c} (1, 1, 1), (7/2, 4, 9/2), (5/2, 3, 7/2), (3/2, 2, 5/2), (5/2, 3, 7/2), \\ (7/2, 4, 9/2), (3/2, 2, 5/2), (2/3, 1, 3/2), (3/2, 2, 5/2) \end{array} \right)$$

<table>
<thead>
<tr>
<th>Best Sub-Criterion</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
<th>$C_5$</th>
<th>$C_6$</th>
<th>$C_7$</th>
<th>$C_8$</th>
<th>$C_9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>EI</td>
<td>AI</td>
<td>VI</td>
<td>FI</td>
<td>VI</td>
<td>AI</td>
<td>FI</td>
<td>WI</td>
<td>FI</td>
</tr>
</tbody>
</table>

Thirdly, the fuzzy reference comparisons for the worst sub-criterion $C_2$ were executed according to Table 1, and the results are listed in Table 5. According to Table 1, the fuzzy Others-to-Worst vector can be obtained as:

$$\tilde{A}_W = \left( \begin{array}{c} (7/2, 4, 9/2), (1, 1, 1), (2/3, 1, 3/2), (5/2, 3, 7/2), (3/2, 2, 5/2), \\ (1, 1, 1), (5/2, 3, 7/2), (7/2, 4, 9/2), (3/2, 2, 5/2) \end{array} \right)$$

Table 4. Fuzzy reference comparisons for the best sub-criterion $C_1$.
Table 5. Fuzzy reference comparisons for the worst sub-criterion $C_2$.

<table>
<thead>
<tr>
<th>Worst Sub-Criterion</th>
<th>$C_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>AI</td>
</tr>
<tr>
<td>$C_2$</td>
<td>EI</td>
</tr>
<tr>
<td>$C_3$</td>
<td>WI</td>
</tr>
<tr>
<td>$C_4$</td>
<td>VI</td>
</tr>
<tr>
<td>$C_5$</td>
<td>FI</td>
</tr>
<tr>
<td>$C_6$</td>
<td>EI</td>
</tr>
<tr>
<td>$C_7$</td>
<td>VI</td>
</tr>
<tr>
<td>$C_8$</td>
<td>AI</td>
</tr>
<tr>
<td>$C_9$</td>
<td>FI</td>
</tr>
</tbody>
</table>

Finally, the optimal fuzzy weights of nine sub-criteria for the comprehensive performance evaluation of four pumped storage power stations could be calculated according to Equations (4)–(6), and the results are shown in Figure 4.

According to the calculation result, the CR is 0.053, which is less than 0.1. Therefore, it can be said that the pairwise comparison is consistent, and the fuzzy weights of nine sub-criteria for the comprehensive performance evaluation of four pumped storage power stations are acceptable.

It can be seen that the internal rate of return sub-criterion ($C_1$) is the most important sub-criterion among all the sub-criteria, the fuzzy weight of which is (0.1847, 0.2115, 0.2115). The second important sub-criterion is CO$_2$ emission reduction sub-criterion ($C_8$), the fuzzy weight of which is (0.1438, 0.1684, 0.1686). The liability ratio sub-criterion ($C_2$) is the least important sub-criterion among all the sub-criteria, the fuzzy weight of which is (0.0429, 0.0429, 0.0429).

5.3. Build the Initial Fuzzy Decision Matrix

For four quantitative sub-criteria of four pumped storage power stations including internal rate of return ($C_1$), asset–liability ratio ($C_2$), pay back period ($C_3$), and CO$_2$ emission reduction ($C_8$), their performance data are from project feasibility study reports and field research. Therefore, the initial fuzzy decision matrix $A$ can be obtained as:
It can be seen that the performances of sub-criteria of four pumped storage power stations are quite different. For example, the internal rate of return sub-criterion ($C_1$), the pay back period sub-criterion ($C_3$), the promotion of regional employment sub-criterion ($C_6$), the renewable energy curtailment reduction sub-criterion ($C_7$), the CO$_2$ emission reduction sub-criterion ($C_8$), and the ecological influence sub-criterion ($C_9$) have good performances for PSPS1, but the other sub-criteria have bad performances. For the other three pumped storage power stations, some sub-criteria have also good performances, but other sub-criteria have bad performances. Therefore, due to the conflicting performance sub-criteria of four pumped storage power stations, the fuzzy MCDM technique needs to be employed to comprehensively evaluate the performance of pumped storage power stations.

### 5.4. Normalize the Initial Fuzzy Decision Matrix and Calculate the Weighted Normalized Fuzzy Decision Matrix

According to the Equations (8)–(11) and the sub-criteria attribute, the initial fuzzy decision matrix can be normalized as:

$$B = \begin{bmatrix}
C_1 & C_2 & C_3 & C_4 & C_5 \\
0.99 & 0.94 & 1.00 & 0.30 & 0.30 \\
1.00 & 0.97 & 0.73 & 0.60 & 0.60 \\
0.73 & 0.96 & 1.00 & 0.30 & 0.30 \\
0.60 & 0.95 & 0.60 & 0.43 & 0.43 \\
0.50 & 0.60 & 0.90 & 0.43 & 0.43 \\
0.60 & 0.50 & 0.84 & 0.43 & 0.43 \\
\end{bmatrix}$$

Then, the weighted normalized fuzzy decision matrix $C$ can be obtained as:

$$C = \begin{bmatrix}
C_1 & C_2 & C_3 & C_4 & C_5 \\
0.18 & 0.40 & 0.05 & 0.03 & 0.02 \\
0.18 & 0.40 & 0.05 & 0.04 & 0.02 \\
0.14 & 0.40 & 0.05 & 0.04 & 0.03 \\
0.11 & 0.40 & 0.05 & 0.03 & 0.02 \\
0.03 & 0.04 & 0.01 & 0.02 & 0.04 \\
0.01 & 0.04 & 0.05 & 0.04 & 0.03 \\
0.01 & 0.04 & 0.05 & 0.04 & 0.03 \\
0.03 & 0.04 & 0.05 & 0.04 & 0.03 \\
\end{bmatrix}$$
5.5. Determine the Fuzzy Positive and Negative Ideal Solution, and Calculate the Distance of Four Pumped Storage Power Stations

According to Equation (14), the fuzzy positive and negative ideal solution can be determined, and then the distances of four pumped storage power stations, PSPS1, PSPS2, PSPS3, and PSPS4, from the fuzzy positive and negative ideal solution can be calculated as:

\[
\begin{align*}
    d_+^1 &= 0.0506, \\
    d_+^2 &= 0.0355, \\
    d_+^3 &= 0.0944, \\
    d_+^4 &= 0.1059
\end{align*}
\]

\[
\begin{align*}
    d_-^1 &= 0.0992, \\
    d_-^2 &= 0.1086, \\
    d_-^3 &= 0.0366, \\
    d_-^4 &= 0.0437
\end{align*}
\]

5.6. Compute the Closeness Coefficient and Rank Four Pumped Storage Power Stations

According to Equation (18), the closeness coefficient of four pumped storage power stations can be computed as:

\[
\begin{align*}
    CC_1 &= \frac{d_-^1}{d_-^1 + d_+^1} = 0.6622, \\
    CC_2 &= \frac{d_-^2}{d_-^2 + d_+^2} = 0.7534 \\
    CC_3 &= \frac{d_-^3}{d_-^3 + d_+^3} = 0.2796, \\
    CC_4 &= \frac{d_-^4}{d_-^4 + d_+^4} = 0.2922
\end{align*}
\]

So,

\[
CC_2 \succ CC_1 \succ CC_4 \succ CC_3
\]

It can be seen that the pumped storage power station PSPS2 outranks the other three pumped storage power stations. Therefore, it can be concluded that the pumped storage power station PSPS2 has the best comprehensive performance, the following two are pumped storage power station PSPS1 and PSPS4, and the pumped storage power station PSPS4 has the worst comprehensive performance.

6. Discussion

The comprehensive performances of four pumped storage power stations in China were evaluated and ranked by the proposed hybrid novel MCDM method, which combines the fuzzy BWM and fuzzy TOPSIS. The ranking result indicates that the pumped storage power station PSPS2 has the best performance, while the pumped storage power station PSPS4 has the worst comprehensive performance. To obtain better insight from the proposed hybrid novel MCDM method application on the comprehensive performance evaluation of pumped storage power stations, the fuzzy weights and fuzzy performances of sub-criteria of pumped storage power stations must be investigated. Meanwhile, the sensitivity analysis and comparative analysis are also conducted in this section.

6.1. Result Analysis

The fuzzy weights of nine sub-criteria of four pumped storage power stations are shown in Figure 4. The fuzzy normalized performances of nine sub-criteria of four pumped storage power stations based on the normalized fuzzy decision matrix \( B \) are displayed in Figure 5.

According to Figure 5, it can be seen that the sub-criteria internal rate of return \( C_1 \), the improvement of the safe and stable operation of electric power system \( C_4 \), renewable energy curtailment reduction \( C_7 \), \( CO_2 \) emission reduction \( C_8 \) and ecological influence \( C_9 \) of pumped storage power station PSPS2 have the best performances, and the sub-criteria \( C_2 \) and \( C_5 \) of pumped storage power station PSPS2 have the second-best performances. Meanwhile, according to Figure 4, it can be seen that sub-criterion \( C_1 \) is the most important sub-criterion for the performance evaluation of pumped storage power stations, followed by sub-criteria \( C_8, C_4, C_7, C_9, C_5, C_3, \) and \( C_6, \) and \( C_2 \) is the least important sub-criterion for the performance evaluation of pumped storage power stations. It can be seen that the best performance sub-criteria (namely, \( C_1, C_4, C_7, C_8, \) and \( C_9 \)) of pumped storage power
station PSPS2 also have important weights. Therefore, the comprehensive performance of pumped storage power station PSPS2 is evaluated as the best among four pumped storage power stations.

![Figure 5. The fuzzy normalized performances of nine sub-criteria of four pumped storage power stations.](image)

For the pumped storage power station PSPS1, the sub-criteria $C_1$, $C_3$, $C_6$, $C_7$, and $C_9$ have the best performances compared with other pumped storage power stations. The sub-criteria $C_2$, $C_4$, and $C_5$ have the worst performances compared with other pumped storage power stations. Meanwhile, with the consideration of sub-criteria weights, the
pumped storage power station PSPS1 has the second-best performance among these four pumped storage power stations.

For the pumped storage power station PSPS4, the sub-criteria $C_4$, $C_5$, $C_7$, $C_8$, and $C_9$ have the worst performances, but the sub-criteria $C_4$ and $C_6$ have good performances. For the the pumped storage power station PSPS3, the sub-criteria $C_4$, $C_6$, $C_7$, $C_8$, and $C_9$ have the worst performances, and other sub-criteria except $C_2$ and $C_3$ also have bad performances. So, these two pumped storage power stations have bad comprehensive performances. Meanwhile, compared with the pumped storage power station PSPS3, the pumped storage power station PSPS4 has better performances related to sub-criteria $C_4$, $C_6$, and $C_8$ compared with that of pumped storage power station PSPS3, and these sub-criteria also have relatively important weights, so the pumped storage power station PSPS4 has relatively better performance than the pumped storage power station PSPS3 from the comprehensive perspective.

6.2. Sensitivity Analysis

In order to test the evaluation result robustness of the comprehensive performance of pumped storage power stations by using the proposed hybrid fuzzy MCDM method, a sensitivity analysis on the impacts of sub-criteria weights on the comprehensive performance ranking of storage power station was performed. Figure 6 shows those cases where the sub-criteria of the comprehensive performance of pumped storage power stations has 10%, 20%, and 30% less weight and 10%, 20%, and 30% more weight than the base weight (i.e., the weight used in Section 4). Taking sub-criteria $C_1$ as an example, it can be seen that as $C_1$ becomes less important, the final scores of comprehensive performances of pumped storage power station PSPS1, PSPS2, and PSPS3 will be decreased, but the final score of comprehensive performance of pumped storage power station PSPS4 will be increased. Meanwhile, as $C_1$ becomes more important, the final scores of the comprehensive performances of pumped storage power stations PSPS1, PSPS2, and PSPS3 will be increased, but the final score of the comprehensive performance of pumped storage power station PSPS4 will be decreased. Moreover, it can be seen that when $C_1$ becomes more important, the comprehensive performance of pumped storage power station PSPS3 will become better than that of pumped storage power station PSPS4, not like the basic case in Section 4. However, the comprehensive performance of pumped storage power station PSPS2 always ranks first among four pumped storage power stations. For other sub-criteria cases, it can be seen that the comprehensive performance of pumped storage power station PSPS2 always ranks first. Therefore, it can be concluded that the comprehensive performance evaluation of pumped storage power stations conducted by the proposed hybrid fuzzy MCDM method in this paper is robust and effective.

6.3. Comparative Analysis

There are many different fuzzy MCDM methods, but it is difficult to determine the best or most suitable one for a practical issue [55]. The proposed hybrid fuzzy MCDM method for the comprehensive performance evaluation of pumped storage power stations in this paper is compared with the recently proposed MCDM method, namely fuzzy Measurement of Alternatives and Ranking according to the Compromise Solution (MARCOS). The fuzzy MARCOS was proposed by Stankovic et al. in 2020, which can make valid decisions under uncertain environments [49]. For a detailed theory of fuzzy MARCOS, readers can refer to Ref. [49], and the detailed calculation process of comprehensive the performance evaluation of pumped storage power stations by using the fuzzy MARCOS is as follows.
Figure 6. Sensitivity analysis result.
According to the initial fuzzy decision matrix $A$, the extended initial fuzzy matrix $\tilde{X}$ can be obtained, and then the normalized fuzzy matrix $\tilde{N}$ can be calculated. Taking sub-criteria $C_9$ as an example, it is as follows:

$$
\tilde{N} = 
\begin{pmatrix}
A_I & (0.3, 0.375, 0.5) \\
PSPS1 & (0.4286, 0.6, 1) \\
PSPS2 & (0.4286, 0.6, 1) \\
PSPS3 & (0.3, 0.375, 0.5) \\
PSPS4 & (0.3, 0.375, 0.5) \\
ID & (0.4286, 0.6, 1)
\end{pmatrix}
$$

The weighted fuzzy matrix $\tilde{V}$ can be then calculated. Taking sub-criteria $C_1$ as an example, it is as follows:

$$
\tilde{V} = 
\begin{pmatrix}
A_I & (0.1137, 0.1301, 0.1301) \\
PSPS1 & (0.1820, 0.2084, 0.2084) \\
PSPS2 & (0.1847, 0.2115, 0.2115) \\
PSPS3 & (0.1847, 0.2115, 0.2115) \\
PSPS4 & (0.1137, 0.1301, 0.1301) \\
ID & (0.1847, 0.2115, 0.2115)
\end{pmatrix}
$$

The fuzzy matrix $\tilde{S}_i$ can be obtained as:

$$
\tilde{S}_i = 
\begin{pmatrix}
A_I & (0.4285, 0.6006, 0.7559) \\
PSPS1 & (0.5843, 0.7995, 1.0028) \\
PSPS2 & (0.6028, 0.8246, 1.0364) \\
PSPS3 & (0.4843, 0.6665, 0.8259) \\
PSPS4 & (0.4744, 0.6585, 0.8239) \\
ID & (0.6553, 0.8875, 1.1032)
\end{pmatrix}
$$

Then, the matrix $\tilde{K}_i^\gamma, \tilde{K}_i^\alpha, \tilde{T}_i$ can be successively calculated as follows:

$$
\tilde{K}_i^\gamma = 
\begin{pmatrix}
PSPS1 & (0.7730, 1.3312, 2.3405) \\
PSPS2 & (0.7974, 1.3729, 2.4187) \\
PSPS3 & (0.6407, 1.1098, 1.9227) \\
PSPS4 & (0.6276, 1.0964, 1.9275) \\
PSPS1 & (0.5296, 0.9008, 1.5303) \\
PSPS2 & (0.5464, 0.9291, 1.5814) \\
PSPS3 & (0.4390, 0.7510, 1.2572) \\
PSPS4 & (0.4300, 0.7420, 1.2603) \\
PSPS1 & (1.3026, 2.2320, 3.8707) \\
PSPS2 & (1.3438, 2.3020, 4.0001) \\
PSPS3 & (1.0797, 1.8608, 3.1799) \\
PSPS4 & (1.0575, 1.8384, 3.1877)
\end{pmatrix}
$$

Based on the above calculation, the utility functions related to the ideal solution and anti-ideal solution can be calculated, and then the values of utility functions for four pumped storage power stations can be calculated as:

$$
f(K_1) = 0.6506; 
f(K_2) = 0.6990; 
f(K_3) = 0.4280; 
f(K_4) = 0.4196.
$$

Therefore, it can be seen that the comprehensive performance of pumped storage power station PSPS2 is the best, followed by PSPS1, PSPS3, and PSPS4. The ranking result for the comprehensive performance of pumped storage power stations by using the fuzzy MARCOS is basically the same as that by using the proposed method in this paper, which verifies that the model proposed in this paper has good robustness.
7. Conclusions

In this paper, a hybrid novel MCDM framework for the comprehensive performance evaluation of pumped storage power stations was proposed, which combines the fuzzy BWM for determining the weights of performance criteria and the fuzzy TOPSIS for ranking the comprehensive performance of pumped storage power station. Empirical analysis focusing on four pumped storage power stations in China was performed, and the results indicate that the pumped storage power station PSPS2 has the best comprehensive performance, followed by the pumped storage power station PSPS1 and PSPS4, and the pumped storage power station PSPS3 has the worst comprehensive performance. Meanwhile, it can also be concluded that the internal rate of return, CO$_2$ emission reduction, the improvement of the safe and stable operation of electric power system, and renewable energy curtailment reduction have relatively strong impacts on the comprehensive performance of pumped storage power stations because they have much larger weights compared with other sub-criteria such as the asset–liability ratio, the promotion of regional employment, and the pay back period. These findings can help investors to make decisions and provide references for policymakers. Meanwhile, sensitivity analysis and comparative analysis were also conducted in detail, which verify the robustness of the proposed hybrid fuzzy MCDM in this paper.

The main contributions of this paper are that a hybrid novel fuzzy MCDM method combining the fuzzy BWM and fuzzy TOPSIS was proposed for the comprehensive performance evaluation of pumped storage power stations, and a new view for the comprehensive performance evaluation of pumped storage power stations was provided, including economic, social, and environmental performances.

With the development of pumped storage power stations in China, the comprehensive performance evaluation index system of a pumped storage power station may be updated in the future. Meanwhile, other decision-making methods can also be used for the comprehensive performance evaluation of pumped storage power stations, such as the hybrid method of BWM and fuzzy VIKOR [56,57], and BWM-COPRAS [58], and the results of different methods can be compared. The proposed hybrid fuzzy MCDM method for the comprehensive performance evaluation of pumped storage power stations in this paper can also be used for other issues, such as the comprehensive performance evaluation of electrochemical energy storage.

The hybrid MCDM method based on fuzzy BWM and fuzzy TOPSIS proposed in this paper has good applicability for evaluating the comprehensive performance of pumped storage power stations, but this paper still has some limitations and needs to be further explored. Firstly, there are some qualitative criteria in the evaluation index system constructed in this paper, which limits the use of the objective weighting method. In the future research, we can update the evaluation index system, and then the objective weighting method can be used when determining the criteria weights. Secondly, in the fuzzy BWM and fuzzy TOPSIS methods, six experts are invited to make fuzzy judgments, and the heterogeneity of different experts’ judgments is homogenized; that is, the final judgment result is obtained directly. In the future research, the heterogeneity of experts’ judgments can be discussed more deeply according to the specialization degree of the experts involved. Finally, the method proposed in this paper has good applicability in the research problems of this paper, but in fact, the applicability of different MCDM methods is still a problem worthy of in-depth discussion. We will use more numerical examples in different fields for detailed analysis in our subsequent research.

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