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A Water-Based Fire-Extinguishing Agent of Lithium Iron Phosphate Battery Fire via an Analytic Hierarchy Process-Fuzzy TOPSIS Decision-Marking Method

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Abstract: It is well known that the safety concerns surrounding lithium-ion batteries (LIBs), such as fire and explosion, are currently a bottleneck problem for the large-scale usage of energy storage power stations. The study of water-based fire-extinguishing agents used for LIBs is a promising direction. How to choose a suitable water-based fire-extinguishing agent is a significant scientific problem. In this study, a comprehensive evaluation model, including four primary indexes and eleven secondary indexes was established, which was used in the scenario of an electrochemical energy storage power station. The model is only suitable for assessing water-based fire extinguishing for suppressing lithium iron phosphate battery fire. Based on the comprehensive evaluation index system and extinguishing experiment data, the analytic hierarchy process (AHP) combined with fuzzy TOPSIS was used to evaluate the performances of the three kinds of water-based fire-extinguishing agents. According to the results of the fuzzy binary contrast method, the three kinds of fire-extinguishing agents could be ranked as follows: YS1000 > F-500 additive > pure water. The study provided a method for choosing and preparing a suitable fire-extinguishing agent for lithium iron phosphate batteries.

Keywords: lithium iron phosphate battery fire; water-based fire-extinguishing agent; analytic hierarchy process; fuzzy TOPSIS



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1. Introduction

China declared that it will strive to peak carbon dioxide release by 2030 and achieve carbon neutrality by 2060, which is called ‘dual carbon goals’ [1]. Electrochemical energy storage is a significant part of dual carbon goals. LIBs make up more than 90% of the installed capacity of electrochemical energy storage in China, and it is increasing year by year [1]. However, the fire and explosion accidents of energy storage power stations caused

by LIBs are becoming increasing obviously. According to an incomplete statistic, more than 100 energy storage fire and explosion accidents happened in the world so far. Therefore, the battery safety problem has been a bottleneck for the large-scale promotion of energy storage power stations.

Fire burning often occurs after thermal runaway (TR) occurs in the battery [2]. The hazard study of LIB fires has garnered attention. Researchers focused on the characteristic parameters of LIB fires, such as heat release rate (HRR) [3,4], battery mass loss [5,6], and toxic fluoride gas emissions [7–9] during the LIB fire process. Larsson et al. [7] investigated the HRR and toxic gases of seven kinds of commercial LIBs. The stages of charge (SOC) and thermal radiations of effect on LIB fire behavior were investigated in recent years [10]. Results indicated that combustion time and explosion time decreased with the increase in SOC. Immersion time is one of the significant factors that affect the combustion behaviors of LIBs. The results showed that combustion time first increased with the increase in immersion time, then kept constant when the immersion time overpassed 3 h [11]. Chen et al. [6,12] conducted an experiment on the effect of environmental pressure on the burning behavior of 18650 types of battery modules. They found that battery fire hazards become larger at high pressure than that at low pressure.

To reduce LIB fire hazards, different fire-extinguishing agents have been investigated using the experimental method [13–18]. Currently, the validities of these fire-extinguishing agents for extinguishing LIB fires mainly rely on three indexes, including inhibiting flame, cooling effect, and inhibiting TR propagation. Research showed the pure water mist (WM) possessed the best cooling effect and suppressing effect compared with HFC-227ea and CO₂ [13]. Compared with C₆F₁₂O and dry power, pure WM possesses the best cooling capacity and suppression capacity in the TR propagation in the battery module [14]. However, WM could hardly fight the open fire of a 243 Ah lithium iron phosphate battery. Therefore, a novel technology combining gaseous fire-extinguishing agent with WM was concerned [15,16]. Research showed that the cooling effectiveness and suppression effectiveness of C₆F₁₂O combined with WM was superior to that of a single fire-extinguishing agent [15]. However, HFC-227ea combined with WM could hardly extinguish a fire and cool the battery [16]. On the other hand, WM additives were concerned with enhancing the fire extinguishing effect and cooling effect of WM [17–20]. Studies on the inhibition of WM additives for LIBs fire are still quite limited. WM additive is mainly classified as chemical additives and surfactants [21]. Research showed that the extinguishing and cooling effects of WM containing KHCO₃ and K₂C₂O₄·H₂O for LIB were superior to that of WM without additives [15]. However, the chemical additive could increase the conductivity of water. Therefore, to avoid the risk of external short circuits, a low-conductivity compound additive was developed for LIBs fire [22]. Yuan [23,24] found that water mist containing a micelle encapsulator F-500 possessed an excellent cooling effect and absorbed combustible gases from LIB fires. According to the summarized research, water-based fire-extinguishing agents possess disadvantages and advantages. Therefore, how to choose a suitable water-based fire-extinguishing is an important scientific problem.

In such a situation, decision makers need methodological support to make a selection among the water-based fire-extinguishing agents, discarding less preferable alternatives quickly. However, there is no or little information about assessment methods for the fire-extinguishing agent utilized for LIBs. In order to determine the main influencing factors of the efficiency of fire-extinguishing agents and provide a basis for preparing an effective fire-extinguishing agent, we need to establish a simple and practicable fire-extinguishing agent evaluation system and evaluation method.

Currently, many methods, such as techniques for order performance by similarity to ideal solution (TOPSIS), AHP, and fuzzy comprehensive evaluation (FCE) method,

have been used in many fields. For example, AHP, as a comprehensive safety evaluation method combining qualitative and quantitative analysis, has been used for various areas, such as fire protection of cultural heritage structures [25], safety measures in the chemical industry [26], and nuclear safety in radiation field [27]. TOPSIS is the method by which the chosen candidate should choose the shortest distance from the ideal solution. However, the real multi-indexes decision-making judgment often involves imprecise and fuzzy. The FCE method is a comprehensive assessment method using fuzzy mathematics theory and fuzzy relation synthesis principle to quantify the fuzzy index of the system by determining membership degree. The FCE method was used widely in fields such as assessing water environmental safety [28] and prediction of freeway accident severity [29]. In addition, fuzzy sets theory is an effective method to solve the imprecision problem of rustling from a lack of data [30]. The triangular fuzzy numbers method was used in evaluating the qualitative criteria of clean agents [31]. There is no ideal solution that optimizes all objectives. In order to optimize evaluation methods, extended AHP methods, such as fuzzy AHP [32], AHP-TOPSIS [33], and AHP, with integration of the quality control analysis method [34], have been studied.

In this study, based on the evaluation indexes of fire-extinguishing agents and the scenario of an electrochemical energy storage power station, the assessment index system of fire-extinguishing agents used for LIBs was constructed. Secondly, the weights of each evaluation index were calculated by the AHP method. Finally, based on the related references and previous data of the fire extinguishing tests, the AHP-fuzzy TOPSIS method was used to perform a comprehensive performance evaluation of three kinds of clean fire-extinguishing agents. The study provided a method for selecting and preparing a suitable fire-extinguishing agent for LIBs, which is valuable for suppressing the electrochemical energy storage power station fire.

2. Methodology

Firstly, the evaluation indexes of fire-extinguishing agents were selected based on the application scenario. The evaluation index generally contains first-level indexes and second-level indexes. Therefore, the fire-extinguishing agent index hierarchy model should be established in this phase. The weight of the index was assessed using by AHP method in this study. The main influencing factors of the efficiency of fire-extinguishing agents were determined, which could provide a basis for preparing an effective fire-extinguishing agent. Secondly, the assessed schemes were chosen, and the three kinds of fire-extinguishing agents were compared in this study. The assessment methods should be confirmed and AHP-fuzzy TOPSIS method was chosen in this work. In this phase, the normalization of the fuzzy decision matrix and weighted normalized fuzzy decision matrix were finished in this study. In addition, the raw data of the evaluation index was obtained from previous references and related references. The evaluation indexes generally contain some unobtainable indexes, such as the qualitative index. The qualitative indexes were evaluated by a panel of experts using languishing variables in this study. Finally, the evaluation objects were obtained from the size of proximity.

3. Materials and Methods

3.1. Evaluation Index

The assessment index system could reflect the exhaustive dimensions of the efficiency of fire-extinguishing agents, and the entirety and correctness of the index system could determine the accuracy of the assessment results. Therefore, a comprehensive assessment index system is an important factor in the assessment capability of the model. In order to assess the performance of fire-extinguishing agents, the indexes mainly have

one or more of the following features. Firstly, the variety of indexes could reflect the extinguishing efficiency; secondly, the indexes must be available. According to literature investigation [35], four first-level indexes consisting of technical index, economic index, environmental protection index, and applicability index were selected in this study. To analyze the comprehensive performances of fire-extinguishing agents quantitatively, most of evaluation indexes are quantitative. The seven secondary-level quantitative indexes were selected in this paper, as shown in Table 1. The mode is only suitable for assessing the water-based fire extinguishing for suppressing lithium iron phosphate battery fire.

Table 1. Evaluation indexes of fire-extinguishing agent.

No.	First-Level Indexes	Second-Level Indexes
1	Technical index	Extinguishing time (s)
2		Heat absorption capacity (kJ)
3		Number of batteries happen to TR
4		H ₂ concentration reduction (ppm)
5	Economic index	Cost (RMB/L)
6	Environmental protection index	GWP
7		ALT
8		NOAEL
9	Applicability index	Boiling point at 1 atm (°C)
10		Electric conductivity ($\mu\text{s}\cdot\text{cm}^{-1}$)
11		Residual quantity

3.1.1. Technical Index

The technical index of a fire-extinguishing agent is an important parameter in its application engineering, which indicates its extinguishing efficiency. In order to prevent TR propagation and re-ignition of LIB, it needs to consider the quick extinguishment of the LIB fire and the immediate stop of TR propagation occurring in the battery module [35]. Therefore, extinguishing time and heat absorption capacity were considered as the technical index in the study. Moreover, the number of batteries that happen to TR is a direct index to assess the ability to suppress TR of fire-extinguishing agents. Obviously, the fewer the number of batteries that happen to TR, the better the extinguishing efficiency of the fire-extinguishing agent. In previous study, it is necessary to improve the battery safety that reduces the concentration of H₂ in vented gases [36]. The reduction of H₂ concentration could reflect the ability to reduce explosion risk of fire-extinguishing agents. Hence, H₂ concentration reduction was considered as a technical index of fire-extinguishing agent in this study.

3.1.2. Economic Index

It needs to consider the cost of the fire-extinguishing agent, which decides its application value to some extent [36]. For instance, the cost of the fire-extinguishing agent is critical to low-profit scenario, which could impact the scope of application. As we know, water is the cheapest fire-extinguishing agent. Hence, three kinds of water-based fire-extinguishing agents were compared in the paper.

3.1.3. Environmental Protection Index

Environmental destruction during TR propagation is an essential index for environmental protection. In order to assess the environmental protection index, including the global warming potential value (GWP), atmospheric lifetime (ALT), and no observable harmful effects (NOAEL) were chosen in the paper based on environmental indexes and

safety indexes of fire-extinguishing agents [37]. The lower these values are, the better the selected environmental protection and safety performance are. These environmental protection indexes are common indexes in assessing the environmental protection performance of fire-extinguishing agents [37].

3.1.4. Applicability Index

The applicability index is important in assessing the reliability of fire-extinguishing agents. Short circuit may be caused in battery system when water connects the anode with the cathode of LIB. Therefore, the insulation performance of fire-extinguishing agents was concerned with assessing the damage degree of the fire-extinguishing agents [36]. The electric conductivity was chosen in this paper. During the early fire accident of electrochemical energy storage power station scenario, the fire-extinguishing agent with good conductor may cause the external short circuit of the intact batteries and then cause the fire. For electric vehicles (EVs) and electric vertical takeoff and landing (eVTOL), the electric conductivity is not so important because these battery packs have passed a strict waterproof test. As we know, the electric conductivity is proportional inversely to the insulation. As a critical point, the temperature of dual-phase and boiling point play significant roles in direct liquid cooling technology [38]. The lower the boiling point of the fire-extinguishing agent, the better the cooling rate of fire-extinguishing. Therefore, the boiling point was chosen as a secondary index in the study. Additionally, residual quantity is also an essential index in evaluating the damage degree after releasing fire-extinguishing agent. The residual quantity would affect the secondary use of LIBs. The more the residual quantity of fire-extinguishing agent on the battery module retain, the worse the reused possibility of batteries is. Therefore, residual quantity was chosen in this study to assess the applicability index of fire-extinguishing agent.

3.2. AHP

The indexes of the target layer are divided into primary layer and secondary layer, and the weights of the indexes are determined scientifically to ensure the comparability of the evaluation indexes. At present, the common weight determination methods include Delphi method, AHP, and principal component analysis of data statistical processing [39]. Delphi method is a qualitative analysis method. However, the method has a certain subjective one-sidedness, and it is easy to ignore the suggestions of a few people, resulting in a great deviation from the actual results. Principal component analysis is a quantitative weight analysis method which requires the perfect dates to calculate. AHP is a qualitative and quantitative analysis method which requires less quantitative data information without losing accuracy. Some evaluation indexes of fire-extinguishing agents are qualitative, such as GWP, ATL, NOAEL, and residual quantity. Different criteria also have different effects on fire-extinguishing agents. Whether or not the weight is scientific would affect the accuracy of fire-extinguishing agent adaptation. Therefore, this paper adopted AHP to build a hierarchical structure model according to four first-level indexes motioned above, as displayed in Figure 1. The main steps of AHP consist of the structure of hierarchical analysis, construction of judgment matrix, and the consistency test calculating the weight. All calculations were verified to be consistent across Excel 2016 (Version 1808).

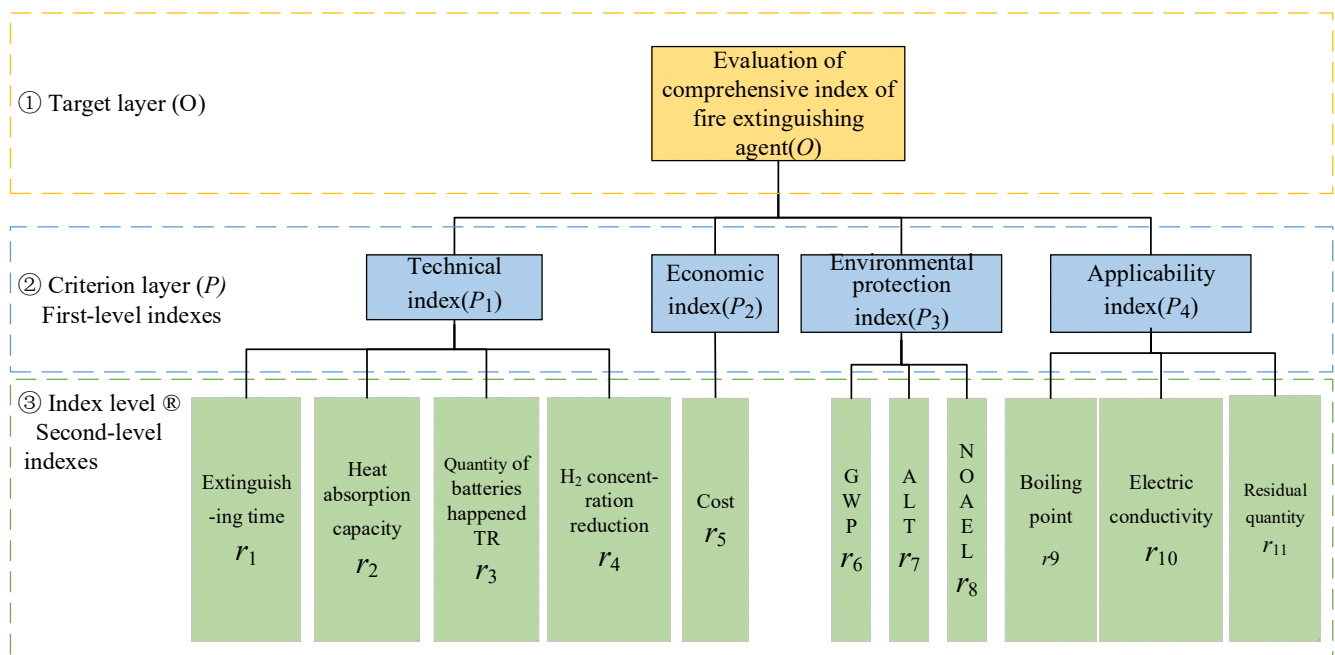


Figure 1. Fire-extinguishing agent index hierarchy model.

3.3. TOPSIS Method

TOPSIS is a common kind of comprehensive evaluation method. The approach could avoid the subjectivity of the data and does not need the objective function. Meanwhile, the approach does not need to pass the test and thoroughly describes the influence of multiple indicators. This method can take full advantage of the original data, and the calculated results could precisely reflect the gap between assessment schemes. Compared with other evaluation methods, TOPSIS is more flexible and convenient to use, and there is no strict restriction on the sample size and the number of indexes. The procedure of the assessment method is shown under the following steps:

- Step 1. Foundation of the index hierarchy model;
- Step 2. Using AHP to determine the weights of indexes;
- Step 3. Normalization of fuzzy decision matrix;
- Step 4. Optimal scheme and the worst scheme are obtained based on the decision matrix;
- Step 5. Calculating the nearness between each evaluation object and the best and worst object;
- Step 6. Ranking the evaluation objects according to the size of proximity.

3.4. AHP–Fuzzy TOPSIS Method

After data processing of four evaluation indexes, including technical index, economic index, environmental protection index, and application index, the improved AHP–fuzzy TOPSIS approach was applied to completely assess the comprehensive performance of fire-extinguishing agents, and the evaluation process is expressed in Figure 2. Based on the improved TOPSIS approach, the performance of fire-extinguishing agent was evaluated comprehensively. Traditional TOPSIS seeks the best and worst values of each index from the evaluation scheme to form positive and negative ideal solutions but does not consider the weights and fuzzy indexes. The weights and the quantitative and qualitative indicators were considered by the improved TOPSIS. Therefore, the decision maker could make the decision with absolute confidence though the fuzzy context affecting the problem.

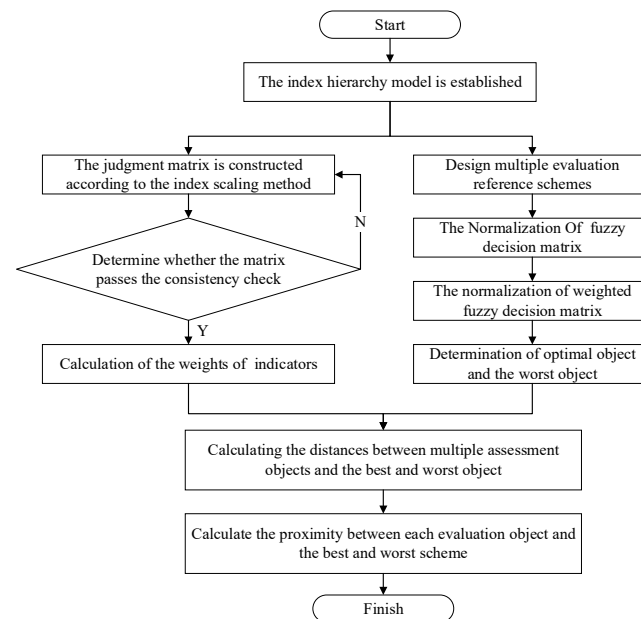


Figure 2. Flow chart of power station safety assessment based on improved AHP-TOPSIS.

4. Results and Discussion

4.1. Determination of Evaluation Index Weights

A pairwise comparison is the process that the indexes mentioned above have been conducted with Saaty's scale [40]. In the study, the weights of both fire-level indexes and second-level indexes are determined subsequently by the AHP method.

Definition 1. The scale was compared, and the judgment matrix was constructed.

As shown in Table 1, the importance of the assessment index was analyzed, and the judgment matrix of the criterion layer and index layer was constructed. The opinion judgment matrixes are shown in Tables 2–5. For example, the target layer elements were associated with the criterion elements P_1 , P_2 , P_3 , and P_4 . Then, the judgment matrix shown in Table 2 was established. The technical index (P_1) is more important than the economic index and environmental protection index, thus, choice 5 in the judgment matrix of $O-P$. For example, the economic index and environmental protection index are equally important, thus, choice 1 in the judgment matrix of $O-P$. The technical index (P_1) is slightly greater than that of the applicability index (P_4), but it is not so significant, thus, choice 3 in the judgment matrix of $O-P$. If criterion A is assigned a value of x compared to criterion B, then criterion B's importance relative to A is $1/x$. In the pairwise comparison between P_4 and P_1 , the reciprocal of the element was taken as. The one criterion is very strongly dominant, thus, choice 7. The importance of one criterion over the other is affirmed to the highest possible order, thus, choice 9 in the judgment matrix of $O-P$. The other elements in the judgment matrixes P_i-r were chosen in the same method. In addition, the judgment matrix of P_2-r is 1 because P_2 has only one index.

Table 2. Judgment matrix of $O-P$.

$O-P$	P_1	P_2	P_3	P_4
P_1	1	5	5	3
P_2	1/5	1	1	1/2
P_3	1/5	1	1	1/2
P_4	1/3	2	2	1

Table 3. Judgment matrix of P_1-r .

P_1-r	r_1	r_2	r_3	r_4
r_1	1	3	5	1
r_2	1/3	1	2	1/3
r_3	1/5	1/2	1	1/4
r_4	1	3	4	1

Table 4. Judgment matrix of P_3-r .

P_3-r	r_6	r_7	r_8
r_6	1	2	3
r_7	1/2	1	1
r_8	1/3	1	1

Table 5. Judgment matrix of P_4-r .

P_4-r	r_9	r_{10}	r_{11}
r_9	1	1/4	1
r_{10}	4	1	5
r_{11}	1	1/5	1

It can be shown in Tables 2–5 that the judgment matrix is a positive definite inverse matrix, so a unique maximum eigenmatrix exists. It is very difficult to obtain the eigenvector w and the exact eigenvalue of the positive definite inverse matrix, and only the approximate value can be calculated, which is generally solved by the root method. The n root of the product of each row of the judgment matrix is calculated:

$$w_{ij} = \sqrt[n]{\prod_{j=1}^n a_{ij}} \quad (1)$$

where $j = 1, 2, 3, \dots, n$; a_{ij} is the ratio of the importance of factor i to factor j .

Definition 2. Consistency check.

The data in Table 2 is substituted into Equation (1) to obtain the approximate value of the weight vector of the evaluation factor, as follows: $w_{ij} = (2.94, 0.56, 0.56, 1.07)^T$. The vector $W_i = (w_{i1}, w_{i2}, \dots, w_{in})$ is normalized as follows:

$$w'_{ij} = w_{ij} / \sum_{j=1}^n w_{ij} \quad (2)$$

Thus, the weight vector of criterion layer indexes was obtained.

$$W'_i = (0.57, 0.11, 0.11, 0.21)^T$$

The greatest eigenvalue of the weight vector was calculated, and the consistency of the judgment matrix was tested as follows:

$$C_i = \frac{\lambda_{\max} - n}{n - 1} \quad (3)$$

where λ_{\max} represents the determination of the maximum eigenvalue of the matrix.

$$\lambda_{\max} = 4.0042$$

The consistency index was calculated according to Equation (3).

$$C_i = \frac{\lambda_{\max} - n}{n - 1} = \frac{4.0042 - 4}{3} = 0.0014$$

Random consistency ratio was calculated as a consistency method between pair judgment matrices.

$$C_R = \frac{C_i}{R_i} \quad (4)$$

where C_i is the consistency test index and R_i is the average consistency index. As shown in Table 6, the fourth-order matrix R_i is 0.89 [41]. It can be calculated according to Equation (4):

$$C_R = \frac{C_i}{R_i} = \frac{0.0014}{0.89} = 0.00156 < 0.1$$

Table 6. Value of R_i .

Rank (n)	1	2	3	4	5	6	7	8	9	10
R_i	0.00	0.00	0.52	0.89	1.12	1.25	1.35	1.42	1.46	1.49

The results show that consistency is satisfied.

A similar process can be obtained:

The P_{1-r} matrix: $\lambda_{\max} = 4.02$; C_i is 0.0065, and R_i is 0.89. Then,

$$C_R = \frac{C_i}{R_i} = \frac{0.0065}{0.89} = 0.0073 < 0.1$$

The same method was used in calculating the consistency test of other matrixes. The results of the consistency test of other matrixes are shown in Table 7.

Table 7. Value of C_R .

	P_{1-r}	P_{3-r}	P_{4-r}
λ_{\max}	4.02	3.02	3.01
C_i	0.0065	0.0091	0.0028
R_i	0.89	0.52	0.52
C_R	0.0073	0.0176	0.0053

Definition 3. *Weight calculation.*

The total hierarchical sorting results are expressed in Table 8. The previous study discussed the comprehensive performance of different fire-extinguishing fires based on many indexes [35]. These indexes were considered equally important. Obviously, the weights of these indexes are different. According to the above calculation, the weight value of fire extinguishing time is 0.228, which is the largest among the 11 s-level indexes. In addition, the weight value of H_2 concentration reduction (ppm) is the second largest index, which is 0.217. This result could provide a significant direction for research in developing fire-extinguishing agents for LIBs. Therefore, in the development of a fire extinguishing agent, it can be considered to add effective flame retardants and adsorption H_2 gas components to the fire extinguishing agent.

Table 8. Hierarchy total sort result.

<i>P-r</i> Sort	<i>O-P</i> Rank				Hierarchical Total Sort Weight
	$P_1 = 0.571$	$P_2 = 0.110$	$P_3 = 0.110$	$P_4 = 0.210$	
r_1	0.40				0.228
r_2	0.14				0.080
r_3	0.08				0.046
r_4	0.38				0.217
r_5		1			0.110
r_6			0.55		0.061
r_7			0.24		0.026
r_8			0.20		0.022
r_9				0.16	0.034
r_{10}				0.69	0.145
r_{11}				0.15	0.033

The calculated weight vector is as follows:

$$\vec{w} = (0.228, 0.080, 0.046, 0.217, 0.110, 0.061, 0.026, 0.022, 0.034, 0.145, 0.033)$$

4.2. Normalization of Fuzzy Decision Matrix

The raw data of eleven indexes is mainly from our previous tests [23,42] and consulted information. As discussed above, qualitative indexes, such as the GWP, ALT, NOAEL, and residual quantity, were assessed by a panel of experts applying languishing variables. The panel consisted of fire protection experts for electrochemical energy storage power plants, one environmental protection expert, and one plant manager. The nine linguistic variables have been used in this study. The variables were transformed into a triangular fuzzy number within the interval 0–1, as shown in Table 9.

Table 9. Qualitative evaluation table of each index based on triangular fuzzy number.

Qualitative Level	Description	Write Code	Grade Function
Level 1	Extremely Disagree	ED	(0.00, 0.00, 0.20)
Level 2	Very Disagree	VD	(0.10, 0.20, 0.30)
Level 3	Disagree	D	(0.20, 0.30, 0.40)
Level 4	Moderately Disagree	MD	(0.30, 0.40, 0.50)
Level 5	Neutral	N	(0.40, 0.50, 0.60)
Level 6	Moderately Agree	MA	(0.50, 0.60, 0.70)
Level 7	Agree	A	(0.60, 0.70, 0.80)
Level 8	Very Agree	VA	(0.70, 0.80, 0.90)
Level 9	Extremely Agree	EA	(0.80, 1.00, 1.00)

These three fire-extinguishing agents include pure water, 3%F-500, and YS1000. The judgments of experts on qualitative indexes and the numerical values on the quantitative indexes are summarized in Table 10.

Table 10. The data of comprehensive evaluation index of fire-extinguishing agents.

Primary Index	Secondary Index	Water	3%F-500	YS1000
Technical index	Extinguishing time (s)	30	22	1
	Q_c (kJ)	43.7	118.2	74.6
	Number of batteries happen to TR	3	1	1.5
	H ₂ concentration reduction (ppm)	259	462	439
Economic index	Cost (YMB/L)	0.004	150	16.6

Table 10. Cont.

Primary Index	Secondary Index	Water	3%F-500	YS1000
Environmental index	GWP	(0.00, 0.00, 0.20)	(0.00, 0.00, 0.20)	(0.00, 0.00, 0.20)
	ALT	(0.00, 0.00, 0.20)	(0.00, 0.00, 0.20)	(0.00, 0.00, 0.20)
	NOAEL	(0.00, 0.00, 0.20)	(0.10, 0.20, 0.30)	(0.20, 0.30, 0.40)
Applicable index	Boiling point (°C)	100	120	≈100
	Electric conductivity (μs·cm ^{−1})	4.48	416	26.9
	Residual quantity	(0.00, 0.00, 0.20)	(0.20, 0.30, 0.40)	(0.20, 0.30, 0.40)

The TOPSIS method gives the normalization of the decision matrix:

$$\tilde{D} = [\tilde{r}_{ij}]_{m \times n} \quad (5)$$

where \tilde{r}_{ij} is the normalized values in Table 10 that state the value for the fire-extinguishing agent i with respect to the generic index j . The indexes could conclude the efficiency index and cost index. The normalization operation is needed:

$$\tilde{r}_{ij} = \frac{[r_{ij} - \min(r_{ij})]}{[\max(r_{ij}) - \min(r_{ij})]} \quad (6)$$

$$\tilde{r}_{ij} = \frac{[\max(r_{ij}) - r_{ij}]}{[\max(r_{ij}) - \min(r_{ij})]} \quad (7)$$

Equation (6) is used when the index represents the efficiency index, such as heat absorption capacity and H₂ concentration reduction. Equation (7) is used when the index is the cost index, such as the number of batteries that happen to TR, cost, GWP, ALT, NOAEL, boiling point, electric conductivity, and residual quantity. Therefore, the value 1 always expresses the best fire-extinguishing agent. For the case study, the normalized fuzzy decision matrix is shown in Table 11. The second step of normalization of the fuzzy decision matrix is to finish the weighted normalized fuzzy decision matrix:

$$\tilde{V} = \begin{bmatrix} w_1 \tilde{r}_{11} & w_2 \tilde{r}_{12} & \cdots & w_n \tilde{r}_{1n} \\ w_1 \tilde{r}_{21} & w_2 \tilde{r}_{22} & \cdots & w_n \tilde{r}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_1 \tilde{r}_{m1} & w_2 \tilde{r}_{m2} & \cdots & w_n \tilde{r}_{mn} \end{bmatrix} = \begin{bmatrix} \tilde{v}_{11} & \tilde{v}_{12} & \cdots & \tilde{v}_{1n} \\ \tilde{v}_{21} & \tilde{v}_{22} & \cdots & \tilde{v}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{v}_{m1} & \tilde{v}_{m2} & \cdots & \tilde{v}_{mn} \end{bmatrix} \quad (8)$$

Table 11. Normalized fuzzy decision matrix.

Denomination	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8	r_9	r_{10}	r_{11}
Water	0.000	0.000	0.000	0.000	1.000	(0.00, 0.00, 0.20)	(0.00, 0.00, 0.20)	(0.00, 0.00, 0.20)	1.000	1.000	(0.00, 0.00, 0.20)
3%F-500	0.276	1.000	1.000	1.000	0.000	(0.00, 0.00, 0.20)	(0.00, 0.00, 0.20)	(0.10, 0.20, 0.30)	0.000	0.000	(0.20, 0.30, 0.40)
YS1000	1.000	0.415	0.750	0.887	0.889	(0.00, 0.00, 0.20)	(0.00, 0.00, 0.20)	(0.20, 0.30, 0.40)	0.000	0.946	(0.20, 0.30, 0.40)

For the case study, the weighted decision matrix is shown in Table 12.

Table 12. Weighted normalized fuzzy decision matrix.

Denomination	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8	r_9	r_{10}	r_{11}
Water	0.000	0.000	0.000	0.000	0.110	(0.000, 0.000, 0.012)	(0.000, 0.000, 0.005)	(0.000, 0.000, 0.004)	0.034	0.145	(0.000, 0.000, 0.007)
3%F-500	0.063	0.080	0.046	0.217	0.000	(0.000, 0.000, 0.012)	(0.000, 0.000, 0.005)	(0.002, 0.004, 0.007)	0.000	0.000	(0.007, 0.010, 0.013)
YS1000	0.228	0.033	0.035	0.192	0.098	(0.000, 0.000, 0.012)	(0.000, 0.000, 0.005)	(0.004, 0.007, 0.008)	0.000	0.137	(0.007, 0.010, 0.013)

Table 12. Cont.

Denomination	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8	r_9	r_{10}	r_{11}
\tilde{V}^+	0.228	0.228	0.228	0.228	0.228	(0.228, 0.228, 0.228)	(0.228, 0.228, 0.228)	(0.228, 0.228, 0.228)	0.228	0.228	(0.228, 0.228, 0.228)
\tilde{V}^-	0.000	0.000	0.000	0.000	0.000	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)	0.000	0.000	(0.000, 0.000, 0.000)

4.3. Determination of Optimal Scheme and the Worst Scheme

The positive ideal solution of profitability index set J_1 represents the biggest value of the row vector, and the negative ideal solution represents the minimum value of the row vector. The value of the economic index set J_2 is the reverse of that of the profitability index, which is calculated by the following Equations:

$$\tilde{V}^+ = \{(\max \tilde{v}_{ij} | j \in J_1), (\min \tilde{v}_{ij} | j \in J_2)\} \quad (9)$$

$$\tilde{V}^- = \{(\min \tilde{v}_{ij} | j \in J_1), (\max \tilde{v}_{ij} | j \in J_2)\} \quad (10)$$

However, Equations (9) and (10) were not preferred in the fuzzy context, the fuzzy positive ideal solution \tilde{V}^+ , and the fuzzy negative ideal solution \tilde{V}^- , taking into account $\tilde{v}_j^+ = (0.228, 0.228, 0.228)$ and $\tilde{v}_j^- = (0.000, 0.000, 0.000)$ since the maximum score in Table 12 is 0.228.

4.4. Calculation of the Distance Between Multiple Assessment Objects and the Best and Worst Object

For the sake of receiving a final rank, a fuzzy distance function was used in this work. The distance of each fire-extinguishing agent from \tilde{V}^+ and \tilde{V}^- could be calculated using the following Equations (11) and (12). In order to simplify the calculation, the sum of fuzzy homologous components was considered as the fuzzy distance. The calculated results are expressed in Table 13.

$$S_i^+ = \sqrt{\sum_{j=1}^n (\tilde{v}_{ij} - \tilde{v}_j^+)^2} \quad (11)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (\tilde{v}_{ij} - \tilde{v}_j^-)^2} \quad (12)$$

Table 13. Result of fuzzy TOPSIS analysis.

Denomination	S_i^+	S_i^-	\tilde{C}_i
Water	(0.689, 0.689, 0.684)	(0.185, 0.185, 0.185)	(0.212, 0.212, 0.213)
3%F-500	(0.665, 0.626, 0.624)	(0.244, 0.244, 0.244)	(0.268, 0.280, 0.281)
YS1000	(0.599, 0.554, 0.551)	(0.346, 0.346, 0.346)	(0.366, 0.384, 0.386)

4.5. Calculating the Proximity Between Each Assessment Scheme and the Best and Worst Object

Subsequently, the proximity combines the two distances by Equation (13):

$$\tilde{C}_i = S_i^- / (S_i^+ + S_i^-) \quad (0 \leq \tilde{C}_i \leq 1) \quad (13)$$

where S_i^+ is the distance between the evaluation scheme and positive ideal solution, S_i^- is the distance between the evaluation scheme and negative ideal solution, and \tilde{C}_i is relative proximity coefficient. The calculated results are expressed in Table 13.

Preference rank of fire-extinguishing agents is determined in decreasing order of \tilde{C}_i . The fuzzy numbers in Figure 3. are the values of \tilde{C}_i and show the fuzzy ranking

associated with every fire-extinguishing agent. The spread of the triangles represents the amount of fuzzy in the experts' judgments. The wider of overlapping zone translates into high uncertainty related to the rank, the harder to obtain a clear preference. As shown in Figure 3, the spread of the triangles of F-500 is almost equal to that of YS1000, while the spread of the triangles is almost 0. The results indicated that the uncertainty related to the rank is low. The result is significant in assessing the reliability of effectiveness of fire-extinguishing agents, which provided more information. However, in the existing literature, the rank of the effectiveness of fire-extinguishing agents is certain, which is not in line with the actual situation [35]. In addition, the results indicated that YS1000 was the best fire-extinguishing agent in the three chosen solutions, which is consistent with previous experimental results [40]. The triangle of each fire-extinguishing agent does not intersect with another, so the decision marker could make the decision with absolute confidence through the fuzzy context affecting the problem. Surely, pure water is not proper for the application considered. An additional conclusion is that the F-500 additive is superior to pure water, which is consistent with the results discussed in the introduction.

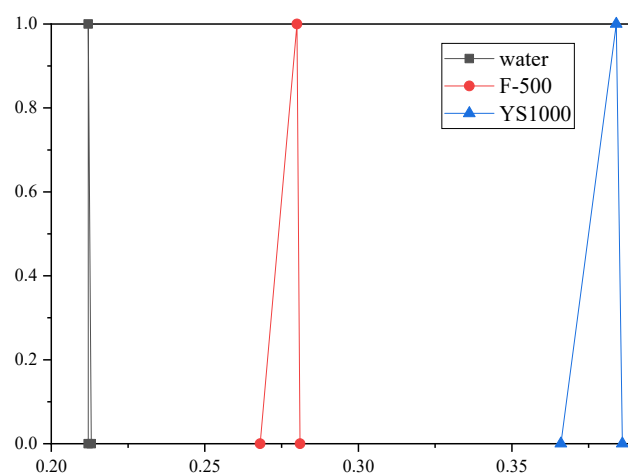


Figure 3. Fuzzy ranking.

5. Conclusions and Future Directions

This study indicated that AHP–fuzzy TOPSIS is a suitable decision-making tool in dealing with the fire-extinguishing agents used for LIBs fire chosen problem, particularly considering the quantitative and qualitative indexes in the assessment hierarchical model. The method could enable the maker to build decision indexes and obtain relative importance depending on the judgments of experts. Results showed that fuzzy sets not only allow to achieve the rank among the chosen solutions but also to confirm the confidence level, and mainly the following conclusions were obtained.

- (1) The comprehensive performance index system of the fire-extinguishing agent was classified, including eleven second-level indexes, including fire extinguishing time, cooling effect, number of thermal runaway batteries, H₂ concentration reduction, cost, GWP, ALT, NOAEL, boiling point, electric conductivity, and residual quantity. The mode is only suitable for assessing the water-based fire extinguishing for suppressing lithium iron phosphate battery fire.
- (2) The AHP was used to calculate the weights of the eleven evaluation indexes, and the consistency test was finished. The weight value of fire extinguishing time is 0.228, which is the largest among the 11 s-level indexes. Therefore, flame retardant should be considered a significant ingredient of fire-extinguishing agents used for LIBs. The weight value of the NOAEL index is 0.022, which is the smallest among

these second-level indexes. The proposed method possesses the more correct and rational direction in determining the best fire-extinguishing agent.

- (3) The AHP–fuzzy TOPSIS calculated method was established, which is used to sort the comprehensive quality of the water-based fire-extinguishing agent used for LIBs fire selection accurately and objectively. The rank of comprehensive properties of fire-extinguishing agents was obtained as follows: YS1000 > F-500 > pure water. The calculated result is consistent with the tested result, which proved the feasibility of the approach. It provides an idea for the selection of other water-based fire-extinguishing agents used for lithium iron phosphate batteries.

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