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Research Article

Semantic Approach for Evaluation of Energy Storage Technologies under Fuzzy Environment

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Energy storage systems are becoming increasingly important, with a growing focus on renewable energy sources that provide highly fluctuating output. Therefore, sound decisions regarding the energy storage systems to be employed need to be made, especially with a systematic and semantic approach. This paper considers the problem of evaluation and selection of energy storage technologies (ESTs). The objective of the proposed research is to decide the best technology for energy storage under the novel idea of hybrid multicriteria decision-making technique under fuzzy environment, that is, fuzzy AHP with fuzzy VIKOR. Electrochemical storage, electrical storage, magnetic storage, mechanical storage, and chemical storage are considered as five alternative energy storage technologies. Energy density, life cycles, cycle efficiency, investment level, suitability to climatic conditions, and required space are considered as six main evaluation criteria. Under each of the main criteria, a set of subcriteria are also considered. The weights of main criteria and subcriteria are determined using fuzzy AHP. With the help of the weights of each set of subcriteria, the weights of alternatives are determined using fuzzy VIKOR. Further, with the help of the main criteria weights and the weights of alternatives determined with respect to each set of subcriteria, the final normalized weights of alternatives are determined. Based on these weights, energy storage technologies are ranked. In addition, the sensitivity analysis is carried out to analyze the variation in ranking pattern of alternatives. From the research findings of this paper, the results are found to be more practical as the evaluation is carried out on an objective basis.

1. Introduction

The energy sector (ES) today is forging its way into uncharted domains with the advent of renewable and alternative energy systems. This brings with it an uncertainty of the viability of such projects [1]. Energy systems engineers and designers do not see eye to eye with the decision-making executives. Engineers' requests and innovations may often get overlooked by the chief financial officer of the company due to various financial jargons.

Working in tandem and fabricating a methodology for analyzing all the aspects, be it technical or commercial, can lead to the effective and successful implementation of a project in the energy sector. Absolute certainty is of essence, and any degree of uncertainty should be avoided at all costs. Energy planners have to consider several criteria while ascertaining the best decision regarding energy projects. The energy sector accounts for large amounts of a nation's economy and is what can make or break a nation's ability for economic growth. Without adequate energy sources, no economy can expect to take giant leaps in terms of development. Therefore, decision analysis can be considered as important as the decision-making procedure itself, if not more.

Moreover, microgrids are becoming state of the art in the domain of energy production and distribution. Microgrids ensure local power reliability, independence, electricity power system, and storage flexibility [2]. Such microgrids attempt to incorporate more sustainable and eco-friendly energy sources in order to emphasize energy independence. Therefore, due to the intermittent nature of renewable energy production, optimum energy storage technology (EST) is mandatory to ensure efficiency and round the clock electrical supply. Energy storage systems serve the role of energy backups or buffers to balance supply and demand [2]. Environment and energy are slated to become the two most complex global challenges shortly [3]. Transmission, distribution, and transport are the three sectors pegged to be the most promising areas where energy storage technologies can be fully utilized. ESTs can also eliminate the need for expensive upgrades and regulate the renewable energy fluctuation that almost definitely occurs according to the climatic conditions [3].

Electrochemical energy storage systems harness the electricity generated by various methods of energy production to drive chemical reactions against the natural flow. This leads to energy generation when the chemicals are allowed to react naturally, leading to the transfer of electrons. Batteries are an example of rechargeable electrochemical ESTs [4]. The battery may consist of one or more cells connected in different combinations according to the application requirement, such as output voltage and capacity [4]. Electrical ESTs employ hardware to separate charges. Therefore, electrical ESTs store energy employing static charge as compared to the electrochemical process used by batteries for energy storage [4]. Supercapacitors are examples of such ESTs. Supercapacitors possess electrolyte layer measuring nanometers to make high surface area capacitors that separate static charges. Once the surfaces come into contact, the usual operating principle of a capacitor applies. Magnetic ESTs store energy in the form of magnetic energy. Superconducting magnetic energy storage (SMES) technologies are considered the sole EST to store flowing electricity [5] as it generates a magnetic field within which the energy is stored. SMES tends to be highly efficient, scalable, eco-friendly, and fast responding, but at the same time, it can be costly as well. There are essentially no losses as superconducting coils are used [5].

Mechanical ESTs use electrical energy to generate kinetic energy [4]. This kinetic energy can then be converted to electrical energy by driving a generator as and when the need arises. A flywheel is one such mechanical EST. It consists of a mass that rotates about a central axis and stores mechanical energy in kinetic energy. Electrical energy is used to accelerate the flywheel and increase the speed of rotation. Therefore, it acts as a mechanical battery in which the energy is stored as moment of inertia of the rotating mass of the flywheel. The energy is then retrieved by attaching the flywheel to a generator, which reduces the speed of rotation, and hence, kinetic energy is thus converted to electrical energy [4]. Chemical ESTs utilize chemical properties of elements such as endotherm and exotherm characteristics to store energy [4]. One such example is that of metal hydrides, where metals readily absorb hydrogen when brought in contact. The absorption is endothermic and, therefore, requires energy in the form of heat. Similarly, the desorption of hydrogen is an exothermic reaction, and hence, heat is evolved during this step, which can harness various forms of energy. There are other hydrogen storage technologies such as liquid hydrogen storage but are in their nascent stages of development and, therefore, experience limited use.

Also, it is a fact that many variables, including economic, technological, social, and environmental, must be considered while choosing energy storage technology. Various methods are used to optimize the selection of energy storage technology by employing cutting-edge techniques such as machine learning and multiobjective optimization methods. Selecting an appropriate energy storage option is an issue with various objectives that cannot all be met by a single technology. Possible trade-offs between the potential benefits and drawbacks of various energy storage systems must be considered. Furthermore, the choice to construct a storage unit frequently involves several stakeholders, each of whom may have different interests and goals in mind. Choosing a storage option that provides the greatest advantage while also meeting all requirements is thus an inherently difficult decision.

From the recent past, the usage of multicriteria decision making (MCDM) methods has been gaining popularity in the field of energy management. To solve complex problems concerning energy planning, MCDM techniques have been turned out to be superior tools. MCDM methods provide amicable solutions to the problems of different projects involved with conflicting objectives. Several techniques have been used for decision analysis in energy sector based weighted means, outranking, different fuzzy principles, and their combinations. Generally, in any project, objectives are conflicting in nature, and therefore, the final preference of the project selection purely depends on the opinion of the decision maker. In several cases of decision-making analysis, more than one group of decision makers are allowed to participate. As the set of criteria considered and viewpoint of each group differs, the problem of biasing in decision making process should be resolved within the context of understanding. Due to the potential application of MCDM methods, the scope of these methods is not confined to only one field. Further, these methods can be used with equal degree of importance in all fields of research.

The remaining work of this paper is classified into four sections. Section 2 presents the detailed review of literature carried out inline to the problem domain. The detailed methodology of the proposed work covering hierarchical structure of alternatives, main criteria, and subcriteria, linguistic scale for main criteria, subcriteria and alternatives, step by step procedure for fuzzy AHP, and fuzzy VIKOR are addressed in Section 3. Numerical illustration of the problem is carried out elaborately in Section 4. In Section 5, conclusions and future scope of the work are addressed. Finally, references are included.

2. Literature Review

In today's landscape, we, humans, cannot thrive without electricity consumption. From using it for daily chores to drive vehicle using it as a fuel, it is omnipresent in every part of land. Hence, electrical energy has indeed become one of the necessities of our lifestyle. Storage of this electrical energy is extremely intricate as complex technology must be utilized. With developments, the sophistication in electrical energy storage technologies have enhanced but also bought with it few drawbacks. These issues must be considered while finalizing the technology and require decision analysis process for that.

Further, in the present era of industrial scenario, the usage of MCDM methods has been proved to be significant in the domain of energy sector. Several methodological approaches and algorithms have developed in order to assess and plan energy structures based on more than one criterion. With ever increasing complexity and multiplicity in the problem of energy sector, the optimization or analysis of single objective is no longer a predominant approach. So, Kumar and Katoch [6] explored in their work that MCDM methods are used to evaluate and solve environmental constraints, socioeconomic issues, technical challenges, and institutional obstructions involved in the power sector.

The usage of MCDM methods has become popular in energy sector as it assists decision makers to keep attention to all available criteria and take appropriate decisions on priority basis. Since a flawless design is administered by various factors, decision makers have to consider several other parameters similar to methodological or economical parameters, which have to be compromised in certain conditions. Fuzzy AHP, fuzzy VIKOR, and a combination of both can be used to evaluate different processes when several stakeholders are involved and when the values may not be quantifiable or discrete [7]. MCDM methods allow a decision maker to quantify particular criteria established on its reputation in the existence of supplementary objectives.

Several possible applications were suggested to streamline the process of decision making by individuals and organizations to maximize gains and minimize efforts. It provides a step-by-step explanation of the utilization method of the AHP [8] process. Another MCDM technique, VIKOR, was developed by Opricovic [9] and served to evaluate alternatives often with conflicting or unrelated criteria [10].

Since then, several MCDM techniques have been formulated with their application niches, such as the PROMETHEE, DEMATEL, TOPSIS, and ANP methods. These methods have been utilized with varying degrees of popularity to provide solutions where numerous evaluation criteria are required to evaluate and find the desired alternative. Technical and nontechnical fields alike have witnessed the benefit of the application of such techniques to business activities. These fields include, but are not limited to, productivity evaluation, operations, optimization, facility and site selection, manufacturing, and robotics.

Duran and Aguilo [11] make use of fuzzy AHP to evaluate advanced manufacturing systems. Duran states that using fuzzy set theory permits the incorporation of information that may not be accurate, complete, or even quantifiable such as the utility of fuzzy MCDM techniques. Augustine et al. [12] present a fuzzy Analytical Hierarchy Process (AHP) framework to determine and rate benchmarks for the service sector. Their approach allows for the involvement of several stakeholders in the business to ensure progressive movement. Finally, Chengl et al. [13] present a novel fuzzy AHP approach for improving worker productivity by setting up the priorities required for the necessary productivity improvement where the unit cost forms a sample criterion for worker productivity.

Rostamzadeh et al. [14] used fuzzy VIKOR to evaluate Green Supply Chain Management (GSCM) indicator among its practitioners. A comparative analysis of the results is then presented. Finally, Sedaghat [15] integrates fuzzy AHP, TOPSIS, VIKOR, and SAW techniques to enable productivity improvement in the industry. The importance and effect of three dimensions, human resources and financial and management performance, were evaluated.

Chatterjee and Stević [16] proposed a two-phase model for supplier selection in a manufacturing environment using fuzzy AHP and fuzzy TOPSIS. They considered several qualitative and quantitative type evaluation criteria and ranked the suppliers. Zavadskas et al. [17] used fuzzy AHP for optimal supplier selection decision towards materials purchasing for the production of preinsulated pipes. They considered five suppliers as alternatives and nine evaluation criteria to ensure the execution of procurement process to be more effective. The other related articles reporting the decision analysis include Gayathri and Nagaraju [18], Varun et al. [19], Hasan et al. [20], and Ali et al. [21].

More recently, Seker and Aydin [22] proposed a novel integrated Fuzzy based SWARA and IVIF-WASPAS method in order to determine the most sustainable method to produce hydrogen energy. They used fuzzy based SWARA method to determine the weights of evaluation criteria, whereas IVIF-WASPAS approach is used to rank the alternatives. Jahangiri et al. [23] addressed the prioritization of solar electricity and hydrogen coproduction stations with the consideration of PV losses and different types of solar trackers using TOPSIS approach. From their research findings, they concluded that the maximum solar electricity yield of 35,276 kWh/yr has been obtained for Zahedan under the scenario of optimal fixed angle mode.

Unlike all the aforementioned articles, in this paper, an attempt is made for the evaluation and selection of the best energy storage technologies under the novel idea of hybrid MCDM techniques under fuzzy environment, that is, fuzzy AHP and fuzzy VIKOR. Electrochemical storage, electrical storage, magnetic storage, mechanical storage, and chemical storage are considered as five alternative energy storage technologies. Energy density, life cycles, cycle efficiency, investment level, suitability to climatic conditions, and required space are considered as six main evaluation criteria. Under each of the main criteria, a set of subcriteria are also considered. In the first phase, the weights of main criteria and subcriteria are determined using fuzzy AHP. With the help of these weights, the final normalized weights of alternatives are determined in the second phase using fuzzy VIKOR, and then, the ranking of energy storage technologies is demonstrated. Also, the sensitivity analysis is carried out to analyze the variation in ranking pattern of alternatives.

3. Methodology

This analysis aims to determine the ideal EST that should be used depending on the opinion of several decision-makers. The different alternatives that are considered are shown in Figure 1. The different criteria, based on which the alternatives are rated, are decided and shown in Figure 2. The final ratings of the alternatives are determined using a single hybrid evaluation scheme of fuzzy AHP and VIKOR [7].

3.1. Fuzzy AHP. AHP is a widely used decision-making tool, which is used to handle multicriteria decision-making statements. Based on pairwise comparisons of different criteria and subcriteria, the alternatives are evaluated [24]. Fuzzy AHP considers the randomness of personal judgements and hence gives a complete result. Linguistic terminologies are utilized to perform pairwise comparisons of criteria and alternatives denoted by triangular numbers [24–29].

Step 1: the criteria are compared following the linguistic distinctions shown in Table 1.

If a decision-maker states that criteria m are fairly important than criteria n, then the TFN scale is (4, 5, 6), and the fuzzy scale for the comparison of criteria m to criteria n would be (1/6, 1/5, 1/4).

Equation (1) shows the pairwise comparison values, where $\widetilde{a}_{ij}^{k}$ denotes the k^{th} decision maker's preference of the i^{th} criterion over j^{th} criterion in terms of TFNs.

$$\widetilde{P}^{k} = \begin{bmatrix} \widetilde{x}_{11}^{k} & \cdots & \widetilde{x}_{1n}^{k} \\ \vdots & \ddots & \vdots \\ \widetilde{x}_{n1}^{k} & \cdots & \widetilde{x}_{nn}^{k} \end{bmatrix}. \tag{1}$$

Step 2: an average value for preferences $\widetilde{x}_{ij}$ is taken in case of multiple decision-makers and is calculated using equation (2), where there are n decision-makers.

$$\widetilde{x}_{ij} = \frac{\sum_{k=1}^{n} \widetilde{x}_{ij}^{k}}{K}. \tag{2}$$

Step 3: thus, the updated pairwise comparison matrix is

$$\widetilde{P} = \begin{bmatrix} \widetilde{x}_{11} & \cdots & \widetilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{x}_{n1} & \cdots & \widetilde{x}_{nn} \end{bmatrix}. \tag{3}$$

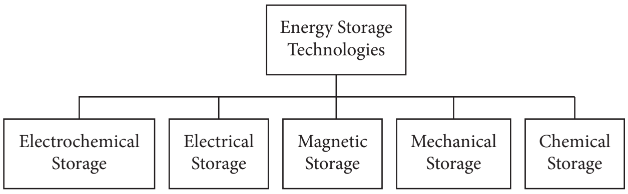

Figure 1: Set of alternative energy storage technologies considered for the analysis.

Step 4: the geometric mean of comparison values for each criterion is determined using equation (4); here, $\widetilde{t}_i$ represents TFN.

$$\widetilde{t}_i = \left(\prod_{j=1}^{n} \widetilde{x}_{ij} \right)^{1/n}, \quad i = 1, 2, 3, \ldots, n. \tag{4}$$

Step 5: summation of each $\widetilde{r}_l$ is calculated to determine the fuzzy weights for every criterion, and the reciprocal summation is calculated following which the TFNs are arranged in ascending order. The weight of criterion I, $(\widetilde{w}_l)$ can be calculated with the help of the following equation:

$$\widetilde{w}_i = \widetilde{t}_i \otimes \left(\widetilde{t}_1 \oplus \widetilde{t}_2 \oplus, \ldots, \widetilde{t}_n\right)^{-1} = \left(lw_i, mw_i, nw_i\right). \tag{5}$$

Step 6: TFNs must undergo defuzzification using the CoA method proposed by [28] using equation (6). This is followed by the normalization of M_i in equation (7).

$$M_i = \frac{lw_i + mw_i + nw_i}{3}, \tag{6}$$

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i}. \tag{7}$$

3.2. Fuzzy VIKOR. The fuzzy VIKOR method is used to solve fuzzy multicriteria problems with conflicting and different units' criteria [26].

Step 1: linguistic terminologies are terms that denote the subjective views of a decision-maker about the subcriterion concerning each alternative being considered [24] from which we obtain TFNs as shown in Table 2.

Step 2: the weight of importance of each criterion is expressed in a vector form by the following equation:

$$\widetilde{W}: \widetilde{W} = \left[\widetilde{a}_1, \widetilde{a}_2, \ldots, \widetilde{a}_n\right], \quad j = 1, 2, \ldots, n. \tag{8}$$

Here, $\widetilde{a}_j$ represents the j^{th} criterion weight based on the linguistic terminology assigned by a decision-maker. In this study, the decision makers' opinions are aggregated. The weight of importance in fuzzy form , $\widetilde{w}_2$ for criterion C_j is obtained by utilizing the following equation:

$$\widetilde{a}_j^{k} = \left(w_{j1}, w_{j2}, w_{j3}\right). \tag{9}$$

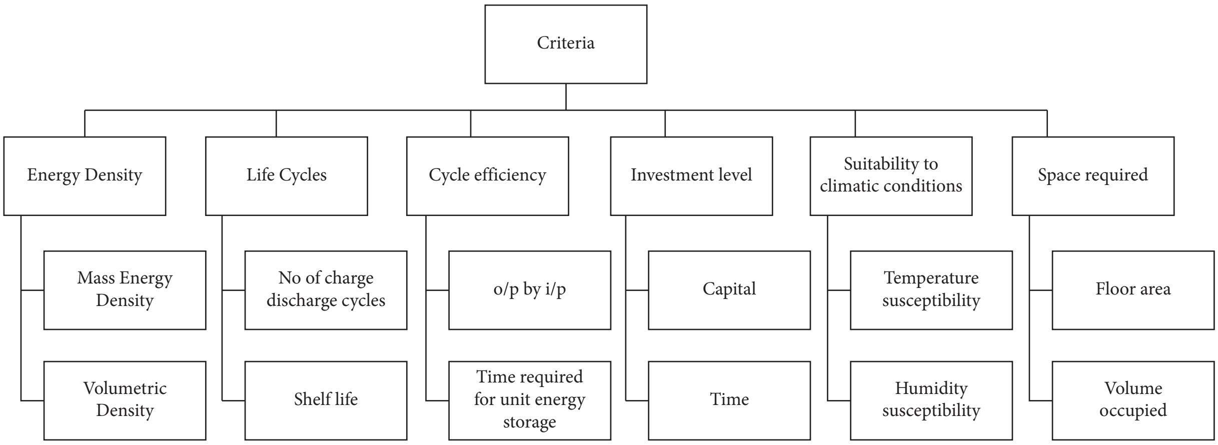

FIGURE 2: Set of main criteria and subcriteria considered for the analysis.

TABLE 1: Linguistic variables for main criteria and subcriteria.

Saaty scale	Definition	Fuzzy triangular number
1	Equally important	(1, 1, 1)
3	Weakly important	(2, 3, 4)
5	Fairly important	(4, 5, 6)
7	Strongly important	(6, 7, 8)
9	Absolutely important	(9, 9, 9)
2	The intermittent values between two adjacent scales	(1, 2, 3)
4		(3, 4, 5)
6		(5, 6, 7)
8		(7, 8, 9)

TABLE 2: Linguistic variables for alternatives.

Linguistic terms	Triangular fuzzy number
Very low (VL)	(0, 0, 0.1)
Medium low (ML)	(0.1, 0.2, 0.3)
Medium (M)	(0.3, 0.4, 0.5)
Medium high (MH)	(0.5, 0.6, 0.7)
Very high (VH)	(0.7, 0.8, 0.9)
Immense (I)	(0.9, 1, 1)

where $w_{j1} = \min_{\mathrm{k}} \{w_{j1}\}$, $w_{j2} = (1/k)\sum_{k=1}^{k} w_{jk2}$, $w_{j3} = \max_k\{w_{jk3}\}w_{jk3}$ for $i = 1$ to m and $j = 1$ to n.

Step 3: a MCDM matrix in fuzzy form is expressed as given in equation (10), with respect to k decision makers ($M_1, M_2, \ldots, M_k$) who were presented with alternatives ($A_1, A_2, \ldots, A_m$) referring to the set of criteria ($C_1, C_2, \ldots, C_n$), where $\tilde{x}_{mn}$ is the rating of alternative A_m with respect to criterion C_j

$$\widetilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix}, \tag{10}$$

where $\tilde{x}_{ij}^k = (p_{ij}^k, q_{ij}^k, r_{ij}^k)$ is a TFN.

Step 4: the fuzzy maximum value $f_i^b = (p_i^b, q_i^b, r_i^b)$ and fuzzy worst vales $f_i^w = (p_i^w, q_i^w, r_i^w)$ are calculated using the following equation:

$$\begin{aligned} \tilde{f}_i^b &= \max_j \tilde{a}_{ij}, \\ \tilde{f}_i^w &= \min_j \tilde{a}_{ij}. \end{aligned} \tag{11}$$

Step 5: the fuzzy difference $\tilde{d}_{ij}$ is calculated using the following equation:

$$\tilde{d}_{ij} = \frac{\left(\tilde{f}_i^b - \tilde{x}_{ij}\right)}{\left(r_i^b - p_i^w\right)}. \tag{12}$$

Step 6: we now calculate the separation $\widetilde{S}_j$ of A_j from the maximum fuzzy value $\tilde{f}_i^b$ and separation $\widetilde{R}_j$ of A_j from the minimum fuzzy value $\tilde{f}_i^w$ using equations (13) and (14). Here, a_j is the weight of importance of the corresponding criterion.

$$\widetilde{S}_j = \sum_{i=1}^{n} \left(\tilde{a}_j \otimes \tilde{d}_{ij}\right), \tag{13}$$

$$\widetilde{R}_j = \max_i\left(\tilde{a}_j \otimes \tilde{d}_{ij}\right). \tag{14}$$

Step 7: $\widetilde{Q}_j = (p_j, q_j, r_j)$ is expressed as TFN and is calculated using the following equation:

$$\widetilde{Q}_j = \frac{v\left(\widetilde{S}_j - \widetilde{S}^{\cdot}\right)}{\left(\widetilde{S}^{oc} - \widetilde{S}^{\cdot a}\right)} \oplus \frac{(1 - v)\left(\widetilde{R}_j - \widetilde{R}^{\cdot}\right)}{\left(\widetilde{R}^{oc} - \widetilde{R}^{\cdot a}\right)}, \tag{15}$$

Table 3: Criteria comparison matrix.

	Energy density	Life cycles	Cycle efficiency	Investment level	Suitability to climatic conditions	Space required
Energy density	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)	(2, 3, 4)	(1/9, 1/9, 1/9)	(6, 7, 8)
Life cycles	(4, 5, 6)	(1, 1, 1)	(1/6, 1/5, 1/4)	(2, 3, 4)	(1/6, 1/5, 1/4)	(5, 6, 7)
Cycle efficiency	(6, 7, 8)	(4, 5, 6)	(1, 1, 1)	(4, 5, 6)	(1/8, 1/7, 1/6)	(7, 8, 9)
Investment level	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1, 1, 1)	(1/8, 1/7, 1/6)	(7, 8, 9)
Suitability to climatic conditions	(9, 9, 9)	(4, 5, 6)	(6, 7, 8)	(6, 7, 8)	(1, 1, 1)	(1/4, 1/3, 1/2)
Space required	(1/8, 1/7, 1/6)	(1/7, 1/6, 1/5)	(1/9, 1/8, 1/7)	(1/9, 1/8, 1/7)	(2, 3, 4)	(1, 1, 1)

where $\tilde{S}^{\cdot} = \min_j \tilde{S}_j$, $\tilde{S}^{oc} = \max_j S^c_j$, $\tilde{R}^{\cdot} = \min_j \tilde{R}_j$, $\tilde{R}^{oc} = \max_j R^c_j$ and $v = ((n+1)/2n)$.

Here, v denotes the strategy weight of maximum criteria, and $(1 - v)$ denotes the weight of the individual regret. Following this calculation, we compute maximum values of S and R, which are $\tilde{S}^b$ and $\tilde{R}^b$ respectively.

Step 8: defuzzification involves the conversion of fuzzy numbers into crisp values. The Centre of Area method is used for ranking the fuzzy numbers that result in crisp values for S, R, and Q [27].

4. Numerical Illustration

4.1. Fuzzy AHP. As demonstrated in Table 3, the pairwise comparison matrix is formulated based on decision-makers opinions and linguistic terminologies defined in Table 1.

The Geometric mean of these given values is calculated using equation (4) in the next step as shown in Table 4. Further, the relative fuzzy weights for each criterion are calculated and presented in Table 5. In the 6th step, each criterion's defuzzified weight is calculated from the average of relative weights given in Table 6. The normalized fuzzy weights are calculated using equation (7), further utilized in the hybrid MCDM techniques. Finally, the values of M_i and N_i are calculated and shown in Table 6.

In a similar manner, based on the opinion of decision makers and the linguistic scale defined in Table 1, the initial decision matrix is formulated for all sets of subcriteria, defined with respect to each main criterion. Further, the normalized weights of all sets of subcriteria are calculated and tabulated as shown in Table 7.

Table 4: Fuzzy comparison values.

Criteria description	$\tilde{t}_i$
Energy density	(0.550320, 0.636770, 0.727415)
Life cycles	(1.017715, 1.237990, 1.479783)
Cycle efficiency	(2.092730, 2.418270, 2.749450)
Investment level	(0.457042, 0.542160, 0.674000)
Sustainability to climatic conditions	(2.620740, 3.004100, 3.464100)
Space required	(0.275880, 0.322069, 0.373643)
Total	(7.014427, 8.161359, 9.468391)
Reciprocal of total	(0.142563, 0.122529, 0.105615)
Increasing value of reciprocal	(0.105615, 0.122529, 0.142563)

4.2. Fuzzy VIKOR. Next, the decision-makers opinions in the form of linguistic terminologies, introduced in Table 2, are shown in Table 8, which are then converted to TFNs for the following steps. In order to keep the paper concise and brief, only one detailed illustration has been shown. The values for the other sets of subcriteria are computed using the methodology, and the numerical illustration is provided. Therefore, Step 2 finds the aggregated fuzzy decision matrix presented in Table 9, giving the aggregated fuzzy weights using equations (8)–(10) to result in Table 10. Maximum and Minimum Fuzzy Values shown in Table 11 are found in step 4 using

Table 5: Relative weights in fuzzy form.

Criteria description	$\tilde{w}_i$
Energy density	(0.058122, 0.078023, 0.103702)
Life cycles	(0.107486, 0.151690, 0.210962)
Cycle efficiency	(0.221024, 0.296308, 0.391970)
Investment level	(0.048270, 0.066430, 0.096087)
Sustainability to climatic conditions	(0.276789, 0.368089, 0.493852)
Space required	(0.029137, 0.039463, 0.053268)

Table 6: Average and normalized final weights of criteria.

Criteria description	M_i	N_i
Energy density	0.079949	0.077604
Life cycles	0.156713	0.152115
Cycle efficiency	0.303101	0.294208
Investment level	0.070263	0.068201
Sustainability to climatic conditions	0.379577	0.368441
Space required	0.040623	0.039431

Table 7: Pairwise comparison matrix and normalized weights for subcriteria.

w.r.t energy density	Mass energy density	Volumetric density	Normalized weights
Mass energy density	(1, 1, 1)	(1/6, 1/5, 1/4)	0.16858
Volumetric density	(4, 5, 6)	(1, 1, 1)	0.83142
w.r.t life cycles	No of charge discharge cycles	Shelf life	Normalized weights
No of charge discharge cycles	(1, 1, 1)	(2, 3, 4)	0.74239
Shelf life	(1/4, 1/3, 1/2)	(1, 1, 1)	0.25761
w.r.t cycle efficiency	o/p by i/p	Time required for unit energy storage	Normalized weights
o/p by i/p	(1, 1, 1)	(4, 5, 6)	0.83142
Time required for unit energy storage	(1/6, 1/5, 1/4)	(1, 1, 1)	0.16858
w.r.t investment level	Capital	Time	Normalized weights
Capital	(1, 1, 1)	(6, 7, 8)	0.87424
Time	(1/8, 1/7, 1/6)	(1, 1, 1)	0.12576
w.r.t suitability to climatic conditions	Temperature susceptibility	Humidity susceptibility	Normalized weights
Temperature susceptibility	(1, 1, 1)	(4, 5, 6)	0.83142
Humidity susceptibility	(1/6, 1/5, 1/4)	(1, 1, 1)	0.16858
w.r.t space required	Floor area	Volume occupied	Normalized weights
Floor area	(1, 1, 1)	(1/8, 1/7, 1/6)	0.12576
Volume occupied	(6, 7, 8)	(1, 1, 1)	0.87424

Table 8: Opinions of decision makers.

Main criterion	Subcriterion	D.M. 1	D.M. 2	D.M. 3
Energy density	Mass energy density	MH	VH	MH
	Volumetric density	M	ML	M
Life cycle	No of charge/discharge cycles	ML	M	MH
	Shelf life	MH	M	M
Cycle efficiency	o/p by i/p	VH	MH	MH
	Time required for unit energy storage	M	ML	M
Investment level	Capital	MH	VH	VH
	Time	M	MH	MH
Suitability to climatic conditions	Temperature susceptibility	M	MH	VH
	Humidity susceptibility	MH	VH	M
Space required	Floor area	ML	VL	ML
	Volume occupied	MH	M	MH

Table 9: Aggregated fuzzy decision matrix.

Subcriteria for energy density	Mass energy density	Volumetric density
Electrochemical storage	(6, 7, 8)	(7, 8, 9)
Electrical storage	(2, 3, 4)	(7, 8, 9)
Magnetic storage	(7, 8, 9)	(9, 9, 9)
Mechanical storage	(1, 1, 1)	(2, 3, 4)
Chemical storage	(5, 6, 7)	(6, 7, 8)

Table 10: Aggregated fuzzy weights for each criterion.

Subcriterion for energy density	Triangular fuzzy number		
Mass energy density	0.5000	0.6667	0.9000
Volumetric density	0.1000	0.3333	0.5000

equation (11).

Table 11: Maximum and minimum fuzzy values.

Subcriterion for energy density	$\tilde{f}_i^b$	$\tilde{f}_i^w$
Mass energy density	(7, 8, 9)	(1, 1, 1)
Volumetric density	(9, 9, 9)	(2, 3, 4)

Table 12: S_j and R_j.

Alternatives	S_j values	R_j values
Electrochemical storage	(−0.0625, 0.1310, 0.4804)	(0.0000, 0.0833, 0.3375)
Electrical storage	(0.1875, 0.4643, 0.9304)	(0.1875, 0.4167, 0.7875)
Magnetic storage	(−0.1250, 0.0000, 0.2250)	(0.0000, 0.0000, 0.2250)
Mechanical storage	(0.4464, 0.8690, 1.4000)	(0.3750, 0.5833, 0.9000)
Chemical storage	(0.0143, 0.2619, 0.6643)	(0.0143, 0.1667, 0.4500)

Table 13: Final Q_j values of alternatives.

	Electrochemical storage	Electrical storage	Magnetic storage	Mechanical storage	Chemical storage
Q_j	1.0047	0.9333	1.0000	0.9721	1.0050

Normalized Fuzzy Differences are calculated using equation (12) in step 5. The S_j and R_j values are calculated using equations (13) and (14) in step 6, and the results are tabulated as shown in Table 12.

In step 7, equation (15) is used to find the value of Q. Defuzzification is carried out using the Centre of Area Method to return crisp values for each of the 6 alternatives in step 8. The final values of Q for the set of subcriteria defined with respect to energy density are tabulated in Table 13.

Thus, the same procedure is repeated for the other sets of subcriteria groups, and Q values are obtained and tabulated as shown in Table 14. Now, we integrate the AHP and VIKOR techniques by taking the product of the Q values and the normalized weights of each of the criteria to obtain the ranks of the alternatives by ranking the highest resulting product first and moving to the lower products. Therefore, we obtain the final ranks given in Table 14. Further, the sensitivity analysis is carried out to analyze the effect of variation in the main criteria weights on the final ranking of alternatives.

4.3. Sensitivity Analysis. This section deeply examines the influence of main criteria weights on the ranking of alternatives. The scenarios are produced by varying the most important main criterion weight obtained by Fuzzy AHP method. At the same time, the weights of the other criteria are adjusted using the following equation [30, 31]:

$$w_i' = \left(1 - w_m'\right)\left(\frac{w_i}{1 - w_m}\right), i = 1, 2, \ldots, n | i \neq m, \tag{16}$$

where w_i is the original weight of the main criterion C_i, w_i' represents the adjusted weight of the main criterion C_i, w_m is the original weight of the most important main criterion C_m, and w_m' is the adjusted weight of the most important main criterion C_m.

In the initial scenario (S_0), the main criteria weights are calculated using Fuzzy AHP method; that is, the weights of energy density, life cycle, cycle efficiency, investment level, suitability to climatic conditions, and space required are $w_1 = 0.077604$, $w_2 = 0.152115$, $w_3 = 0.294208$, $w_4 = 0.068201$, $w_5 = 0.368441$, and $w_6 = 0.039431$, respectively. From the obtained weights, the suitability to climatic conditions criterion has the highest value. Therefore, it (C_5) is the preeminent criterion. Now, for scenario 1 (S_1), the weight of C_5 is reduced by 10%, and the weights of other main criteria are adjusted using equation (16). Fuzzy VIKOR methodology is now applied to obtain the ranking of the alternatives. A similar procedure is followed for S2–S10. All scenarios are summarized in Figure 3.

In all the scenarios, the ranks of the two alternatives, that is, magnetic (A_3) and electrochemical (A_1) storage, remain unchanged. For the remaining three alternatives, that is, electrical storage (A_2), mechanical storage (A_4), and chemical storage (A_5), there are slight changes in the rank. For scenarios 1–3, the initial rank of the alternatives (i.e., $A_3 > A_1 > A_5 > A_4 > A_2$) is retained. The ranks of the alternatives for scenarios 4-5 are obtained as $A_3 > A_1 > A_5 > A_2 > A_4$, for scenarios 6-7, they are obtained as $A_3 > A_1 > A_2 > A_5 > A_4$, and for scenarios 8–10, they are obtained as $A_3 > A_1 > A_2 > A_4 > A_5$.

According to the sensitivity analysis results, it can be outlined that the utilized hybrid approach of fuzzy AHP and fuzzy VIKOR for energy storage technology selection is stable. Here, the magnetic storage alternative is the prominent solution among all other energy storage technologies.

Table 14: Overall Ranking of Energy storage technologies.

Alternatives	Overall priority weights of main criteria						Overall priority weights of alternatives	Normalized priority weights of alternatives	Overall ranking of alternatives
	Energy density 0.077604	Life cycle 0.152115	Cycle efficiency 0.294208	Investment level 0.068201	Suitability to climatic conditions 0.368441	Space required 0.039431			
	Priority weights of alternatives								
	w.r.t energy density	w.r.t life cycle	w.r.t cycle efficiency	w.r.t investment level	w.r.t suitability to climatic conditions	w.r.t space required			
Electrochemical storage	1.0047	1.0341	1	0.9039	0.9914	0.9996	0.995813	0.201454997	**2**
Electrical storage	0.9333	1.0000	1.0063	1.0219	0.9377	0.9963	0.975071	0.197258848	**5**
Magnetic storage	1.0000	1.0684	0.9857	1.0000	1.0000	1.0000	1.006197	0.203555701	**1**
Mechanical storage	0.9721	0.9839	1.0000	0.9818	0.9636	0.9631	0.979278	0.198109933	**4**
Chemical storage	1.0050	0.9817	0.9857	0.9712	0.9881	0.9923	0.986745	0.199620522	**3**

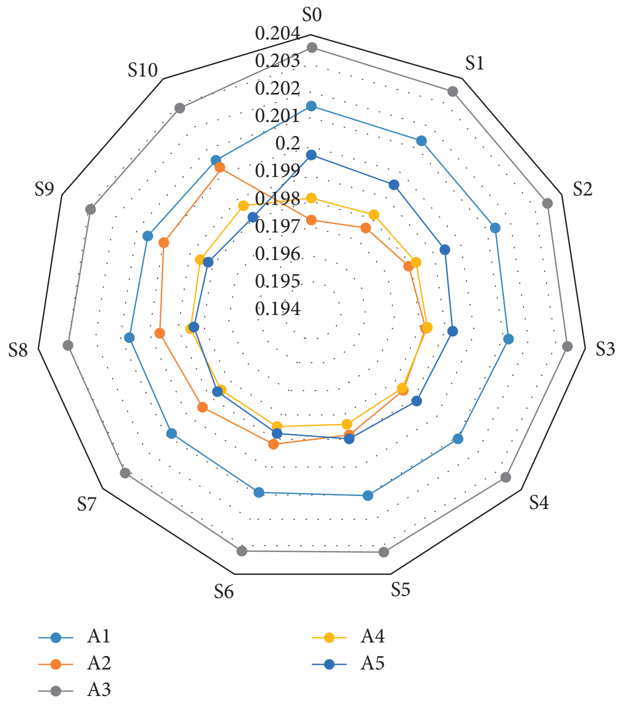

Figure 3: Sensitivity analysis.

5. Conclusion

The importance of employing energy storage techniques (EST) for power evacuation and their respective advantages has been emphasized. ESTs such as electrochemical storage, electrical storage, magnetic storage, mechanical storage, and chemical storage have been selected as the alternatives. The final decision was made to decide the best storage technology. The criteria being considered were energy density, life cycles, cycle efficiency, investment level, suitability to climatic conditions, and storage space required. The alternatives have been evaluated using the novel idea of hybrid multicriteria decision-making technique under fuzzy environment prioritizing different ESTs. A numerical illustration for a sample scenario was provided with detailed descriptions linked to the various mathematical procedures, alternatives, and criteria.

The sample scenario evaluated using the set of criteria, subcriteria, and alternatives resulted in magnetic storage being the most effective EST based on the opinion of the decision-makers and the subsequent fuzzy techniques used. The final weight of magnetic storage was the highest, and it decreased with subsequent alternatives. Other alternative EST followed hierarchical ranking order as electrochemical storage, chemical storage, mechanical storage, and electrical storage following most effective to least effective. Hence, fuzzy AHP and fuzzy VIKOR have thus been integrated into a hybrid multiple-criteria decision-making methodology to find the best storage technology.

From the sensitivity analysis, it is concluded that utilized hybrid approach of fuzzy AHP and fuzzy VIKOR for energy storage technology selection is stable. The magnetic storage alternative is the most prominent solution among all other energy storage technologies.

Data Availability

All data are included inside in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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