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ORIGINAL ARTICLE

Solar energy plant project selection with AHP decision-making method based on hesitant fuzzy linguistic evaluation

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Abstract

Increased energy demand is expected to be met by reliable and continuous energy sources. Renewable energy which is obtained from nature and can continuously reload itself from natural sources is a new generation energy type. The sun, which is the main source of renewable energies and produces heat and electricity by direct and indirect methods, is an important renewable energy source. The installation of solar energy systems takes place under the basic technical, economic and political factors. Alternative solar energy plant projects are evaluated linguistically under the main criteria based on the knowledge and experience of the experts. Hesitant fuzzy linguistic terms are used to incorporate the uncertain and hesitant expressions into the decision-making process. The decision-making process that takes place with hesitant linguistic expressions in multiple sub-criteria is based on the AHP model. The inclusion of hesitant statements in the decision-making process with the AHP model enables more realistic choices among the alternatives. System technology (0.18), energy policy (0.15) and energy price change (0.13) appear as the most important factors in the pairwise comparison of the factors based on hesitant fuzzy linguistic evaluations. The results coincide with the need for high efficiency in solar energy systems, the importance of governmental supportive policies and the effects of price competition in the energy sector. Also, the closeness of the overall priority values of all projects (0.189, 0.23, 0.287, 0.135, 0.158) indicates that the decision makers take into account the effective factors.

Keywords Hesitant fuzzy linguistic terms · AHP · Solar energy · Decision making

Introduction

Fossil-based energy sources (coal, natural gas, oil) are used as primary sources to meet rising energy demand with population growth and industrialization. The emission of harmful gases (carbon dioxide, nitrous oxide) caused by the combustion of fossil-based resources causes the greenhouse effect. Greenhouse effect-based global warming and climate change reveal environmental, economic and social problems on a global scale. Renewable energy (solar, wind, hydro, geothermal, biomass) is the most important energy source that is proposed as an alternative to fossil-based energy sources to remove the environmental and social hazards. The sun, which is the main source of the energies on earth (except tidal, nuclear, geothermal), emerges as the most important renewable energy source with its unlimited, equal distribution and economic advantages. Renewable energy sources, especially solar energy, should be included in the global energy strategy to meet the growing energy demand.

Solar rays are used to obtain heat and electricity from direct and indirect ways by active and passive methods. The sun's rays are converted into electrical energy by directly or using thermal methods with high-tech flat plate and concentrated photovoltaic (PV) and concentrated solar power (CSP) solar energy systems. Technological developments in recent years have increased the efficiency values of solar energy systems and have ensured the spread of independent and grid related solar energy systems. Although solar energy systems have the advantages of environmental sensitivity and low operating costs, the rapid advances in solar energy technologies could not prevent the high initial cost problem. Therefore, high-tech PV and CSP solar power systems should be installed in the right place and on the right conditions. Hence, investors need to decide on the most optimum

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project by evaluating alternative solar energy projects balancing social, ecological, technical and economic aspects.

The average daily radiation values and the number of sunny days are important starting criteria for the development of solar energy systems. Countries that meet these leading criteria are developing policies to direct and control solar energy investments. Investors should make the right choice among alternative solar projects under these natural and artificial factors. Investors face complex investment decision problems due to uncertainties and variations in the factors affecting the plant installation process. Direct or indirect interaction between factors complicates the decision-making process and causes a great risk for investors. Investors start the decision-making process for solar energy investment projects with the principle of low risk and high profitability.

This study deals with the application of the AHP (Analytic Hierarchy Process) method in determining the most suitable project according to the defined criteria among alternative PV solar power plant projects proposed for solar energy investment. Decision makers make pairwise evaluations among criteria and alternative solar power plants based on their knowledge and experience. The uncertainties in the evaluations are transformed into more stable results using hesitant linguistic expressions and included in the decision-making process.

The contributions of the study to the literature are as follows: (1) the practicality of fuzzy logic based approaches used in AHP decision-making method is once again demonstrated with HFLTS. (2) Factors affecting solar power plant selection are examined in detail using HFLTS and included in the decision-making process. The application of selecting solar power plant using HFLTS based AHP model is the first study in the literature. The study explains in detail the decision makers' evaluation in hesitant conditions and the effects of the decisions made on the alternative selection based on the original AHP decision-making model. Linguistic expressions are used to enable decision makers to reflect their knowledge and experience naturally and clearly. The fact that single linguistic terms (such as low, medium, high) are insufficient to meet the evaluations in the decision-making process requires the use of hesitant fuzzy linguistic terms. In addition, detailed explanation of the study provides opportunity for the application and development of the method easily by academicians and sector employees at all levels.

The continuation of the paper is organized under the following headings. "Overview of AHP methodology" describes the purpose and application steps of basic AHP, Fuzzy AHP based on fuzzy logic decision-making methods and hesitant fuzzy sets and linguistic terms. "Fuzzy AHP based on hesitant fuzzy linguistic evaluation" discusses hesitant fuzzy linguistic expressions, the process of transforming these expressions into trapezoidal fuzzy numbers and incorporating them into the AHP model. "An application: solar energy plant project selection" describes the application of the proposed model among five alternative solar projects under thirteen sub-criteria. In "Comparison and sensitivity analyses", the validity of the methods and factors is questioned by making a comparison and sensitivity analysis. In "Conclusions", the findings are evaluated and recommendations are made for future studies.

Overview of AHP methodology

AHP model

MCDM (Multiple Criteria Decision Making) method is applied to make the most suitable choice among the alternatives offered under multiple criteria and different targets [1]. The AHP technique developed in 1980 to solve unstructured problems by Saaty is an important MCDM method which is used to determine the most appropriate option among alternative options under multiple criteria and different targets. Saaty proposed the AHP method as a decision-making tool for the solution of unstructured MCDM problems in 1980 [2]. AHP is a powerful and useful MCDM technique that can solve complex decision-making problems requiring high flexibility and reliability. AHP provides flexibility and reliability to solve complex MCDM problems with its usable structure [3]. In AHP method, pairwise comparisons are made according to the indices and options determined by the decision tree created by the decision maker. The AHP method, which offers comprehensive and rational solutions, is widely used in decision-making problems for the development of renewable energy systems [4–6]. The criteria and alternatives defined in the hierarchical decision tree created by the decision maker are operated to the pairwise comparison process in the AHP method. This method comprehensively carries out the decision-making process by prioritizing the criteria and evaluating the alternatives according to the criteria separately. The basic steps of the AHP approach are as follows [2]:

- The problem, including decision goals, alternatives and criteria for evaluating alternatives is modeled hierarchically.
- Priorities are defined among the elements in the hierarchy by making pairwise comparisons.
- Evaluations based on pairwise comparisons are synthesized to define general priorities for the hierarchy.
- Consistency of evaluations is checked.
- Alternatives are evaluated and the most appropriate decision is obtained under this process.

Fuzzy AHP

Fuzzy logic is used to include uncertainty and hesitancy in calculations in the AHP decision-making method that

Table 1 The linguistic terms and fuzzy number representation for pairwise comparisons [7]

Linguistic scales	Abbreviations	Triangular Fuzzy number
Equally important	EI	(1, 1, 3)
Low important	LI	(1, 3, 5)
Medium important	MI	(3, 5, 7)
Strongly important	SI	(5, 7, 9)
Absolute important	AI	(7, 9, 9)

compares and evaluates alternatives on the basis of criteria. Subjective uncertainties in the decision-making process can be better reflected in the pairwise comparisons by fuzzy numbers. Although there are various types of fuzzy numbers, fuzzy triangular numbers (TFNs) and fuzzy trapezoidal numbers (TrFNs) are more commonly used to reflect the linguistic evaluations of experts.

The impact weights for each criterion in the decision-making process are determined either directly by experts based on their knowledge and experience or by pairwise comparisons of criteria [4]. In this study, experts make their evaluations with linguistic expressions using linguistic term set defined in Table 1.

- Conversion of linguistic expressions in the comparison matrix to fuzzy numbers.
- Checking the consistency values of the pairwise comparison matrices.
- Calculation of weights (priorities) of criteria and alternatives with respect to each criterion.
- Calculating the overall priority values of the alternatives based on the criteria and sorting the alternatives according to these values.

If there are n criteria in the decision problem, C_i refers to the ith criterion $(i = 1, 2, 3, \ldots, n)$. Experts compare the criteria with the linguistic evaluations and generate the comparison matrix (nxn). Comparative linguistic expressions of experts are converted into triangular or trapezoidal fuzzy numbers and the new numeric matrix is obtained as $\tilde{P}$.

The relative importance between the two criteria ith and jth is expressed by the $\tilde{p}_{ij} = (l_{ij}, m_{ij}, n_{ij}, u_{ij})$ trapezoidal fuzzy number, and also the inverse relative importance relationship between them is shown as $\tilde{p}_{ji} = \frac{1}{\tilde{p}_{ij}} = \left(\tilde{p}_{ij}\right)^{-1} = (u_{ij}^{-1}, n_{ij}^{-1}, m_{ij}^{-1}, l_{ij}^{-1}) \quad (i,j = 1,2,\ldots,n)$ [12].

Pairwise comparison matrix $(\tilde{P})$ is represented as;

$$\tilde{P} = \begin{array}{c|cccccc} & C_1 & C_2 & C_3 & \cdots & C_{n-1} & C_n \\ \hline C_1 & \tilde{1} & \tilde{p}_{12} & \tilde{p}_{13} & \cdots & \tilde{p}_{1(n-1)} & \tilde{p}_{1n} \\ C_2 & \tilde{p}_{21} & \tilde{1} & \tilde{p}_{23} & \cdots & \tilde{p}_{2(n-1)} & \tilde{p}_{2n} \\ C_3 & \tilde{p}_{31} & \tilde{p}_{32} & \tilde{1} & \cdots & \tilde{p}_{3(n-1)} & \tilde{p}_{3n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ C_{n-1} & \tilde{p}_{(n-1)1} & \tilde{p}_{(n-1)2} & \tilde{p}_{(n-1)3} & \cdots & \tilde{1} & \tilde{p}_{(n-1)n} \\ C_n & \tilde{p}_{n1} & \tilde{p}_{n2} & \tilde{p}_{n3} & \cdots & \tilde{p}_{n(n-1)} & \tilde{1} \end{array}$$

The linguistic evaluations of the experts for pairwise comparisons are transformed into triangular or trapezoidal fuzzy numbers and a comparison matrix which reflects the fuzzy weights is obtained. Different approaches are proposed for the evaluation of the fuzzy weighted matrix and for the weighting of the criteria and alternatives in the AHP decision model [8–11]. The main process steps in the Fuzzy AHP method are as follows:

- Generation of a comparison matrix of the criteria and the alternatives with respect to the criteria using linguistic terms.

The primary stage of the calculation process is to check the consistency of the comparison matrix. Consistency calculations are made by converting the elements of the comparison matrix created by trapezoidal fuzzy numbers into crisp values by defuzzification method [11]. The transformation of a trapezoidal fuzzy number $\tilde{A} = (a, b, c, d)$ into a crisp value with defuzzification method is as follows [13]:

$$\text{def}(\tilde{A}) = \frac{(a + 2b + 2c + d)}{6} \tag{1}$$

The form of the fuzzy comparison matrix, $\tilde{P}$ converted to crisp values is shown as traditional P comparison matrix:

Table 2 The random index (RI) scale [15]

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58	1.59

$$P = \begin{array}{c|cccccc} & C_1 & C_2 & C_3 & \cdots & C_{n-1} & C_n \\ \hline C_1 & 1 & p_{12} & p_{13} & \cdots & p_{1(n-1)} & p_{1n} \\ C_2 & p_{21} & 1 & p_{23} & \cdots & p_{2(n-1)} & p_{2n} \\ C_3 & p_{31} & p_{32} & 1 & \cdots & p_{3(n-1)} & p_{3n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ C_{n-1} & p_{(n-1)1} & p_{(n-1)2} & p_{(n-1)3} & \cdots & 1 & p_{(n-1)n} \\ C_n & p_{n1} & p_{n2} & p_{n3} & \cdots & p_{n(n-1)} & 1 \end{array}$$

The consistency of the P matrix reflects the consistency state of the fuzzy comparison matrix, $\tilde{P}$. The consistency check steps for the comparison matrix, P are as follows:

- Determination of the largest eigenvalue of the matrix [14]:

$$\text{Pw} = \lambda_{\max} w, \tag{2}$$

  where w represents the eigenvector of the comparison matrix, P.
- The consistency of the comparison matrix is evaluated according to the calculated consistency ratio (CR) based on consistency index (CI) and random index (RI) in Table 2. As a general acceptance, if the consistency ratio is less than 0.1 ($CR < 0.1$), the comparison matrix is considered appropriate, otherwise pairwise comparisons should be reassessed by experts.

$$\text{CR} = \text{CI}/\text{RI}, \tag{3}$$

$$\text{CI} = (\lambda_{\max} - n)/(n-1), \tag{4}$$

  where n refers to the size of the matrix.

In the next step, weights are calculated for the pairwise comparison matrices that are valid according to the consistency index. The weights are calculated through the fuzzy weight matrix, $\tilde{W}$ that is obtained on the basis of fuzzy pairwise comparison matrix, $\tilde{P}$ [11, 16]. The steps for calculating fuzzy weight vectors are as follows:

- A geometric mean is calculated for each boundary value of trapezoidal fuzzy numbers.

$$a_i = \left[\prod_{j=1}^{n} l_{ij}\right]^{1/n}, b_i = \left[\prod_{j=1}^{n} m_{ij}\right]^{1/n},$$
$$c_i = \left[\prod_{j=1}^{n} n_{ij}\right]^{1/n}, d_i = \left[\prod_{j=1}^{n} u_{ij}\right]^{1/n}, (i = 1,2,\ldots,n). \tag{5}$$

- The geometric mean values calculated for the comparison headers are added under each boundary value of the trapezoidal number.

$$a = \sum_{j=1}^{n} a_j, b = \sum_{j=1}^{n} b_j, c = \sum_{j=1}^{n} c_j, d = \sum_{j=1}^{n} d_j. \tag{6}$$

- The boundary values of the trapezoid fuzzy number are divided into the sum of the boundary values in inverse ranking, and a fuzzy weight vector is obtained for each comparison value as in Eq. 7. The weight vectors are defuzzified ($\text{def}\left(\tilde{w}_i\right)$) according to equation Eq. 1 and these values are normalized over the overall sum of the weights as in Eq. 8. Normalized weight vector (W) refers the weight value for each comparison value.

$$\tilde{w}_i = \left(a_i d^{-1}, b_i c^{-1}, c_j b^{-1}, d_j a^{-1}\right)(i = 1,2,\ldots,n), \tag{7}$$

$$w_i = \frac{\text{def}\left(\tilde{w}_i\right)}{\sum_{i=1}^{n} \text{def}\left(\tilde{w}_i\right)}, \tag{8}$$

$$W = \left[w_1 w_2 w_3 \ldots w_n\right]. \tag{9}$$

In addition, experts evaluate the criteria individually using linguistic expressions in Table 3 and determine the impact values of the criteria for use in the decision-making process [11].

Decision makers evaluate the factors linguistically to determine the impact strength of the criteria. Fuzzy evaluation vectors of criteria are calculated with decision makers, D_a ($a = 1,2,\ldots,m$) and criteria, e_i ($i = 1,2,\ldots,n$) using the linguistic term set, $\{VL, L, M, H, VH\}$. The fuzzy evaluation value of the criteria defined by decision makers' linguistic assessments is calculated as follows:

$$\tilde{e}_i = \frac{1}{m}\left(\tilde{e}_i^1 + \tilde{e}_i^2 + \cdots + \tilde{e}_i^m\right), \tag{10}$$

Table 3 Linguistic terms and their trapezoidal fuzzy numbers for evaluation [17]

Linguistic variables	Trapezoidal fuzzy numbers
Very low	(0, 1, 2, 3)
Low	(1, 2, 3, 4)
Medium	(3, 4, 5, 6)
High	(5, 6, 7, 8)
Very high	(7, 8, 9, 10)

where decision maker's (m) evaluation value for the criteria e_i is defined with trapezoidal fuzzy number $\tilde{e}_i = (l, m, n, u)$ with respect to Table 3 [11]. The fuzzy evaluating matrix for all criteria is shown in Eq. 11:

$$\tilde{E}= \left[\tilde{e}_1 \tilde{e}_2 \ldots \tilde{e}_n\right]. \tag{11}$$

Impact values of the criteria are calculated according to the process followed in weight calculation process. The Fuzzy evaluating matrix ($\tilde{E}$) is operated following the Eqs. 5–9 process and the normalized evaluating matrix (E) is obtained. The weight values (W) obtained from the pairwise comparison of the criteria are combined with the impact values of the criteria (E) to calculate the actual weight values (A) for the criteria.

$$a_i = w_i e_i. \tag{12}$$

The weights of the alternatives obtained from the pairwise comparison with respect to the each criterion are combined with the weights of the criteria (A). The priority values of the alternatives are calculated and the alternative with the highest priority value is preferred.

Hesitant Fuzzy Sets and linguistic terms

Hesitant Fuzzy Sets (HFS) was introduced by Torra [18]. The concept of hesitant fuzzy sets reflects the possible values of membership values that belong to the fuzzy set. HFSs, which are extension of fuzzy sets, have been used in different scientific studies along with other fuzzy logic extensions (type-2, intuitionistic, neutrosophic). The use of HFS in various interdisciplinary research fields (Automation control system, Computer science, Engineering, Mathematics, Operations research management science) proves that it is an important application tool [19–21].

HFSs which are extended fuzzy clusters, define the membership degrees of an element in the range [0,1] [22]. $h_E(x)$ ($h = h_E(x)$, hesitant fuzzy element (HFE), [23]) represents the membership degrees of the element $x \in X$ where X is a fixed set. HFS is shown mathematically as follows:

$$E = \left\{\langle x, h_E(x)\rangle | x \in X\right\}.$$

Linguistic information is an important concept related to HFS.

Real-life problems include non-numerical properties and evaluation criteria as well as numerical values. Linguistic variables defined by Zadeh [24] are used in problems involving the grading and evaluation of qualitative features. Linguistic expressions that provide freedom of evaluation in uncertain and uncertain conditions are developed with new approaches (decision-making approaches, aggregation operators, linguistic intuitionistic, linguistic interval-valued intuitionistic) [22, 25, 26].

$S = \left\{s_i | i = 0,1, \ldots, g\right\}$ is defined a finite Linguistic term sets (LTS) where g is a positive even number and s_i is a linguistic term. Accordingly, LTS can be defined as [25]:

- $s_i \le s_j$, where $i < j$ (LTS is ordered set)
- $\mathrm{Neg}\left(s_i\right) = s_j$, where $j = g - i$ (negation of linguistic term)
- $\max\left(s_i, s_j\right) = s_i$, where $s_i \ge s_j$
- $\min\left(s_i, s_j\right) = s_i$, where $s_i \le s_j$

Addition and multiplication of any two linguistic terms ($s_i, s_j \in S_{[0,g]}$) takes place on the basis of t-norm and t conorm.

$$s_i \oplus s_j = s_j \oplus s_i = s_{g\left(\frac{i}{g}, \frac{j}{g}\right)_{t\text{-conorm}}},$$
$$s_i \otimes s_j = s_j \otimes s_i = s_{g\left(\frac{i}{g}, \frac{j}{g}\right)_{t\text{-norm}}},$$

The HFLTSs (H_S) proposed by Rodriguez and colleagues [27] aim to overcome the hesitations of decision makers in the evaluation process. H_S is defined as a ordered and finite subset of the linguistic term set $S = \{s_0, s_1, \ldots, s_g\}$. Linguistic evaluations expressed by decision makers using context-free grammar are converted into HFLTSs with the transformation function. HFSs developed with linguistic expressions allow decision makers to make their evaluations with a wide set of linguistic expressions. Thus, HFLTS provides an opportunity to be used in various scientific fields with different approaches [26, 28–30].

Fuzzy AHP based on hesitant fuzzy linguistic evaluation

The pairwise comparisons made by the decision makers with the crisp values defined by Saaty [2] limits the decision makers to make an accurate assessment in the AHP technique. The use of linguistic expressions [31] in pairwise comparisons allows the decision makers to make a more realistic and natural assessments. Nevertheless, the linguistic form of evaluations based on the knowledge and experience of the decision maker involves a hesitant situation. Therefore, pairwise comparisons are defined with hesitant fuzzy linguistic

Table 4 Sample linguistic pairwise comparison matrix

	PM	EP	EPC	VCM
Permission (PM)	1	(–) between EI and LI	(–) greater than MI	At most MI
Energy policy (EP)		1	At least SI	At least SI
Energy price change (EPC)			1	Greater than SI
Value change of money (VCM)				1

Table 5 Sample HFLTS of linguistic pairwise comparisons

	PM	EP	EPC	VCM
Permission (PM)	1	(–) {EI, LI}	(–) {SI, AI}	{EI, LI, MI}
Energy policy (EP)		1	{SI, AI}	{SI, AI}
Energy price change (EPC)			1	{AI}
Value change of money (VCM)				1

term sets (HFLTS) [32] such as "at most strongly more important", "between equally important and very strongly more important", and "lower that moderately more important" to better reflect uncertain and hesitant evaluations of decision makers.

The fuzzy envelope method is implemented using the Ordered Weighted Average (OWA) aggregation operator [33] which aggregates the hesitant fuzzy expressions. The fuzzy envelop form of HFLTS represents a linguistic interval defined by the linguistic upper bound and lower bound. The application steps of the AHP decision-making technique based on hesitant linguistic evaluations are as follows;

- The decision goal, the criteria for the goal, and the alternatives to be evaluated according to the criteria is defined in the hierarchical model. Criteria and alternatives based on criteria are evaluated in the pairwise comparison matrices. Evaluations are expressed linguistically based on the knowledge and experience of decision makers. Hesitant linguistic evaluations that are words in a natural language are generated by context-free grammar,G_H. A context-free grammar is defined based on the extension of the Backus-Naur Form [32]. HFLTS is defined as a finite subset of consecutive linguistic terms in the linguistic term set S = {equally important (EI), low important (LI), medium important (MI), strongly important (SI), and absolute important (AI)}. Membership functions of linguistic terms defined in triangular form are normal and their fuzzy values are shown in Table 1 with respect to linguistic terms respectively. Sample hesitant linguistic expressions generated by G_H are defined as; at least low important, greater than equally important, and between medium important and absolute important. Experts specify the inverse relations in pairwise evaluations by putting the word "(–)" symbol before the linguistic expression such that (–) lower than EI, (–) between EI and MI (Table 4).
- Comparative linguistic evaluations of experts are converted to HFLTS (Hesitant Fuzzy Linguistic Term Sets, H_S) using transformation functions (E_{G_H}) to include in decision-making calculations [32]. The functions used to transform hesitant linguistic expressions to HFLTS are as follows [32] (Table 5):

$$E_{G_H}\left(s_i\right) = \left\{s_i | s_i \in S\right\}$$

$$E_{G_H}\left(\text{at least } s_i\right) = \left\{s_j | s_j \in S \text{and } s_j \geq s_i\right\} \text{ or}$$
$$E_{G_H}\left(\text{atmost } s_i\right) = \left\{s_j | s_j \in \ S \text{ and } s_j \leq s_i\right\}$$

$$E_{G_H}\left(\text{lower than } s_i\right) = \left\{s_j | s_j \in \ S \text{ and } s_j < s_i\right\} \text{ or}$$
$$E_{G_H}\left(\text{greater than } s_i\right) = \left\{s_j | s_j \in \ S \text{ and } s_j > s_i\right\}$$

$$E_{G_H}\left(\text{between } s_i \text{ and } s_j\right) = \left\{s_k | s_k \in \ S \text{ and } s_i \leq s_k \leq s_j\right\}$$

where $S = \{s_0 : EI, s_1 : LI, s_2 : MI, s_3 : SI, s_4 : AI\}$ is a linguistic term and sample transformation operations are as follows:

$$E_{G_H}(\text{lower than medium important}) = \{\text{equalimportant, low important}\}$$

$$E_{G_H}(\text{at least strong important}) = \{\text{strong important, absolute important}\}$$

$$E_{G_H}(\text{between low and strong important}) = \{\text{low important, medium important, strong important}\}$$

- Envelope of HFLTS (env$\left(H_S\right)$), which defines linguistic expressions with linguistic intervals, allows for easier comparison of HFLTS. The enveloping method, expressed by the lower (H_{S^-}) and upper (H_{S^+}) limits of the linguistic expression, is shown as follows:

$$\text{env}\left(H_S\right) = \left[H_{S^-}, H_{S^+}\right], H_{S^-} \leq H_{S^+}$$

In this study, fuzztty envelopes of HFLTS are defined using trapezoidal fuzzy membership functions, $\tilde{A}=(a, b, c, d)$. The parameters of the trapezoidal fuzzy number are determined using OWA aggregation operations [33, 34]. Actually, the OWA aggregation operator is used to find intermediate parameters (b and c) of the trapezoidal fuzzy membership function (Table 6). The parameters of the trapezoidal membership functions obtained by the OWA aggregation process represent the fuzzy envelope of the linguistic expression.

- The obtained trapezoidal membership functions are defuzzified and crisp values are obtained for weight calculations. The consistency of the decisions is controlled according to the consistency ratio (CR) of the crisp pairwise comparison matrices of the criteria and alternatives with respect to the criteria (Table 7).
- The priority values (weights) for the criteria and alternatives are calculated depending on the trapezoidal fuzzy numbers and defuzzified values in the pairwise comparison tables. Alternatives' weights based on the criteria are synthesized with weights of the criteria and general weight (composition impact) values are obtained for the alternatives. The overall composition impact value is calculated for each alternative and the alternatives are sorted according to their impact values. The alternative with the highest combined effect value is preferred as the most suitable solution.

In the AHP decision model, the hesitant fuzzy linguistic term set is used as an assessment tool to enable decision makers to reflect their thoughts more comfortably in evaluations. Since the study was developed based on the ordinary AHP model, the applied method has a similar mathematical operation process as current studies [35, 36]. In contrast, the proposed set of terms for describing hesitant fuzzy linguistic expressions differs from existing methods. In this study, alternative PV solar energy projects are evaluated by AHP method based on hesitant fuzzy linguistic evaluations and the most suitable project is preferred.

Table 7 Sample defuzzification of trapezoidal fuzzy envelope using Eq. 1

	PM	EP	EPC	VCM
Permission (PM)	1	0.3147	0.4222	1.3333
Energy policy (EP)	5.222	1	0.8889	4.1111
Energy price change (EPC)	3	1.3333	1	3.5556
Value change of money (VCM)	0.8889	0.4440	0.4103	1

An application: solar energy plant project selection

Determining the most suitable project among alternative PV solar energy installation projects is discussed as the main goal of the decision problem in the application phase. The decision group was formed by eight academicians and seven sector managers working on renewable energy and solar energy issues. Thirteen sub-criteria are defined by three basic criteria as technical (T), economic (E) and political (P). Operation management (OM,), technical infrastructure (TI), solar irradiance (SI), system technology (ST), plant location (PL), contingency plan (CP) and maintenance and repair (MR) are technical criterion; energy price change (EPC), value change of money (VCM), power demand (PD) and project finance (PF) are economic criterion; and permission (PM) and energy policy (EP) are technical criterion [37–40] (Table 8). The problem is modeled hierarchically based on the defined goal, criteria and alternatives (Fig. 1).

Decision makers evaluate the criteria and alternative projects with respect to sub-criteria linguistically by pairwise comparison according to Table 8 to collect the evaluation data. Criteria defined for PV power plant projects are evaluated by experts using linguistic expressions in

Table 6 Sample fuzzy envelope of HFLTS of linguistic pairwise comparisons

	PM	EP	EPC	VCM
Permission (PM)	(1, 1, 1, 1)	(0.11, 0.16, 0.23, 1)	(0.2, 0.33, 0.33, 1)	(1, 1, 1, 3)
Energy policy (EP)	(1, 4.33, 6.33, 9)	(1, 1, 1, 1)	(0.33, 1, 1, 1)	(1, 1.67, 5.67, 9)
Energy price change (EPC)	(1, 3, 3, 5)	(1, 1, 1, 1)	(1, 1, 1, 1)	(1, 2.33, 4.33, 7)
Value change of money (VCM)	(0.33, 1, 1, 1)	(0.11, 0.18, 0.6, 1)	(0.14, 0.23, 0.43, 1)	(1, 1, 1, 1)

Table 8 Main and sub-criteria that affect to selection of PV solar energy plant

Main criteria	Sub-criteria	Definitions
Technical	Operation management	The processing of the project, the generation of energy and the transmission of the generated energy takes place with the operation management of the project. The energy generated is utilized efficiently with the correct management of the project
	Technical infrastructure	The proposed project is expected to have the technical competence to realize energy production, to distribute the generated energy and to solve the technical problems encountered
	Solar irradiance	The main factor that determines the energy to be obtained from the solar energy system is the solar radiation potential of the system. The amount of sunshine duration per year of the proposed project directly determines the energy potential obtained from the project and the return period of the economic investment
	System technology	The developments in solar energy technologies in the last decade have increased the efficiency of solar energy systems. The features of the system equipment used in the project are an important factor determining the cost of installation and the amount of energy generated
	Plant location	The direct and indirect interaction of the energy system with the environment in which it is established is taken into consideration in the evaluation of the project. The project is evaluated by considering the impact of the proposed project on agricultural, habitat and social life
	Contingency plan	Possible disaster scenarios are developed by considering the current and future situations of the projects. Projects are taken into risk groups based on these scenarios and are evaluated comparatively
	Maintenance and repair	Maintenance and repair costs are taken into account in the long-term economic evaluation of projects. The technological features of the energy system, the ability to use the system and environmental conditions are important factors affecting the maintenance and repair costs
Economic	Energy price change	Energy prices should be taken into account in the economic analysis of long-term solar energy investments
	Value change of money	In the economic analysis of energy investment, the value changes of money at local and global scale should be taken into consideration in evaluating whether or not it is economically viable
	Power demand	The general energy demand and the expectation of meeting this demand with renewable energy affect the evaluation of solar energy projects
	Project finance	The realization of solar energy projects with high initial cost is provided by financing the project. The financing of the proposed project demonstrates the realization of the project
Political	Permission	Permission criterion refers to the compliance of the energy system with the rules and regulations of local and national government
	Energy policy	The change in renewable energy policies at national and global extent can affect investment decisions

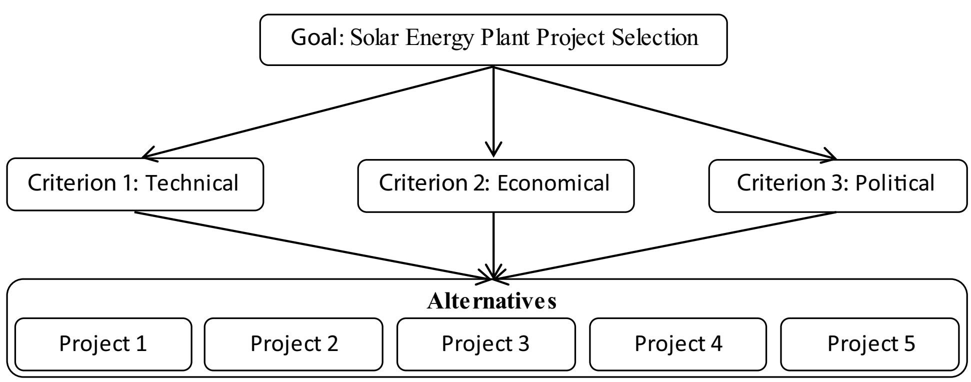

Fig. 1 Hierarchy model for project selection

pairwise comparison matrix. For example, the comparison between PM and EP criteria is linguistically defined as "at least SI" and the fuzzy envelope is obtained in the form of a trapezoidal fuzzy membership function as $\underset{\sim}{A}$=(1, 1.67, 5.67, 9) using OWA operators. The linguistic comparison evaluations for criteria and alternative projects are transformed into a trapezoidal fuzzy membership function. Then the trapezoidal fuzzy forms are defuzzified into crisp values using the weighted average method and the AHP decision is applied. The hesitant linguistic evaluations, trapezoidal fuzzy numbers of HFLTS, defuzzified representations, and consistency control of pairwise comparison matrices for criteria and alternative projects with respect to criteria are given between Tables 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, and 25. While the criteria are evaluated comparatively, it is desirable to

Table 9 Hesitant linguistic pairwise comparison matrix of criteria

	PM	EP	EPC	VCM	PD	PF	OM	TI	SI	ST	PL	CP	MR
PM	Lower thanEI	(–)between-LISI	(–)isLI	Lower thanLI	Lower thanSI	Lower thanLI	Betwee-nEILI	(–)lower thanMI	(–)lower thanMI	(–)lower thanSI	Lower thanLI	Lower thanSI	Lower tha-nAI
EP		Lower thanEI	(–)lower thanLI	betwee-nEISI	Greater thanMI	isLI	isAI	Lower thanMI	Lower thanMI	Lower thanEI	isAI	isAI	Greater thanAI
EPC			Lower thanEI	Betwee-nEIMI	Greater thanMI	Lower thanSI	Between-LISI	Lower thanLI	Lower thanEI	(–)lower thanMI	Lower thanAI	isMI	Greater thanAI
VCM				Lower thanEI	Lower thanMI	(–)betwee-nEILI	Betwee-nEILI	(–)between-LISI	(–)lower thanSI	(–)greater thanMI	(–)lower thanLI	isAI	Greater thanAI
PD					Lower thanEI	(–)greater thanEI	(–)lower thanMI	(–)greater thanMI	(–)greater thanLI	(–)greater thanLI	(–)between-LISI	betweeneili	Between-LIMI
PF						Lower thanEI	Lower thanSI	(–)lower thanMI	(–)lower thanMI	(–)between-LISI	Lower thanLI	Greater thanEI	Greater thanLI
OM							Lower thanEI	(–)between-LISI	(–)greater thanLI	(–)isMI	(–)betwee-nEIMI	Lower thanMI	Lower thanSI
TI								Lower thanEI	(–)betwee-nEILI	(–)betwee-nEIMI	betwee-neimi	isAI	BetweenLISI
SI									Lower thanEI	(–)lower thanMI	Greater thanMI	isAI	Greater thanMI
ST										Lower thanEI	isAI	isAI	Greater thanAI
PL											Lower thanEI	Betwee-neimi	BetweenLIAI
CP												Lower thanEI	isLI
MR													Lower thanEI

Table 10 Trapezoidal membership functions of HFLTS of hesitant linguistic comparison

	PM	EP	EPC	VCM	PD	PF	OM	TI	SI	ST	PL	CP	MR
PM	(1 1 1 1)	(0.1 0.16 0.23 1)	(0.2 0.3 0.3 1)	(1 1 1 3)	(1 1 3.5 7)	(1 1 1 3)	(1 1 3 5)	(0.2 0.67 1 1)	(0.2 0.67 1 1)	(0.1 0.29 1 1)	(1 1 1 3)	(1 1 3.5 7)	(1 1 6.34 9)
EP	(1 4.3 6.3 9)	(1 1 1 1)	(0.3 1 1 1)	(1 1.67 5.67 9)	(5 7.5 9 9)	(1 3 3 5)	(7 9 9 9)	(1 1 1.5 5)	(1 1 1.5 5)	(1 1 1 1)	(7 9 9 9)	(7 9 9 9)	(9 9 9 9)
EPC	(1 3 3 5)	(1 1 1 3)	(1 1 1 1)	(1 2.33 4.33 7)	(5 7.5 9 9)	(1 1 3.5 7)	(1 4.33 6.33 9)	(1 1 1 3)	(1 1 1 1)	(0.2 0.67 1 1)	(1 1 6.34 9)	(3 5 5 7)	(9 9 9 9)
VCM	(0.3 1 1 1)	(0.1 0.18 0.6 1)	(0.1 0.23 0.43 1)	(1 1 1 1)	(1 1 1.5 5)	(0.2 0.3 1 1)	(1 1 3 5)	(0.1 0.16 0.23 1)	(0.1 0.29 1 1)	(0.1 0.1 0.13 0.2)	(0.3 1 1 1)	(7 9 9 9)	(9 9 9 9)
PD	(0.1 0.3 1 1)	(0.1 0.1 0.13 0.2)	(0.1 0.1 0.13 0.2)	(0.2 0.67 1 1)	(1 1 1 1)	(0.1 0.1 0.27 1)	(0.2 0.67 1 1)	(0.1 0.1 0.13 0.2)	(0.1 0.1 0.15 0.3)	(0.1 0.1 0.15 0.3)	(0.1 0.16 0.23 1)	(1 1 3 5)	(1 3 5 7)
PF	(0.3 1 1 1)	(0.2 0.3 0.3 1)	(0.1 0.29 1 1)	(1 1 3 5)	(1 3.66 9 9)	(1 1 1 1)	(1 1 3.5 7)	(0.2 0.67 1 1)	(0.2 0.67 1 1)	(0.1 0.16 0.23 1)	(1 1 1 3)	(1 3.66 9 9)	(3 6.5 9 9)
OM	(0.2 0.3 1 1)	(0.1 0.1 0.1 0.1)	(0.1 0.16 0.23 1)	(0.2 0.3 1 1)	(1 1 1.5 5)	(0.1 0.29 1 1)	(1 1 1 1)	(0.1 0.16 0.23 1)	(0.1 0.1 0.15 0.3)	(0.1 0.2 0.2 0.3)	(0.1 0.23 0.43 1)	(1 1 1.5 5)	(1 1 3.5 7)
TI	(1 1 1.5 5)	(0.2 0.67 1 1)	(0.3 1 1 1)	(1 4.33 6.33 9)	(5 7.5 9 9)	(1 1 1.5 5)	(1 4.33 6.33 9)	(1 1 1 1)	(0.2 0.3 1 1)	(0.1 0.23 0.43 1)	(1 2.33 4.33 7)	(7 9 9 9)	(1 4.33 6.33 9)
SI	(1 1 1.5 5)	(0.2 0.67 1 1)	(1 1 1 1)	(1 1 3.5 7)	(3 6.5 9 9)	(1 1 1.5 5)	(3 6.5 9 9)	(1 1 3 5)	(1 1 1 1)	(0.2 0.67 1 1)	(5 7.5 9 9)	(7 9 9 9)	(5 7.5 9 9)
ST	(1 1 3.5 7)	(1 1 1 1)	(1 1 1.5 5)	(5 7.5 9 9)	(3 6.5 9 9)	(1 4.33 6.33 9)	(3 5 5 7)	(1 2.33 4.33 7)	(1 1 1.5 5)	(1 1 1 1)	(7 9 9 9)	(7 9 9 9)	(9 9 9 9)
PL	(0.3 1 1 1)	(0.1 0.1 0.1 0.1)	(0.1 0.16 1 1)	(1 1 1 3)	(1 4.3 6.3 9)	(0.3 1 1 1)	(1 2.33 4.33 7)	(0.1 0.23 0.43 1)	(0.1 0.1 0.13 0.2)	(0.1 0.1 0.1 0.1)	(1 1 1 1)	(1 2.33 4.33 7)	(1 3.67 7.67 9)
CP	(0.1 0.3 1 1)	(0.1 0.1 0.1 0.1)	(0.1 0.2 0.2 0.3)	(0.1 0.1 0.1 0.1)	(0.2 0.3 1 1)	(0.1 0.1 0.27 1)	(0.2 0.67 1 1)	(0.1 0.1 0.1 0.1)	(0.1 0.1 0.1 0.1)	(0.1 0.1 0.1 0.1)	(0.1 0.23 0.43 1)	(1 1 1 1)	(1 3 3 5)
MR	(0.1 0.2 1 1)	(0.1 0.1 0.1 0.1)	(0.1 0.1 0.1 0.1)	(0.1 0.1 0.1 0.1)	(0.1 0.2 0.3 1)	(0.1 0.1 0.15 0.3)	(0.1 0.29 1 1)	(0.1 0.16 0.23 1)	(0.1 0.1 0.13 0.2)	(0.1 0.1 0.1 0.1)	(0.1 0.13 0.27 1)	(0.2 0.3 0.3 1)	(1 1 1 1)

Table 11 Defuzzified form of trapezoidal membership functions of comparison matrix and consistency

	PM	EP	EPC	VCM	PD	PF	OM	TI	SI	ST	PL	CP	MR	Consistency	
PM	1	0.32	0.42	1.33	2.83	1.33	2.33	0.76	0.76	0.62	1.33	2.83	4.11	CI	0.075
EP	5.22	1	0.89	4.11	7.83	3	8.67	1.83	1.83	1	8.67	8.67	9	CR	0.048
EPC	3	1.33	1	3.56	7.83	2.83	5.22	1.33	1	0.76	4.11	5	9	RI	1.56
VCM	0.89	0.44	0.41	1	1.83	0.64	2.33	0.32	0.62	0.13	0.89	8.67	9	λ_{max}	13.91
PD	0.62	0.13	0.13	0.76	1	0.31	0.76	0.13	0.16	0.16	0.32	2.33	4	n	13
PF	0.89	0.42	0.62	2.33	5.89	1	2.83	0.76	0.76	0.32	1.33	5.89	7.17		
OM	0.64	0.12	0.32	0.64	1.83	0.62	1	0.32	0.16	0.21	0.41	1.83	2.83		
TI	1.83	0.76	0.89	5.22	7.83	1.83	5.22	1	0.64	0.41	3.56	8.67	5.22		
SI	1.83	0.76	1	2.83	7.17	1.83	7.17	2.33	1	0.76	7.83	8.67	7.83		
ST	2.83	1	1.83	7.83	7.17	5.22	5	3.56	1.83	1	8.67	8.67	9		
PL	0.89	0.12	0.57	1.33	5.22	0.89	3.56	0.41	0.13	0.12	1	3.56	5.44		
CP	0.62	0.12	0.21	0.12	0.64	0.31	0.76	0.12	0.12	0.12	0.41	1	3		
MR	0.57	0.11	0.11	0.11	0.36	0.16	0.62	0.32	0.13	0.11	0.32	0.42	1		

Table 12 Weight calculation of comparison matrix of criteria and normalized form of weight

	a_i	b_i	g_i	d_i	Fuzzy weight vector				w	w_{norm}
					w_1	w_2	w_3	w_4		
PM	0.5	0.68	1.25	2.33	0.02	0.03	0.08	0.23	0.08	0.0602
EP	1.93	2.91	3.55	4.73	0.06	0.13	0.23	0.47	0.21	0.1605
EPC	1.29	1.97	2.83	4.13	0.04	0.09	0.18	0.41	0.16	0.1274
VCM	0.46	0.67	1.08	1.59	0.01	0.03	0.07	0.16	0.06	0.0478
PD	0.21	0.29	0.47	0.77	0.01	0.01	0.03	0.08	0.03	0.0217
PF	0.5	0.96	1.63	2.38	0.02	0.04	0.1	0.23	0.09	0.0704
OM	0.25	0.32	0.57	1.08	0.01	0.01	0.04	0.11	0.04	0.0279
TI	0.81	1.65	2.4	3.46	0.03	0.07	0.15	0.34	0.14	0.1061
SI	1.38	2.02	2.97	3.92	0.04	0.09	0.19	0.39	0.17	0.1280
ST	2.14	3.03	3.98	5.53	0.07	0.14	0.26	0.54	0.23	0.1800
PL	0.37	0.66	0.97	1.35	0.01	0.03	0.06	0.13	0.05	0.0423
CP	0.18	0.25	0.35	0.49	0.01	0.01	0.02	0.05	0.02	0.0157
MR	0.14	0.17	0.26	0.41	0	0.01	0.02	0.04	0.02	0.0121
	10.16	15.59	22.31	32.17						
	a	b	g	d						

know the impact weights of the criteria. The criteria are evaluated linguistically by 15 experts according to Table 3 and the number of linguistic evaluations for each criterion is shown in Table 26.

The consistency values of the comparison matrices are calculated before starting the evaluation process. Since the consistency ratio based on consistency indexes is smaller than 0.1 ($CR < 0.1$) as shown in the tables, all comparison matrices are said to be consistent.

The pairwise comparison matrix of the criteria defined by the hesitant fuzzy linguistic expressions is converted into trapezoidal fuzzy numbers with HFLTS and OWA operations respectively. These trapezoidal fuzzy numbers are converted to real numbers using the defuzzification method defined in Eq. 1. The fuzzy weight vector and weights of the criteria are calculated based on the defuzzified comparison matrix (Table 12).

While the most effective criteria are system technology, energy policy, solar irradiance and energy price change respectively, the weakest criteria are maintenance and repair, contingency plan and power demand respectively according to the normalized weight of the criteria.

Alternative solar energy projects are evaluated using hesitant fuzzy linguistic expressions in the pairwise comparison matrix for each criterion. Hesitant linguistic expressions are converted to HFLTS and trapezoidal fuzzy numbers with the help of the OWA aggregation process respectively.

Trapezoidal fuzzy numbers are converted to actual values and the consistency of the comparison matrix of the projects is measured. The comparison matrices of the projects based

Table 13 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on permission criterion

PM	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consistency		w_{norm}
PR_1	Lower thanEI	(–)at leastMI	(–)at leastSI	Lower thanEI	Lower thanEI	(1 1 1 1)	(0.1 0.1 0.2 0.3)	(0.1 0.1 0.13 0.2)	(1 1 1 1)	(1 1 1 1)	1	0.2	0.13	1	1	CI	0.001	0.06
PR_2		Lower thanEI	(–)lower thanEI	Between-MISI	Between-MISI	(3 6.5 9 9)	(1 1 1 1)	(1 1 1 1)	(3 5 7 9)	(3 5 7 9)	6.2	1	1	6	6	CR	0.001	0.39
PR_3			Lower thanEI	At leastLI	Greater thanEI	(5 7.5 9 9)	(1 1 1 1)	(1 1 1 1)	(1 3.7 9 9)	(1 3.66 9 9)	7.5	1	1	5.9	5.9	RI	1.11	0.39
PR_4				Lower thanEI	(–)lower thanEI	(1 1 1 1)	(0.1 0.14 0.2 0.3)	(0.1 0.1 0.3 1)	(1 1 1 1)	(1 1 1 1)	1	0.2	0.2	1	1	λ_{max}	5.00	0.07
PR_5					Lower thanEI	(1 1 1 1)	(0.1 0.14 0.2 0.3)	(0.1 0.1 0.3 1)	(1 1 1 1)	(1 1 1 1)	1	0.2	0.2	1	1	n	5	0.0 7

Table 14 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on energy policy criterion

EP	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consistency		w_{norm}
PR_1	Lower thanEI	(–)between-MIAI	(–) between-SIAI	At mostEI	Lower thanLI	(1 1 1 1)	(0.1 0.1 0.2 0.3)	(0.11 0.11 0.14 0.2)	(1 1 1 3)	(1 1 1 3)	1	0.17	0.14	1.33	1.33	CI	0.009	0.07
PR_2		Lower thanEI	(–)lower thanEI	Greater thanEI	At leastLI	(3 6.3 8.3 9)	(1 1 1 1)	(1 1 1 1)	(1 3.66 9 9)	(1 3.66 9 9)	5.99	1	1	5.88	5.88	CR	0.008	0.38
PR_3			Lower thanEI	At leastLI	Between-LIAI	(5 7 9 9)	(1 1 1 1)	(1 1 1 1)	(1 3.66 9 9)	(1 3.67 7.67 9)	7.33	1	1	5.88	5.44	RI	1.11	0.38
PR_4				Lower thanEI	(–)lower thanLI	(0.3 1 1 1)	(0.11 0.11 0.3 1)	(0.11 0.11 0.27 1)	(1 1 1 1)	(0.33 1 1 1)	0.75	0.17	0.17	1	0.89	λ_{max}	5.035	0.077
PR_5					Lower thanEI	(0.3 1 1 1)	(0.11 0.11 0.3 1)	(0.11 0.13 0.27 1)	(1 1 1 3)	(1 1 1 1)	0.75	0.17	0.18	1.125	1	n	5	0.088

Table 15 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on energy price change criterion

EPC	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consist-ency		w_{norm}
PR_1	Lower thanEI	At leastMI	Betwee-nEILI	Lower thanAI	Between-SIAI	(1 1 1 1)	(5 7 7 9)	(1 1 3.5 7)	(1 3 5 7)	(5 7.5 9 9)	1	7	2.83	4	7.83	CI	0.05	0.46
PR_2		Lower thanEI	(–)between-LIAI	Betwee-nEILI	At mostMI	(0.1 0.14 0.14 0.2)	(1 1 1 1)	(0.1 0.13 0.27 1)	(1 1 1,5 5)	(1 1 3 5)	0.14	1	0.32	1.83	2.33	CR	0.05	0.10
PR_3			lower thanEI	isEI	Between-LISI	(0.14 0.3 1 1)	(1 3.7 7.7 9)	(1 1 1 1)	(1 1 1,5 5)	(1 1 9 9)	0.35	3.13	1	1.83	5	RI	1.11	0.27
PR_4				Lower thanEI	Betwee-nEIMI	(0.14 0.2 0.3 1)	(0.2 0.7 1 1)	(0.2 0.7 1 1)	(1 1 1 1)	(1 3 3 5)	0.25	0.55	0.55	1	3	λ_{max}	5.20	0.12
PR_5					Lower thanEI	(0.1 0.1 0.1 0.2)	(0.2 0.3 1 1)	(0.1 0.1 1 1)	(0.2 0.3 0.3 1)	(1 1 1 1)	0.13	0.43	0.2	0.33	1	n	5	0.06

Table 16 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on value change of money criterion

VCM	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consist-ency		w_{norm}
PR_1	Lower thanEI	At leastMI	Betwee-nEILI	Lower thanAI	Between-SIAI	(1 1 1 1)	(3 6.5 9 9)	(1 1 3 5)	(1 1 6.3 9)	(5 7 9 9)	1	7.17	2.33	4.11	7.67	CI	0.086	0.45
PR_2		Lower thanEI	(–)between-LIAI	Betwee-nEILI	At mostMI	(0.1 0.1 0.2 0.3)	(1 1 1 1)	(0.1 0.1 0.3 1)	(1 1 3 5)	(1 1 3.5 7)	0.14	1	0.32	2.33	2.83	CR	0.078	0.11
PR_3			Lower thanEI	isEI	Between-LISI	(0.2 0.3 1 1)	(1 3.7 7.7 9)	(1 1 1 1)	(1 1 1 3)	(1 4.3 6.3 9)	0.43	3.13	1	1.33	5.22	RI	1.11	0.25
PR_4				Lower thanEI	Betwee-nEIMI	(0.1 0.2 1 1)	(0.2 0.3 1 1)	(0.3 1 1 1)	(1 1 1 1)	(1 2.3 4.3 7)	0.24	0.43	0.75	1	3.56	λ_{max}	5.35	0.13
PR_5					Lower thanEI	(0.1 0.1 0.1 0.2)	(0.1 0.3 1 1)	(0.1 0.2 0.2 1)	(0.1 0.2 0.4 1)	(1 1 1 1)	0.13	0.35	0.19	0.28	1	n	5	0.05

Table 17 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on power demand criterion

PD	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consistency		w_{norm}
PR_1	Lower thanEI	(–)between-MIAI	(–)at leastSI	Lower thanEI	Lower thanEI	(1 1 1 1)	(0.1 0.1 0.2 0.3)	(0.1 0.1 0.1 0.2)	(1 1 1 1)	(1 1 1 1)	1	0.17	0.13	1	1	CI	0.003	0.06
PR_2		Lower thanEI	(–)lower thanEI	Between-LIAI	Greater thanEI	(3 6.3 8.3 9)	(1 1 1 1)	(1 1 1 1)	(1 3.7 7.7 9)	(1 3.7 9 9)	6	1	1	5.44	5.89	CR	0.002	0.38
PR_3			Lower thanEI	At leastLI	Between-MISI	(5 7.5 9 9)	(1 1 1 1)	(1 1 1 1)	(1 3.7 9 9)	(3 5 7 9)	7.5	1	1	5.89	6	RI	1.11	0.40
PR_4				Lower thanEI	(–)lower thanLI	(1 1 1 1)	(0.1 0.1 0.3 1)	(0.1 0.1 0.3 1)	(1 1 1 1)	(0.3 1 1 1)	1	0.18	0.17	1	0.89	λ_{max}	5.010	0.08
PR_5					Lower thanEI	(1 1 1 1)	(0.1 0.1 0.3 1)	(0.1 0.1 0.2 0.3)	(1 1 1 3)	(1 1 1 1)	1	0.17	0.17	1.13	1	n	5	0.08

Table 18 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on project finance criterion

PF	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consistency		w_{norm}
PR_1	Lower thanEI	(–)isSI	(–)between-SIAI	At mostLI	(–)isEI	(1 1 1 1)	(0.1 0.1 0.1 0.2)	(0.1 0.1 0.1 0.2)	(1 1 1.5 5)	(0.3 1 1 1)	1	0.15	0.14	1.83	0.89	CI	0.030	0.06
PR_2		Lower thanEI	Lower thanLI	Between-MISI	Between-LISI	(5 7 7 9)	(1 1 1 1)	(1 1 1 3)	(3 5 7 9)	(1 4.3 6.3 9)	6.8	1	1.33	6	5.22	CR	0.027	0.40
PR_3			Lower thanEI	Between-MIAI	Between-LIAI	(5 7 9 9)	(0.3 1 1 1)	(1 1 1 1)	(3 6.3 8.3 9)	(1 3.7 7.7 9)	7.33	0.75	1	6.89	5.44	RI	1.11	0.38
PR_4				Lower thanEI	isEI	(0.2 0.7 1 1)	(0.1 0.1 0.2 0.3)	(0.1 0.1 0.2 0.3)	(1 1 1 1)	(1 1 1 3)	0.55	0.17	0.15	1	1.33	λ_{max}	5.121	0.07
PR_5					Lower thanEI	(1 1 1 3)	(0.1 0.2 0.2 1)	(0.1 0.1 0.3 1)	(0.3 1 1 1)	(1 1 1 1)	1.13	0.19	0.18	0.75	1	n	5	0.09

Table 19 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on operation management criterion

OM	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consistency		w_{norm}
PR_1	lower thanEI	between-MISI	greater thanMI	lower thanEI	(–)isEI	(1 1 1 1)	(3 5 7 9)	(5 7.5 9 9)	(1 1 1 1)	(0.3 1 1 1)	1	6	7.83	1	0.89	CI	0.013	0.29
PR_2		lower thanEI	at mostEI	(–)between-MIAI	(–)at leastMI	(0.1 0.1 0.2 0.3)	(1 1 1 1)	(1 1 1 3)	(0.1 0.1 0.2 0.3)	(0.1 0.1 0.2 0.3)	0.17	1	1.33	0.17	0.16	CR	0.012	0.05
PR_3			lower thanEI	(–)between-MISI	(–)isMI	(0.1 0.1 0.1 0.2)	(0.3 1 1 1)	(1 1 1 1)	(0.1 0.1 0.2 0.3)	(0.1 0.2 0.2 0.3)	0.13	0.75	1	0.19	0.21	RI	1.11	0.05
PR_4				lower thanEI	isEI	(1 1 1 1)	(3 6.3 8.3 9)	(3 5 7 9)	(1 1 1 1)	(1 1 1 3)	1	6	5.31	1	1.33	λ_{max}	5.053	0.31
PR_5					lower thanEI	(1 1 1 3)	(3 6.5 9 9)	(3 5 5 7)	(0.3 1 1 1)	(1 1 1 1)	1.13	6.16	4.7	0.75	1	n	5	0.30

Table 20 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on technical infrastructure criterion

TI	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consistency		w_{norm}
PR_1	Lower thanEI	At leastLI	Between-SIAI	(–)lower thanLI	(–)at mostLI	(1 1 1 1)	(1 3.7 9 9)	(5 7 9 9)	(0.3 1 1 1)	(0.2 0.7 1 1)	1	5.89	7.67	0.89	0.76	CI	0.012	0.27
PR_2		Lower thanEI	(–)lower thanMI	(–)isSI	(–)at leastSI	(0.1 0.1 0.3 1)	(1 1 1 1)	(0.2 0.7 1 1)	(0.1 0.1 0.1 0.2)	(0.1 0.1 0.1 0.2)	0.17	1	0.76	0.15	0.13	CR	0.011	0.05
PR_3			Lower thanEI	(–)isMI	(–)between-MISI	(0.1 0.1 0.1 0.2)	(1 1 1.5 5)	(1 1 1 1)	(0.1 0.2 0.2 0.3)	(0.1 0.1 0.2 0.3)	0.13	1.32	1	0.21	0.19	RI	1.11	0.06
PR_4				Lower thanEI	(–)lower thanEI	(1 1 1 3)	(5 7 7 9)	(3 5 5 7)	(1 1 1 1)	(1 1 1 1)	1.13	6.8	4.7	1	1	λ_{max}	5.047	0.30
PR_5					Lower thanEI	(1 1 1.5 5)	(5 7.5 9 9)	(3 5 7 9)	(1 1 1 1)	(1 1 1 1)	1.32	7.5	5.31	1	1	n	5	0.33

Table 21 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on solar irradiance criterion

SI	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consistency		w_{norm}
PR_1	Lower thanEI	Between-MIAI	At leastSI	(–)lower thanEI	(–)betwee-nEILI	(1 1 1 1)	(3 6.3 8.3 9)	(5 7.5 9 9)	(1 1 1 1)	(0.2 0.3 1 1)	1	6.89	7.83	1	0.64	CI	0.026	0.25
PR_2		Lower thanEI	(–)lower thanLI	(–)isAI	(–)isAI	(0.1 0.1 0.2 0.3)	(1 1 1 1)	(0.3 1 1 1)	(0.1 0.1 0.1 0.1)	(0.1 0.1 0.1 0.1)	0.15	1	0.89	0.12	0.12	CR	0.023	0.04
PR_3			Lower thanEI	(–)greater thanEI	(–)between-MIAI	(0.1 0.1 0.1 0.2)	(1 1 1 3)	(1 1 1 1)	(0.1 0.1 0.3 1)	(0.1 0.1 0.2 0.3)	0.13	1.13	1	0.31	0.17	RI	1.11	0.05
PR_4				Lower thanEI	(–)lower thanSI	(1 1 1 1)	(7 9 9 9)	(1 3.7 9 9)	(1 1 1 1)	(0.1 0.3 1 1)	1	8.59	3.19	1	0.62	λ_{max}	5.103	0.25
PR_5					Lower thanEI	(1 1 3 5)	(7 9 9 9)	(3 6.3 8.3 9)	(1 1 3.5 7)	(1 1 1 1)	1.55	8.59	6	1.62	1	n	5	0.42

Table 22 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on system technology criterion

ST	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consistency		w_{norm}
PR_1	Lower thanEI	(–)at leastMI	(–)isAI	At mostEI	(–)isEI	(1 1 1 1)	(0.1 0.1 0.2 0.3)	(0.1 0.1 0.1 0.1)	(1 1 1 3)	(0.3 1 1 1)	1	0.16	0.12	1.33	0.89	CI	0.009	0.06
PR_2		Lower thanEI	(–)lower thanMI	Between-LIAI	Greater thanEI	(3 6.5 9 9)	(1 1 1 1)	(0.2 0.7 1 1)	(1 3.7 7.7 9)	(1 3.7 9 9)	6.16	1	0.76	5.44	5.89	CR	0.008	0.35
PR_3			Lower thanEI	Between-MIAI	Between-MISI	(7 9 9 9)	(1 1 1.5 5)	(1 1 1 1)	(3 6.3 8.3 9)	(3 5 7 9)	8.59	1.32	1	6.89	6	RI	1.11	0.44
PR_4				Lower thanEI	(–)betwee-nEILI	(0.3 1 1 1)	(0.1 0.1 0.3 1)	(0.1 0.1 0.2 0.3)	(1 1 1 1)	(0.2 0.3 1 1)	0.75	0.18	0.15	1	0.64	λ_{max}	5.037	0.06
PR_5					Lower thanEI	(1 1 1 3)	(0.1 0.1 0.3 1)	(0.1 0.1 0.2 0.3)	(1 1 3 5)	(1 1 1 1)	1.13	0.17	0.17	1.55	1	n	5	0.09

Table 23 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on plant location criterion

PL	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consistency		w_{norm}
PR_1	Lower thanEI	(–)isSI	(–)at leastAI	Lower thanEI	Lower thanLI	(1 1 1 1)	(0.1 0.1 0.1 0.2)	(0.1 0.1 0.1 0.1)	(1 1 1 1)	(1 1 1 3)	1	0.15	0.12	1	1.33	CI	0.021	0.06
PR_2		Lower thanEI	(–)betwee-nEILI	Between-LISI	Greater thanEI	(5 7 7 9)	(1 1 1 1)	(0.2 0.3 1 1)	(1 4.3 6.3 9)	(1 3.7 9 9)	6.8	1	0.64	5.22	5.89	CR	0.019	0.33
PR_3			Lower thanEI	At leastMI	At leastLI	(7 9 9 9)	(1 1 3 5)	(1 1 1 1)	(3 6.5 9 9)	(1 3.7 9 9)	8.59	1.55	1	7.17	5.89	RI	1.11	0.46
PR_4				Lower thanEI	(–)at mostMI	(1 1 1 1)	(0.1 0.2 0.2 1)	(0.1 0.1 0.2 0.3)	(1 1 1 1)	(0.1 0.3 1 1)	1	0.19	0.14	1	0.62	λ_{max}	5.08	0.06
PR_5					Lower thanEI	(0.3 1 1 1)	(0.1 0.1 0.3 1)	(0.1 0.1 0.3 1)	(1 1 3.5 7)	(1 1 1 1)	0.75	0.17	0.17	1.62	1	n	5	0.10

Table 24 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on contingency plan criterion

CP	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consistency		w_{norm}
PR_1	Lower thanEI	(–)between-SIAI	(–)greater thanLI	At mostLI	(–)lower thanMI	(1 1 1 1)	(0.1 0.1 0.1 0.2)	(0.1 0.1 0.2 0.3)	(1 1 1.5 5)	(0.2 0.7 1 1)	1	0.14	0.16	1.83	0.76	CI	0.027	0.06
PR_2		Lower thanEI	(–)betwee-nEIAI	At mostAI	Between-LISI	(5 7 9 9)	(1 1 1 1)	(0.1 0.2 1 1)	(1 1 9 9)	(1 4.3 6.3 9)	7.33	1	0.59	5	5.22	CR	0.024	0.30
PR_3			Lower thanEI	Between-MIAI	Greater thanEI	(3 6.5 9 9)	(1 1 5 9)	(1 1 1 1)	(3 6.3 8.3 9)	(1 3.7 9 9)	6.16	1.71	1	6.89	5.89	RI	1.11	0.46
PR_4				Lower thanEI	(–)lower thanAI	(0.2 0.7 1 1)	(0.1 0.1 1 1)	(0.1 0.1 0.2 0.3)	(1 1 1 1)	(0.1 0.2 1 1)	0.55	0.2	0.15	1	0.57	λ_{max}	5.11	0.06
PR_5					Lower thanEI	(1 1 1.5 5)	(0.1 0.2 0.2 1)	(0.1 0.1 0.3 1)	(1 1 6.3 9)	(1 1 1 1)	1.32	0.19	0.17	1.75	1	n	5	0.12

Table 25 Hesitant linguistic pairwise comparison matrix, trapezoidal membership functions of HFLTS, fuzzy weight vector, consistency and normalized weights of alternatives based on maintenance and repair criterion

MR	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	PR_1	PR_2	PR_3	PR_4	PR_5	Consist-ency		w_{norm}
PR_1	Lower thanEI	Greater thanLI	Greater thanEI	(−)at leastEI	Lower thanLI	(1 1 1 1)	(3 6.5 9 9)	(1 3.7 9 9)	(0.1 0.1 1 1)	(1 1 1 3)	1	7.17	5.89	0.56	1.33	CI	0.06	0.25
PR_2		Lower thanEI	Betwee-nEILI	(−)isMI	(−)between-MIAI	(0.1 0.1 0.2 0.3)	(1 1 1 1)	(1 1 3 5)	(0.1 0.2 0.2 0.3)	(0.1 0.1 0.2 0.3)	0.14	1	2.33	0.21	0.17	CR	0.05	0.06
PR_3			Lower thanEI	(−)isSI	(−)at leastLI	(0.1 0.1 0.3 1)	(0.2 0.3 1 1)	(1 1 1 1)	(0.1 0.1 0.1 0.2)	(0.1 0.1 0.3 1)	0.17	0.43	1	0.15	0.31	RI	1.11	0.05
PR_4				Lower thanEI	At mostLI	(1 1 9 9)	(3 5 5 7)	(5 7 7 9)	(1 1 1 1)	(1 1 1.5 5)	1.8	4.7	6.8	1	1.83	λ_{max}	5.24	0.40
PR_5					Lower thanEI	(0.3 1 1 1)	(3 6.3 8.3 9)	(1 3.7 9 9)	(0.2 0.7 1 1)	(1 1 1 1)	0.75	6	3.19	0.55	1	n	5	0.25

on criteria appear to be consistent, and the calculation results are shown in Tables 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24 and 25. The fuzzy weight vectors are calculated by the trapezoidal fuzzy numbers obtained from the comparison matrix of projects with respect to the criteria and the weight values of the alternative projects are determined for each criterion. The weight values obtained for alternative projects under the criteria are combined with the weight values of the criteria and the general priority values are calculated for alternative projects (Table 27). The priorities of the projects differ according to the criteria, for example, the first project has the highest priority value (0.489) according to the CVM criterion, whereas it has the lowest priority value (0.063) according to the PD criterion.

In addition to the comparative evaluation of the criteria, the independent impact weights of the criteria are also calculated. Decision makers evaluate criteria linguistically using linguistic expressions as defined in Table 26 and the number of linguistic values defined for each criterion is shown in Table 26. The fuzzy evaluation vectors are obtained for the criteria based on the number of decision makers' evaluations defined for each criterion and the trapezoidal fuzzy number of linguistic expressions from Table 3. The weight values obtained from the pairwise comparison matrix are combined with the fuzzy evaluation vectors according to the weight calculation process and the general fuzzy weight vectors are obtained for the criteria (Table 26). The ranking of the weight values of the criteria obtained from the evaluation process and the weight values of the criteria obtained from pairwise comparison matrix are the same. The general weight values obtained from evaluation process of criteria are used in the general priority calculations of alternative projects.

In the final stage of the decision-making process, the impact values of the criteria and the priority values of alternative solar energy projects for each criterion are brought together. Calculations are made separately for each project. The priority value of a project by a criterion and the weight value of that criterion are multiplied and this process is repeated under all criteria for the defined project. The values obtained are summed and the priority value (composition impact) is calculated for the defined project as shown in Table 27. The obtained AHP output defines the general priority values of the PV project alternatives as 0.189, 0.23, 0.287, 0.135, 0.158 respectively. The third project option with the highest overall priority value is selected as the most appropriate project.

In summary, alternative solar power plant projects are evaluated using the AHP model based on HFLTS. Factors used in the selection of the solar power plant are compared by experts using HFLTSs. System technology (0.18), Energy Policy (0.15), Energy price change (0.13), Solar irradiance (0.13) and Technical infrastructure (0.11) factors are defined

Table 26 Experts' evaluation for criteria and their impact weights

	Evaluation numbers for each criterion					Fuzzy evaluating vectors				Weights of criteria from comparison matrix	a_i	b_i	g_i	d_i	Fuzzy weight vector				w	General weights of criteria
	VP	P	M	G	CG										w_1	w_2	w_3	w_4		
PM	1	2	9	1	2	3.2	4.2	5.2	6.2	0.0602	0.19	0.25	0.31	0.37	0.03	0.05	0.08	0.12	0.07	0.062223
EP	2	3	7	2	1	2.73	3.73	4.73	5.73	0.1605	0.44	0.6	0.76	0.92	0.07	0.12	0.19	0.3	0.16	0.150091
EPC	0	4	7	3	1	3.13	4.13	5.13	6.13	0.1274	0.4	0.53	0.65	0.78	0.07	0.1	0.16	0.26	0.14	0.129858
VCM	1	2	6	5	1	3.47	4.47	5.47	6.47	0.0478	0.17	0.21	0.26	0.31	0.03	0.04	0.06	0.1	0.06	0.05204
PD	1	3	8	1	2	3.07	4.07	5.07	6.07	0.0217	0.07	0.09	0.11	0.13	0.01	0.02	0.03	0.04	0.02	0.021837
PF	1	4	7	2	1	2.8	3.8	4.8	5.8	0.0704	0.2	0.27	0.34	0.41	0.03	0.05	0.08	0.13	0.07	0.066823
OM	2	2	6	3	2	3.27	4.27	5.27	6.27	0.0279	0.09	0.12	0.15	0.17	0.02	0.02	0.04	0.06	0.03	0.029245
TI	2	3	6	2	2	3	4	5	6	0.1061	0.32	0.42	0.53	0.64	0.05	0.08	0.13	0.21	0.12	0.105185
SI	0	4	7	4	0	3	4	5	6	0.128	0.38	0.51	0.64	0.77	0.06	0.1	0.16	0.25	0.14	0.126911
ST	2	1	8	3	1	3.13	4.13	5.13	6.13	0.18	0.56	0.74	0.92	1.1	0.09	0.15	0.23	0.36	0.2	0.183556
PL	1	2	8	3	1	3.2	4.2	5.2	6.2	0.0423	0.14	0.18	0.22	0.26	0.02	0.04	0.05	0.09	0.05	0.04368
CP	1	3	6	4	1	3.2	4.2	5.2	6.2	0.0157	0.05	0.07	0.08	0.1	0.01	0.01	0.02	0.03	0.02	0.016231
MR	2	3	5	3	2	3.13	4.13	5.13	6.13	0.0121	0.04	0.05	0.06	0.07	0.01	0.01	0.02	0.02	0.01	0.012321
											3.04	4.04	5.04	6.04						
											a	b	g	d						

Table 27 Calculation of alternative projects' overall priority and order the alternatives

General weights of criteria	0.0622	0.1501	0.12986	0.05204	0.02184	0.06682	0.029245	0.105185	0.1269	0.1836	0.04368	0.0162	0.0123	Priority values	Ranking
Alternatives	PM	EP	EPC	VCM	PD	PF	OM	TI	SI	ST	PL	CP	MR		
PR_1	0.0602	0.0707	0.46162	0.453277	0.06011	0.06397	0.29253	0.272385	0.2519	0.0565	0.05458	0.0568	0.253	0.1894	3
PR_2	0.3979	0.3817	0.09629	0.110911	0.38347	0.40116	0.053216	0.046504	0.0356	0.3483	0.32733	0.2999	0.0551	0.2302	2
PR_3	0.3968	0.3822	0.26495	0.248054	0.39766	0.38371	0.04829	0.055648	0.0504	0.4427	0.46239	0.4634	0.0511	0.287	1
PR_4	0.0726	0.0776	0.11804	0.134378	0.07947	0.06543	0.310302	0.294133	0.2452	0.0612	0.06025	0.0613	0.396	0.1355	5
PR_5	0.0726	0.0878	0.0591	0.053381	0.07929	0.08573	0.295662	0.331329	0.417	0.0913	0.09545	0.1185	0.2448	0.1579	4

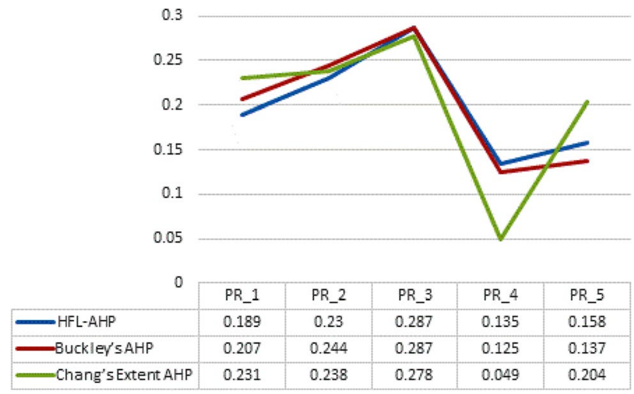

Fig. 2 General priority values of alternative projects according to AHP based methods

as the most effective factors and Maintenance and repair (0.012), Contingency plan (0.016), Power demand (0.02) and Operation management (0.03) are defined as the weakest factors according to expert evaluations. Taking into consideration the effective and ineffective factors, the latent activities that direct managerial activities and investments can be defined as follows: technological developments increase system efficiency, government supports and incentives direct investors, price changes in alternative energy sources affect consumer behavior, geographical location and environmental factors maximize solar radiation reaching the system, technical infrastructure competence provides ease of system installation and energy distribution, high-tech system ignores maintenance, repair, operational management and emergency activities and the prevalence of alternative energy sources gives consumers choice flexibility. Alternative solar energy projects are evaluated under each factor by pairwise comparison and the project that prevails over other projects under effective factors is preferred in the overall evaluation (Table 27).

Comparison and sensitivity analyses

A comparison and sensitivity analysis is performed to evaluate the suitability of the HFLTS based AHP decision-making model and the consistency of the solar power plant selection application. Decision makers evaluate alternative projects under the same criteria according to Buckley's AHP and Chang's extent analysis methods. Expert evaluations are processed under Buckley's AHP and Chang's extent analysis methods, and the general priority values of alternative projects for each method are shown in Fig. 2.

The order of alternative projects is the same in all methods and the third project is preferred as the best alternative (Fig. 2). Chang's extent analysis method reveals the distinctions among alternative projects more clearly. HFL-AHP

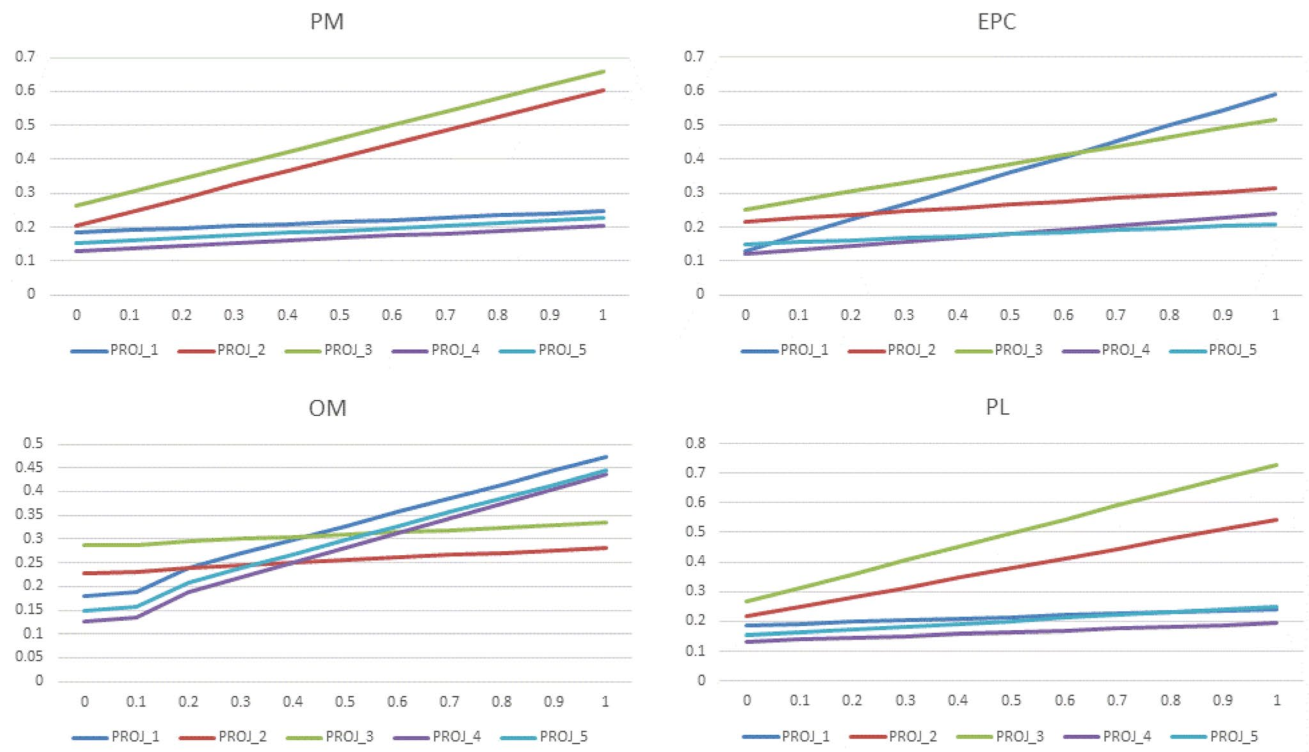

Fig. 3 Sensitivity analysis reflecting the effects of factors

and Buckley's AHP methods show more similar breaks and differences among alternative projects are clearly reflected in these methods. The fact that the order of preference of alternative projects is the same in all methods indicates that AHP decision-making method is an effective and consistent decision-making tool. The difference among the priority values of the projects is due to the different evaluation scales, pairwise comparison methods and aggregation tools.

Sensitivity analysis is performed to observe the effect degrees of the factors used in the selection of the solar energy project (Fig. 3). While the weight values of PM, EP, PD, PF, ST factors increase, the preference order of alternative projects does not change, and the 3rd and 2nd alternatives are more clearly distinguished from other alternatives.

As the weight values of EPC and VCM factors increase, the order of choice of alternative projects differs. These factors have a significant impact on project 1, and change is more limited in projects 2 and 5. Increasing the weight value of OM, TI, SI, MR factors causes significant changes on the order of preference of 1st, 5th and 4th projects. These factors do not have a significant impact on the preferences of the 3rd and 2nd projects. As the weight value of PL and CP factors increases, alternative projects 3 and 2 appear more prominently, and the order of alternatives 1 and 5 does not change. These results show that the identified factors have important effects in evaluating alternative projects. Therefore, factors should be correctly defined and comparative evaluations should be done carefully by experts.

Conclusions

In this study, it is aimed to select the most suitable PV solar energy plant project among the alternative projects affected by economic, political and technical factors. The evaluation of alternative projects under different criteria has led to the preference of the AHP MCDM model. Criteria and alternatives cannot be evaluated with exact numerical values, so evaluations are made linguistically by experts. Because evaluations based on the knowledge and experience of the experts involve uncertainty and hesitancy, evaluations are made on the basis of hesitant fuzzy linguistic terms.

The hesitant fuzzy linguistic expressions used in the comparison of criteria and alternative projects are converted to HFLTS and to the trapezoidal fuzzy numbers through the OWA aggregation operation. The consistency of the comparison matrices is measured by defuzzifying the trapezoidal fuzzy numbers derived from the hesitant linguistic terms. Trapezoidal fuzzy numbers are also converted to fuzzy weight vectors to calculate the weight values of criteria and alternative projects. Criteria are evaluated singularly with a set of linguistic expressions and trapezoidal fuzzy numbers are generated. These trapezoidal fuzzy numbers are combined with the comparative weight values of the criteria and the overall weight values are generated for the criteria. The priority value of the alternative projects according to the criteria and the weight vector of the criteria are evaluated together and the overall priority values (composition impact) of the alternative projects are calculated. The project with the highest overall priority value is preferred.

According to this study, while the effect of "system technology", "energy policy", "solar irradiance" and "energy price change" criteria is strong, the effect of "power demand", "contingency plan" and "maintenance and repair" criteria is weak in the selection of solar energy projects. The projects have different priorities according to the criteria. According to the criteria, the third project has the highest priority value with five times, while the other projects get the highest priority value with two times. However, the first project has the lowest priority value with seven times, while the fourth project that is the last in the overall evaluation does not have the lowest priority value. In the general evaluation, while the third project preferred according to the criteria with high impact values is the first in the ranking, the fourth project preferred according to the criteria with low impact values is the last. This result demonstrates the importance of the impact weights of criteria on the decision-making process. In future studies, it is planned to develop the defined criteria and to develop decision-making models based on linguistic evaluations for renewable energy projects.

Factors affecting the selection of solar energy system obtained by literature review are an important source for academic and sector studies. However, the impact values of the factors may change due to geographical location, environmental, social, political and economic differences. Therefore, the factors and expert evaluations defined in the application section cannot be used for each problem. In addition, the usefulness of the HFLTS evaluation method, the validity of AHP decision-making tools and the success of using these tools together are gained in literature. The fact that a large number of decision makers are involved in the decision-making process and that the scope of HFLTS is insufficient in the evaluation process are important limitations for the study.

In the future studies, the new method should be developed according to the size of the decision makers and the decision-making criteria used by the decision makers. The study applied for solar energy systems can be extended to other renewable energy systems. Group decision-making methods based on linguistic interval-valued intuitionistic fuzzy set and hybrid models can be used in the development process [21, 25, 41]. The developed methods can be used in the selection of the most suitable renewable energy systems and the validity of the methods can be verified with comparative analysis.

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