SOLAR PV POWER PLANT LOCATION SELECTION USING A Z-FUZZY NUMBER BASED AHP

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ABSTRACT

One of the most used renewable energy systems to produce clean and sustainable energy are solar energy photovoltaic (PV) plants. The selection among solar energy PV plant location alternatives requires a multi-criteria decision making approach with several conflicting and linguistic criteria. The assessment process is generally done in a vague and imprecise environment. Fuzzy set theory is often very beneficial for evaluating the subjective judgments of decision makers. The Analytic Hierarchy Process is the most used multi-criteria decision making method in the world because of its simplicity and efficiency. In this paper, we select a location for a solar energy PV plant using a 4-level hierarchy. We consider several criteria and sub-criteria including initial cost, maintenance cost, slope and distance to highways. A Z-fuzzy number is a relatively new concept in fuzzy set theory that enables one to circumvent the limitations of ordinary fuzzy numbers. Z-fuzzy numbers can be viewed as a combination of crisp numbers, intervals, fuzzy numbers and random numbers because of their generality. They give a better representation than ordinary fuzzy numbers. This study solves the multi-criteria solar PV power plant location selection problem with a Z-fuzzy based AHP method. To check the applicability of the method proposed here, a real-life case study from Turkey is presented and solved.

Keywords: Solar PV power plant; location selection; fuzzy AHP; Z-fuzzy number; multi-criteria; uncertainty

1. Introduction

The location selection for a solar photovoltaic (PV) power plant is a common problem in a sustainable and renewable energy supply chain. A PV power plant is a PV system composed of a lot of PV cells that convert energy from light directly to electricity. The main steps in a solar PV project are as follows: i. Concept development and plant site

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identification, ii. Pre-feasibility study, iii. Feasibility study, iv. Legal and financial issues and contracts. v. Engineering, construction and commercial operations.

The location of a photovoltaic (PV) power plant is a critical issue because of its direct impact on the performance, economic, environmental and social aspects of the plant. In the literature, there are many valuable studies about the problem of power plant location. For instance, Khan and Rathi (2014) focused on the problem of site selection for a solar PV power plant in India that employed a Geographical Information System (GIS) to solve the problem. Samanlioglu and Ayağ (2017) used an integrated fuzzy approach by integrating the Analytic Hierarchy Process (AHP) and PROMETHEE II to locate a power plant in Turkey. Garni and Awasthi (2018) conducted a literature review of 50 papers on selecting locations for solar PV power plants. The results show that the Analytical Hierarchy Process and its extensions are the most commonly used methodology, followed by overlay tool analysis in a GIS environment. Ozdemir and Sahin (2018) studied the location selection for a solar PV power plant location using a Photovoltaic Geographical Information System (PVGIS) and AHP.

As mentioned above, the first step in a solar PV project is identifying the site for a plant. This requires several criteria and alternatives to be considered under uncertainty. The uncertainty arises in assessing the alternatives with respect to the various criteria because linguistic assessments are preferred by decision makers (DM) to exact numerical evaluations. Linguistic assessments can best be treated by fuzzy set theory according to the literature. Each linguistic assessment is represented by a fuzzy number having a membership function that may be linear or nonlinear.

Fuzzy set theory has been extended to several types since the original fuzzy set theory that emerged in 1965. Figure 1 summarizes the progress of fuzzy set theory from 1965 to today. The main aim of all the extensions is to provide a new point of view when defining the membership function. Membership functions of ordinary fuzzy sets are defined by a membership degree and a non-membership degree whose sum is exactly equal to 1. Membership functions of type-2 fuzzy sets are represented by three dimensional graphs with an upper function and a lower function. Membership functions of intuitionistic fuzzy sets are represented by a membership degree and a non-membership degree whose sum is at most equal to 1. If the sum is less than 1, the difference is called the hesitancy of the DM. Membership functions of Pythagorean fuzzy sets offer a larger domain to the DM since their squared sum is at most equal to 1. Membership functions of neutrosophic fuzzy sets are composed of truthiness, indeterminacy and falsity degrees whose sum might be between 0 and 3. Hesitant fuzzy sets are different from other fuzzy sets since they offer techniques for treating more than one possible membership degree for a certain X value.

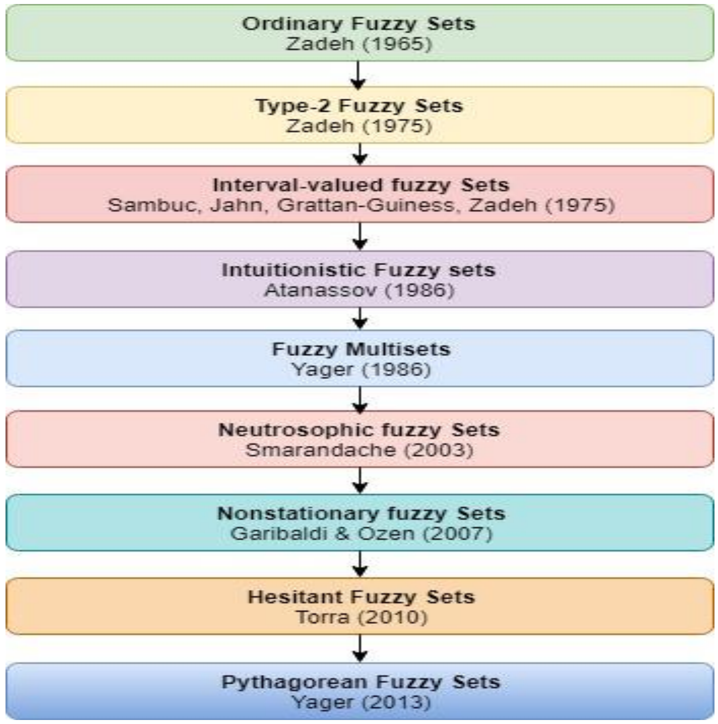

Figure 1 Extensions of fuzzy sets

Within the framework of ordinary fuzzy sets, Zadeh (2011) proposed the Z-fuzzy number which is an ordered pair of fuzzy numbers (A, B). The first component *A* represents the fuzzy restriction while the second component *B* is the reliability of the first component. Researchers claim Z-numbers perform better when describing human judgments and dealing with uncertainty than traditional fuzzy numbers since they can handle restraint and reliability functions (Deng & Chan, 2011). In this paper, we convert the linguistic assessments to Z-fuzzy numbers and evaluate the PV power plant location alternatives based on the AHP. To the best of our knowledge, this is the first study employing a Z-fuzzy number-based AHP method for solving the solar PV power plant location problem.

The rest of the paper is organized as follows: Section 2 gives a literature review of fuzzy AHP; Section 3 explains Z-fuzzy numbers, including their arithmetic operations; Section 4 gives the proposed method Z-fuzzy AHP step-by-step; Section 5 is an application of the proposed method to a PV plant location problem; Section 6 presents the conclusions and directions for further research.

2. Fuzzy AHP in the literature

Fuzzy extensions of AHP have been obtained by using fuzzy numbers. Recently, ordinary fuzzy numbers have been extended to several different types of fuzzy numbers such as intuitionistic fuzzy numbers, Pythagorean fuzzy numbers and type-2 fuzzy numbers. These extensions have allowed new fuzzy AHP extensions to be developed in the literature that are briefly summarized as follows.

2.1 Ordinary Fuzzy AHP

Ordinary fuzzy AHP methods have been proposed by various authors. The first one was introduced by Van Laarhoven and Pedrycz (1983). They used triangular fuzzy numbers and Lootsma's logarithmic least squares method for deriving fuzzy weights and fuzzy performance scores of alternatives. Buckley (1985) used trapezoidal fuzzy numbers and derived fuzzy weights and fuzzy performance scores by using a geometric mean method. Boender et al. (1989) modified Van Laarhoven and Pedrycz's (1983) method and proposed a more robust approach to the normalization of the local priorities. Chang (1996) proposed an extent analysis method for deriving priorities from comparison matrices whose elements are defined as triangular fuzzy numbers. The drawback of this method is that it is possible to obtain the value of zero for initial weights or local priorities for some elements of the decision structure (Wang et al., 2008). Such a computed zero local priority may cause some of the information to not be considered in the calculations (Li et al., 2008). Cheng (1997) proposed a fuzzy AHP method based on both probability and possibility measures in which performance scores are represented by membership functions and the aggregate weights are calculated by using entropy concepts. Mikhailov (2003) proposed a fuzzy extension of AHP which obtains crisp priorities based on an α-cut of fuzzy numbers by using a technique called fuzzy preference programming (FPP). The main drawback of this approach is that each comparison matrix must be constructed as an individual FPP model which increases the complexity of the solution (Yu & Cheng, 2007).

2.2 Type-2 fuzzy AHP

The concept of a type-2 fuzzy set was introduced by Zadeh (1975) as an extension to an ordinary fuzzy set called a type-1 fuzzy set. Kahraman et al. (2014) developed an interval type-2 (IT2) fuzzy AHP method together with a new ranking method for type-2 fuzzy sets and then applied the method to supplier selection. Kilic and Kaya (2015) proposed a new evaluation model for investment projects for development agencies operating in Turkey to address the ambiguities and relativities in real world scenarios by using type-2 fuzzy sets and crisp sets simultaneously. Abdullah and Najib (2014a) proposed a new fuzzy AHP characterized by IT2 FS for linguistic variables. It was different from the typical FAHP which directly utilized trapezoidal type-1 fuzzy numbers. This method introduced IT2 FS to enhance judgments in the fuzzy decision-making environment. This new model included linguistic variables in IT2 FS and a rank-value method for normalizing upper and lower memberships of IT2 FS.

2.3 Intuitionistic fuzzy AHP

Atanassov (1986)'s intuitionistic fuzzy sets (IFSs) include the membership value as well as the non-membership value for describing any x in X such that the sum of membership and non-membership is at most equal to 1. Sadiq and Tesfamariam (2009) applied the concept of IFS to AHP which is called IF-AHP to handle both vagueness and ambiguity related uncertainties in the environmental decision making process. Abdullah et al. (2009) applied IFS to the AHP method called IF-AHP to quantify vagueness uncertainties in AHP using IFS for the decision-making problem. The authors constructed several linear programming models to generate optimal weights for attributes. Wang et al. (2011) proposed an IF-AHP method in which the decision information was represented by intuitionistic fuzzy values. The method synthesizes the eigenvectors of the intuitionistic fuzzy comparison matrix in which all the decision information is intuitionistic fuzzy.

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Zhang et al. (2011) discussed the approximation of IFS to fuzzy sets based on the relationships between IFS and fuzzy sets. They also showed that the intuitionistic fuzzy complementary judgement matrix approximates the fuzzy complementary judgement matrix and proved that the consistency adjustments of both are equal. Based on these results, the authors proposed an AHP method based on an intuitionistic judgment matrix. Feng et al. (2012) proposed a Dempster Shafer – AHP (DS-AHP) method combined with intuitionistic fuzzy information. The expected utility was used to transform a decision matrix having intuitionistic fuzzy information obtained from the assessments and then a non-linear optimization model was used to combine the attributes. Wu et al. (2013) proposed an interval valued intuitionistic fuzzy AHP (IVIF-AHP) method for MCDM problems developing a score function for interval valued intuitionistic fuzzy numbers (IVIFNs) and introducing some new concepts such as antisymmetric interval matrix, the transfer interval matrix and the approximate optimal transfer matrix. Kaur (2014) proposed a triangular intuitionistic fuzzy number based (TIFN) approach for the vendor selection problem using AHP. Xu and Liao (2014) proposed a new way to check the consistency of the intuitionistic preference relation and then introduced an automatic procedure to repair the most inconsistent one. Abdullah and Najib (2014a) proposed a new preference scale in the framework of the interval-valued intuitionistic fuzzy AHP (IVIF-AHP). The comparison matrix judgment was expressed in IVIFNs with degree of hesitation. Abdullah and Najib (2014b) proposed a new method of intuitionistic fuzzy AHP (IF-AHP) to deal with uncertainty in decision-making. The new IF-AHP was applied to establish a preference in the sustainable energy planning decision-making problem. Dutta and Guha (2015) proposed a preference programming based weight determination method of IF-AHP in which decision makers expressed their pair-wise comparisons by using generalized triangular intuitionistic fuzzy numbers. Keshavarzfard and Makui (2015) presented an intuitionistic fuzzy Multiple Attribute Decision Making (MADM) approach for modelling and solving AHP problems with a small amount of relationships among various criteria. IF-AHP was used to evaluate the weighting for each criterion and then intuitionistic fuzzy DEMATEL method was applied to establish contextual relationships among the criteria. Onar et al. (2015) proposed an interval valued intuitionistic fuzzy AHP (IVIF-AHP) approach to measure the overall performance of wind energy alternatives.

2.4 Hesitant fuzzy AHP

Hesitant fuzzy sets (HFS) are useful for dealing with situations where decision makers are hesitant to provide their preferences about objects, preferring to offer a margin of error. HFSs permit the membership degree of an element to be a set which is represented as several possible values between 0 and 1. Tuysuz and Simsek (2017) developed a hesitant fuzzy linguistic term sets based AHP approach and applied it to the performance comparison of cargo firms. Kahraman et al. (2017) developed a hesitant fuzzy linguistic AHP and applied it to Business-to-Customer marketplace prioritization. Oztaysi et al. (2015) developed a hesitant fuzzy AHP method involving multi-expert's linguistic evaluations aggregated by ordered weighted averaging (OWA) operator.

2.5 Pythagorean fuzzy AHP

Yager (2013) introduced a Pythagorean fuzzy set (PFS) characterized by a membership degree and a non-membership degree satisfying the condition that the square sum of its membership degree and non-membership degree is equal to or less than 1 which is a generalization of IFS. Ilbahar et al. (2018) developed a novel approach to risk assessment for occupational health and safety using Pythagorean fuzzy AHP and fuzzy inference system.

2.6 Neutrosophic AHP

The neutrosophic sets developed by Smarandache (1998) extend the concept of Intuitionistic Fuzzy Sets (IFSs) that were introduced by Atanassov (1983) for a new point of view to uncertainty, impreciseness, inconsistency and vagueness. Smarandache (1998) introduced the degree of indeterminacy/neutrality as a new and independent component of fuzzy sets and defined a neutrosophic set composed of three components: truth membership, indeterminacy membership, and falsity membership. Radwan et al. (2016) developed a novel hybrid neutrosophic AHP approach in learning management systems in decision making to handle indeterminacy of information. Abdel-Basset et al. (2017) integrated AHP into a Delphi framework under a neutrosophic environment and introduced a new technique for checking consistency and calculating the consensus degree of an expert's opinions.

3. Preliminaries: Z-fuzzy numbers

Zadeh (1975) defined a Z-number associated with an uncertain variable *Z* as an ordered pair of fuzzy numbers (A, B) where *A* is a fuzzy subset of the domain *X* of the variable *Z* and *B* is a fuzzy subset of the unit interval. The concept of a Z-number is intended to provide a basis for computation with numbers which are not totally reliable. A Z-number can be used to represent information about an uncertain variable of the type where *A* represents a value of the variable and *B* represents an idea of certainty or probability. There are a limited number of studies on Z-fuzzy numbers. Biswas (2012) observed the drawback of the existing fuzzy numbers, studied Z-fuzzy numbers and presented fundamental arithmetic operations for Z-fuzzy numbers. Abu Bakar and Gegov (2014) conducted a study ranking Z-numbers by proposing a multi–layer decision making methodology. Biswas (2016) discussed whether or not the fuzzy set theory was appropriate for large size problems with a number of universes and a lot of elements in these universes. In the study, the researcher also focused on Z-fuzzy numbers and their mathematical operations.

Definition 1. A *Z*-number is an ordered pair of fuzzy numbers denoted as $\mathrm{Z} = (\widetilde{\mathrm{A}}, \widetilde{\mathrm{R}})$. The first component $\widetilde{\mathrm{A}}$, a restriction on the values, is a real-valued uncertain variable X. The second component $\tilde{R}$ is a measure of reliability for the first component, described in Figure 2. When $a_2 equals a_3$, a trapezoidal fuzzy number becomes a triangular fuzzy number.

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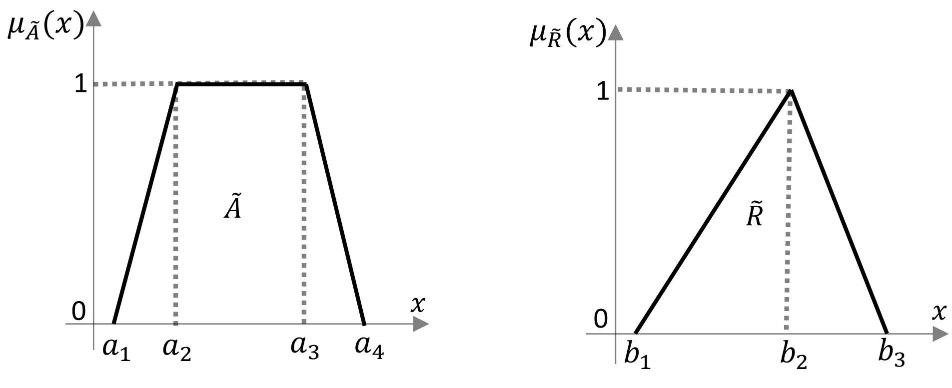

$Z = (\tilde{A}, \tilde{R})$

Figure 2 A simple *Z*-fuzzy number

Definition 2. Let a fuzzy set A be defined on a universe X be given as: $\mathrm{A} = \{\langle \mathrm{x}, \mu_{\mathrm{A}}(\mathrm{x})\rangle \,|\mathrm{x}\epsilon\mathrm{X}\}$ where $\mu_{\mathrm{A}}: \mathrm{X} \to [0,1]$ is the membership function A. The membership value $\mu_{\mathrm{A}}(\mathrm{x})$ describes the degree of belonging of $\mathrm{x} \in \mathrm{X}$ in A. The Fuzzy Expectation of a fuzzy set is denoted as:

$$E_A(x) = \int_x \; x\mu_A(x)\, dx \tag{1}$$

which is not the same as the meaning of the Expectation of Probability Space. It can be considered to be the information strength supporting the fuzzy set A.

Definition 3: Converting a Z-number to a regular fuzzy number

Consider a Z-number $Z = (\widetilde{A}, \tilde{R})$ described by Figure 2. The left is the part of restriction, and the right is the part of reliability. Let $\tilde{A} = \{\langle x, \mu_{\tilde{A}}(x)\rangle | \mu(x) \in [0,1]\}$ and $\tilde{R} = \{\langle x, \mu_{\tilde{R}}(x)\rangle | \mu(x) \in [0,1]\}$, $\mu_{\tilde{A}}(x)$ is a trapezoidal membership function, and $\mu_{\tilde{R}}(x)$ is a triangular membership function.

1. Convert the second part (reliability) into a crisp number using Equation 2.

$$\alpha = \frac{\int x\mu_{\tilde{R}}(x)\, dx}{\int \mu_{\tilde{R}}(x)\, dx} \tag{2}$$

where $\int$ denotes an algebraic integration.
Alternatively, Equation 3 can be used for this defuzzification:

$$\alpha = \frac{a_1 + 2*(a_2 + a_3) + a_4}{6} \tag{3}$$

2. Add the weight of the second part (reliability) to the first part (restriction). The weighted Z-number can be denoted as $\tilde{Z}^{\alpha} = \{\langle x, \mu_{\tilde{A}^{\alpha}}(x)\rangle | \mu_{\tilde{A}^{\alpha}}(x) = \alpha\mu_{\tilde{A}}(x), \mu(x) \in [0,1]\}$

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3. Convert the irregular fuzzy number (weighted restriction) to a regular fuzzy number. The ordinary fuzzy set can be denoted as $\tilde{Z}' = \left\{\langle x, \mu_{\tilde{Z}'}(x)\rangle \middle| \mu_{\tilde{Z}'}(x) = \mu_{\tilde{A}}\left(\frac{x}{\sqrt{\alpha}}\right), \mu(x) \in [0,1]\right\}$. $\tilde{Z}'$ has the same Fuzzy Expectation with $\tilde{Z}^{\alpha}$, and they are equal with respect to Fuzzy Expectation, which can be denoted by Figure 3.

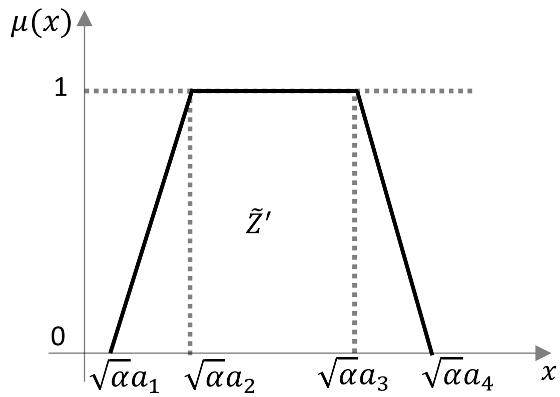

Figure 3 Ordinary fuzzy number transformed from Z-number

4. If the restriction function and reliability function are defined as in Figure 4 (their heights may be any value between 0 and 1), the calculations are modified as follows:
Let $\tilde{A}_{\delta} = \{\langle x, (\mu_{\tilde{A}}(x);\ \delta)\rangle | \mu(x) \in [0,1]\}$ and $\tilde{R}_{\beta} = \{\langle x, (\mu_{\tilde{R}}(x);\ \beta)\rangle | \mu(x) \in [0,1]\}$; $\boldsymbol{\mu_{\tilde{A}}^{\delta}(x)}$ is a trapezoidal membership function and $\boldsymbol{\mu_{\tilde{R}}^{\beta}(x)}$ is a triangular membership function. When $a_2 = a_3$, a trapezoidal membership function becomes a triangular membership function.

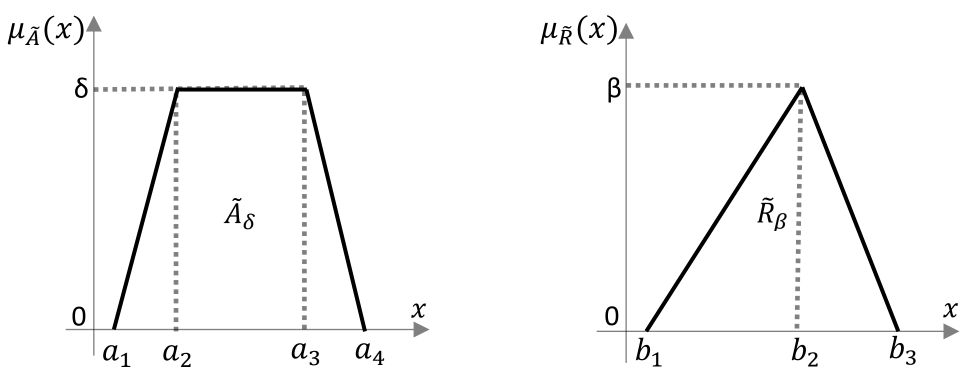

Figure 4 A simple $\tilde{Z}_{\delta,\beta}$ number, $\tilde{Z}_{\delta,\beta} = \left(\tilde{A}_{\delta}, \tilde{R}_{\beta}\right)$

In this case, restriction and reliability functions are defined as in Equations 4-5, respectively. The reliability membership function in Equation 4 is substituted into the defuzzification formula (Equation 2 or Equation 3) so that Equation 6 is obtained.

$$\mu_{\tilde{A}}^{\delta}(x)=\begin{cases}\frac{x-a_1}{a_2-a_1}\ \delta\ , if a_1\le x\le a_2\\ \delta, \qquad if a_2\le x\le a_3\\ \frac{a_4-x}{a_4-a_3}\ \delta, if a_3\le x\le a_4\\ 0, \qquad Otherwise\end{cases} \tag{4}$$

$$\mu_{\tilde{R}}^{\beta}(x)=\begin{cases}\frac{x-b_1}{b_2-b_1}\ \beta\ , if b_1\le x\le b_2\\ \frac{b_3-x}{b_3-b_2}\ \beta\ , if b_2\le x\le b_3\\ 0, \qquad Otherwise\end{cases} \tag{5}$$

Thus, we have

$$\sqrt{\alpha}=\sqrt{\frac{\int x\boldsymbol{\mu}_{\tilde{R}}^{\boldsymbol{\beta}}(x)\,dx}{\int \boldsymbol{\mu}_{\tilde{R}}^{\boldsymbol{\beta}}(x)\,dx}} \tag{6}$$

Then, the weighted $\tilde{Z}_{\delta,\beta}$ number can be denoted as in Equation 6.

$$\tilde{Z}_{\delta,\beta}^{\alpha}=\left\{\langle x,\boldsymbol{\mu}_{\tilde{A}^{\alpha}}^{\boldsymbol{\delta}}(\boldsymbol{x})\rangle \middle| \boldsymbol{\mu}_{\tilde{A}^{\alpha}}^{\boldsymbol{\delta}}(\boldsymbol{x})=\frac{\int x\boldsymbol{\mu}_{\tilde{R}}^{\boldsymbol{\beta}}(x)\,dx}{\int \boldsymbol{\mu}_{\tilde{R}}^{\boldsymbol{\beta}}(x)\,dx}\boldsymbol{\mu}_{\tilde{A}}^{\boldsymbol{\delta}}(\boldsymbol{x}), \mu(x)\in[0,1]\right\} \tag{7}$$

The ordinary fuzzy number converted from Z-fuzzy number can be given as in Equation 8.

$$\tilde{Z}'_{\delta,\beta}=\left\{\langle x,\boldsymbol{\mu}_{\tilde{Z}'}^{\boldsymbol{\delta}}(\boldsymbol{x})\rangle \middle| \boldsymbol{\mu}_{\tilde{Z}'}^{\boldsymbol{\delta}}(\boldsymbol{x})=\boldsymbol{\mu}_{\tilde{A}}^{\boldsymbol{\delta}}\left(\boldsymbol{x}\ \frac{\int \boldsymbol{\mu}_{\tilde{R}}^{\boldsymbol{\beta}}(x)\,dx}{\int x\boldsymbol{\mu}_{\tilde{R}}^{\boldsymbol{\beta}}(x)\,dx}\right),\ \mu(x)\in[0,1]\right\} \tag{8}$$

4. Z- fuzzy number based AHP

In this method we integrate z-fuzzy numbers with AHP. The advantage of this integration is to incorporate vagueness in the evaluations and reliabilities to these evaluations into the AHP. The steps of the proposed Z-fuzzy number based-AHP are presented in the following:

Step 1. Define the multi-criteria decision making problem and design a hierarchical structure of the problem.

Step 2. Use the scale of linguistic restriction function given in Table 1 and the scale of reliability function presented in Table 2. These are the scales that have been proposed by the authors.

Table 1
Triangular Z-fuzzy restriction scale

Linguistic Terms	Restriction function
Equally Better (E)	(1,1,1;1)
Slightly Better (SLB)	(1,1,3;1)
Moderately Better (MB)	(1,3,5;1)
Strongly Better (STB)	(3,5,7;1)
Very Strongly Better (VSTB)	(5,7,9;1)
Certainly Better (CB)	(7,9,10;1)
Absolutely Better (AB)	(9,10,10;1)

Table 2
Reliability scale with its corresponding triangular Z-fuzzy numbers

Linguistic Reliability	Triangular Z-fuzzy reliability function
Absolutely Reliable (AR)	(0.8,0.9,1;1)
Strongly Reliable (SR)	(0.7,0.8,0.9;1)
Very Highly Reliable (VHR)	(0.6,0.7,0.8;1)
Highly Reliable (HR)	(0.5,0.6,0.7;1)
Fairly Reliable (FR)	(0.4,0.5,0.6;1)
Weakly Reliable (WR)	(0.3,0.4,0.5;1)
Very Weakly Reliable (VWR)	(0.2,0.3,0.4;1)
Strongly Unreliable (SU)	(0.1,0.2,0.3;1)
Absolutely Unreliable (AU)	(0,0.1,0.2;1)

Decision makers may assign different values for the given linguistic terms and correspondingly different fuzzy restriction functions in Table 1 if s/he wants to assign intermediate values.

Step 3. Construct the pairwise comparison matrices and fill them in with their corresponding Z-fuzzy numbers using the linguistic scales in Tables 1 and 2.

Step 4. Transform Z-fuzzy numbers to their corresponding equivalent ordinary fuzzy numbers.

Step 5. Check the consistency of each fuzzy pairwise comparison matrix. Assume $\tilde{A} = \lfloor \tilde{a}_{ij} \rfloor$ is a fuzzy positive pairwise comparison matrix and $A = \lfloor a_{ij} \rfloor$ is its defuzzified positive pairwise comparison matrix. If the result of the comparisons of $A = \lfloor a_{ij} \rfloor$ is consistent; then, it can imply that the result of the comparisons of $\tilde{A} = \lfloor \tilde{a}_{ij} \rfloor$ is also consistent. In the

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consistency measurement, reliability functions are ignored since they cause a consistent pairwise comparison matrix to become an inconsistent one when they are converted to regular fuzzy numbers.

Step 6. Apply Buckley's ordinary fuzzy AHP method (Buckley, 1985). The steps of this method are summarized as follows:

Step 6.1. Calculate the geometric mean for each parameter of $\tilde{a}_{ij}$ in the n dimensional pairwise comparison matrix of criteria. Thus, $n \times n$ matrix is converted to an $n \times 1$ matrix. This is the step that converts Z-fuzzy numbers to regular fuzzy numbers.
Step 6.2. Sum the values of each parameter in the column then normalize the values in the $n \times 1$ matrix.
Step 6.3. Apply the fuzzy division operation to get the normalized weights vector.
Step 6.4. Defuzzify the normalized weights vector using the center of gravity method given by Equation 2.
Step 6.5. Normalize the weights so their sum is equal to 1.
Step 6.6. Apply Steps (6.1-6.5) for the rest of the pairwise comparison matrices of sub-criteria and alternatives.
Step 6.7. Combine all the weight vectors, to obtain the global weights and determine the best alternative as in the classical AHP.

5. Application

In this section, a real life problem of a newly founded facility is solved using the proposed Z-AHP method. A brief problem definition is presented, followed by the results of the proposed method as illustrated with a figure and tables.

5.1 Problem definition

In 2015, the Renewable Energy General Directorate reported by the Solar Energy Map (SEM) of Turkey highlighted that "the total annual insolation time is 2.737 hours, and the total solar energy derived per year is 1.527 kwh/m2 per year" (https://www.rvo.nl/sites/default/files/2015/10/Renewable%20Energy %20Turkey.pdf). The research has shown that capacity additions for renewable energy sources in Turkey have increased remarkably especially in recent years. The report of Shura (2018) noted that in 2017 there was a net renewable energy capacity of 3.2 GW versus 1.5 GW for non-renewables. The report also said that the PV capacity of 1.79 GW added in 2017 was more than three times what was added in 2016 (Shura, 2018).

According to the Republic of Turkey Ministry of Energy and Natural Resources, by the end of June 2018 the total PV solar power plant installed capacity will be 4,723 MW comprised of a total of 4,703 MW unlicensed and 23 MW licensed plants (http://www.enerji.gov.tr/en-US/Pages/Solar). Thus, Turkey will have one of the largest solar PV markets in Europe (Shura, 2018).

This study aims to solve the location selection problem of a private company for one of its newly installed PV energy production facilities in the southwest part of Turkey. Based

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on the meetings held with investors and managers, the possible alternative locations are marked in Figure 5 (http://www.pv-financing.eu/wp-content/uploads/2017/06/PV-Financing-webinar-IT-ES-TR-business-models-slides-170517.pdf), are Antalya, İçel and Muğla.

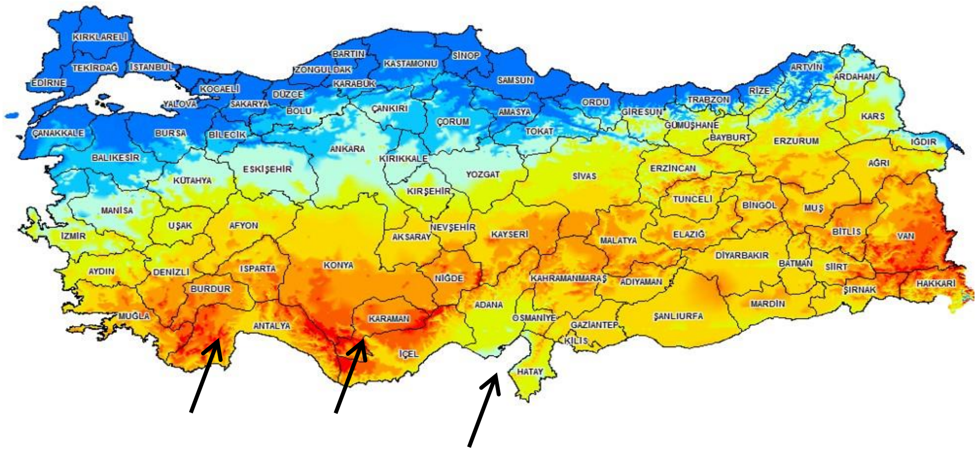

Figure 5 Solar map of Turkey showing the alternative locations for the facility (http://www.pv-financing.eu/wp-content/uploads/2017/06/PV-Financing-webinar-IT-ES-TR-business-models-slides-170517.pdf)

After a detailed literature review and a meeting with the management, a 4-level hierarchy was designed that is illustrated in Figure 6. As seen from the figure, there are seven main criteria: geological & topographic factors, political & legal factors, technical factors, economical factors, environmental factors, location-related factors, and social factors with a total of 18 sub-criteria such as slope, legislation and social support.

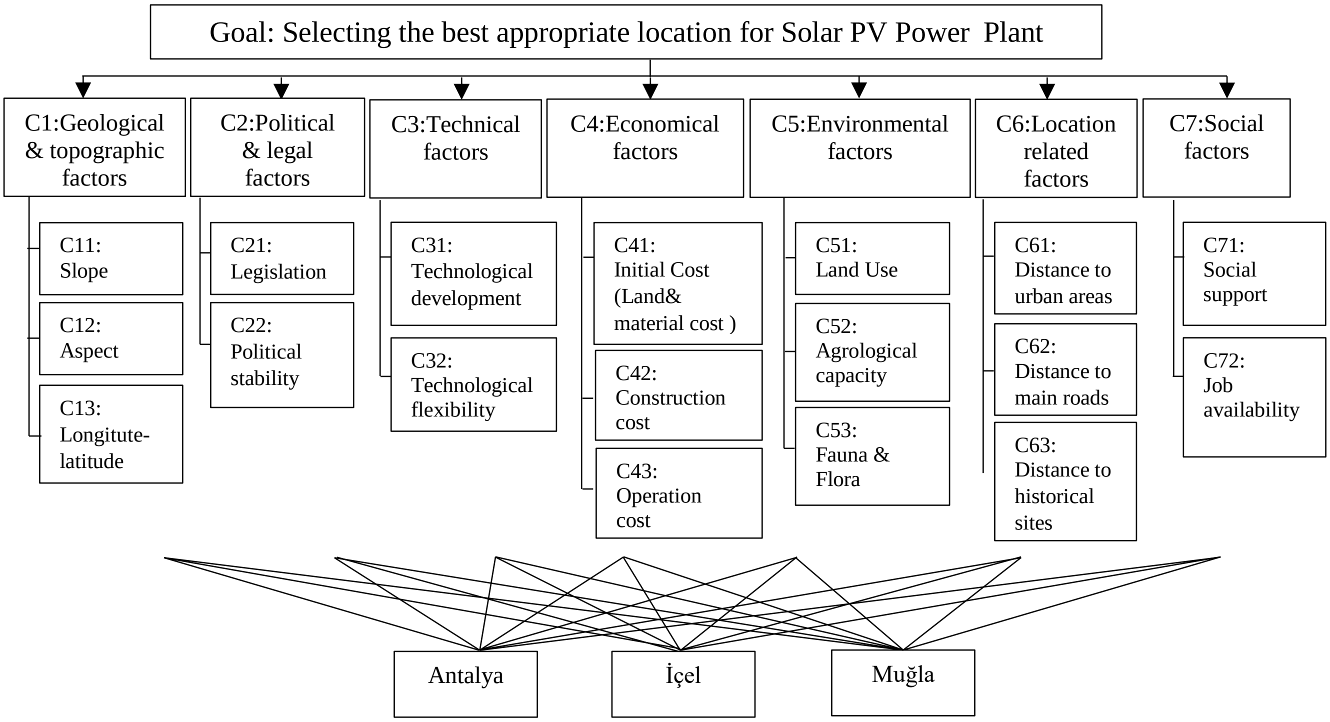

Figure 6 Hierarchical structure of the problem

Once the hierarchical structure of the problem was ready, linguistic judgments were obtained from the decision makers, who are three experts from the Energy Institute of Istanbul Technical University. Table 3 presents the pairwise comparison matrix of the criteria based on the linguistic restriction and reliability values on which the decision makers arrived at consensus, while Table 4 illustrates the pairwise comparison matrix of the criteria with corresponding values from Tables 1 and 2.

Table 3
Pairwise comparison matrix of the criteria

Criteria	C1	C2	C3	C4	C5	C6	C7
C1	E, E	SLB, VHR	1/CB, HR	1/VSTB, FR	1/MB, SR	1/STB, VHR	MB, SR
C2	1/SLB, VHR	E, E	1/AB, SR	1/CB, AR	1/MB, SR	1/STB, FR	SLB, HR
C3	CB, HR	AB, SR	E, E	1/SLB, VHR	STB, SR	SLB, SR	CB, SR
C4	VSTB, FR	CB, AR	SLB, VHR	E, E	VSTB, SR	MB, VHR	AB, AR
C5	MB, SR	MB, SR	1/STB, SR	1/VSTB, SR	E, E	1/MB, SR	STB, VHR
C6	STB, VHR	STB, FR	1/SLB, SR	1/MB, VHR	MB, SR	E, E	VSTB, AR
C7	1/MB, SR	1/SLB, HR	1/CB, SR	1/AB, AR	1/STB, VHR	1/VSTB, AR	E, E

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Table 4
Pairwise comparison matrix with corresponding triangular Z-fuzzy restriction and reliability scales

Criteria	C1	C2	C3	C4	C5	C6	C7
C1	((1,1,1;1), (1,1,1;1))	((1,1,3;1), (0.6,0.7,0.8;1))	((0.1,0.11,0.14;1), (0.5,0.6,0.7;1))	((0.11,0.14,0.2;1), (0.4,0.5,0.6;1))	((0.2,0.33,1;1), (0.7,0.8,0.9;1))	((0.14,0.2,0.33;1), (0.6,0.7,0.8;1))	((1,3,5;1), (0.7,0.8,0.9;1))
C2	((0.33,1,1;1), (0.6,0.7,0.8;1))	((1,1,1;1), (1,1,1;1))	((0.1,0.1,0.11;1), (0.7,0.8,0.9;1))	((0.1,0.11,0.14;1), (0.8,0.9,1;1))	((0.2,0.33,1;1), (0.7,0.8,0.9;1))	((0.14,0.2,0.33;1), (0.4,0.5,0.6;1))	((1,1,3;1), (0.5,0.6,0.7;1))
C3	((7,9,10;1), (0.5,0.6,0.7;1))	((9,10,10;1), (0.7,0.8,0.9;1))	((1,1,1;1), (1,1,1;1))	((0.33,1,1;1), (0.6,0.7,0.8;1))	((3,5,7;1), (0.7,0.8,0.9;1))	((1,1,3;1), (0.7,0.8,0.9;1))	((7,9,10;1), (0.7,0.8,0.9;1))
C4	((5,7,9;1), (0.4,0.5,0.6;1))	((7,9,10;1), (0.8,0.9,1;1))	((1,1,3;1), (0.6,0.7,0.8;1))	((1,1,1;1), (1,1,1;1))	((5,7,9;1), (0.7,0.8,0.9;1))	((1,3,5;1), (0.6,0.7,0.8;1))	((9,10,10;1), (0.8,0.9,1;1))
C5	((1,3,5;1), (0.7,0.8,0.9;1))	((1,3,5;1), (0.7,0.8,0.9;1))	((0.14,0.2,0.33;1), (0.7,0.8,0.9;1))	((0.11,0.14,0.2;1), (0.7,0.8,0.9;1))	((1,1,1;1), (1,1,1;1))	((0.2,0.33,1;1), (0.7,0.8,0.9;1))	((3,5,7;1), (0.6,0.7,0.8;1))
C6	((3,5,7;1), (0.6,0.7,0.8;1))	((3,5,7;1), (0.4,0.5,0.6;1))	((0.33,1,1;1), (0.7,0.8,0.9;1))	((0.2,0.33,1;1), (0.6,0.7,0.8;1))	((1,3,5;1), (0.7,0.8,0.9;1))	((1,1,1;1), (1,1,1;1))	((5,7,9;1), (0.8,0.9,1;1))
C7	((0.2,0.33,1;1), (0.7,0.8,0.9;1))	((0.33,1,1;1), (0.5,0.6,0.7;1))	((0.1,0.11,0.14;1), (0.7,0.8,0.9;1))	((0.1,0.1,0.11;1), (0.8,0.9,1;1))	((0.14,0.2,0.33;1), (0.6,0.7,0.8;1))	((0.11,0.14,0.2;1), (0.8,0.9,1;1))	((1,1,1;1), (1,1,1;1))

When only the restriction functions are considered in the calculation of the consistency ratio for the matrix, we obtained 0.083 which is lower than the desirable 0.1. After the Z-fuzzy numbers have been converted to their corresponding equivalent ordinary fuzzy numbers, Table 4 is transformed into Table 5. Table 5 now represents the pairwise comparison matrix of the criteria using ordinary fuzzy numbers.

Table 5
Z-fuzzy numbers converted to ordinary fuzzy numbers

	C1	C2	C3	C4	C5	C6	C7
C1	(1,1,1;1)	(0.84,0.84,2.51;1)	(0.08,0.09,0.11;1)	(0.08,0.10,0.14;1)	(0.18,0.30,0.89;1)	(0.12,0.17,0.28;1)	(0.89,2.68,4.47;1)
C2	(0.28,0.84,0.84;1)	(1,1,1;1)	(0.09,0.09,0.10;1)	(0.09,0.11,0.14;1)	(0.18,0.30,0.89;1)	(0.10,0.14,0.24;1)	(0.77,0.77,2.32;1)
C3	(5.42,6.97,7.75;1)	(8.05,8.94,8.94;1)	(1,1,1;1)	(0.28,0.84,0.84;1)	(2.68,4.47,6.26;1)	(0.89,0.89,2.68;1)	(6.26,8.05,8.94;1)
C4	(3.54,4.95,6.36;1)	(6.64,8.54,9.49;1)	(0.84,0.84,2.51;1)	(1,1,1;1)	(4.47,6.26,8.05;1)	(0.84,2.51,4.18;1)	(8.54,9.49,9.49;1)
C5	(0.89,2.68,4.47;1)	(0.89,2.68,4.47;1)	(0.13,0.18,0.30;1)	(0.10,0.13,0.18;1)	(1,1,1;1)	(0.18,0.30,0.89;1)	(2.51,4.18,5.86;1)
C6	(2.51,4.18,5.86;1)	(2.12,3.54,4.95;1)	(0.30,0.89,0.89;1)	(0.17,0.28,0.84;1)	(0.89,2.68,4.47;1)	(1,1,1;1)	(4.74,6.64,8.54;1)
C7	(0.18,0.30,0.89;1)	(0.26,0.77,0.77;1)	(0.09,0.10,0.13;1)	(0.09,0.09,0.11;1)	(0.12,0.17,0.28;1)	(0.11,0.14,0.19;1)	(1,1,1;1)

After that, Buckley's ordinary fuzzy AHP method is applied to find the weights of the criteria. By following the steps of the methodology in Section 4, the fuzzy weights of the criteria are calculated. The values are defuzzified using the center of gravity method and the defuzzified values are normalized. In this study, because of the space constraints, only the calculations for the main criteria are shown.

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Table 6
Weights of main criteria

Criteria	Fuzzy weights	Normalized fuzzy weights	Defuzified weights	Normalized crisp weights
C1	(0.27, 0.37, 0.64)	(0.02, 0.04, 0.09)	0.05	0.04
C2	(0.23, 0.31, 0.48)	(0.02, 0.03, 0.07)	0.04	0.03
C3	(2.10, 2.89, 3.66)	(0.15, 0.29, 0.54)	0.32	0.28
C4	(2.51, 3.40, 4.67)	(0.18, 0.35, 0.69)	0.39	0.35
C5	(0.46, 0.80, 1.28)	(0.03, 0.08, 0.19)	0.10	0.09
C6	(1.02, 1.82, 2.61)	(0.07, 0.18, 0.39)	0.21	0.18
C7	(0.18, 0.24, 0.34)	(0.01, 0.02, 0.05)	0.03	0.02

Table 6 demonstrates the results of the fuzzy, defuzzified and normalized crisp weights of the criteria. According to the results, the most important criterion is C4 Economical factors with a weight of 0.35. It is followed by the criterion C3 Technical factors with a weight of 0.28. The least important criteria are C7 Social factors and C2 Political and legal factors.

After repeating the steps of the proposed procedure, the calculations for the pairwise comparison matrices of sub-criteria with respect to each main criterion are obtained and the results are illustrated in Table 7.

Table 7
Pairwise comparison matrices of sub-criteria

wrt C1	C11	C12	C1	weight
C11	E.E	E.SR		0.145
C12		E.E		0.142
C13	STB.A	STB.S	E.E	0.713
CR=0.05				

wrt C2	C21	C22	weights
C21	E. E		0.453
C22	SLB. HR	E. E	0.547
CR=0.00			

wrt C3	C31	C32	weights
C31	E.E	E. VHR	0.50
C32		E. E	0.50
CR=.00			

wrt C4	C41	C42	C43	weights
C41	E. E	E. SR		0.321
C42		E. E		0.312
C43	E. VHR	SLB. AR	E. E	0.367
CR=0.08				

wrt	C51	C52	C53	weights
C51	E. E	STB.	STB.	0.713
C52		E. E	E. SR	0.145
C53			E. E	0.142
C=0.05				

wrt C6	C61	C62	C63	weights
C61	E. E	E. AR	STB. SR	0.458
C62		E. E	STB. VHR	0.448
C63			E. E	0.094
CR=0.05				

wrt C7	C71	C72	weights
C71	E. E	MB. SR	0.652
C72		E. E	0.348
CR=0.00			

Table 8 contains the linguistic pairwise comparison matrices of the alternatives with respect to the sub-criteria.

Table 8
Linguistic pairwise comparison matrices of the alternatives

wrt C11	A1	A2	A3	weights
A1	E	AB, AR	CB, AR	0.820
A2		E		0.080
A3		SLB, SR	E	0.101
CR=0.08				

wrt C12	A1	A2	A3	weights
A1	E	E, SR		0.087
A2		E		0.083
A3	AB, AR	AB, VHR	E	0.829
CR=0.00				

wrt C13	A1	A2	A3	weights
A1	E	AB, VHR	AB, HR	0.828
A2		E	E, VHR	0.087
A3			E	0.085
CR=0.00				

wrt C21	A1	A2	A3	weights
A1	E	CB, SR	CB, HR	0.807
A2		E	E, AR	0.099
A3			E	0.094
CR=0.01				

wrt C22	A1	A2	A3	weights
A1	E	AB, HR	VSTB, VHR	0.788
A2		E		0.088
A3		SLB, AR	E	0.125
CR=0.08				

wrt C31	A1	A2	A3	weights
A1	E	SLB, FR		0.096
A2		E		0.077
A3	CB, HR	AB, VHR	E	0.827
CR=0.08				

wrt C32	A1	A2	A3	weights
A1	E	SLB. AR		0.104
A2		E		0.082
A3	CB. VHR	AB. SR	E	0.814
CR=0.08				

wrt C41	A1	A2	A3	weights
A1	E		SLB. AR	0.099
A2	AB. SR	E	AB. VHR	0.822
A3			E	0.080
CR=0.08				

wrt C42	A1	A2	A3	weights
A1	E		E. HR	0.085
A2	AB. FR	E	AB. HR	0.828
A3			E	0.088
CR=0.00				

wrt C43	A1	A2	A3	weights
A1	E		SLB. SR	0.123
A2	VSTB. VHR	E	CB. VHR	0.784
A3			E	0.093
CR=0.09				

wrt C51	A1	A2	A3	weights
A1	E	AB. AR	SLB. SR	0.531
A2		E		0.050
A3		CB. SR	E	0.418
CR=0.08				

wrt C52	A1	A2	A3	weights
A1	E	VSTB. HR	VSTB. AR	0.788
A2		E		0.103
A3		E. FR	E	0.110
CR=0.03				

wrt C53	A1	A2	A3	weights
A1	E			0.097
A2	CB. HR	E	CB. HR	0.806
A3	E. SR		E	0.097
CR=0.01				

wrt C61	A1	A2	A3	weights
A1	E	AB. SR	AB. AR	0.838
A2		E		0.080
A3		E. HR	E	0.082
CR=0.00				

wrt C62	A1	A2	A3	weights
A1	E	CB.	VSTB.	0.796
A2		E		0.089
A3		SLB. FR	E	0.115
CR=0.00				

wrt C63	A1	A2	A3	weights
A1	E			0.094
A2	CB. HR	E	CB. SR	0.807
A3	E. AR		E	0.099
CR=0.01				

wrt C71	A1	A2	A3	W
A1	E	E. SR	E. AR	0.331
A2		E		0.331
A3		E. AR	E	0.338
CR=0.00				

wrt C72	A1	A2	A3	W
A1	E	AB.	CB.	0.821
A2		E		0.076
A3		SLB.	E	0.103
CR=0.08				

When we combine these weights in Table 9, we obtain the alternative locations rank as follows: İçel > Mugla > Antalya. The best location is İçel with a weight of 0.359. It is followed by Mugla (0.324) and Antalya (0.307), respectively.

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Table 9
Combination of the weights

Alternatives	$w_{C_{11}}$=0.145	$w_{C_{12}}$=0.142	$w_{C_{13}}$=0.713	Local Weights
A1	0.820	0.087	0.828	0.722
A2	0.080	0.083	0.087	0.085
A3	0.101	0.829	0.085	0.193

Alternatives	$w_{C_{21}}$=0.453	$w_{C_{22}}$=0.547	Local Weights
A1	0.807	0.788	0.797
A2	0.099	0.088	0.093
A3	0.094	0.125	0.111

Alternatives	$w_{C_{31}}$=0.50	$w_{C_{32}}$=0.50	Local Weights
A1	0.096	0.104	0.100
A2	0.077	0.082	0.080
A3	0.827	0.814	0.821

Alternatives	$w_{C_{41}}$=0.321	$w_{C_{42}}$=0.312	$w_{C_{43}}$=0.367	Local Weights
A1	0.099	0.085	0.123	0.103
A2	0.822	0.828	0.784	0.810
A3	0.080	0.088	0.093	0.087

Alternatives	$w_{C_{51}}$=0.713	$w_{C_{52}}$=0.145	$w_{C_{53}}$=0.142	Local Weights
A1	0.531	0.788	0.097	0.507
A2	0.050	0.103	0.806	0.165
A3	0.418	0.110	0.097	0.328

Alternatives	$w_{C_{61}}$=0.458	$w_{C_{62}}$=0.448	$w_{C_{63}}$==0.094	Local Weights
A1	0.838	0.796	0.094	0.749
A2	0.080	0.089	0.807	0.152
A3	0.082	0.115	0.099	0.098

Alternatives	$w_{C_{71}}$=0.652	$w_{C_{72}}$=0.348	Local Weights
A1	0.331	0.821	0.502
A2	0.331	0.076	0.242
A3	0.338	0.103	0.256

Alternatives	w_{C_1}=0.04	w_{C_2}=0.03	w_{C_3}=0.28	w_{C_4}=0.35	w_{C_5}=0.09	w_{C_6}=0.18	w_{C_7}=0.02	Global Weights
A1	0.722	0.797	0.100	0.103	0.507	0.749	0.502	0.307
A2	0.085	0.093	0.080	0.810	0.165	0.152	0.242	0.359
A3	0.193	0.111	0.821	0.087	0.328	0.098	0.256	0.324

In Table 10, we present the comparison of the proposed method with classical AHP.

Table10
Comparison with classical AHP

	Alternatives		
Method	Antalya	Icel	Mugla
z-Fuzzy number based AHP	0.307	0.359	0.324
Classical AHP	0.312	0.362	0.326

The rankings in both methods are the same, and the priorities are close as well. However, Z-fuzzy AHP considers a different uncertainty environment. This may well cause a different ranking in another problem.

6. Conclusions and future research directions

Solar PV power plant location selection is a typical multi-criteria decision making problem based on many tangible and intangible criteria that are appropriate for assessing linguistically. Z-fuzzy AHP is a relatively new approach to classical AHP with a fuzzy environment. Z-fuzzy numbers are represented by restriction and reliability membership

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functions. The study fills the gap in the literature by proposing a Z-fuzzy number based AHP method to determine the best location for a solar PV power plant. In this study, Z-fuzzy numbers are converted to regular fuzzy numbers and then ordinary fuzzy operations are applied. We applied Buckley's fuzzy AHP approach after the conversion in our Z-fuzzy AHP approach. The comparative analysis showed that the proposed extension of fuzzy AHP produced the same rank of the PV power plant location alternatives as the classical AHP did. The consistency of each fuzzy pairwise comparison matrix was calculated after they were defuzzified.

The proposed method should be used under vagueness and when reliability to this vagueness is not equal to one. It has been observed that reliability levels have a significant effect on the weights that are obtained. As the reliability values are largely different from one another in a pairwise comparison matrix, the weights can be quite different from each other. Hence, reliability levels should be carefully determined when using this method.

For further research, there are many possible ways to extend this work. For instance, intuitionistic Z-fuzzy numbers can be replaced with ordinary Z-fuzzy numbers. Another possibility is to replace intuitionistic Z-fuzzy numbers with Pythagorean Z-fuzzy numbers, neutrosophic Z-fuzzy numbers or hesitant Z-fuzzy numbers. The results can then be compared with the ones obtained in this study. Future studies can also perform a sensitivity analysis to see if there is a change when the parameters change.

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