

## AN UNCERTAINTY-AWARE APPROACH TO SOLAR ENERGY SYSTEMS ESTIMATION USING FUZZY Z-NUMBER MODELING

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**Abstract:** The study and assessment of renewable energy sources contributes to the state regional energy planning process and helps identify weaknesses in the region's infrastructure (electricity grid, road network). This article uses a fuzzy logic method to assess solar energy resources in the study area, describes and develops a multi-criteria analysis method combined with fuzzy logic. The main beneficiaries and target audience of fuzzy logic methods in solar power systems are solar power policy decision makers. They use them to determine decision models, ranking criteria, and weights, and to evaluate the possible location of solar power plants under specific conditions. In practice, fuzzy logic allows for simple and efficient tuning of controllers in non-linear control systems, such as solar modules. This study investigates the role and contribution of fuzzy logic in solar power based on its implementation. The results of the study showed that the use of fuzzy logic allows for the evaluation and selection appropriate solar energy systems in given and uncertainty conditions, Fuzzy logic methods include fuzzy modeling, hybrid modeling, multi-attribute decision making. This study demonstrated the usefulness of these methods in solving problems related to solar energy systems.

**Keywords:** Solar energy, Fuzzy logic, Fuzzy Z-numbers, Multi-criteria decision making.

### Introduction

Renewable energy is essential for sustainable development and helps address the issues of non-renewable and finite resource depletion [1]. These power generation resources are regarded clean energy and provide to energy supply stability, which is a critical issue, particularly, at the time of power shortages. Renewable energy is utilized in various scientific and technological fields, including automobiles, industry, and thermal power plants. Over the past decade, renew-

able energy has demonstrated a trend of replacing fossil fuels with solar energy and electricity, and integrating them into vehicles (motorcycles, cars, etc.), serving as an example of sustainable development. Therefore, renewable energy is the best alternative to fossil fuels, which have limited reserves and are harmful to the environment. Solar energy is a renewable energy source derived from the sun, which reaches the earth in different forms as thermal and optical energy. It is one of the most wider utilized forms of energy [2]. This is utilized to produce electricity, water

desalination, and heat production, etc. Alongside other renewable energy options, solar energy is the most widely used renewable energy source and may be the best choice for the future [3]. Fuzzy logic is used in many fields, such as automation process, computer vision identification, multimedia signal processing, forecasting, pattern classification, problem solving, optimal control, and sequence modeling. This is also applied for solar power systems. Although fuzzy logic methods are favored by renewable energy experts, their contribution to decision making in solar power systems lies in their ability to represent risk factors and linguistic variables in data obtained from solar power implementations. In different countries, two types of solar energy systems such as photovoltaic (PV) and solar thermal are utilized [4]. Photovoltaic energy is one of the favored solar energy technologies and is considered encouraging energy source for the future [5]. Occurrences of photovoltaic technologies incorporate multilayer photovoltaic cells concentrated photovoltaic cells, thermoelectric converters, floating photovoltaic generators, and high-energy photon down conversion [6]. Solar thermal energy is generated by transforming radiant energy into thermal energy. Solar thermal techniques incorporate solar water heaters and solar air heaters, cooking with solar energy, and solar-thermal electricity generation [7]. The efficiency of a solar power plant depends on several factors, including installation location, the number and quality of solar panels, panel tilt angle, solar orientation, panel surface quality, and conversion efficiency [8]. Solar power plant installation location means that solar insolation levels vary greatly depending on geographic location. A solar panel converts solar energy into electrical energy. A panel's efficiency is determined by its coefficient of performance, which is typically 15-25%. The higher the efficiency, the more solar energy is converted into electricity [9]. The tilt angle of solar panels determines their orientation toward the sun. The more directly they are tilted, the more sunlight reaches the panels and the more electricity they generate. The optimal tilt angle depends on geographic location and time of year. It is important that solar panels are oriented toward the sun to maximize energy production. This is achieved using a solar tracking system, which automatically rotates the

panels to follow the sun's movement [10]. The panel surface must be clean and free of dust, dirt, and other contaminants that can reduce solar energy conversion efficiency. Regular surface cleaning helps maintain high energy production [11]. The inverter converts the direct current generated by the panels into alternating current used by the grid. Some energy is lost during the conversion process, so the higher the inverter's efficiency, the lower the losses. Typically, modern inverters are approximately 99% efficient.

This study is formulated as follows: Preliminaries illustrates key definitions. Case study represents the problem statement and techniques for evaluation solar energy technologies, and conclusion represents basic results of the study.

### Preliminaries

**Definition 1.** Triangular fuzzy numbers are widely utilized kind of fuzzy numbers in practical terms and determined as  $\tilde{f} = (f_1, f_2, f_3)$  [12]. The chart representation of triangular fuzzy numbers is illustrated in Fig. 1.

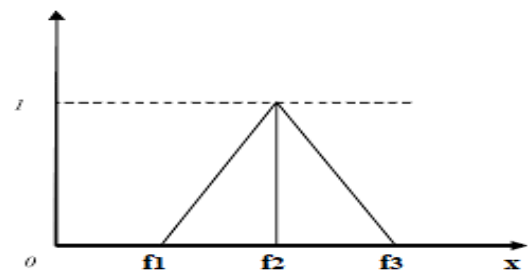


Fig. 1. A triangular fuzzy number

Membership function  $\mu_{\tilde{f}}(x)$  of triangular fuzzy number  $\tilde{f} = (f_1, f_2, f_3)$  is depicted as below:

$$\mu_{\tilde{f}}(x) = \begin{cases} 0, & x \leq f_1 \\ \frac{x - f_1}{f_2 - f_1}, & f_1 < x < f_2 \\ \frac{x - f_2}{f_3 - f_2}, & f_2 < x < f_3 \\ 0, & x \geq f_3 \end{cases} \quad (1)$$

$f_1, f_2, f_3$  are real numbers and  $f_1 < f_2 < f_3$  [13].

**Definition 2.**  $Z = (\tilde{A}, \tilde{B})$  number includes two elements  $\tilde{A}$  and  $\tilde{B}$ .  $\tilde{A}$  is a fuzzy value of variable,  $\tilde{B}$  is fuzzy number that show reliability of  $\tilde{A}$  [14]. Pairwise comparison matrix  $(Z_{ij})$  is square matrix of  $Z$  -numbers [15]:

$$(Z_{ij} = (A_{ij}, B_{ij})) = \begin{pmatrix} Z_{11} = (A_{11}, B_{11}) & \dots & Z_{1n} = (A_{1n}, B_{1n}) \\ \vdots & \dots & \vdots \\ Z_{ni} = (A_{ni}, B_{ni}) & \dots & Z_{nn} = (A_{nn}, B_{nn}) \end{pmatrix} \quad (2)$$

$Z_{ij} = (A_{ij}, B_{ij}), i, j = 1, \dots, n$  number represents partially reliable information on degree of preference for  $i$ -th criterion against  $j$ -th criteria.  $\tilde{A}$  and  $\tilde{B}$  can be linguistic terms selected from linguistic set  $\tilde{A}_Z$  and  $\tilde{B}_Z$ , respectively [16]. Let  $D = [D_{ij}]$  is decision-making matrix, where  $D_{ij}$  is the estimation of any option with respect to criteria [17].  $D_{ij} = Z_{ij}(\tilde{A}, \tilde{B})$  and the  $Z$ -number  $Z_{ij}(\tilde{A}, \tilde{B}), i = 1, 2, \dots, m, j = 1, 2, \dots, n$  is the estimation of the  $j$ -th criteria for  $i$ -th alternative. Thus, the problem may be modeled as below.

$$D = \begin{pmatrix} Z_{11}(\tilde{A}, \tilde{B}) & Z_{12}(\tilde{A}, \tilde{B}) & \dots & Z_{1n}(\tilde{A}, \tilde{B}) \\ Z_{21}(\tilde{A}, \tilde{B}) & Z_{22}(\tilde{A}, \tilde{B}) & \dots & Z_{2n}(\tilde{A}, \tilde{B}) \\ \vdots & \vdots & \dots & \vdots \\ Z_{m1}(\tilde{A}, \tilde{B}) & Z_{m2}(\tilde{A}, \tilde{B}) & \dots & Z_{mn}(\tilde{A}, \tilde{B}) \end{pmatrix} \quad (3)$$

**Definition 3.** Suppose  $z_1 = ((a_1^l, a_1^m, a_1^u), (b_1^l, b_1^m, b_1^u))$ ,  $z_2 = ((a_2^l, a_2^m, a_2^u), (b_2^l, b_2^m, b_2^u))$  are given. Normalization second reliability components provided as below [17].

$$z_1 = ((x_1^l, x_1^m, x_1^u), (y_1^l/y_1, y_1^m/y_1, y_1^u/y_1)), \\ z_2 = ((x_2^l, x_2^m, x_2^u), (y_2^l/y_2, b_2^m/y_2, y_2^u/y_2)) \quad (4)$$

where  $y_1 = y_1^l + y_1^m + y_1^u, y_2 = y_2^l + y_2^m + y_2^u$ .

**Definition 4.** For  $Z$ -numbers  $Z, Z'$  holds.

$$ZZ' \text{ if } D(Z, (1,1)) \geq D(Z', (1,1)) \quad (5)$$

$D$  is previously defined distance,  $(1,1)$  is a fuzzy singletons-based  $Z$ -number [17].

**Definition 5.** Hellinger distance is a methodology for measuring the similarity between two probability distributions. It generally used in decision-making processes to assess the differences between two distributions using a  $Z$ -score. Calculation of Hellinger distance is shown below.

$$H(P, Z) = \frac{1}{\sqrt{2}} \sqrt{\sum_i (\sqrt{P(i)} - \sqrt{Z(i)})^2} \quad (6)$$

$P(i)$  and  $Z(i)$  are probability functions of  $P$  and  $Z$  distributions.

### Case Study: A comparison of photovoltaic technologies

Assume a comparison of three photovoltaic technologies: thin-film ( $A$ ), perovskite ( $B$ ), and organic solar cells ( $C$ ). They are evaluated according to four criteria – reliability ( $C_1$ ), efficiency ( $C_2$ ), service life ( $C_3$ ), and environmental impact ( $C_4$ ) employing a fuzzy MCDM methodology employing  $Z$ -numbers for evaluation options and criteria. The  $Z$ -number approach to solar technology evaluation is a contemporary technique that synthesizes fuzzy  $Z$ -number with solar energy decision-making procedures.  $Z$ -numbers extend the framework of fuzzy logic and allow for the consideration of uncertainty, incompleteness, and reliability of information in real-world settings. Unlike traditional methods based on fuzzy sets or multi-criteria analysis, which rely on quantitative evaluation of criteria,  $Z$ -numbers provide a more accurate description of ambiguous and imprecise data. Linguistic scales are often used in fuzzy logic to handle qualitative and imprecise information. These metrics enable for illustration individual assessments utilizing linguistic expressions, which are subsequently transformed to fuzzy numbers for evaluation and choices. Chart form of expressions for first restriction part of fuzzy  $Z$ -number is presented in Fig. 2.

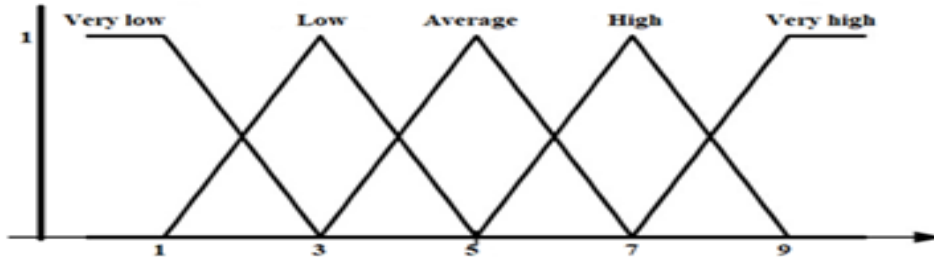


Fig. 2. Linguistic terms for first component of Z-number

Chart form of expressions for second reliability part of fuzzy Z-number is presented in Fig. 2.

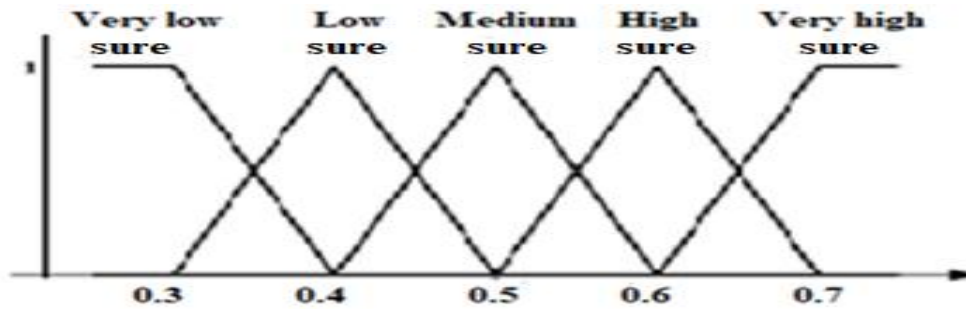


Fig. 3. Linguistic terms for second component of Z-number

Step 1. Alternatives are evaluated according to criteria. Decision matrix using Z-numbers constructed and represented in Table 1.

Table 1. Decision matrix for estimation alternatives and criteria

$C_1$	$C_2$	$C_3$	$C_4$
(5, 7, 9; 0.3,0.4,0.5)	(3, 5, 7; 0.5, 0.6, 0.7)	(3, 5, 7; 0.3,0.4, 0.5)	(1, 3, 5; 0.5,0.6, 0.7)
(3, 5, 7; 0.4,0.5,0.6)	(5, 7, 9; 0.3, 0.4, 0.5)	(3, 5, 7; 0.4, 0.5, 0.6)	(3, 5, 7; 0.4, 0.5, 0.6)
(5, 7, 9; 0.5,0.6,0.7)	(5, 7, 9; 0.5, 0.6, 0.7)	(3, 5, 7; 0.4, 0.5, 0.6)	(1, 3, 5; 0.5,0.6, 0.7)

Step 2. Pairwise comparison matrix for evaluating weight of each attribute developed as demonstrated in Table 2.

Table 2. Pairwise comparison matrix

	$C_1$	$C_2$	$C_3$	$C_4$
$C_1$	(1, 1, 1; 0.6, 0.7, 0.8)	(0.2,0.25,0.29; 0.5, 0.6, 0.7)	(1.5, 2, 2.5; 0.4, 0.5, 0.6)	(3, 4, 5; 0.5, 0.6, 0.7)
$C_2$	(3.5, 4, 4.5; 0.5, 0.6, 0.7)	(1, 1, 1; 0.6, 0.7, 0.8)	(4.5, 5, 5.5; 0.7, 0.8, 0.9)	(3, 4, 5; 0.4, 0.5, 0.6)
$C_3$	(0.33,0.5,0.67; 0.4, 0.5, 0.6)	(0.19,0.2,0.23; 0.7, 0.8, 0.9)	(1, 1, 1; 0.6, 0.7, 0.8)	(0.2,0.25,0.32; 0.5, 0.6, 0.7)
$C_4$	(0.2,0.25,0.32; 0.5, 0.6, 0.7)	(0.2,0.25,0.32; 0.4, 0.5, 0.6)	(3, 4, 5; 0.5, 0.6, 0.7)	(1, 1, 1; 0.6, 0.7, 0.8)

Step 3. Determining weights of criteria. When we take into account eigenvalues and eigenvectors in terms of Z numbers, we handling with matrices whose items are not crisp data, they are Z numbers. Calculating eigenvalues includes solution the characteristic equations in background. This implies broadening the concepts of determinants and integer-domain Eigen functions in polynomial form. The comparable eigenvectors are calculated by solving  $Zv = \lambda v$  for each eigenvalue  $\lambda$ . In this expression,  $Z$  is  $n \times n$  matrix,  $\lambda$  is eigenvalue, and  $v$  is eigenvector.

Weight of criteria  $C_1$  is (0.1756, 0.1759, 0.176; 0.29, 0.31, 0.34),

Weight of criteria  $C_2$  is (0.543, 0.5428, 0.543; 0.281, 0.283, 0.2828),

Weight of criteria  $C_3$  is (0.0884, 0.0886, 0.0888; 0.28, 0.281, 0.283),

Weight of criteria  $C_4$  is (0.1931, 0.1933, 0.193; 0.28, 0.2802, 0.2803).

Step 4. Normalization of weighted decision matrix is illustrated in Table 3.

Table 3. Weighted decision matrix

$C_1$	$C_2$	$C_3$	$C_4$
(0.25,0.57,0.66; 0.3, 0.4, 0.5)	(0.002,0.19,0.41; 0.5, 0.6, 0.7)	(0.003,0.20, 0.40, 0.3, 0.4, 0.5)	(0.002, 0.3, 0.44; 0.5, 0.6, 0.7)
(0.002,0.18,0.41; 0.4, 0.5, 0.6)	(0.25, 0.47, 0.68; 0.3, 0.4, 0.5)	(0.002, 0.19, 0.41; 0.4, 0.5, 0.6)	(0.24, 0.45, 0.66; 0.4, 0.5, 0.6)
(0.25, 0.47, 0.68; 0.5, 0.6, 0.7)	(0.25, 0.47, 0.68; 0.5, 0.6, 0.7)	(0.002, 0.19, 0.41; 0.4, 0.5, 0.6)	(0.002,0.22,0.43; 0.5, 0.6, 0.7)

Step 5. Ranking alternatives. For ranking alternatives, we determine Hellinger distance for each alternative. Closeness of option  $A$  and  $Z(1)$  is 1.65, closeness of option  $B$  and  $Z(1)$  is 2.23, closeness of option  $C$  and  $Z(1)$  is 2.43. So, results for  $A = 1.65$ ,  $B = 2.23$ ,  $C = 2.43$ . Alternatives ordering indicates that option thin-film solar technology ( $A$ ) is best alternative.

**Conclusion**

Weighting determination for attributes employing Z-numbers is a powerful way to incorporate both the importance and confidence of various factors in a decision-making procedure. In this study fuzzy Z-number based MCDM technique is employed for evaluation options thin-film ( $A$ ), perovskite ( $B$ ), and organic solar cells ( $C$ ) in solar technology selection. Options are estimated using four criteria  $C_1$ - reliability,  $C_2$ - efficiency,  $C_3$ - lifespan, and  $C_4$ - environmental impact. Utilizing fuzzy Z-number methodology in fuzzy multi-criteria decision making improves the solar technology evaluation process by successfully managing fuzziness and making sure that decisions founded on trustwor-

thy information. Comparative analysis of options indicates that alternative thin-film ( $A$ ) is best option in solar technology selection.

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## **GÜNƏŞ ENERJISI SİSTEMLƏRİNİN QEYRI-MÜƏYYƏNLİK NƏZƏRƏ ALINMAQLA FUZZY Z-SAYI MODELƏSDİRİLMƏSİ VASİTƏSİLƏ QIYMƏTLƏNDİRİLMƏSİ**

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**Xülasə:** Bərpa olunan enerji mənbələrinin öyrənilməsi və qiymətləndirilməsi dövlətin regional enerji planlaşdırma prosesinə töhfə verir və regionun infrastrukturundakı (elektrik şəbəkəsi, yol şəbəkəsi) zəif cəhətləri müəyyən etməyə kömək edir. Bu məqalədə tədqiqat ərazisində günəş enerjisi ehtiyatlarını qiymətləndirmək üçün qeyri-səlis məntiq metodundan istifadə olunur, qeyri-səlis məntiqlə birləşdirilmiş çoxmeyarlı analiz metodu təsvir edilir və istifadə etdirilir. Günəş enerjisi sistemlərində qeyri-səlis məntiq metodlarının əsas faydalananları və hədəf auditoriyası günəş enerjisi siyasəti qərar qəbul edənlərdir. Onlar bunlardan qərar modellərini, sıralama meyarlarını və çəkirlərini müəyyən etmək, həmçinin müəyyən şərtlər

altında günəş elektrik stansiyalarının mümkün yerini qiymətləndirmək üçün istifadə edirlər. Qeyri-səlis məntiq günəş modulları kimi qeyri-xətti idarəetmə sistemlərində tənzimləyicilərin sadə və səmərəli şəkildə istifadəsinə imkan verir. Bu tədqiqat qeyri-səlis məntiqin günəş enerjisindəki rolunu və töhfəsini onun tətbiqinə əsasən araşdırır. Tədqiqatın nəticələri göstərdi ki, qeyri-səlis məntiqin istifadəsi qeyri-müəyyənlik şəraitində müvafiq günəş enerjisi sistemlərinin qiymətləndirilməsinə və seçilməsinə imkan verir. Qeyri-səlis məntiq texnologiyalarına qeyri-səlis modelləşdirmə, hibrid modelləşdirmə, çoxmeyarlı qərar qəbuletmə daxildir. Bu tədqiqat bu texnologiyaların günəş enerjisi sistemləri ilə əlaqəli problemlərin həllində faydalılığını nümayiş etdirir.

**Açar sözlər:** Günəş enerjisi, Qeyri-səlis məntiq, qeyri-səlis Z-ədədlər, Çoxmeyarlı qərar qəbuletmə.

## ПОДХОД К ОЦЕНКЕ СОЛНЕЧНЫХ ЭНЕРГЕТИЧЕСКИХ СИСТЕМ С УЧЕТОМ НЕОПРЕДЕЛЕННОСТИ НА ОСНОВЕ МОДЕЛИРОВАНИЯ НЕЧЕТКИМИ Z-ЧИСЛАМИ

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**Резюме:** Изучение и оценка возобновляемых источников энергии способствует процессу государственного регионального энергетического планирования и помогает выявлять слабые места в региональной инфраструктуре (электросети, дорожная сеть). В данной статье для оценки ресурсов солнечной энергии в исследуемой области используется метод нечеткой логики, описывается и разрабатывается метод многокритериального анализа в сочетании с нечеткой логикой. Основными бенефициарами и целевой аудиторией методов нечеткой логики в системах солнечной энергетики являются лица, принимающие решения в области политики солнечной энергетики. Они используют их для определения моделей принятия решений, критериев ранжирования и весов, а также для оценки возможного размещения солнечных электростанций в конкретных условиях. На практике нечеткая логика позволяет легко и эффективно настраивать контроллеры в нелинейных системах управления, таких как солнечные модули. В данном исследовании изучается роль и вклад нечеткой логики в солнечную энергетику на основе ее применения. Результаты исследования показали, что использование нечеткой логики позволяет оценивать и выбирать подходящие системы солнечной энергии в заданных и неопределенных условиях. Методы нечеткой логики включают нечеткое моделирование, гибридное моделирование, многокритериальное принятие решений. Данное исследование продемонстрировало полезность этих методов в решении задач, связанных с системами солнечной энергии.

**Ключевые слова:** Солнечная энергия, нечеткая логика, нечеткие Z-числа, многокритериальное принятие решений.