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Prioritization of renewable energy resources using intuitionistic fuzzy AHP and VIKOR methods: TR33 region example

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Abstract

Growing economies and the increasing world population increase electricity demand, one of the most important requirements of social and economic life. A large part of electricity generation is provided by fossil fuels, which brings environmental problems. Various initiatives are being taken around the world to overcome ecological problems. The last of these initiatives is the Paris Climate Agreement, in which Türkiye recently became a party. In accordance with this agreement, Türkiye is carrying out studies towards the net-zero carbon target in line with the 2030 interim target and the 2053 final target. Within the scope of studies carried out in the energy field, it aims to reduce carbon emission levels by increasing the installed capacity of renewable energy. The subject of this study is prioritizing renewable energy resources for the TR33 Region covering Manisa, Uşak, Kütahya and Afyonkarahisar provinces. An integrated methodology is used to prioritize energy resources. In this study, the Intuitionistic Fuzzy AHP method was applied to determine criteria weights, after which the Intuitionistic Fuzzy VIKOR method was used to rank the energy alternatives. In the study, five main criteria and 17 sub-criteria related to these main criteria were used, and five renewable energy alternatives were evaluated. The research outcomes reveal that geothermal energy represents the optimal renewable alternative for the region, followed sequentially by biomass, hydroelectric, wind, and solar sources.

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1. Introduction

The growth of national economies around the world, as well as population growth, significantly increases energy consumption. By the 2050s, the world population is expected to approach 10 billion, and national economies are expected to grow by an average of 5% [1]. Moreover, Türkiye's annual population growth is expected to exceed 10% by 2050. Accordingly, Türkiye's final energy demand is projected to grow by around 40% over the next 20 years, and electricity demand is projected to grow twice as fast. With this increase, the share of electricity in final energy demand is expected to increase to 30% in 2040 [2]. The distribution of renewable energy (RE) resources in Türkiye's electricity production in 2020 is as follows; hydroelectric (67%), wind (16%), solar (12%), geothermal (3%) and biomass (2%) [3]. For 2021, approximately 33% of electricity production came from renewable energy, and this ratio varies from year to year. However, the rapid increase in demand over the years makes it difficult to reach the desired level of electricity production from renewable energy [1]. One of the most important reasons for this situation is that access to fossil fuels is cheap, and renewable energy is limited. It is estimated that coal, which is among the fossil resources, has a reserve life of 200 years, natural gas 65 years and oil 40 years [4]. Because fossil fuels are not an infinite source of energy and they cause damage to nature, the use of alternative energy sources is becoming more and more critical every day. Sources of renewable energy, such as geothermal, hydroelectric, biomass, wind, tidal, solar, and wave energy, are considered the best alternatives to fossil fuels in terms of their minimal damage to nature compared to fossil fuels, their derivation from natural resources and their sustainability.

The use of fossil fuels to generate electricity not only increases imports but also has environmental impacts. Despite the Kyoto Protocol and the Paris Agreement, the global temperature is rising, with CO2 emissions exceeding record levels, posing an increasing number of climate challenges and accelerating global warming at an alarming rate [5]. However, climate change and the effects of global warming have become urgent issues that need to be addressed in recent years. In this regard, Türkiye signed the latest International Paris Climate Agreement in 2021. Within the scope of this agreement, it announced its interim target for 2030 as 41% carbon reduction and its final target as net zero carbon by 2053. Using fossil fuels is one of the biggest obstacles to achieving net zero carbon. Although Türkiye is fossil fuel poor, it has rich renewable energy resources. However, despite its high renewable energy potential due to its geographical location, as of 2021, Türkiye ranks 18th among European Union (EU) countries in renewable energy use. Therefore, there is a need to focus on using renewable energy potential. Türkiye is a country with high potential, and studies on the correct use of this potential have recently gained momentum [1,4,6,7].

The application of MCDM approaches is common in evaluating, ranking, and selecting renewable energy alternatives. Recently, hybrid studies integrated with fuzzy logic have been included in the literature. During the use of MCDM methods, expert evaluations can sometimes be subjective. To eliminate this subjectivity and uncertainty at the decision point, fuzzy set approaches are integrated into the studies. Various fuzzy numbers have been developed so far, and intuitionistic fuzzy (IF) numbers, extensions of type 1 fuzzy numbers, provide more information than traditional ones because it includes values for non-membership in addition to the membership values. The intuitionistic fuzzy set proposed by Atanassov allows for a better transfer of the uncertainty contained in the problems [8].

In this study, the ranking of five different renewable energy types (solar, wind, geothermal, biomass, hydroelectric) will be realized for the region called TR33 development region, which is one of the 26 development regions of Türkiye. The TR33 region, which includes the provinces of Manisa, Kütahya, Uşak, and Afyonkarahisar, ranks sixth for population density and fifth for electricity consumption, disregarding large metropolitan regions such as Istanbul, Ankara, and Izmir. [9]. The transition to suitable clean energy sources for the region, which is at the forefront regarding population density and industry, is essential to achieve the net zero carbon target. For this purpose, renewable energy ranking for the TR33 region was carried out using five main criteria (technological, economic, environmental, social and power quality) and 17 sub-criteria. The Intuitionistic Fuzzy AHP (IF-AHP) method was used to calculate criteria weights, which served as input for the Intuitionistic Fuzzy VIKOR (IF-VIKOR) approach to perform the ranking of energy alternatives.

2. Literature Review

MCDM methods have become more prevalent in the energy sector as different alternatives have emerged over time, and other evaluation criteria, especially environmental ones, have started to be considered. Various methods or hybrid studies are used for evaluation because each method has different advantages and disadvantages [2]. While the results obtained with these methods may differ for the region studied, different results can be produced even for the same area. Hybrid approaches are used to overcome such situations, and fuzzy numbers are included in the models.

Early research in the energy field reveals the use of MCDM methods applied individually. For instance, the ANP method has been used to identify suitable energy policies for Türkiye [10], while the Electre method has evaluated both fossil fuel and renewable energy plants [11]. Similarly, the Promothee method was employed for assessing various renewable energy scenarios at national and regional levels in Australia [12] and for sustainability assessment of renewable technologies in Scotland [13]. The AHP method determined priority rankings for RE investments in Türkiye [14], and the Electre method evaluated site selection for renewable energy sources in another Turkish study [15]. By evaluating different renewable and fossil fuels with the AHP method, an energy resource planning model for the microgrid is presented [16]. There is also literature integrating different MCDM methods. Terrados et al. proposed a methodology combining the Delphi method and SWOT analysis for regional renewable energy development [17]. The SWARA-ARAS hybrid method ranked four RE technologies using five sustainability criteria and fourteen sub-categories [18]. Büyüközkan and Güleryüz (2016) developed an integrated framework for evaluating and selecting the RES for Türkiye, employing the DEMATEL method to analyse interrelations among criteria and the ANP method for ranking [19]. Another study utilized a methodology integrating SWARA and TOPSIS for selecting Türkiye 's most appropriate renewable energy sources [20].

Fuzzy numbers are often incorporated into MCDM methods to address subjectivity and uncertainty in expert opinions. The fuzzy AHP method was utilized to evaluate renewable energy resources in Taiwan [21]. In a study conducted in a Chinese province, a linguistic hesitant fuzzy set (LHFS) was proposed to better capture decision-makers' hesitation and inconsistencies [22]. Other approaches include TOPSIS based on triangular fuzzy numbers [23] and interval Type-2 fuzzy numbers [24]. In Türkiye, renewable energy investment alternatives have been assessed using the DEMATEL-weighted TOPSIS approach, considering standard interval fuzzy type-2 and hesitant fuzzy sets for comparative analysis [25]. Deveci et al. (2020) evaluated Türkiye’s renewable energy options using the intuitionistic fuzzy CODAS method [26]. In the research carried out for Türkiye, intuitionistic fuzzy TOPSIS [2], distance to ideal solution using interval type 2 fuzzy sets [27] and a new hypervolume-based evaluation and ranking technique based on intuitionistic fuzzy sets [28] was performed. In another study using the intuitionistic fuzzy EDAS method, the most suitable renewable energy types for Türkiye were listed [29]. Fuzzy AHP based MCDM approach was used to determine microgrid component groups for rural area of Tanzania [30].

Table 1 summarizes renewable energy selection studies for Türkiye. For example, Kahraman et al. (2009) used fuzzy axiomatic design for ranking renewable energies, yielding similar results to fuzzy AHP [31]. A 2011 study combined fuzzy AHP and TOPSIS to evaluate renewable, fossil fuel, and nuclear energy options [32]. Ertay et al. (2013) compared the Macbeth and AHP methods under a fuzzy environment, finding wind and solar energy to be the most critical sources [33]. Another Turkish study ranked renewable energy systems with the fuzzy TOPSIS method while determining criteria weights using the Interval Shannon Entropy methodology [34]. Advanced methodologies have also been applied. For instance, hesitant fuzzy numbers were incorporated into the TOPSIS method to better model uncertainties in decision-making, with interval fuzzy type-2 AHP used for criteria weighting [35]. COPRAS and MULTIMOORA methods were applied separately, using AHP for criteria weighting, and yielded consistent results [36]. Eroğlu and Şahin (2020) introduced a neutrosophic number-based VIKOR framework for selecting renewable energy sources in Türkiye, proposing a novel score and distance function [37]. Lastly, Deveci and Güler (2024) presented the HEART technique, a hypervolume-based evaluation and ranking method, for assessing Türkiye's energy alternatives. This study compared results from fossil fuels and renewable energy types using distance-based methods such as TOPSIS, VIKOR, and CODAS, finding consistent outcomes across methods [28].

Various ranking and weighting methods are employed both globally and in Türkiye. Of these methods, VIKOR, designed to obtain a consensus-oriented solution, is widely applied as a ranking tool in existing studies. For example, renewable energy selection for the Spanish energy system utilized the VIKOR method, with criteria weighting performed using the AHP method [38]. Similarly, in India, the VIKOR method was applied for selecting renewable energy for a university campus, with AHP used for criteria weighting; the results indicated wind energy as the optimal choice for the campus [39]. In this study, an integrated MCDM methodology was used to rank renewable energy alternatives in Istanbul, with fuzzy AHP assigning weights to the criteria and fuzzy VIKOR performing the alternative ranking. [40]. Rani et al. (2019) proposed a VIKOR method based on Pythagorean fuzzy sets, incorporating novel measures of divergence and entropy [41]. In Pakistan, a methodology integrating AHP and fuzzy VIKOR was utilized to select suitable sites for solar installations [42]. For determining the renewable energy mix in tourist resorts, the VIKOR method was applied considering three main and nine sub-criteria [43]. In Egypt, hybrid renewable energy systems for a desalination plant were evaluated using an integrated approach combining fuzzy AHP and fuzzy VIKOR, with ten performance criteria considered [44]. In Kenya and sub-Saharan Africa, an integrated methodology combining BMW-TOPSIS-VIKOR methods was developed for evaluating and selecting hybrid renewable energy systems. The BMW method determined criteria weights, while TOPSIS and VIKOR ranked the alternatives [45]. In another study, a combined AHP–VIKOR approach was proposed to identify the most suitable renewable energy alternative for electricity generation. [46].

Table 1. Summary of studies on renewable energy selection in Türkiye using MCDM approaches.

Source	Method(s) Used	Aim of the Study	Result(s)
[31]	Fuzzy axiomatic design and fuzzy AHP	Selecting the optimal renewable energy alternative	1. Wind 2. Solar 3. Biomass 4. Geothermal 5. Hydropower
[32]	Fuzzy TOPSIS	Selecting the best energy technology alternative	1. Wind 2. Biomass 3. Solar 4. Combined heat and power 5. Hydropower 6. Conventional Energy
[33]	Fuzzy Macbeth and Fuzzy AHP	Evaluating renewable energy alternatives under fuzziness	1.Wind 2. Solar 3. Biomass 4. Geothermal 5. Hydropower (for AHP)
[12]	Fuzzy TOPSIS	Renewable energy supply systems ranking	1. Hydropower 2. Geothermal 3. Regulator 4. Wind
[19]	DEMATEL and AHP	Investment-oriented renewable energy selection	1.Wind 2. Solar 3. Biomass 4. Hydropower 5. Geothermal
[35]	Hesitant Fuzzy TOPSIS	Prioritization of renewable energy alternatives	1.Wind 2. Solar 3. Hydropower 4. Biomass 5. Geothermal 6. Wave Energy 7. Hydrogen Energy
[36]	COPRAS and MULTIMOORA	Selecting the optimal renewable energy alternative	1. Hydropower 2. Solar 3. Wind 4. Geothermal 5. Biomass
[26]	Intuitionistic Fuzzy CODAS	Multi-criteria approach for evaluating renewable energy alternatives	1. Onshore wind 2. Solar 3. Biomass 4. Geothermal 5. Hydropower
[37]	Neutrosophic Fuzzy VIKOR	Selecting the renewable energy alternative and ranking of them	1 Solar 2. Wind 3. Biomass 4. Geothermal 5. Hydropower
[28]	HEART	Presentation of a new MCDM methodology for ranking alternatives	1. Solar 2. Wind 3. Natural Gas 4. Geothermal 5. Biomass 6. Hydropower 7. Coal

The number of studies on energy choice, particularly renewable energy, has increased significantly recently. As summarized in Table 1, these studies are generally conducted throughout Türkiye, but Türkiye's diverse geographic characteristics also necessitate regional studies. Although there are studies conducted in different regions or at the provincial level in Türkiye, no renewable energy selection study has been conducted for our study area.

MCDM methods have been implemented using different criteria and hybrid approaches for energy selection. Various techniques, primarily the AHP method, have been used for criterion weighting under fuzziness, and rankings have been performed using different MCDM methods. Recent studies have incorporated fuzzy numbers into models to eliminate potentially subjective decision-makers' assessments and to cope with uncertain information. Intuitionistic fuzzy numbers provide a flexible model for accounting for uncertainty in real-world problems.

This study determined criteria weights using the intuitionistic fuzzy AHP method, while alternative rankings were actualized using the intuitionistic fuzzy VIKOR method. Extending the hybrid approach to intuitionistic numbers yields more accurate information for both methods. Furthermore, the regional study adds value to the ranking of alternatives due to the inclusion of regional characteristics.

3. Methodology

To prioritize renewable energy resources in the TR33 region, encompassing the provinces of Manisa, Afyonkarahisar, Kütahya, and Uşak, MCDM methods were employed. More precisely, the IF-AHP served to compute the criteria weights, and the IF-VIKOR method was adopted to establish the ranking of renewable energy alternatives. This integrated approach ensured a systematic evaluation and prioritization of the region's renewable energy options.

3.1. Preliminaries

The notion of intuitionistic fuzzy sets was introduced by Atanassov and is defined as follows [8]. Given a universe of discourse U, an intuitionistic fuzzy set A is expressed as:

$$A = \left\{ \langle x, \mu_A(x), \vartheta_A(x) \rangle \mid x \epsilon U \right\} \quad \mu_A : U \rightarrow [0,1], \vartheta_A : U \rightarrow [0,1] \tag{1}$$

Here, where x is any element and A is a set, μ_A denotes the degree of membership and ϑ_A denotes the degree of non-membership.

$$0 \leq \mu_A(x) + \vartheta_A(x) \leq 1 \tag{2}$$

π is the degree of hesitation for the intuitionistic fuzzy set, and π can be defined as a heuristic index of x in A as follows [47].

$$\pi_A(x) = 1 - \mu_A(x) - \vartheta_A(x) \tag{3}$$

Arithmetic operations for intuitionistic fuzzy numbers $\widetilde{A} = (\mu_{\widetilde{A}}, \vartheta_{\widetilde{A}})$ and $\widetilde{B} = (\mu_{\widetilde{B}}, \vartheta_{\widetilde{B}})$ can be defined as follows [48].

$$\tilde{A} \oplus \tilde{B} = (\mu_{\tilde{A}} + \mu_{\tilde{B}} - \mu_{\tilde{A}}\mu_{\tilde{B}}, \vartheta_{\tilde{A}}\vartheta_{\tilde{B}}) \tag{4}$$

$$\tilde{A} \otimes \tilde{B} = (\mu_{\tilde{A}}\mu_{\tilde{B}}, \vartheta_{\tilde{A}} + \vartheta_{\tilde{B}} - \vartheta_{\tilde{A}}\vartheta_{\tilde{B}}) \tag{5}$$

$$\lambda\tilde{A} = \left(1 - (1 - \mu_{\tilde{A}})^{\lambda}, \vartheta_{\tilde{A}}^{\lambda}\right) \tag{6}$$

$$\tilde{A}^{\lambda} = \left(\mu_{\tilde{A}}^{\lambda}, 1 - (1 - \vartheta_{\tilde{A}})^{\lambda}\right) \quad (7)$$

For equations (3) and (4), λ is a positive integer.

3.2. IF-AHP

The Intuitionistic Fuzzy AHP method is employed to determine the criteria weights. This approach is an adaptation of the methodology proposed by Büyüközkan and Güleryüz (2016b) [49]. Similar to the classical AHP method, decision-makers express their preferences using intuitionistic fuzzy sets and construct pairwise comparison matrices within the intuitionistic fuzzy AHP framework. The weighted intuitionistic fuzzy matrix is derived using the IFWA operator. Following the assessment of pairwise matrix consistency, the IF-AHP weights are determined. The method's steps are outlined below.

Step 1: In the first stage, the purpose of the problem, its criteria and sub-criteria, if any, are determined. In addition, alternatives are added to the model to create the hierarchy of the problem.

Step 2: The scale of evaluation is utilized to determine and compare the significance of the criteria. Table 2 shows the definitions and equivalent linguistic term forms in the intuitionistic fuzzy set for the nine-scale AHP evaluation.

Table 2. The conversion of AHP preferences into intuitionistic fuzzy sets and their reciprocal forms.

Definition of linguistic preference	AHP Equivalent	Intuitionistic fuzzy set (IFS)	Reciprocal IFS
Equally significant (ES)	1	(0.02,0.18,0.80)	(0.02,0.18,0.80)
Midpoint value (MV1)	2	(0.06,0.23,0.70)	(0.23,0.06,0.70)
Moderately more significant (MS)	3	(0.13,0.27,0.60)	(0.27,0.13,0.60)
Midpoint value (MV2)	4	(0.22,0.28,0.50)	(0.28,0.22,0.50)
Strongly more significant (SS)	5	(0.33,0.27,0.40)	(0.27,0.33,0.40)
Midpoint value (MV3)	6	(0.47,0.23,0.30)	(0.23,0.47,0.30)
Very strongly more significant (VSS)	7	(0.62,0.18,0.20)	(0.18,0.62,0.20)
Midpoint value (MV4)	8	(0.80,0.10,0.10)	(0.10,0.80,0.10)
Extremely more significant (EMS)	9	(1,0,0)	(0,1,0)

Step 3: At this stage, the weights of the decision-makers are determined. As seen in Table 2, the importance levels of the decision makers are realized using the intuitionistic fuzzy set linguistic terms. This approach may change the importance levels of the decision-makers according to their experiences and knowledge on the subject. Equation (8) can be used to calculate the weight of the relevant decision maker if the kth decision maker is expressed as the intuitionistic fuzzy number $D_k = [\mu_k, \vartheta_k, \pi_k]$.

$$\lambda_k = \frac{\left(\mu_k + \pi_k\left(\frac{\mu_k}{\mu_k+\vartheta_k}\right)\right)}{\sum_{k=1}^{l}\left(\mu_k + \pi_k\left(\frac{\mu_k}{\mu_k+\vartheta_k}\right)\right)} \text{ ve } \sum_{k=1}^{l}\lambda_k = 1 \quad (8)$$

Step 4: Decision makers' intuitionistic preference relationships are determined. Here, to establish intuitionistic preference relationships, each pairwise comparison matrix must be obtained. The importance levels of each criterion can be denoted by "W'' and $\lambda = (\lambda_1, \lambda_2, \dots, \lambda_l)$ is the weight of each decision maker and is also $\sum_{k=1}^{l}\lambda_k = 1$, $\lambda_k \in [0,1]$. The opinions of all decision-makers need to be brought together. Therefore, the IFWA operator aggregates decision-makers' evaluations to rank the importance levels of criteria and alternatives. Let's assume that $W_j^{(k)} = \left[\mu_j^{(k)}, \vartheta_j^{(k)}, \pi_j^{(k)}\right]$ is an intuitionistic fuzzy set given to criterion x_j by the kth decision maker. For the aggregation process, the IFWA operator given in equation (9) is used and the criteria weights are calculated in this way.

$$W_j = IFWA_{\lambda}\left(W_j^{(1)}, W_j^{(2)}, \dots, W_j^{(l)}\right) = \lambda_1 W_j^{(1)} \oplus \lambda_2 W_j^{(2)} \oplus \dots \oplus \lambda_l W_j^{(l)}$$

$$= \left[1 - \prod_{k=1}^{l}\left(1 - \mu_j^{(k)}\right)^{\lambda_k}, \prod_{k=1}^{l}\left(\vartheta_j^{(k)}\right)^{\lambda_k}, \prod_{k=1}^{l}\left(1 - \mu_j^{(k)}\right)^{\lambda_k} - \prod_{k=1}^{l}\left(\vartheta_j^{(k)}\right)^{\lambda_k}\right] \tag{9}$$

$$W = [W_1, W_2, \dots, W_j]$$

$$W_j = [\mu_j, \vartheta_j, \pi] \; (j = 1,2, \dots, n)$$

Step 5: Construction of the total weighted IF decision matrix is required. It is obtained by combining the criterion weights (W) with the total intuitionistic decision matrix, as follows.

$$R \otimes W = \{x, \mu_{A_i}(x). \mu_w(x), \vartheta_{A_i}(x) + \vartheta_w(x) - \vartheta_{A_i}(x). \vartheta_w(x) I \; x \in X\} \tag{10}$$

$$\pi_{A_i} w(x) = 1 - \vartheta_{A_i}(x) - \vartheta_w(x) - \mu_{A_i}(x). \mu_w(x) + \vartheta_{A_i}(x). \vartheta_w(x) \tag{11}$$

In the final step, the total weighted intuitionistic fuzzy decision matrix is established as follows:

$$R^* = \begin{bmatrix} \mu_{A_1}w(x_1), \vartheta_{A_1}w(x_1), \pi_{A_1}w(x_1) \;\; \mu_{A_1}w(x_2), \vartheta_{A_1}w(x_2), \pi_{A_1}w(x_2) \dots \mu_{A_1}w(x_n), \vartheta_{A_1}w(x_n), \pi_{A_1}w(x_n) \\ \mu_{A_2}w(x_1), \vartheta_{A_2}w(x_1), \pi_{A_2}w(x_1) \;\; \mu_{A_2}w(x_2), \vartheta_{A_2}w(x_2), \pi_{A_2}w(x_2) \dots \mu_{A_2}w(x_n), \vartheta_{A_2}w(x_n), \pi_{A_2}w(x_n) \\ . \\ . \\ . \\ \mu_{A_m}w(x_1), \vartheta_{A_m}w(x_1), \pi_{A_m}w(x_1) \;\; \mu_{A_m}w(x_2), \vartheta_{A_m}w(x_2), \pi_{A_m}w(x_2) \dots \mu_{A_m}w(x_n), \vartheta_m w(x_n), \pi_{A_m}w(x_n) \end{bmatrix} \tag{12}$$

$$R' = \begin{bmatrix} r'_{11} & r'_{12} & r'_{13} \dots r'_{1m} \\ r'_{21} & r'_{22} & r'_{23} \dots r'_{2m} \\ r'_{31} & r'_{32} & r'_{33} \dots r'_{3m} \\ & & . \\ & & . \\ & & . \\ r'_{n1} & r'_{n2} & r'_{n3} \dots r'_{nm} \end{bmatrix} \tag{13}$$

$r'_{ij} = (\mu^*_{ij}, \vartheta^*_{ij}, \pi^*_{ij}) = \left(\mu_{A_i}x(x_j), \vartheta_{A_i}x(x_j), \pi_{A_i}x(x_j)\right)$ constitutes an element within the complete weighted intuitionistic decision matrix.

Step 6: At this stage, the consistency of the pairwise comparison matrices of preference relations needs to be checked. For this purpose, the consistency ratio (CR) is computed, and the ratio is expected to be less than 0.10. The calculation for CR is given in equation (14). Table 3 can be used for the random index.

$$CR = \frac{(\lambda_{max} - n)/(n-1)}{RI} \tag{14}$$

Table 3. Random index (RI) values depending on matrix size.

Random Index (RI)															
n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56	1.57	1.59

Step 7: Intuitionistic fuzzy entropy weights and final entropy weights are calculated using equations (15) and

(16).

$$\bar{\bar{w}}_i = -\frac{1}{nln2}[\mu_i ln\mu_i + \vartheta_i ln\vartheta_i - (1-\pi_i)\ln(1-\pi_i) - \pi_i ln2] \tag{15}$$

$$w_i = \frac{1-\bar{\bar{w}}_i}{n-\sum_{j=1}^{n}\bar{\bar{w}}_i} \text{ where } \sum_{j=1}^{n}\bar{\bar{w}}_i = 1 \tag{16}$$

3.3. IF-VIKOR

The application steps of the IF-VIKOR method are given below [50].

Step 1: The values of the alternatives should be given as intuitionistic fuzzy numbers on a criterion basis. Therefore, the values of the quantitative criteria should be converted into intuitive fuzzy numbers. Equation (17) converts quantitative data into intuitive fuzzy numbers.

$$\mu_{ij}(x_{ij}) = w_j \frac{1}{1+e^{-z_{ij}}} \text{ ve } \vartheta_{ij}(x_{ij}) = w_j^* \frac{1}{1+e^{z_{ij}}} \tag{17}$$

Where;

$w_j = w_j^* = \frac{|1-s_j|}{|1+s_j|}$ ve $z_{ij} = \frac{x_{ij}-\bar{x}_j}{s_j}$; $\bar{x}_j$ and s_j are the mean and standard deviation of the criterion C_j.

Following the completion of the transformation process, the intuitionistic fuzzy decision matrix is generated as follows:

$$D = \begin{bmatrix} (\mu_{11},\vartheta_{11}) & (\mu_{12},\vartheta_{12}) & \dots & (\mu_{1m},\vartheta_{1m}) \\ (\mu_{21},\vartheta_{21}) & (\mu_{22},\vartheta_{22}) & \dots & (\mu_{2m},\vartheta_{2m}) \\ & & . & \\ & & . & \\ & & . & \\ (\mu_{n1},\vartheta_{n1}) & (\mu_{n2},\vartheta_{n2}) & \dots & (\mu_{nm},\vartheta_{nm}) \end{bmatrix} \tag{18}$$

Step 2: For the benefit criterion (J_1) and cost criterion (J_2), the intuitionistic fuzzy negative ideal solution $f^- = (\mu_j^-, \vartheta_j^-)$ and the intuitionistic fuzzy positive ideal solution $f^* = (\mu_j^*, \vartheta_j^*)$ are defined. The definitions are given in equations (19) and (20).

$$\mu_j^- = \left\{\left(\min_i(\mu_{ij}) \mid j \in J_1\right), \left(\max_i(\mu_{ij}) \mid j \in J_2\right)\right\}; \vartheta_j^- = \left\{\left(\max_i(\vartheta_{ij}) \mid j \in J_1\right), \left(\min_i(\vartheta_{ij}) \mid j \in J_2\right)\right\} \tag{19}$$

$$\mu_j^* = \left\{\left(\max_i(\mu_{ij}) \mid j \in J_1\right), \left(\min_i(\mu_{ij}) \mid j \in J_2\right)\right\}; \vartheta_j^* = \left\{\left(\min_i(\vartheta_{ij}) \mid j \in J_1\right), \left(\max_i(\vartheta_{ij}) \mid j \in J_2\right)\right\} \tag{20}$$

Step 3: Normalized intuitionistic fuzzy difference $\bar{d}_{ij}$ is calculated with the help of equation (21).

$$\bar{d}_{ij} = \frac{\sqrt{\frac{1}{2}\left[\left(\mu_{ij}-\mu_j^*\right)^2 + \left(\vartheta_{ij}-\vartheta_j^*\right)^2 + \left(\pi_{ij}-\pi_j^*\right)^2\right]}}{\sqrt{\frac{1}{2}\left[\left(\mu_j^*-\mu_j^-\right)^2 + \left(\vartheta_j^*-\vartheta_j^-\right)^2 + \left(\pi_j^*-\pi_j^-\right)^2\right]}} \tag{21}$$

Step 4: Calculate the values of S_i, R_i and Q_i by equations (22) and (23).

$$S_i = \sum_{j=1}^{m} w_j * \bar{d}_{ij} \text{ and } R_i = \max_j\left(w_j * \bar{d}_{ij}\right) \tag{22}$$

$$Q_i = \vartheta \frac{S_i - S^*}{S^- - S^*} + (1-\vartheta)\frac{R_i - R^*}{R^- - R^*} \tag{23}$$

Here; $S^* = \min_i(S_i),\ S^- = \max_i(S_i)\ , R^* = \min_i(R_i), R^- = \max_i(R_i)$ and the weight of the jth criterion is expressed by w_j. ϑ represents the weight of the maximum group benefit strategy, while (1- ϑ) represents the weight of the minimum individual regret.

Step 5: The alternative (A_1) ranked best according to the Q measure (minimum) is recommended as a compromise solution if the following two conditions are met.

(1) Acceptable advantage: $Q(A_2)-Q(A_1) \geqslant DQ$, where ($A_2$) is the second-ranked alternative in the ranking list according to Q. DQ = 1/(m-1), where "m" is the number of alternatives.
(2) Acceptable stability in decision making: Alternative (A1) must also be the best ranked alternative in terms of S and/or R. The best ranked alternative in terms of Q is the alternative with the lowest Q value.

3.4. Assessment criteria of renewable energy sources

Selecting renewable energy options is a complex process that needs to take multiple viewpoints into account. Depending on the evaluation objectives, it can be examined from various perspectives, and different criteria can be used for evaluation. While technical and economic criteria were initially considered for evaluation, over time, environmental and social criteria were included in the evaluation models. The fluctuating output of renewable energy sources, notably solar and wind, necessitates incorporating power quality into the set of evaluation criteria.

Following the literature review and consultations with three decision-makers, five primary criteria and seventeen sub-criteria were established for the assessment of renewable energy options. Table 4 presents explanations of these main criteria and their sub-criteria. The hierarchical structure of the model is given in Figure 1. The energy sources evaluated are five: solar (A_1), hydroelectric (A_2), wind (A_3), biomass (A_4) and geothermal (A_5).

Table 4. Criteria for evaluation and corresponding explanations.

Main Criteria	Sub-Criteria	Explanations	Type of sub-criteria	References
Technological (C_1)	Technological maturity (C_{11})	Analysis of technological development expresses how widely technology has spread at national levels.	Qualitative	[2, 4, 22]
	Delivery time (C_{12})	Measures how long it takes to complete a process from start to finish.	Quantitative	[2, 4, 7]
	Productivity (C_{13})	It refers to how often we can get enough power from a potential source.	Qualitative	[7, 10, 19]
	Risk (C_{14})	Addresses the risk of disruption/failure of the power policies and technologies used.	Qualitative	[4, 28, 31]
Economic (C_2)	Investment cost (C_{21})	These are the costs incurred during the feasibility and installation stages of renewable energy plants.	Quantitative	[2, 7, 28]
	Operation and maintenance cost (C_{22})	It refers to all operating and maintenance expenses incurred after the installation of the power plants.	Quantitative	[2, 7, 28]
	Service life (C_{23})	It is the concept that expresses the maximum period in which a renewable energy power plant can be operated.	Quantitative	[4, 20, 23]
	Payback period (C_{24})	It refers to the time when renewable energy sources reach the break-even point.	Quantitative	[24, 26]
Environmental (C_3)	Land Requirement (C_{31})	It refers to the total area use in terms of land size when making power plant investment decisions.	Quantitative	[28, 34]

	Greenhouse Emissions (C_{32})	It covers CO_2 emissions resulting from the use of renewable energy sources.	Quantitative	[34, 35]
	Environmental damage (C_{33})	It expresses the impact of the power plant on the areas in terms of both visual and biodiversity.	Qualitative	[19, 26]
	Necessity of waste disposal (C_{34})	It refers to the level of waste that may occur after energy production.	Qualitative	[10, 19]
Social (C_4)	Social acceptance (C_{41})	It expresses the level of acceptance of all kinds of facilities built in the local community.	Qualitative	[26, 28]
	Job creation (C_{42})	These are the economic benefits that the power plant offers to society during the installation and production phase.	Quantitative	[4, 7, 26]
Power Quality (C_5)	Sustainability (C_{51})	It is the measure of uninterrupted supply of electricity obtained from energy sources.	Qualitative	[7, 20]
	Resource potential (C_{52})	It includes the evaluation of the possible potential of energy types for the region within the scope of the project.	Qualitative	[34, 41]
	Durability (C_{53})	This criterion refers to the use of energy resources against various situations, especially natural events.	Qualitative	[26, 28]

The TR33 region has high potential for renewable energy resources, particularly geothermal. Accurately analysing this potential and developing appropriate investment plans are crucial for the region's development. All five energy types under consideration are located in the area. Furthermore, the criteria were evaluated by decision-makers familiar with the region. This allowed for an assessment based on the region's characteristics.

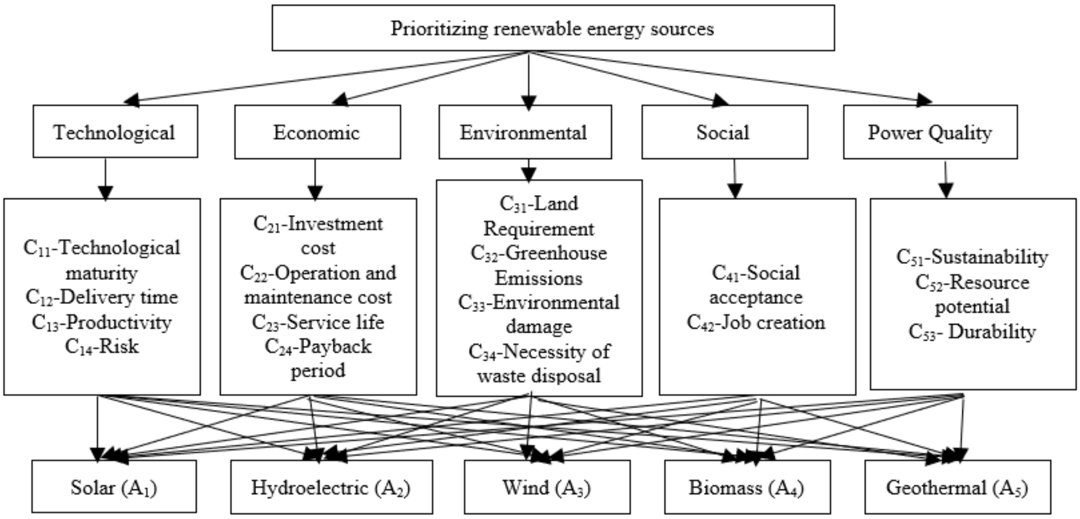

Fig. 1. Hierarchical structure for renewable energy source selection in TR33 region.

4. Case Study

An integrated IF-AHP–VIKOR methodology will be utilized to determine the optimal renewable energy alternatives for the TR33 region. In the previous sections, the main and sub-criteria that emerged as a result of the study's literature review were explained. In addition, the details of the methods were provided in the methodology section. To perform the analyses, the evaluation of three different decision-makers was taken. The first of these three decision-makers is an expert who has worked in the field of renewable energy at Kütahya Dumlupınar University, the other is an expert who works in the field of energy and works in the project development and implementation unit within the Zafer Development Agency, and the final evaluator is an expert who works as a mechanical engineer in the field of renewable energy production in the private sector. It was presumed that the decision-makers had identical importance levels, and as a result, a uniform weight of 0.33 was applied to all.

The relevant calculations will be shown on the technology sub-criteria. Expert evaluations on the technology sub-criteria are given in Table 5. The relevant assessments were converted into intuitionistic preferences, and intuitionistic preference relationship evaluations are shown in Table 6. Missing data in the table are completed with the "Reciprocal IFS" values in Table 2.

Table 5. Linguistic evaluation matrices of technology sub-criteria.

	DM1				DM2				DM3			
	C_{11}	C_{12}	C_{13}	C_{14}	C_{11}	C_{12}	C_{13}	C_{14}	C_{11}	C_{12}	C_{13}	C_{14}
C_{11}	ES	SS		MS	ES	MV3		MS	ES			MV1
C_{12}		ES				ES			MV2	ES	MV2	MV3
C_{13}	MV1	MV3	ES	MV2	MS	SS	ES	MV3	MV2		ES	MV3
C_{14}		MS		ES		MV1		ES				ES
	CR = 0.0296				CR = 00.0617				CR = 0.0973			

Table 6. IFS equivalents of technology sub-criteria.

	C_{11}	C_{12}	C_{13}	C_{14}
DM1	(0.02,0.18,0.80)	(0.33,0.27,0.40)	(0.23,0.06,0.70)	(0.13,0.27,0.60)
	(0.27,0.33,0.40)	(0.02,0.18,0.80)	(0.23,0.47,0.30)	(0.27,0.13,0.60)
	(0.06,0.23,0.70)	(0.47,0.23,0.30)	(0.02,0.18,0.80)	(0.22,0.28,0.50)
	(0.27,0.13,0.60)	(0.13,0.27,0.60)	(0.28,0.22,0.50)	(0.02,0.18,0.80)
DM2	(0.02,0.18,0.80)	(0.47,0.23,0.30)	(0.27,0.13,0.60)	(0.13,0.27,0.60)
	(0.23,0.47,0.30)	(0.02,0.18,0.80)	(0.27,0.33,0.40)	(0.23,0.06,0.70)
	(0.13,0.27,0.60)	(0.33,0.27,0.40)	(0.02,0.18,0.80)	(0.47,0.23,0.30)
	(0.27,0.13,0.60)	(0.06,0.23,0.70)	(0.23,0.47,0.30)	(0.02,0.18,0.80)
DM3	(0.02,0.18,0.80)	(0.28,0.22,0.50)	(0.28,0.22,0.50)	(0.06,0.23,0.70)
	(0.22,0.28,0.50)	(0.02,0.18,0.80)	(0.22,0.28,0.50)	(0.47,0.23,0.30)
	(0.22,0.28,0.50)	(0.28,0.22,0.50)	(0.02,0.18,0.80)	(0.47,0.23,0.30)
	(0.23,0.06,0.70)	(0.23,0.06,0.70)	(0.23,0.47,0.30)	(0.02,0.18,0.80)

The opinions of the kth decision maker are calculated collectively using the IFWA operator and Equations (9)-(11). For example, the calculations of μ_1, υ_1 and π_1 of the first decision-maker are given below:

- $$\mu_1 = 1 - ((1-0.02)^{0,33} * (1-0.33)^{0,33} * (1-0.23)^{0,33} * (1-0.13)^{0,33}) = 0.24 \quad (24)$$
- $$\vartheta_1 = (0.18)^{0,33} * (0.27)^{0,33} * (0.06)^{0,33} * (0.27)^{0,33} = 0.09 \quad (25)$$
- $$\pi_1 = 1 - (0.24 + 0.09) = 0.67 \quad (26)$$

Similarly, μ, ϑ and π values are calculated for other decision makers. The calculations of the technology sub-criteria for each decision maker are given in Table 7.

Table 7. Intuitionistic fuzzy judgment matrices of decision-makers regarding technology sub-criteria.

	DM_1			DM_2			DM_3		
	μ	ϑ	π	μ	ϑ	π	μ	ϑ	π
C_{11}	**0.24**	**0.09**	**0.67**	0.31	0.12	0.57	0.22	0.13	0.65
C_{12}	0.26	0.16	0.58	0.25	0.12	0.63	0.32	0.15	0.53
C_{13}	0.27	0.14	0.59	0.33	0.15	0.52	0.33	0.14	0.53
C_{14}	0.24	0.11	0.65	0.20	0.14	0.66	0.23	0.07	0.70

As there is no distinction in weight among the decision makers, the aggregated values were calculated using the arithmetic mean and are shown in Table 8.

Table 8. Aggregate intuitionistic fuzzy judgment matrix of technology sub-criteria.

	μ	ϑ	π
C_{11}	0.26	0.11	0.63
C_{12}	0.28	0.14	0.58
C_{13}	0.31	0.14	0.55
C_{14}	0.22	0.11	0.67

The intuitionistic fuzzy entropy weights for decision-maker 1 are calculated via equation (15).

$$\bar{\bar{w}}_1 = -\frac{1}{4In2}[0.24 * (In0.24) + 0.09 * (In0.09) - (1-0.63) * In(1-0.63) - (0.63 * In2)] = 0.23 \quad (27)$$

The values of $\bar{\bar{w}}_2$, $\bar{\bar{w}}_3$ and $\bar{\bar{w}}_4$ were calculated in the same way and were found to be 0.25, 0.24 and 0.24, respectively. The final entropy weight of decision maker 1 is calculated using equation (16):

$$w_1 = \frac{1-0.23}{4-(0.23+0.25+0.24+0.24)} = 0.25 \tag{28}$$

Table 9 summarizes the entropy weights of the three decision makers' evaluations of the technology sub-criteria and the total final entropy weights.

Table 9. Aggregate intuitionistic fuzzy judgment matrix of technology sub-criteria.

	DM1	DM2	DM3	Final Weight
C_{11}	0.25	0.23	0.26	0.25
C_{12}	0.25	0.18	0.20	0.21
C_{13}	0.25	0.32	0.30	0.29
C_{14}	0.25	0.27	0.24	0.25

To derive the final entropy weights of all criteria, each matrix is calculated individually. Table 10 summarizes these final entropy weights, and the normalized matrices yield the final evaluation criteria weights, also shown in Table 10.

Table 10. Technology sub-criteria weights and final entropy weight.

Main Criteria	Weighs	Sub-Criteria	Final entropy weights	Final evaluation criteria weights
Technological (C_1)	0.22	C_{11}	0.25	0.055
		C_{12}	0.21	0.046
		C_{13}	0.29	0.064
		C_{14}	0.25	0.055
Economic (C_2)	0.25	C_{21}	0.44	0.110
		C_{22}	0.15	0.038
		C_{23}	0.18	0.045
		C_{24}	0.23	0.058
Environmental (C_3)	0.20	C_{31}	0.14	0.028
		C_{32}	0.48	0.096
		C_{33}	0.20	0.040
		C_{34}	0.18	0.036
Social (C_4)	0.15	C_{41}	0.29	0.043
		C_{42}	0.71	0.107
Power Quality (C_5)	0.18	C_{51}	0.40	0.072
		C_{52}	0.43	0.077
		C_{53}	0.17	0.030

Following the calculation of criteria weights through the intuitionistic fuzzy AHP method, the steps of the intuitionistic fuzzy VIKOR method are executed. Expert opinions regarding the qualitative criteria are given in Table 11, with linguistic variables used as shown in Table 12.

Table 11. Qualitative sub-criteria evaluations of decision makers.

Alternatives	Decision Makers	C_{11}	C_{13}	C_{14}	C_{33}	C_{34}	C_{41}	C_{51}	C_{52}	C_{53}
Solar (A_1)	DM1	EG	F	EP	EP	P	G	G	EG	EG
	DM2	F	F	F	F	P	F	F	G	F
	DM3	P	EG	EP	EP	EP	G	EG	G	EG
Hydroelectric (A_2)	DM1	F	P	F	G	EP	EG	EG	P	P
	DM2	EP	G	F	F	F	EP	F	P	F
	DM3	G	F	P	F	EP	P	F	P	P
Wind (A_3)	DM1	EP	P	P	F	P	F	P	P	F
	DM2	G	F	F	F	P	P	F	G	F

	DM3	G	F	EP	F	EP	F	EG	EG	EG
Biomass (A_4)	DM1	G	EP	EG	EP	G	F	EP	F	P
	DM2	F	G	P	P	F	F	G	F	G
	DM3	F	P	EP	P	EG	G	F	F	F
Geothermal (A_5)	DM1	G	P	G	P	G	F	G	G	P
	DM2	G	EG	EP	P	F	P	EG	G	G
	DM3	G	G	P	F	F	F	P	EP	P

Table 12. Evaluation scale for qualitative criteria.

Linguistik Variable	Extrelmely Poor (EP)	Poor (P)	Fair (F)	Good (G)	Extrelmely Good (EG)
Assigned Value	1	2	3	4	5

The data on quantitative criteria are presented in Table 13. The obtained data is based on literature review study. The units of quantitative criteria are as follows: Delivery time, service life, payback period; year, investment cost; \$/kw, operation and maintenance cost; \$/mw-year, land requirement; km^2/mw, greenhouse emissions; gCO_2/kw-hour, job creation; person/mw. Based on this evaluation and data, an intuitionistic fuzzy decision matrix needs to be created.

Table 13. Evaluation scale for qualitative criteria.

Energy Resources	Delivery time	Investment Cost	Operation and Maintenance Cost	Service Life	Payback Period	Land Requirement	Greenhouse Emission	Job Creation
A_1	2	3838	56780	25	1,850	0,040	41	0,530
A_2	1	1887	4120	25	0,900	8,100	24	0,400
A_3	4	3753	24050	30	11,800	0,050	11	0,330
A_4	2	2112	8660	20	1,920	20,000	230	1,000
A_5	2	3681	164640	25	5,700	0,007	38	2,130

For all criteria except the qualitative criteria, the transformation process in equation (17) was used, and after completing the transformation, the decision matrix was obtained as shown in Table 14.

Table 14. Intuitionistic fuzzy decision matrix.

	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}
A_1	[0.6,0.3]	[0.565, 0.386]	[0.7,0.2]	[0.5,0.5]	[0.456,0.415]	[0.512,0.418]	[0.521,0.286]	[0.705,0.156]
A_2	[0.5,0.5]	[0.456,0.315]	[0.5,0.5]	[0.6,0.3]	[0.523,0.382]	[0.706,0.173]	[0.471,0.423]	[0.621,0.205]
A_3	[0.6,0.3]	[0.654,0.310]	[0.6,0.3]	[0.5,0.5]	[0.614,0.216]	[0.605,0.256]	[0.652,0.215]	[0.523,0.356]
A_4	[0.7,0.2]	[0.521,0.388]	[0.6,0.3]	[0.6,0.3]	[0.557,0.389]	[0.546,0.247]	[0.356,0.348]	[0.612,0.247]
A_5	[0.6,0.3]	[0.725,0.186]	[0.5,0.5]	[0.6,0.3]	[0.415,0.487]	[0.386,0.596]	[0.622,0.279]	[0.425,0.268]

Table 14. Intuitionistic fuzzy decision matrix (Continue).

	C_{31}	C_{32}	C_{33}	C_{34}	C_{41}	C_{42}	C_{51}	C_{52}	C_{53}
A_1	[0.569,0.268]	[0.416,0.287]	[0.6,0.3]	[0.5,0.5]	[0.6,0.3]	[0,548,0.312]	[0.705,0.125]	[0.548,0.321]	[0.5,0.5]
A_2	[0.705,0.200]	[0.561,0.349]	[0.7,0.2]	[0.6,0.3]	[0.5,0.5]	[0.388,0.356]	[0.269,0.598]	[0.402,0.345]	[0.6,0.3]
A_3	[0.564,0.312]	[0.515,0.109]	[0.5,0.5]	[0.5,0.5]	[0.5,0.5]	[0.412,0.456]	[0.804,0.107]	[0.625,0.274]	[0.6,0.3]
A_4	[0.515,0.213]	[0.614,0.205]	[0.6,0.3]	[0.6,0.3]	[0.6,0.3]	[0.658,0.298]	[0.564,0.321]	[0.515,0.320]	[0.7,0.2]
A_5	[0.385,0.396]	[0.489,0.345]	[0.6,0.3]	[0.5,0.5]	[0.6,0.3]	[0.705,0.123]	[0.608,0.204]	[0.632,0196]	[0.5,0.5]

After the creation of the decision matrix, it is necessary to define the intuitionistic fuzzy negative ideal solutions $f^{-} = (\mu_j^{-}, \vartheta_j^{-})$ and the intuitionistic fuzzy positive ideal solutions $f^{*} = (\mu_j^{*}, \vartheta_j^{*})$ for the benefit and cost criteria. Technological maturity (C_{11}), productivity (C_{13}), service life (C_{23}), social acceptance (C_{41}), job creation (C_{42}), sustainability (C_{51}), resource potential (C_{52}) and durability (C_{53}) are the benefit criteria. Remaining delivery time (C_{12}), risk (C_{14}), investment cost (C_{21}), operation and maintenance cost (C_{22}), payback period (C_{24}), land Requirement (C_{31}), greenhouse emissions (C_{32}), environmental damage (C_{33}) and necessity of waste disposal (C_{34}) are the cost criteria.

Intuitionistic fuzzy negative ideal solutions and intuitionistic fuzzy positive ideal solutions are defined below, respectively.

$$f^- = \begin{Bmatrix} (0.5,0.5),(0.456,0.315),(0.5,0.5),(0.5,0.5),(0.456,0.415),(0.386,0.596),(0.356,0.348) \\ (0.425,0.268),(0.385,0.396),(0.416,0.287),(0.5,0.5),(0.5,0.5),(0.5,0.5),(0.388,0.356) \\ (0.269,0.598),(0.402,0.345),(0.5,0.5) \end{Bmatrix}$$

$$f^* = \begin{Bmatrix} (0.7,0.2),(0.725,0.186),(0.7,0.2),(0.6,0.3),(0.614,0.216),(0.706,0.173),(0.622,0.279) \\ (0.705,0.156),(0.705,0.200),(0.614,0.205),(0.7,0.2),(0.6,0.3),(0.6,0.3),(0.705,0.123) \\ (0.804,0.107),(0.632,0196),(0.7,0.2) \end{Bmatrix}$$

After obtaining the best and worst values, normalized intuitive fuzzy difference $\bar{d}_{ij}$ values need to be calculated. Normalized intuitive fuzzy $\bar{d}_{ij}$ difference values for all alternatives according to the criteria are presented in Table 15.

Table 15. Normalized intuitionistic fuzzy difference values.

	Criteria								
Alternatives	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}
A_1	0.455	0.985	0.000	0.656	0.480	0.480	0.756	0.515	0.385
A_2	0.000	0.550	0.000	0.998	0.480	0.655	0.385	0.880	0.880
A_3	1.000	0.000	0.480	0.550	0.650	0.385	0.550	0.600	0.550
A_4	0.000	0.998	0.850	0.656	0.480	0.660	0.550	0.600	0.550
A_5	1.000	0.0000	0.920	0.310	0.000	0.500	0.880	0.455	0.010

Table 15. Normalized intuitionistic fuzzy difference values (Continue).

	Criteria							
Alternatives	C_{32}	C_{33}	C_{34}	C_{41}	C_{42}	C_{51}	C_{52}	C_{53}
A_1	0.300	0.385	0.885	0.500	0.888	0.550	0.860	0.550
A_2	0.550	1.000	0.885	0.385	0.554	0.500	0.550	0.550
A_3	0.000	0.385	0.550	0.500	0.900	0.500	1.000	0.720
A_4	0.300	0.500	0.630	0.650	0.995	0.550	0.995	0.800
A_5	0.000	0.000	0.385	0.650	1.000	0.500	1.000	0.800

S_i, R_i and Q_i values are calculated for each alternative according to equations (22) and (23). The calculated values are presented in Table 37.

Table 16. S_i, R_i and Q_i values.

	S_i	R_i	Q_i
Solar (A_1)	0.720	0.250	1.000
Hydroelectric (A_2)	0.568	0.155	0.350
Wind (A_3)	0.612	0.200	0.500
Biomass (A_4)	0.422	0.100	0.095
Geothermal (A_5)	0.315	0.085	0.000

According to Table 37, when the alternatives are ranked in the increasing order of Q_i, the best alternative is geothermal energy. The order of the alternatives is geothermal, biomass, hydroelectric, wind and solar, respectively.

5. Conclusion

One of the primary methods of transition to clean energy is accelerating the transition to renewable energy. During this transition, it is essential to prefer regionally appropriate resources. Many factors affect the decision to invest in renewable energy with high investment financing. Within the scope of this study, the aim is to evaluate renewable energy resources for the TR33 region, which includes Uşak, Kütahya, Afyonkarahisar, and Manisa provinces. For this purpose, it is aimed to use the intuitionistic fuzzy AHP-VIKOR integrated method. Solar, hydroelectric, wind, biomass and geothermal energy resources were evaluated during the evaluation process. Depending on these criteria, analyses were carried out using five main criteria (technological, economic, environmental, social, and power quality) and seventeen sub-criteria. Criteria weights were obtained with the intuitionistic fuzzy AHP method. Then, the obtained criteria weights were used as the input of the intuitionistic fuzzy VIKOR method.

According to the results of the analysis, geothermal energy has emerged as the most suitable energy type. The order of results obtained using intuitionistic fuzzy numbers was geothermal, biomass, hydroelectric, wind and solar. Especially according to the acceptable advantage criterion, which is the first condition of the VIKOR method, hydroelectric and biomass energy have emerged as preferable options. Table 1 presents the results of major studies conducted for Turkey. Generally, wind and solar energy are ranked first in these studies. Geothermal energy, on the other hand, is usually ranked last. Geothermal energy has a higher capacity utilization factor than other renewable energy types. Due to geographical features, the installed capacity is located in the Aegean region. While it ranks last for Turkey overall, it ranks first for the TR33 region covered by the study. The high installed capacity and potential of geothermal energy in this region, along with the high biomass potential due to agriculture and animal husbandry, provide a glimmer of hope regarding the feasibility of this ranking.

In this direction, priority should be given to biomass and hydroelectric energy types, respectively, starting with geothermal energy, for the TR33 region. Future studies could compare the results using different MCDM methods or fuzzy number extensions. Furthermore, criteria that prioritize public interest, such as social acceptance, could be incorporated into the model.

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Author contribution

BY: Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Review & Editing. **EA:** Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing–original draft, Writing. **NŞ**: Conceptualization, Data curation, Investigation, Validation, Visualization. **HO:** Conceptualization, Data curation, Investigation, Validation, Visualization. **SHİ:** Conceptualization, Data curation, Investigation, Validation, Visualization

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