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Wind Power Plant Location Selection with Fuzzy Logic and Multi-Criteria Decision-Making Methods

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ABSTRACT

This study aims to examine the effectiveness of the fuzzy multi-criteria decision-making methods, especially Fuzzy Weight by Envelope and Slope (F-WENSLO) and Fuzzy Ranking Alternatives with Weights of Criterion (F-RAWEC) for evaluating the potential locations for wind power plants. The study's objective is to provide a solid framework for deciding which locations are most suitable for wind energy projects, taking into account various criteria and expert opinion. The study includes the evaluation of five potential places including Gürün, Kangal, Divriği, Ulaş and Zara in Sivas province of Turkey. The evaluation criteria include wind speed and direction, altitude, land use, environmental impacts, infrastructure proximity, social acceptance, economic costs, security and risk factors, climatic conditions and legal and permit requirements. Scores from experts from various fields and weights of criteria were determined. The analysis revealed that Ulaş and Kangal got the highest point for the wind power plant installation. As Ulaş gets the highest point due to favorable wind conditions, favorable altitude and advantageous land use; Kangal stood out as a strong candidate because of its acceptable wind speed, positive social acceptance and low economic costs. The study highlights the importance of integrating multiple criteria and expert assessments in the decision-making process. The findings suggest that fuzzy multi-criteria decision-making methods can be effectively supportive of wind power plant site selection. The study provides valuable information for project managers and policy makers, emphasizing the importance of criteria such as security in the choice of location, legal requirements and social acceptance. Future research may expand these findings to examine the integration of additional criteria, alternative locations, and other multi-criteria decision-making techniques.

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1. Introduction

The growing demand for energy worldwide and the environmental impacts of fossil fuels increase the importance of renewable energy sources day by day. In this context, wind energy stands out as one of the most promising energy sources in terms of low carbon emissions and sustainability. Wind power plants are becoming more and more common thanks to low energy production costs and technological developments [1].

Wind power plant installation requires a process that takes into account not only the areas where the wind source is abundant, but also environmental, economic and social factors. The choice of suitable location is critical to both energy efficiency and environmental and societal impacts. Choosing the wrong location can lead to loss of efficiency, cost increase and environmental problems in energy production [2-4]

Therefore, multi-criteria decision making (MCDM) methods are necessary for the wind farm site selection process. These methods enable the evaluation of different criteria by weighting and the selection of the optimum location. However, real-world uncertainties and subjective judgments of decision-makers may limit the effectiveness of classic MCDM methods. At this point, fuzzy logic-based MCDM methods offer an effective solution for managing uncertainties and subjectivity [5-7]. The use of fuzzy MCDM methods in wind farm site selection offers several advantages:

- ✓ Managing uncertainty and ambiguity: Traditional MCDM methods may have a hard time dealing with the uncertainty and ambiguity present in real-world decision-making processes. However fuzzy MCDM methods are designed to effectively manage these uncertainties. By using fuzzy logic, uncertainty and uncertainties in criteria such as expert opinions, environmental conditions and socio-economic factors can be modelled, allowing for more robust and realistic decisions to be made.
- ✓ Inclusion of Subjective Judgments: Expert opinions and stakeholder preferences play an important role in wind farm site selection. Fuzzy MCDM methods enable these subjective judgments to be converted into quantitative values through linguistic variables and fuzzy numbers. This flexibility allows the decision-making process to consider different perspectives and experiences, allowing for a more comprehensive assessment of potential locations.
- ✓ Increasing Decision Making Accuracy: Fuzzy MCDM methods increase the accuracy of the decision-making process by providing a more precise assessment of alternatives. These methods allow for the simultaneous evaluation of multiple criteria and the appropriate weights are assigned according to the relative importance of each criterion. The fuzzy logic framework allows the decision process to capture the complexity of the criteria and their dependence on each other, which leads to more accurate and informed location choices.
- ✓ Supporting Multi-Criteria Analysis: Wind power plant location selection requires evaluation of various criteria such as wind speed, proximity to infrastructure, environmental impact and land-use suitability. Fuzzy MCDM methods perfectly support multi-criteria analysis by providing a structured approach to evaluating these various factors. Sorting alternatives based on a combination of fuzzy criteria ensures a balanced and holistic assessment, so that the selected location is aligned with strategic goals and constraints.
- ✓ Increasing Decision Making Flexibility: Fuzzy MCDM methods offer flexibility to adapt to changes in criteria, preferences or environmental conditions. This flexibility is of great importance, especially in renewable energy planning, in dynamic and uncertain contexts where new knowledge or changing priorities may arise. Decision makers can easily adjust fuzzy models to reflect these changes, making the location selection process responsive to current and evolving needs.

- ✓ Facilitating Consensus Building: In wind farm site selection, reconciliation between stakeholders can often be challenging because of different priorities and interests. Fuzzy MCDM methods support reconciliation building by providing a transparent and systematic approach to evaluating alternatives. The use of fuzzy logic allows stakeholders to express their preferences in a flexible and understandable way, leading to more collaborative and acceptable decision outcomes.

In general, the application of fuzzy MCDM methods in wind farm site selection offers a comprehensive and effective approach to managing the complexities and uncertainties of the decision-making process. These methods contribute to making more informed, accurate and harmonious decisions, allowing the selection of the most suitable places for wind energy development. In this study, we will examine how fuzzy logic and MCDM methods can be applied for wind power plant location selection. In the light of the determined criteria, the most appropriate location will be determined by evaluating alternative places. Thus, it is aimed to make the most efficient use of wind energy potential and to minimize environmental impacts.

1.1. Aim of the Study

The aim of this study is to examine the applicability of Fuzzy WENSLO and Fuzzy RAWEC methods for managing uncertainties in wind power plant location selection and the complexity of decision-making. In the study, it is aimed to determine the most suitable wind power plant location considering various environmental, economic and technical criteria. The Fuzzy WENSLO method takes advantage of the flexibility provided by fuzzy logic in weighting criteria, while the Fuzzy RAWEC method offers a gradual selection process based on the rational preference of alternatives. The combination of these two methods aims to contribute to making more informed and sustainable decisions in the wind power plant location selection process. Within the scope of the study, alternative places will be evaluated in accordance with the criteria determined and the results will be analysed.

1.2. Contributions and Innovations

The contributions and innovations of this work are summarized below:

- ✓ Integration of Fuzzy MCDM Methods: This study is one of the first to examine the combination of Fuzzy WENSLO and Fuzzy RAWEC methods in wind power plant location selection. The integration of these methods aims to manage uncertainties and complexities more effectively in the decision-making process.
- ✓ Managing Uncertainties: The study shows how uncertainties encountered in wind farm site selection can be managed with fuzzy logic-based methods. This approach can deliver more precise and realistic results to decision-makers, increasing the chances of wind energy projects succeeding.
- ✓ Weighting Criteria: Defining the weights of the criteria using the Fuzzy WENSLO method and detailed analysis of the effect of these weights on the decision process provide a more objective and systematic assessment of wind farm location selection. This contributes to making more informed choices in the decision-making process.
- ✓ Evaluation of Alternatives: The progressive evaluation of alternatives with Fuzzy RAWEC method brings a new perspective to the decision-making process. This method plays an important role in optimal location selection, taking into account the preferences between alternatives in a more rational way.

- ✓ Practical Application and Information Presentation: The results provide practical information and recommendations that can be used in the selection of wind power plant locations. It can be used in the planning and implementation stages of wind energy projects by providing useful results for decision makers and stakeholders.
- ✓ Contribution to Literature: The study details how fuzzy MCDM methods are applied to wind power plant site selection and the contribution of these methods to the literature. This creates a reference source for future research and applications, providing insights into how fuzzy logic-based methods can be used in other energy projects.

These contributions and innovations emphasise the value and potential of fuzzy FCDM methods in wind farm site selection and aim to fill the existing knowledge and application gaps in this field.

1.3. Literature Review

In this section, both the existing literature on the selection of a suitable location for a wind farm is reviewed and examples are given from the literature on how the WENSLO and RAWEC methodologies have been used in previous studies.

1.3.1. Studies on the selection of suitable places for the wind power plant

Wind power plant location selection is a critical process in terms of energy efficiency, environmental sustainability and economic costs. Previous studies in this process detail the methods and criteria used in wind farm site selection. Here are some current studies in this area: [5] This study is focused on identifying the appropriate wind power plant locations in Sivas, Turkey, using geographic information systems (GIS) technology and fuzzy multi-criteria decision making (MCDM) methods. Fuzzy SWARA method determined the weights of the criteria, and Fuzzy MARCOS method was used to determine the most suitable locations. The results revealed that the district of Ulaş is the most suitable place [8] analysing the potential of wind energy in the eastern region of Saudi Arabia, this study integrated multi-criteria decision making and spatial analysis methods for wind power plant site selection. The study assessed wind power plant location selection with 17 different criteria and determined “very high”, “high” and “medium” eligibility ratings. Wind power density was the most important factor [9]. This study provides a framework that uses machine learning (ML) techniques for wind power plant site selection. In this study conducted in the Balıkesir province, the XGBoost algorithm achieved the highest accuracy rate (0.9607). The study determined that criteria such as wind speed, distance to transmission lines, distance to protected areas and altitude were the most important contributing factors [10]. In this study, Geographical Information Systems (GIS) and Analytical Hierarchy Process (AHP) methods were used for wind power plant selection in Western Iran. As a result of the analysis conducted in the Kermanshah region, six critical regions were found to be suitable for wind power plant installation. The total capacity of these regions is 216 MW [11]. In the study conducted in Burundi about wind power plant location selection, the Fuzzy Analytical Hierarchy Process (FAHP) and Geographical Information Systems (GIS) tools were used. The study revealed that the regions located in the west of the country are the most suitable places for wind power plant installation [12]. This study developed a model that included global scoring for wind power plant site selection using support vector regression (SVR) method. According to the study conducted in Iran, SVR provides a more comprehensive view than MCDM methods and makes vast areas suitable for wind power [13]. The study presented an integration of BWM-AHP-MARCOS methods for wind power plant location selection in Libya. The city of Derna has been the region that this model has determined as the most suitable place. The study was supported by a sensitivity analysis that tested the stability of the results even if the criteria weights changed.

This literature review provides an overview of the studies conducted in different methods and regions for wind power plant site selection. Each study, taking into account regional differences and the methods used, proposes a variety of approaches to identifying the most suitable locations for wind energy projects.

1.3.2. Studies with WENSLO and RAWEC methods

Recent studies involving newly developed methods in the literature have added valuable insights to various fields [14]. Examined how consumers' opinions are shaped by the environmental responsibilities of businesses and their green activities to address the idea of sustainable brand equity. In this case, the T2NN-WENSLO-ARLON model was created to measure sustainable brand equity. The basic inputs of the model are the opinions of experts, criteria and brands. The WENSLO technique is used to determine the weight of the criteria, and the ARLON approach is used to rank the brands. In one case study, “green product leadership” was shown to be the most important component of the criterion and Misbahce A.S. emerged as the business with the highest sustainable brand value. Another study by [15] focused on assessing the green growth performance of countries using WENSLO and ALWAS methods. The WENSLO method enables objective determination of criterion weights, while the ALWAS method ranks available alternatives. When the study was conducted on G7 countries, it was found that environmental elements were more important than social and economic elements. The most important factors affecting the success of green growth have been found to be carbon dioxide emissions, water resources and marine protected areas. In the agricultural sector, a study [16] introduced the RAWEC method to solve the problem of site selection for agricultural distribution centers. In the study, the criteria weights calculated using the LMAW method and the different locations in the Brŏko Region were evaluated. The RAWEC method is distinguished from other MCDM methods due to its simplicity and consistency in the sorting process.

2. Methodology

2.1. Working Area

Province of Sivas is located in Upper Kızılırmak Section of Central Anatolia Region. Its area is the second largest province in Turkey with an area of 27.386 km^2. The Sivas city which is located between eastern longitudes of 36^o and 39^o and northern latitudes of 38^o and 41^o is shown in Figure 1.

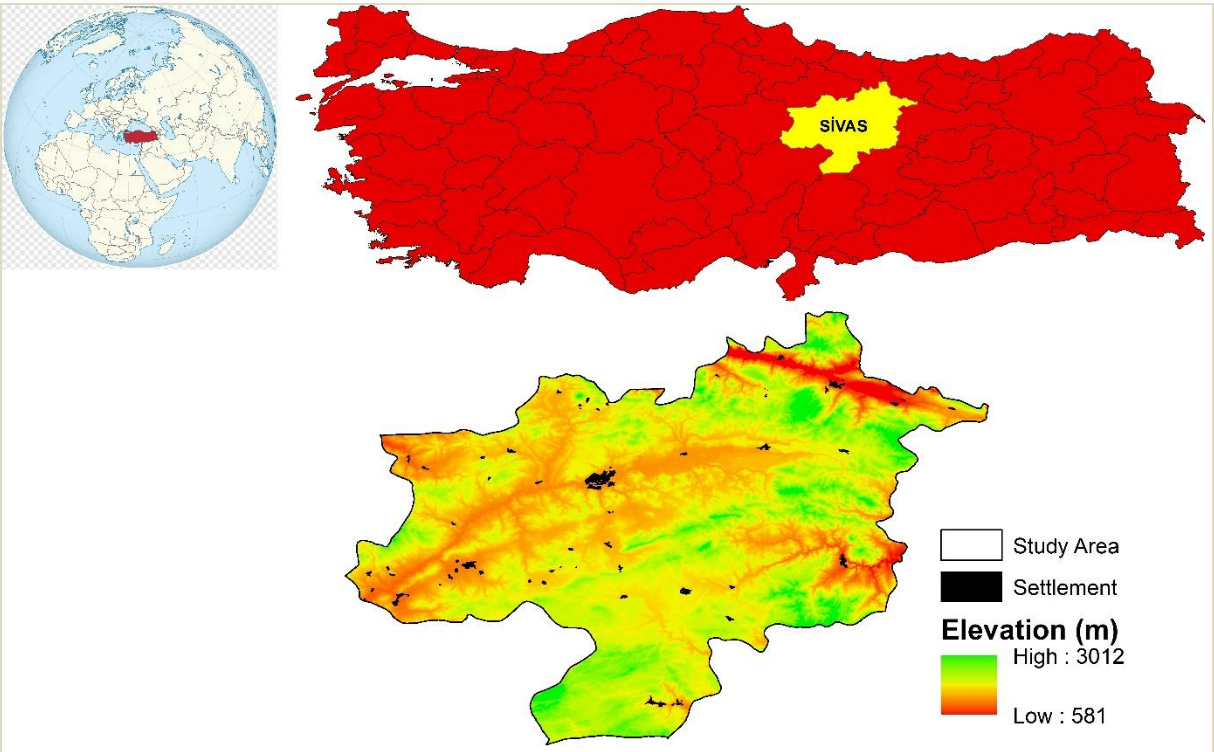

Fig. 1. Work area location

The annual average wind speed of the province ranges from 1.25 m/s to 3.48 m/s. The areas with the lowest average wind speed (1.25-1.87 m/s) are found in and near Sivas city centre, while the largest areas (2.95-3.48 m/s) are concentrated in and near Gürün and Suşehri regions. The minimum average wind speed values (0.76-1.27 m/s) are seen in the autumn season and the maximum values (3.76-4.63 m/s) in the summer. In the last three decades, the wind speed has shown a decline with values ranging from 0.97 m/s to 3.19 m/s. The regions with the highest wind speed (2.48-3.19 m/s) are near Ulaş and Gürün. The minimum average wind speed (0.76-1.27 m/s) is recorded in the fall, while the highest values (2.98-3.75 m/s) can be observed during the summer season [17].

2.2. Fuzzy theory set

Zadeh, [18] established fuzzy set theory, which is a system that represents uncertainty while also allowing decision makers to make judgments using linguistic variables. Fuzzy numbers can exist in theory and practice in a variety of forms. These are idioms used to represent unknown numbers. However, triangular fuzzy numbers are the most common kind. Triangular fuzzy numbers have been used in various studies to translate qualitative comments into quantitative ones. Triangular fuzzy numbers portray each number as three numbers. The first, second, and third integers that characterize a fuzzy number represent the lowest, most likely, and biggest possible values, respectively.

Suppose $\tilde{A} = (a_l, a_m, a_u)$ and $\tilde{B} = (b_l, b_m, b_u)$ are two triangular fuzzy numbers. The mathematical computations for these integers are described in Eqs. (1)-(4).

$$\tilde{A} + \tilde{B} = (a_l + b_l, a_m + b_m, a_u + b_u) \quad (1)$$

$$\tilde{A} - \tilde{B} = (a_l - b_u, a_m - b_m, a_u - b_l) \quad (2)$$

$$\tilde{A} x \tilde{B} = (a_l b_l, a_m b_m, a_u b_u) \quad (3)$$

$$\frac{\tilde{A}}{\tilde{B}} = \left(\frac{a_l}{b_u}, \frac{a_m}{b_m}, \frac{a_u}{b_l}\right) \tag{4}$$

Triangular fuzzy numbers can be converted to crisp numbers using a variety of formulae. In this study, Eq. (5) is used to defuzzify a fuzzy integer, such as $\tilde{A} = (a_l, a_m, a_u)$.

$$A = \frac{a_l + 4a_m + a_u}{6} \tag{5}$$

2.3. F-WENSLO method for prioritization of criteria affecting strategies

Pamučar *et al*, [15] presented the WENSLO technique for determining weight coefficients of criterion (crisp version). In this work, the WENSLO technique is fuzzification using triangular fuzzy numbers.

Step 1. Construction of the initial decision matrix

The selected experts prioritized the criteria using linguistic phrases from the fuzzy scale in Table 1.

Table 1
Fuzzy scale, linguistic expressions and triangular numbers

Fuzzy Linguistic Descriptive	Abbreviation	Fuzzy Number
Absolutely low	AL	(1,1,1)
Very low	VL	(1,1.5,2)
Low	L	(1.5,2,2.5)
Medium	M	(2,2.5,3)
Equal	E	(2.5,3,3.5)
Medium-high	MH	(3,3.5,4)
High	H	(3.5,4,4.5)
Very high	VH	(4,4.5,5)
Absolutely high	AH	(4.5,5,5)

Source: Božanić *et al.,* [19]

The combined decision matrix ($\tilde{Z}$) is obtained using Eq. (6).

$$\tilde{Z} = \left[\tilde{z}_{ij}\right]_{kxn} = \begin{bmatrix} \tilde{z}_{11} & \cdots & \tilde{z}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{z}_{k1} & \cdots & \tilde{z}_{kn} \end{bmatrix} \tag{6}$$

$\tilde{z}_{ij} = \left(z_{ij}^l, z_{ij}^m, z_{ij}^u\right)$ represents fuzzy value of criterion j. in alternative i.

Step 2. Creating the normalization matrix $\left(\tilde{T}\right)$.

Eq. (7) is used to normalise the combined decision matrix.

$$\tilde{t}_{ij} = \left(t_{ij}^l, t_{ij}^m, t_{ij}^u\right) = \frac{\tilde{z}_j}{\sum_{j=1}^n \tilde{z}_j} = \left(\frac{z_j^l}{\sum_{j=1}^n z_j^u}, \frac{z_j^m}{\sum_{j=1}^n z_j^m}, \frac{z_j^u}{\sum_{j=1}^n z_j^l}\right) \tag{7}$$

Step 3. Calculation of criterion class interval ($\tilde{\rho}_j$).

The size of the j-th criteria class interval is determined using Sturges' rule, Eq. (8):

$$\tilde{\rho}_j = \left(\rho_j^l, \rho_j^m, \rho_j^u\right) = \left(\frac{max(z_j^l) - min(z_j^l)}{1 + 3.322 * log(k)}, \frac{max(z_j^m) - min(z_j^m)}{1 + 3.322 * log(k)}, \frac{max(z_j^u) - min(z_j^u)}{1 + 3.322 * log(k)}\right) \tag{8}$$

Step 4. Determination of the criterion slope ($\tan\tilde{\varphi}_j$).

The slope of the criterion is calculated by Eq. (9).

$$tan\tilde{\varphi}_j = \frac{\sum_{i=1}^{k} \tilde{z}_j}{(k-1)\tilde{\rho}_j} = \left(\frac{\sum_{i=1}^{k} z_j^l}{(k-1)\rho_j^u}, \frac{\sum_{i=1}^{k} z_j^m}{(k-1)\rho_j^m}, \frac{\sum_{i=1}^{k} z_j^u}{(k-1)\rho_j^l}\right) \tag{9}$$

Step 5. Determination of the criterion envelope ($\tilde{\varepsilon}_j$)

Eq. (10) calculates the total of the partial Euclidean distances between two consecutive criteria.

$$\tilde{\varepsilon}_j = \left(\sum_{i=1}^{k-1} \sqrt{\left(z_{i+1,j}^l - z_{ij}^l\right)^2 + \left(\rho_j^l\right)^2}, \sum_{i=1}^{k-1} \sqrt{\left(z_{i+1,j}^m - z_{ij}^m\right)^2 + \left(\rho_j^m\right)^2}, \sum_{i=1}^{k-1} \sqrt{\left(z_{i+1,j}^u - z_{ij}^u\right)^2 + \left(\rho_j^u\right)^2}\right) \tag{10}$$

Step 6. Determine the envelope slope ratio ($\tilde{\delta}_j$)

The ratio of the total Euclidean distance to the criteria slope is calculated using Eq. (11).

$$\tilde{\delta}_j = \frac{\tilde{\varepsilon}_j}{tan\tilde{\varphi}_j} = \left(\frac{\varepsilon_j^l}{tan\varphi_j^u}, \frac{\varepsilon_j^m}{tan\varphi_j^m}, \frac{\varepsilon_j^u}{tan\varphi_j^l}\right) \tag{11}$$

Step 7. Obtaining fuzzy weights $\left(\tilde{w}_j\right)$ of each of the criterion

Weights are determined using Eq. (12) depending on the criteria's significance coefficients.

$$\tilde{w}_j = \left(w_j^l, w_j^m, w_j^u\right) = \frac{\tilde{\delta}_j}{\sum_{j=1}^{n} \tilde{\delta}_j} = \left(\frac{\delta_j^l}{\sum_{j=1}^{n} \delta_j^u}, \frac{\delta_j^m}{\sum_{j=1}^{n} \delta_j^m}, \frac{\delta_j^u}{\sum_{j=1}^{n} \delta_j^l}\right) \tag{12}$$

2.4. F-RAWEC Method for Ranking Strategies

Puška *et al.,* (2024) presented the RAWEC technique for ranking alternatives (crisp version). In this study, the RAWEC technique is fuzzified using triangular fuzzy numbers.

Step 1. Construction of the initial decision matrix

The selected experts prioritized the criteria using linguistic phrases from the fuzzy scale in Table 1. The combined decision matrix ($\tilde{X}$) is obtained using Eq. (13).

$$\tilde{X} = \left[\tilde{x}_{ij}\right]_{kxn} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{k1} & \cdots & \tilde{x}_{kn} \end{bmatrix} \tag{13}$$

$\tilde{x}_{ij} = \left(x_{ij}^l, x_{ij}^m, x_{ij}^u\right)$ represents fuzzy value of criterion j. in alternative i.

Step 2. Creating the normalization matrix $\left(\tilde{N}\right)$.

When normalising the initial decision matrix, double normalisation is performed with Eq. (14) for the benefit normalization ($\tilde{n}_{ij}$) and Eq. (15) for the cost normalization $\left(\tilde{n}_{ij}\right)'$.

$$\tilde{n}_{ij} = \left(n_{ij}^l, n_{ij}^m, n_{ij}^u\right) = \frac{\tilde{x}_j}{max(\tilde{x}_{ij})} = \left(\frac{x_{ij}^l}{max(x_{ij}^u)}, \frac{x_{ij}^m}{max(x_{ij}^u)}, \frac{x_{ij}^u}{max(x_{ij}^u)}\right) \tag{14}$$

and

$$\left(\tilde{n}_{ij}\right)' = \left(n_{ij}^l, n_{ij}^m, n_{ij}^u\right) = \frac{min(\tilde{x}_{ij})}{\tilde{x}_{ij}} = \left(\frac{min(x_{ij}^l)}{x_{ij}^u}, \frac{min(x_{ij}^l)}{x_{ij}^m}, \frac{min(x_{ij}^l)}{x_{ij}^l}\right) \tag{14}$$

$$\tilde{n}_{ij} = \left(n_{ij}^l, n_{ij}^m, n_{ij}^u\right) = \frac{min(\tilde{x}_{ij})}{\tilde{x}_{ij}} = \left(\frac{min(x_{ij}^l)}{x_{ij}^u}, \frac{min(x_{ij}^l)}{x_{ij}^m}, \frac{min(x_{ij}^l)}{x_{ij}^l}\right) \tag{15}$$

and

$$\left(\tilde{n}_{ij}\right)' = \left(n_{ij}^l, n_{ij}^m, n_{ij}^u\right) = \frac{\tilde{x}_j}{max(\tilde{x}_{ij})} = \left(\frac{x_{ij}^l}{max(x_{ij}^u)}, \frac{x_{ij}^m}{max(x_{ij}^u)}, \frac{x_{ij}^u}{max(x_{ij}^u)}\right) \tag{15}$$

Step 3. Calculate the deviation from the criteria weight

Eqs. (16) and (17) yield the total deviation from the weight of the criterion after first calculating the deviations of the normalized data from the maximum values denoted by the number 1. The deviation is then multiplied by the weights of the criteria.

$$\tilde{\vartheta}_{ij}=\left(\sum_{i=1}^{n}\left[\left(1-n_{ij}^{u}\right)*w_{j}^{l}\right],\sum_{i=1}^{n}\left[\left(1-n_{ij}^{m}\right)*w_{j}^{m}\right],\sum_{i=1}^{n}\left[\left(1-n_{ij}^{l}\right)*w_{j}^{u}\right]\right) \quad (16)$$

$$(\tilde{\vartheta}_{ij})'=\left(\sum_{i=1}^{n}\left[\left(1-(n_{ij}^{u})'\right)*w_{j}^{l}\right],\sum_{i=1}^{n}\left[\left(1-(n_{ij}^{m})'\right)*w_{j}^{m}\right],\sum_{i=1}^{n}\left[\left(1-(n_{ij}^{l})'\right)*w_{j}^{u}\right]\right) \quad (17)$$

Step 4. Calculation of the value of the RAWEC method

The value of the RAWEC method obtained by Eq. 18 takes a value between (-1,1).

$$\tilde{Q}_{i}=\frac{(\tilde{\vartheta}_{ij})'-\tilde{\vartheta}_{ij}}{(\tilde{\vartheta}_{ij})'+\tilde{\vartheta}_{ij}}=\left(\frac{(\vartheta_{ij}^{l})'-\vartheta_{ij}^{u}}{(\vartheta_{ij}^{u})'+(\vartheta_{ij}^{u})},\frac{(\vartheta_{ij}^{m})'-\vartheta_{ij}^{m}}{(\vartheta_{ij}^{m})'+(\vartheta_{ij}^{m})},\frac{(\vartheta_{ij}^{u})'-\vartheta_{ij}^{l}}{(\vartheta_{ij}^{l})'+(\vartheta_{ij}^{l})}\right) \quad (18)$$

The degree to which the value of an alternative's technique is high determines its superiority. The best option is indicated by the alternative with the highest value.

3. Results

People from various specialties have been brought together to form a decision-making group to work on the location selection of the wind farm. Table 2 shows the structure of the decision-making group, which includes representatives from each area of expertise.

Table 2

Structure of Decision-Making Group

Expert Group Member	Role	Responsibilities
Energy Engineer (E1)	Technical evaluation of wind energy systems	- Analyzing the performance of wind turbines and equipment - Assessing the performance of wind turbines and equipment
Environmental Engineer/Environmental Scientist(E2)	Assessment of environmental impacts and sustainability criteria	- Examining environmental impacts - Analyzing impacts on natural habitats, water resources and soil quality
Geographic Information Systems (GIS) Specialist (E3)	Analysis of geographical data and spatial assessment	- Evaluate geographical criteria such as land use, altitude, wind speed and direction - Creating compliance maps
Economist (E4)	Economic analysis and financial assessments	- Calculating installation, operating and maintenance costs - Conducting return-on-investment analysis and evaluating economic sustainability

Social Scientist/Society Specialist (E5)	Evaluation of social acceptance and community impacts	- Examining the attitude of local people to the project -Analyzing social impacts and assessing social acceptance

By clearly defining the roles and responsibilities of each specialist, it is ensured that the decision-making process is carried out in a comprehensive and effective manner.

3.1. Defining and explaining criteria

The criteria used in the choice of location of the wind power plant are explained in detail by the decision-making group and given in Table 3.

Table 3
Criteria Used in Wind Power Plant Site Selection

Criterium	Description
Wind Speed and Direction (C1)	Evaluation of wind speeds and directions required for the efficient generation of wind energy.
Altitude (C2)	Determination of more suitable areas for wind turbines due to increased wind speed in high regions.
Land Use (C3)	Assessment of existing land use types (agriculture, industry, housing, etc.) and determination of their suitability for wind power plants.
Environmental Impacts(C4)	Investigation of environmental impacts for the protection of natural habitats, water resources and soil.
Proximity to Infrastructure (C5)	Assessment of distance to power transmission lines and other important infrastructures.
Social Acceptence (C6)	Evaluation of local people's attitude to wind farm projects and examination of social acceptance.
Economic Costs(C7)	Analysis of wind farm installation, maintenance and operation costs and evaluation of economic feasibility.
Safety and Risk Factors (C8)	Analysis of natural disasters and other safety risks.
Climate Conditions (C9)	Evaluation of the effect of annual temperature changes, humidity and other climatic factors on wind energy production.
Legal and Permit Requirements (C10)	Examination of the requirements of the regulations and permits in wind farm installation.

These criteria aim to comprehensively evaluate and prioritize wind farm site selection. The decision-making group will determine the most appropriate place based on these criteria.

3.2. Recommended places for wind power plant

Figure 2 offers several maps that assess the wind energy potential of the province of Sivas. Figure 2a shows the geographical distribution of districts belonging to the province of Sivas. This map allows the evaluation of geographical factors in the choice of location. In Figure 2b, the annual average wind speed distribution at a height of 100 meters for the Sivas province is presented. This distribution is a critical factor in determining wind energy potential and is an important indicator for the detection of appropriate locations. Figure 2c features an annual average wind power density distribution at a height of 100 meters. Wind power density is an important parameter used to estimate wind power generation capacity in a given region. This map visualizes the potential energy generation capacity in different regions. Finally, in Figure 2d, the capacity factor distribution at a height of 100 meters is shown. The capacity factor is a measure that expresses the actual production capacity of a wind turbine according to its theoretical maximum capacity. This distribution is used to understand inter-regional energy efficiency differences and helps identify the most suitable locations for wind farm installation.

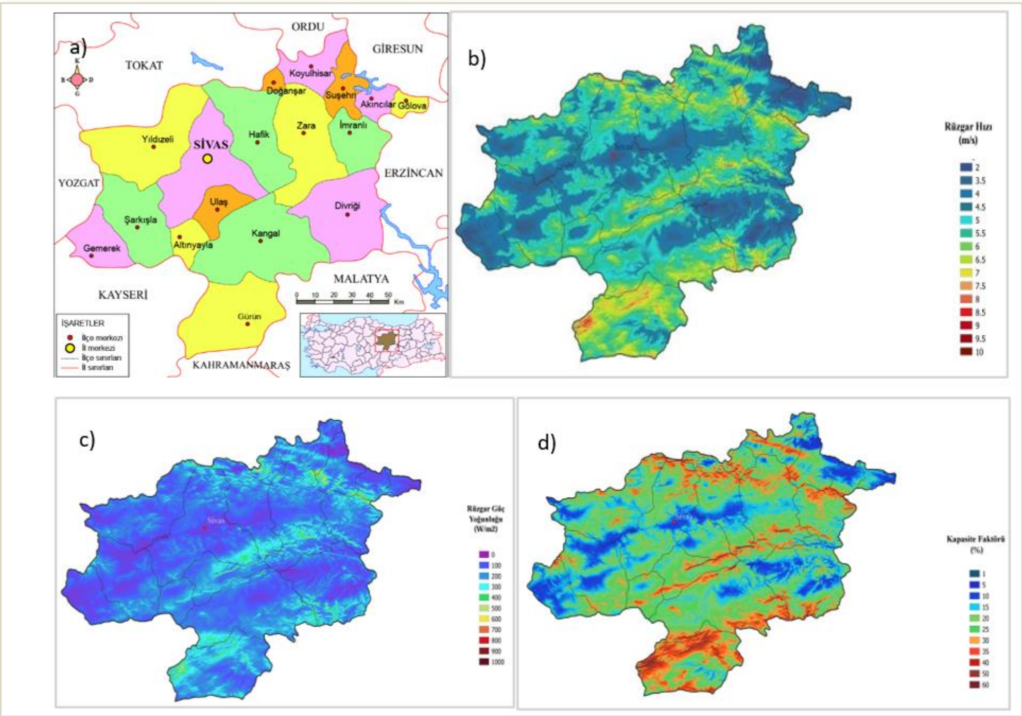

Fig. 2. Wind related information of Sivas districts
Source: T.C. Ministry of Energy and Natural Resources, General Directorate of Energy Affairs, [20]

These images allow a comprehensive analysis of wind energy potential and play a critical role in the wind farm site selection process.

The most suitable areas for wind farm site selection have been determined by the decision-making group based on the geographic and wind energy potential data presented in Figure 2. These images provided a comprehensive analysis of wind energy potential and provided critical data for the detection of appropriate locations.

In the light of these data, the decision-making group selected the most suitable places for wind power plant installation in Sivas province and presented the features of these places in Table 4.

Table 4
Recommended Places for Wind Power Plant

Recommended Location	Features
Gürün (A1)	Wind speed is high, infrastructure is close, environmental impacts are low
Kangal (A2)	Wind speed is sufficient, social acceptance is positive, economic cost is low
Divriği (A3)	Height is appropriate, easy to access infrastructure, environmental effects are minimal
Ulaş (A4)	Wind speed is moderate, land use is convenient, climatic conditions are favorable
Zara (A5)	The wind speed is high, the altitude is convenient, the environmental effects are minimal

Each area in Table 4 was assessed according to various criteria such as wind speed, proximity to infrastructure, environmental impacts, social acceptance and economic costs. This table summarizes the criteria used to determine the most suitable places for wind power plant installation and the results of the evaluations made according to these criteria. Places such as the Gürün, Divriği and Zara were in the high suitability category due to their advantages such as high wind speed and minimal environmental impacts, while places such as Kangal and Ulaş were evaluated in moderate suitability. These assessments have contributed to selecting the most efficient and sustainable areas for wind farm installation.

3.3. Data Collection and Analysis

The decision-making group evaluated both the criteria and the appropriate locations for the current and proposed wind power plants according to Table 1. According to expert (E) opinions, evaluation of criteria is given in Table 5 and evaluation of alternatives is given in Table 6.

Table 5
Experts' Evaluation of Criteria

Experts/Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
E1	VH	H	MH	AH	AH	MH	E	M	MH	H
E2	MH	E	VH	H	VH	H	VH	AH	H	MH
E3	H	VH	AH	VH	H	MH	MH	E	H	MH
E4	AH	VH	H	MH	MH	E	H	E	MH	VH
E5	MH	H	VH	H	AH	AH	AH	MH	AH	MH

This table provides a summary of the scores that experts give to certain criteria. The criteria have been evaluated and scored by each specialist within the framework of their area of expertise. This scoring will help determine the weight of the criteria to be used in the final decision-making process.

Table 6.
Experts' Evaluation of Alternatives

Recommended Places/Criteria	Experts	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A1	**E1**	VH	H	MH	H	AH	H	VH	MH	AH	H
	E2	H	MH	VH	VH	H	VH	AH	H	VH	MH
	E3	VH	H	AH	H	VH	MH	VH	H	VH	H
	E4	AH	VH	H	VH	AH	VH	VH	H	AH	VH
	E5	AH	VH	H	VH	H	AH	VH	MH	AH	H
A2	**E1**	H	MH	VH	MH	VH	VH	H	E	VH	MH
	E2	MH	H	MH	H	VH	H	VH	VH	H	H
	E3	H	MH	VH	MH	H	H	H	MH	VH	MH
	E4	H	MH	VH	H	VH	H	H	MH	VH	MH
	E5	H	MH	VH	H	VH	VH	H	E	VH	MH
A3	**E1**	AH	VH	H	VH	H	MH	VH	H	VH	H
	E2	VH	VH	H	AH	H	H	VH	H	VH	MH
	E3	AH	VH	H	VH	H	H	VH	H	VH	H
	E4	AH	H	VH	VH	VH	VH	VH	H	VH	H
	E5	VH	H	VH	H	VH	AH	VH	MH	AH	H
A4	**E1**	MH	E	MH	H	VH	H	MH	E	H	MH

	E2	MH	E	MH	H	H	MH	H	VH	H	MH
	E3	MH	E	MH	H	H	MH	H	MH	H	MH
	E4	MH	E	H	MH	H	MH	H	MH	H	MH
	E5	MH	E	MH	MH	H	H	MH	H	H	MH
A5	**E1**	H	H	VH	H	AH	VH	AH	MH	AH	H
	E2	VH	H	VH	VH	VH	AH	AH	H	VH	H
	E3	VH	H	VH	VH	VH	H	AH	H	AH	H
	E4	VH	H	VH	H	VH	H	VH	H	VH	H
	E5	VH	H	VH	H	VH	VH	AH	MH	AH	H

These evaluations help to understand the strengths and weaknesses of the proposed places in the decision-making process, providing information on the criteria to be considered in the final election.

3.4. Determining the weights with F-WENSLO method

The initial decision matrix obtained as a result of the evaluation of the experts and presented in Table 5 is normalized using Eq. (7). The obtained normalized matrix is given in Table 7.

Table 7
Normalized decision matrix

	C1			**C2**			**C3**			**C4**			**C5**		
E1	0,1778	0,2195	0,2778	0,1556	0,2000	0,2571	0,1277	0,1628	0,2105	0,1957	0,2381	0,2703	0,1915	0,2273	0,2564
E2	0,1333	0,1707	0,2222	0,1111	0,1500	0,2000	0,1702	0,2093	0,2632	0,1522	0,1905	0,2432	0,1702	0,2045	0,2564
E3	0,1556	0,1951	0,2500	0,1778	0,2250	0,2857	0,1915	0,2326	0,2632	0,1739	0,2143	0,2703	0,1489	0,1818	0,2308
E4	0,2000	0,2439	0,2778	0,1778	0,2250	0,2857	0,1489	0,1860	0,2368	0,1304	0,1667	0,2162	0,1277	0,1591	0,2051
E5	0,1333	0,1707	0,2222	0,1556	0,2000	0,2571	0,1702	0,2093	0,2632	0,1522	0,1905	0,2432	0,1915	0,2273	0,2564
max	0,2000	0,2439	0,2778	0,1778	0,2250	0,2857	0,1915	0,2326	0,2632	0,1957	0,2381	0,2703	0,1915	0,2273	0,2564
Min	0,1333	0,1707	0,2222	0,1111	0,1500	0,2000	0,1277	0,1628	0,2105	0,1304	0,1667	0,2162	0,1277	0,1591	0,2051
	C6			C7			C8			C9			C10		
E1	0,1429	0,1842	0,2424	0,1136	0,1500	0,2000	0,1053	0,1471	0,2069	0,1364	0,1750	0,2286	0,1628	0,2105	0,2727
E2	0,1667	0,2105	0,2727	0,1818	0,2250	0,2857	0,2368	0,2941	0,3448	0,1591	0,2000	0,2571	0,1395	0,1842	0,2424
E3	0,1429	0,1842	0,2424	0,1364	0,1750	0,2286	0,1316	0,1765	0,2414	0,1591	0,2000	0,2571	0,1395	0,1842	0,2424
E4	0,1190	0,1579	0,2121	0,1591	0,2000	0,2571	0,1316	0,1765	0,2414	0,1364	0,1750	0,2286	0,1860	0,2368	0,3030
E5	0,2143	0,2632	0,3030	0,2045	0,2500	0,2857	0,1579	0,2059	0,2759	0,2045	0,2500	0,2857	0,1395	0,1842	0,2424
max	0,2143	0,2632	0,3030	0,2045	0,2500	0,2857	0,2368	0,2941	0,3448	0,2045	0,2500	0,2857	0,1860	0,2368	0,3030
Min	0,1190	0,1579	0,2121	0,1136	0,1500	0,2000	0,1053	0,1471	0,2069	0,1364	0,1750	0,2286	0,1395	0,1842	0,2424

The normalized values of the evaluation of the criterion C7 in Table 1 by E1 are obtained as follows.

$$\tilde{t}_{11} = \left(\frac{4}{5+4+4{,}5+5+4}, \frac{4{,}5}{4{,}5+3{,}5+4+5+3{,}5}, \frac{5}{4+3+3{,}5+4{,}5+3}\right) = (0{,}1178 \quad 0{,}2195 \quad 0{,}2778)$$

All elements of the matrix are calculated similarly.

Subsequently, the criterion class range was calculated using Eq.(8), the criterion slope Eq.(9), the criterion envelope Eq.(10), the envelope slope ratio Eq.(11), and the fuzzy weight of each criterion Eq.(12) and presented in Table 8.

Table 8
Calculations according to F-WENSLO method for criteria

	C1			**C2**			**C3**			**C4**			**C5**		
$\tilde{\rho}_j$	0,0201	0,0220	0,0167	0,0201	0,0226	0,0258	0,0192	0,0210	0,0158	0,0196	0,0215	0,0163	0,0192	0,0205	0,0154

$tan\tilde{\varphi}_j$	0,7200	1,0250	1,5625	0,6806	1,1111	1,8080	0,6064	1,0750	1,6148	0,7440	1,0500	1,5886	0,8090	1,1000	1,5734
$\tilde{\varepsilon}_j$	0,5897	0,6040	0,5530	0,4864	0,5028	0,5223	0,5274	0,5397	0,5014	0,5304	0,5430	0,5471	0,5576	0,5670	0,5392
$\tilde{\delta}_j$	0,3774	0,5893	0,7681	0,2690	0,4525	0,7675	0,3266	0,5021	0,8268	0,3339	0,5172	0,7353	0,3544	0,5155	0,6664
$\tilde{w}_j$	0,0455	0,1023	0,2170	0,0324	0,0785	0,2168	0,0394	0,0871	0,2336	0,0403	0,0898	0,2077	0,0427	0,0895	0,1883
			C6			**C7**			**C8**			**C9**			**C10**
$\tilde{\rho}_j$	0,0287	0,0317	0,0274	0,0274	0,0301	0,0258	0,0396	0,0443	0,0415	0,0205	0,0226	0,0172	0,0140	0,0158	0,0182
$tan\tilde{\varphi}_j$	0,6482	0,9500	1,4848	0,6960	1,0000	1,5365	0,5533	0,8500	1,3831	0,6960	1,0000	1,5365	0,6331	0,8611	1,7509
$\tilde{\varepsilon}_j$	0,6108	0,6266	0,6102	0,5548	0,5694	0,5408	0,5786	0,6001	0,5910	0,5663	0,5802	0,5537	0,5592	0,5770	0,5979
$\tilde{\delta}_j$	0,4113	0,6596	0,9414	0,3611	0,5694	0,7770	0,4183	0,7059	1,0681	0,3686	0,5802	0,7955	0,3194	0,6700	0,9444
$\tilde{w}_j$	0,0496	0,1145	0,2659	0,0436	0,0988	0,2195	0,0505	0,1225	0,3017	0,0445	0,1007	0,2247	0,0385	0,1163	0,2668

All calculations are shown in the C1 criterion.

$$\tilde{\rho}_{C1} = \left(\frac{0{,}2000 - 0{,}1333}{1 + 3{,}322 * log5}, \frac{0{,}2439 - 0{,}1707}{1 + 3{,}322 * log5}, \frac{0{,}2778 - 0{,}2222}{1 + 3{,}322 * log5}\right) = (0{,}0201 \;\; 0{,}0220 \;\; 0{,}0167)$$

$$tan\tilde{\varphi}_{C1} = \begin{pmatrix} \frac{0{,}1778 + 0{,}1333 + 0{,}1556 + 0{,}2000 + 0{,}1333}{4 * 0{,}2778}, \\ \frac{0{,}2195 + 0{,}1707 + 0{,}1951 + 0{,}2439 + 0{,}1707}{4 * 0{,}2439}, \\ \frac{0{,}2778 + 0{,}2222 + 0{,}2500 + 0{,}2778 + 0{,}2222}{4 * 0{,}2000} \end{pmatrix} = (0{,}7200 \;\; 1{,}0250 \;\; 1{,}5625)$$

$$\tilde{\varepsilon}_{C1} = \begin{pmatrix} \sqrt{((0{,}1333 - 0{,}1778)^2 + 0{,}0201^2) + ((0{,}1556 - 0{,}1333)^2 + 0{,}0201^2) + ((0{,}2000 - 0{,}1556)^2 + 0{,}0201^2) + ((0{,}1333 - 0{,}2000)^2 + 0{,}0201^2)}, \\ \sqrt{((0{,}1707 - 0{,}2195)^2 + 0{,}0220^2) + ((0{,}1951 - 0{,}1707)^2 + 0{,}0220^2) + ((0{,}2439 - 0{,}1951)^2 + 0{,}0220^2) + ((0{,}1707 - 0{,}2439)^2 + 0{,}0220^2)}, \\ \sqrt{((0{,}2222 - 0{,}2778)^2 + 0{,}0167^2) + ((0{,}2500 - 0{,}2222)^2 + 0{,}0167^2) + ((0{,}2778 - 0{,}2500)^2 + 0{,}0167^2) + ((0{,}2222 - 0{,}2778)^2 + 0{,}0167^2)} \end{pmatrix}$$

$$\tilde{\varepsilon}_{C1} = (0{,}5897 \;\; 0{,}6040 \;\; 0{,}5530)$$

$$\tilde{\delta}_{C1} = \left(\frac{0{,}5897}{1{,}5625}, \frac{0{,}6040}{1{,}0250}, \frac{0{,}5530}{0{,}7200}\right) = (0{,}3774 \;\; 0{,}5893 \;\; 0{,}7681)$$

$$\tilde{w}_{C1} = \begin{pmatrix} \frac{0{,}3774}{0{,}7681 + 0{,}7675 + \ldots + 0{,}7955 + 0{,}9444}, \\ \frac{0{,}5893}{0{,}5893 + 0{,}4525 + \ldots + 0{,}5802 + 0{,}6700}, \\ \frac{0{,}7681}{0{,}3774 + 0{,}2690 + \ldots + 0{,}3686 + 0{,}3194} \end{pmatrix} = (0{,}0455 \;\; 0{,}1023 \;\; 0{,}2170)$$

Later crips weights were obtained using Eq. (5).

$$w_{C1} = \frac{0{,}0455 + 4 * 0{,}1023 + 0{,}2170}{6} = 0{,}1119$$

Normalized weight values have been obtained since, N$\sum_{j=1}^{10} w_j = 1$ for all weights.

$$\omega_{C1} = \frac{0{,}1119}{0{,}1119 + 0{,}0939 + 0{,}1036 + 0{,}1012 + 0{,}0981 + 0{,}1289 + 0{,}1097 + 0{,}1404 + 0{,}1120 + 0{,}1284} = 0{,}0992$$

Similarly, the same operations were performed for other weights.

$$\omega_j = (0{,}0992\ \ 0{,}0832\ \ 0{,}0918\ \ 0{,}0897\ \ 0{,}0870\ \ 0{,}1143\ \ 0{,}0973\ \ 0{,}1244\ \ 0{,}0993\ \ 0{,}1138)$$

According to the given weight, the first of the three most important criteria is C8: Safety and Risk Factors (0,1244), which stands out as the most critical criterion in wind power plant location selection. This indicates that factors such as natural disaster risk, technical failures, or human-induced risks should be carefully evaluated in the region where the plant will be installed. Safety issues can directly affect the operational continuity of the plant and the safety of employees and the people of the environment. Therefore, this criterion, which has the highest weight, should be considered as a priority in the decision-making process. In the second place, C6: Social Admission (0,1143) is of great importance for the successful implementation and sustainability of the wind power plant. Support from local people and stakeholders to the project minimizes the social and legal barriers the project may face in the long run. Social acceptance, assessed by a high weight, indicates that public support and adoption of the project plays a critical role in the success of the plant. This criterion emphasizes that when choosing a place, social reactions and acceptance rate should be carefully analysed. In the third place, C10: Legal and Permit Requirements (0,1138) covers the process of the legal execution of the project and obtaining all necessary permits. The fact that this criterion has a high weight indicates how important legal compliance is when choosing a place. Neglecting legal requirements can cause the project to be stopped or delayed, which can lead to serious financial losses. Therefore, legal requirements play a fundamental role in determining the most suitable location for the wind farm. These criteria are the most important factors to consider in order to ensure the sustainability of the project both technically and socially.

3.5. F-RAWEC method application results

Table 6 was accepted as the initial decision matrix; a combined decision matrix was obtained by taking arithmetic averages and given in Table 9.

Table 9
Combined decision matrix

	C1			C2			C3			C4			C5		
A1	4,1000	4,6000	4,9000	3,6000	4,1000	4,6000	3,7000	4,2000	4,6000	3,8000	4,3000	4,8000	4,0000	4,5000	4,8000
A2	3,4000	3,9000	4,4000	3,1000	3,6000	4,1000	3,8000	4,3000	4,8000	3,4000	3,9000	4,4000	4,0000	4,5000	5,0000
A3	4,3000	4,8000	5,0000	3,8000	4,3000	4,8000	3,7000	4,2000	4,7000	4,0000	4,5000	4,9000	3,7000	4,2000	4,7000
A4	3,0000	3,5000	4,0000	2,5000	3,0000	3,5000	3,1000	3,6000	4,1000	3,3000	3,8000	4,3000	3,6000	4,1000	4,6000
A5	3,9000	4,4000	4,9000	3,5000	4,0000	4,5000	4,0000	4,5000	5,0000	3,7000	4,2000	4,7000	4,1000	4,6000	5,0000
min	3,0000	3,5000	4,0000	2,5000	3,0000	3,5000	3,1000	3,6000	4,1000	3,3000	3,8000	4,3000	3,6000	4,1000	4,6000
max	4,3000	4,8000	5,0000	3,8000	4,3000	4,8000	4,0000	4,5000	5,0000	4,0000	4,5000	4,9000	4,1000	4,6000	5,0000
	C6			C7			C8			C9			C10		
A1	3,8000	4,3000	4,7000	4,1000	4,6000	5,0000	3,3000	3,8000	4,3000	4,3000	4,8000	5,0000	3,5000	4,0000	4,5000
A2	3,7000	4,2000	4,7000	3,6000	4,1000	4,6000	3,0000	3,5000	4,0000	3,9000	4,4000	4,9000	3,1000	3,6000	4,1000
A3	3,7000	4,2000	4,6000	4,0000	4,5000	5,0000	3,4000	3,9000	4,4000	4,1000	4,6000	5,0000	3,4000	3,9000	4,4000
A4	3,2000	3,7000	4,2000	3,3000	3,8000	4,3000	3,2000	3,7000	4,2000	3,5000	4,0000	4,5000	3,0000	3,5000	4,0000
A5	3,9000	4,4000	4,8000	4,4000	4,9000	5,0000	3,3000	3,8000	4,3000	4,3000	4,8000	5,0000	3,5000	4,0000	4,5000
min	3,0000	3,5000	4,0000	2,5000	3,0000	3,5000	3,1000	3,6000	4,1000	3,3000	3,8000	4,3000	3,6000	4,1000	4,6000
max	4,3000	4,8000	5,0000	3,8000	4,3000	4,8000	4,0000	4,5000	5,0000	4,0000	4,5000	4,9000	4,1000	4,6000	5,0000

By using Eqs. (14) and (15), the decision matrices are obtained that normalize utility and cost. These matrices are given in Table 10 and Table 11 respectively.

Table 10

The utility normalization matrix

	C1			C2			C3			C4			C5		
A1	0,6122	0,6522	0,7317	0,5435	0,6098	0,6944	0,6739	0,7381	0,8378	0,6875	0,7674	0,8684	0,7500	0,8000	0,9000
A2	0,6818	0,7692	0,8824	0,6098	0,6944	0,8065	0,6458	0,7209	0,8158	0,7500	0,8462	0,9706	0,7200	0,8000	0,9000
A3	0,6000	0,6250	0,6977	0,5208	0,5814	0,6579	0,6596	0,7381	0,8378	0,6735	0,7333	0,8250	0,7660	0,8571	0,9730
A4	0,7500	0,8571	1,0000	0,7143	0,8333	1,0000	0,7561	0,8611	1,0000	0,7674	0,8684	1,0000	0,7826	0,8780	1,0000
A5	0,6122	0,6818	0,7692	0,5556	0,6250	0,7143	0,6200	0,6889	0,7750	0,7021	0,7857	0,8919	0,7200	0,7826	0,8780
	C6			C7			C8			C9			C10		
A1	0,6809	0,7442	0,8421	0,6600	0,7174	0,8049	0,6977	0,7895	0,9091	0,7000	0,7292	0,8140	0,6667	0,7500	0,8571
A2	0,6809	0,7619	0,8649	0,7174	0,8049	0,9167	0,7500	0,8571	1,0000	0,7143	0,7955	0,8974	0,7317	0,8333	0,9677
A3	0,6957	0,7619	0,8649	0,6600	0,7333	0,8250	0,6818	0,7692	0,8824	0,7000	0,7609	0,8537	0,6818	0,7692	0,8824
A4	0,7619	0,8649	1,0000	0,7674	0,8684	1,0000	0,7143	0,8108	0,9375	0,7778	0,8750	1,0000	0,7500	0,8571	1,0000
A5	0,6667	0,7273	0,8205	0,6600	0,6735	0,7500	0,6977	0,7895	0,9091	0,7000	0,7292	0,8140	0,6667	0,7500	0,8571

The C1 criterion utility normalized values of alternative A1 are obtained as follows.

$$\tilde{n}_{11} = \left(\frac{3}{4,9}, \frac{3}{4,6}, \frac{3}{4,1}\right) = (0,6122 \;\; 0,6522 \;\; 0,7317)$$

All elements of the matrix are calculated similarly.

Table 11

Cost normalization matrix

	C1			C2			C3			C4			C5		
A1	0,8200	0,9200	0,9800	0,7500	0,8542	0,9583	0,7400	0,8400	0,9200	0,7755	0,8776	0,9796	0,8000	0,9000	0,9600
A2	0,6800	0,7800	0,8800	0,6458	0,7500	0,8542	0,7600	0,8600	0,9600	0,6939	0,7959	0,8980	0,8000	0,9000	1,0000
A3	0,8600	0,9600	1,0000	0,7917	0,8958	1,0000	0,7400	0,8400	0,9400	0,8163	0,9184	1,0000	0,7400	0,8400	0,9400
A4	0,6000	0,7000	0,8000	0,5208	0,6250	0,7292	0,6200	0,7200	0,8200	0,6735	0,7755	0,8776	0,7200	0,8200	0,9200
A5	0,7800	0,8800	0,9800	0,7292	0,8333	0,9375	0,8000	0,9000	1,0000	0,7551	0,8571	0,9592	0,8200	0,9200	1,0000
	C6			C7			C8			C9			C10		
A1	0,7917	0,8958	0,9792	0,8200	0,9200	1,0000	0,7500	0,8636	0,9773	0,8600	0,9600	1,0000	0,7778	0,8889	1,0000
A2	0,7708	0,8750	0,9792	0,7200	0,8200	0,9200	0,6818	0,7955	0,9091	0,7800	0,8800	0,9800	0,6889	0,8000	0,9111
A3	0,7708	0,8750	0,9583	0,8000	0,9000	1,0000	0,7727	0,8864	1,0000	0,8200	0,9200	1,0000	0,7556	0,8667	0,9778
A4	0,6667	0,7708	0,8750	0,6600	0,7600	0,8600	0,7273	0,8409	0,9545	0,7000	0,8000	0,9000	0,6667	0,7778	0,8889
A5	0,8125	0,9167	1,0000	0,8800	0,9800	1,0000	0,7500	0,8636	0,9773	0,8600	0,9600	1,0000	0,7778	0,8889	1,0000

The cost normalized values for the C1 criterion of the A1 alternative are obtained as follows.

$$(\tilde{n}_{11})' = \left(\frac{4,1}{5}, \frac{4,6}{5}, \frac{4,9}{5}\right) = (0,8200 \;\; 0,9200 \;\; 0,9800)$$

All elements of the matrix are calculated similarly.
Subsequently, deviations from criterion weights are obtained by Eqs. (16) and (17). These matrices are given in Table 12 and Table 13 respectively.

Table 12

Deviations from criterion weights (Utility)

			C1			C2			C3			C4			C5
A1	0,0122	0,0356	0,0841	0,0099	0,0307	0,0990	0,0064	0,0228	0,0762	0,0053	0,0209	0,0649	0,0043	0,0179	0,0471
A2	0,0054	0,0236	0,0690	0,0063	0,0240	0,0846	0,0073	0,0243	0,0827	0,0012	0,0138	0,0519	0,0043	0,0179	0,0527
A3	0,0138	0,0384	0,0868	0,0111	0,0329	0,1039	0,0064	0,0228	0,0795	0,0070	0,0239	0,0678	0,0012	0,0128	0,0441
A4	0,0000	0,0146	0,0542	0,0000	0,0131	0,0619	0,0000	0,0121	0,0570	0,0000	0,0118	0,0483	0,0000	0,0109	0,0409
A5	0,0105	0,0325	0,0841	0,0093	0,0295	0,0964	0,0089	0,0271	0,0888	0,0044	0,0192	0,0619	0,0052	0,0194	0,0527
			C6			C7			C8			C9			C10
A1	0,0078	0,0293	0,0849	0,0085	0,0279	0,0746	0,0046	0,0258	0,0912	0,0083	0,0273	0,0674	0,0055	0,0291	0,0889
A2	0,0067	0,0273	0,0849	0,0036	0,0193	0,0620	0,0000	0,0175	0,0754	0,0046	0,0206	0,0642	0,0012	0,0194	0,0716
A3	0,0067	0,0273	0,0809	0,0076	0,0264	0,0746	0,0059	0,0283	0,0960	0,0065	0,0241	0,0674	0,0045	0,0268	0,0849
A4	0,0000	0,0155	0,0633	0,0000	0,0130	0,0510	0,0032	0,0232	0,0862	0,0000	0,0126	0,0499	0,0000	0,0166	0,0667
A5	0,0089	0,0312	0,0886	0,0109	0,0323	0,0746	0,0046	0,0258	0,0912	0,0083	0,0273	0,0674	0,0055	0,0291	0,0889

The deviations from the criterion weight for the C1 criterion of the A1 alternative were obtained as follows.

$$\tilde{\vartheta}_{11} = \big((1-0{,}7317)*0{,}0455 \;\; (1-0{,}6522)*0{,}1023 \;\; (1-0{,}6122)*0{,}2170\big) = (0{,}0122 \;\; 0{,}0356 \;\; 0{,}0841)$$

All elements of the matrix are calculated in a similar way.

Table 13
Deviations from criterion weights (Cost)

			C1			C2			C3			C4			C5
A1	0,0009	0,0082	0,0391	0,0014	0,0115	0,0542	0,0032	0,0139	0,0607	0,0008	0,0110	0,0466	0,0017	0,0089	0,0377
A2	0,0055	0,0225	0,0694	0,0047	0,0196	0,0768	0,0016	0,0122	0,0561	0,0041	0,0183	0,0636	0,0000	0,0089	0,0377
A3	0,0000	0,0041	0,0304	0,0000	0,0082	0,0452	0,0024	0,0139	0,0607	0,0000	0,0073	0,0382	0,0026	0,0143	0,0489
A4	0,0091	0,0307	0,0868	0,0088	0,0295	0,1039	0,0071	0,0244	0,0888	0,0049	0,0202	0,0678	0,0034	0,0161	0,0527
A5	0,0009	0,0123	0,0477	0,0020	0,0131	0,0587	0,0000	0,0087	0,0467	0,0016	0,0128	0,0509	0,0000	0,0072	0,0339
			C6			C7			C8			C9			C10
A1	0,0010	0,0119	0,0554	0,0000	0,0079	0,0395	0,0011	0,0167	0,0754	0,0000	0,0040	0,0315	0,0000	0,0129	0,0593
A2	0,0010	0,0143	0,0609	0,0035	0,0178	0,0615	0,0046	0,0251	0,0960	0,0009	0,0121	0,0494	0,0034	0,0233	0,0830
A3	0,0021	0,0143	0,0609	0,0000	0,0099	0,0439	0,0000	0,0139	0,0686	0,0000	0,0081	0,0405	0,0009	0,0155	0,0652
A4	0,0062	0,0262	0,0886	0,0061	0,0237	0,0746	0,0023	0,0195	0,0823	0,0044	0,0201	0,0674	0,0043	0,0258	0,0889
A5	0,0000	0,0095	0,0499	0,0000	0,0020	0,0263	0,0011	0,0167	0,0754	0,0000	0,0040	0,0315	0,0000	0,0129	0,0593

The deviations from criterion weight for the C1 criterion of the A1 alternative were obtained as follows.

$$\left(\tilde{\vartheta}_{11}\right)' = \big((1-0{,}9800)*0{,}0455 \;\; (1-0{,}9200)*0{,}1023 \;\; (1-0{,}8200)*0{,}2170\big) = (0{,}0009 \;\; 0{,}0082 \;\; 0{,}0391)$$

All elements of the matrix are calculated similarly. The value of the RAWEC method is obtained with Equality (18) and given in Table 14.

Table 14
Ranking of suitable places for wind power plant

		$\tilde{\boldsymbol{\vartheta}}_{ij}$			$(\tilde{\boldsymbol{\vartheta}}_{ij})'$			$\tilde{\boldsymbol{Q}}_i$		$\boldsymbol{Q}_i$	Rank
A1	0,0728	0,2672	0,7783	0,0101	0,1070	0,4994	-0,6012	-0,4280	5,1450	0,4719	4
A2	0,0405	0,2076	0,6991	0,0293	0,1741	0,6544	-0,4949	-0,0879	8,7963	1,3250	2
A3	0,0708	0,2636	0,7859	0,0079	0,1095	0,5025	-0,6039	-0,4129	5,4918	0,5394	3

A4	0,0032	0,1434	0,5796	0,0567	0,2362	0,8019	-0,3785	0,2446	13,3550	2,3258	1
A5	0,0764	0,2734	0,7947	0,0057	0,0992	0,4803	-0,6188	-0,4674	4,9207	0,4054	5

The ranking value of the A1 alternative is obtained as follows.

$$\tilde{Q}_1 = \left(\frac{0{,}0101 - 0{,}7783}{0{,}4994 + 0{,}7783}, \frac{0{,}1070 - 0{,}2672}{0{,}1070 + 0{,}2672}, \frac{0{,}4994 - 0{,}0728}{0{,}0101 + 0{,}0728}\right) = (-0{,}6012 \quad -0{,}4280 \quad 5{,}1450)$$

As a result of the ranking of the proposed places for the wind power plant location selection, the evaluations made according to the determined criteria, Ulaş (A4) was considered the most suitable place in terms of wind plant location selection. This result shows that Ulaş has superior performance in the most important criteria such as security and risk factors, social acceptance, legal requirements and is more advantageous than other alternatives. Factors such as high wind speed, proper infrastructure proximity and low environmental impacts may also have supported this preference. Kangal (A2) was ranked second in the ranking. It is understood that Kangal is a suitable place for wind farm installation, but in some critical criteria it is staying behind Ulaş. This suggests that Kangal performs well in factors such as social acceptance, economic costs and security, but not strongly enough to rank top in other criteria. Divriği (A3) ranks third, which indicates that it is a potential location for wind power plants. It appears that the Divriği performed well in factors such as wind speed, environmental impacts and infrastructure proximity, but stayed behind Kangal and Ulaş in the most important criteria. Still, features such as proper altitude and environmental compatibility have moved Divriği to the top. Gürün (A1) is placed in the fourth position in the ranking. This result shows that Gürün performs above average in certain criteria, but not strong enough to rank higher in the most critical factors. Although the wind speed is high, it may have stayed behind other places in terms of social acceptance or safety. Zara (A5) ranks last, which suggests it is less suitable than other alternatives. Zara's low ranking indicates that it is probably not performing well enough in critical criteria (e.g., safety and risk factors, social acceptance).

However, this ranking does not mean that Zara is completely inappropriate; it simply means that it is less preferable compared to the advantages of other places. This ranking indicates that Ulaş is the most suitable place for wind farm installation, followed by the Kangal and Divriği, while Gürün and Zara are of lower suitability. The ranking provides a roadmap for determining the most appropriate place within the framework of the specified criteria and provides strategic direction to decision makers.

4. Conclusions

The ranking of the proposed locations for the development of wind farms-Ulaş (A4), Kangal (A2), Divriği (A3), Gürün (A1), and Zara (A5)- was made in line with the MCDM process, taking into account various factors. It offers inferences for the analysis of the results and the selection of the most suitable place. Ulaş has been identified as the most suitable place due to its superior performance in areas such as safety and risk factors (C8), social acceptance (C6) and legal and permit requirements (C10), which are critical criteria. This high ranking suggests that Ulaş offers a balanced combination with sufficient wind speed, proximity to proper infrastructure and minimal environmental impacts. The decision-making group considered this field to be the most promising candidate because it meets both technical and socio-economic requirements. The fact that Kangal is in second place suggests that it has strong potential but is lagging behind Ulaş due to some limitations. Kangal probably performed well on criteria such as economic costs (C7) and social acceptance (C6), which reflects that it has cost-effectiveness and community support. However, it may have performed slightly lower in areas such as safety and risk factors (C8) or legal compliance (C10). Still, this area can be considered a highly suitable option if certain difficulties are overcome. The third ranking of Divriği indicates that it is a strong candidate but cannot perform as consistently as Ulaş and Kangal on all criteria. Divriği performed well in areas such as altitude (C2), land use (C3) and environmental impacts (C4), providing an option that was environmentally friendly and had appropriate topographic conditions. However, factors such as social acceptance (C6) or economic costs (C7) may be somewhat disadvantageous. This area can be assessed where environmental suitability takes precedence over other concerns. The fact that Gürün ranks fourth suggests that it has some positive conditions but is not as competitive as the top ranked areas. Gürün has probably been advantageous in factors such as high wind speed (C1) and proximity to infrastructure (C5), but may have lagged behind in critical criteria such as safety and risk factors (C8) or social acceptance (C6). This indicates that Gürün is a potential area, but that additional strategies may be needed to improve its weaknesses. The determination of Zara as the least suitable place indicates that it has encountered significant difficulties in many criteria. Zara may have performed lower in key areas such as social acceptance (C6), economic costs (C7) or legal and permit requirements (C10) compared to other locations. This low ranking means that Zara is less preferable than other options, but this does not mean that it is completely inappropriate. It can be evaluated when other areas become unenforceable or when certain criteria that Zara is strong become critical.

4.1. Practical Applications

The findings of this study provide important practical contributions to the decision-making process for selecting the most suitable location in the wind farm development process. Prioritizing certain criteria and resulting place rankings provide valuable insights for stakeholders such as policy makers, engineers and environmental planners to make informed decisions.

- ✓ Focusing on Key Criteria: The study highlights the importance of prioritizing criteria such as safety and risk factors (C8), social acceptance (C6) and legal and permit requirements (C10). These factors have come to the fore as the most effective elements in determining the suitability of places. Decision makers must ensure that these critical areas are thoroughly evaluated during the planning stages, thereby maximizing the project's success by minimizing potential risks.
- ✓ Strategic Location Selection: The rankings for the study show that Ulaş (A4) and Kangal (A2) locations are the most suitable places for wind farm development, and Ulaş has come to the fore as the first choice. These places should be prioritized in feasibility studies, environmental assessments and project planning. Their strong performance across multiple criteria shows that these locations offer the best balance in terms of technical applicability, environmental sustainability and socio-economic suitability.
- ✓ Reduction Strategies for Lower Ranks Places: Places that rank lower, such as Zara (A5) and Gürün (A1), should not be completely ignored. Instead, targeted reduction strategies can be developed to address identified weaknesses. For example, steps such as increasing community engagement or improving infrastructure can be taken to improve the overall availability of these places. Thus, when places that rank higher face unexpected challenges, these places can become more viable options.
- ✓ Informed Policy and Investment Decisions: The findings of the study may provide support to policymakers to create more targeted incentives and regulations that align with the key criteria set. For investors and developers, an understanding of ranking and related factors can drive resource allocation and help focus efforts and investments on the most promising

locations. This means more efficient use of resources and increased likelihood of project success.

- ✓ Compliance with Local Conditions: The results also highlight the need for compliance in the decision-making process. Each place has unique characteristics that may require special approaches in the development process. For example, a location may excel in wind speed and power density, but may require additional investment in infrastructure or community relationships. Decision makers must optimize results by remaining flexible and responsive to these local conditions.

The practical applications of this study highlight the importance of a comprehensive and balanced approach to wind farm site selection. By focusing on key criteria and developing strategic, locally-specific plans, stakeholders can improve the overall success and sustainability of wind energy projects. The information obtained from this analysis can serve as a valuable reference for future projects and ensure that these projects are both technically feasible and socially responsible.

4.2. Administrative Inferences

The results of this study provide valuable managerial information to decision makers about the effective planning, development and implementation of wind energy projects. Understanding the importance of specific criteria and the rankings of potential places allows managers to make more informed and strategic decisions.

- ✓ Strategic Resource Allocation: The fact that Ulaş (A4) and Kangal (A2) places are ranked highest suggests that resources should be allocated to these places in a more strategic way. Managers can prioritize these places in project planning and direct investments and resources to where the highest return will be achieved. This strategic focus can improve the efficiency of the project and reduce the risks associated with less suitable locations.
- ✓ Risk Management: Emphasizing criteria such as security and risk factors (C8) and legal and permit requirements (C10) demonstrates the importance of strong risk management strategies. Managers, especially for places with high potential but significant risks, should ensure comprehensive risk assessments are carried out in the early stages of the project lifecycle. By proactively addressing these risks, managers can avoid costly delays and make the project run more smoothly.
- ✓ Stakeholder Engagement: Social acceptance (C6) has come to the fore as an important factor in location selection, demonstrating the importance of interaction with local communities and stakeholders. Managers should prioritize communication and promotion efforts to build trust with these groups and get their support. Effective stakeholder engagement can reduce opposition, increase community support, and enable project approval processes to go more smoothly.
- ✓ Compliance and Regulatory Compliance: Given the importance of legal and permit requirements (C10) in the decision-making process, managers are required to ensure that projects are fully compliant with relevant regulations. Early and detailed legal assessments can help identify potential regulatory barriers and speed up permitting processes. By aligning projects with local, regional and national regulations, managers can avoid legal issues that may delay or hinder the project.
- ✓ Flexibility in Project Planning: Changes in rankings across different locations highlight the importance of flexibility in project planning. Managers must be prepared to adapt their strategies according to local conditions. For example, when a place with the highest rankings

faces unexpected challenges, a backup plan to evaluate alternative locations that rank slightly lower could ensure that the project stays on track.

- ✓ Long-Term Sustainability: Environmental impacts (C4) and land use (C3) criteria highlight the importance of long-term sustainability assessments in location selection. Managers must prioritize locations that not only meet current project needs but also align with broader sustainability goals. This approach can increase the environmental and social responsibility of the project and contribute to its long-term success and reputation.

The managerial implications of this study emphasize that strategic decision making, risk management, stakeholder engagement and regulatory compliance play a critical role in the successful development of wind energy projects. By leveraging insights from criteria rankings and location assessments, managers can optimize project planning processes and sign for more efficient, sustainable and successful wind energy initiatives.

This study evaluated the effectiveness of fuzzy multi-criteria decision-making (MCDM) methods such as Fuzzy WENSLO and Fuzzy RAWEC during the wind farm site selection process. Within the scope of the study, the evaluations made on the five potential places (Gürün, Kangal, Divriği, Ulaş and Zara) proposed for Sivas province were carried out within the framework of various criteria such as wind speed and direction, altitude, land use, environmental impacts, proximity to infrastructure, social acceptance, economic costs, safety and risk factors, climatic conditions and legal and permit requirements.

The results show that Ulaş (A4) and Kangal (A2) places stand out as the most suitable places. These results highlight how critical the selection of suitable locations for the successful implementation of wind energy projects is. The findings of the study can provide guidance to managers and policy makers in determining the most appropriate locations in wind energy projects and contribute to making strategic decisions to increase energy production capacity.

4.3. Limitations

This work has some limitations. First, the criteria and weights used in the study are specific to a specific region and group of specialists. Studies in different geographical regions or with different groups of experts may have different results. Secondly, only five potential locations have been evaluated. Studying a larger geographic area or more alternative locations can improve the generalization of results.

Furthermore, the fuzzy MCDM methods used are based on subjective assessments of the decision-maker group. Therefore, individual biases or experiences of specialists can influence the results. Additional studies with the participation of different groups of experts can improve the robustness and reliability of the results.

Future studies may focus on the following areas to overcome the limitations of this study and achieve broader results:

- ✓ Applications in Different Geographical Regions: The study can be repeated in other regions and the effects of different geographical features on wind farm site selection can be examined. This will contribute to achieving results that have general validity.
- ✓ Wider Criteria Sets and Alternatives: Expanding criteria sets and evaluating more alternative locations allows for a more comprehensive and detailed analysis of location selection processes. This can lead to more accurate and reliable results.

- ✓ Integration of New Decision-Making Techniques: As well as Fuzzy WENSLO and Fuzzy RAWEC methods, more complex decision-making processes can be studied with the integration of other modern MCDM techniques. This can improve the accuracy and flexibility of the decision-making process.
- ✓ Variety among Experts: By working with different groups of experts, it is possible to study the differences in the results of the assessment and reduce the impact of subjective biases. This type of approach can increase the neutrality of the decision-making process.

The results of this study provide an important basis for the improvement of the decision-making processes used in the choice of location of wind power plants and provide guidance for future studies.

Author Contributions

For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, GD. and EIU.; methodology, GD.; software, GD.; validation, GD..; formal analysis, GD.; investigation, GD; resources, EIU.; data curation, GD.; writing—original draft preparation, EIU.; writing—review and editing, GD.; visualization, GD.; supervision, GD.; project administration, GD.; funding acquisition, EIU. All authors have read and agreed to the published version of the manuscript." Authorship must be limited to those who have contributed substantially to the work reported.

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