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A Novel Interval Type-2 Fuzzy MCDM Model for Evaluation of Suitable Systems of Renewable Sources from Financial and Sustainable Aspect

Abstract. *Growing concern for the environment and natural resources has imposed the importance of utilising renewable energy sources (RES) for electricity generation. Various RES systems are increasingly being used in practice. However, the territory of the Brčko District of BiH lags behind the entities of BiH in the application of RES. Based on that, this research aims to answer the question of which RES systems has the best indicators for future investments. To achieve this, a methodology based on interval fuzzy 2 logic with the PIPRECIA (PIvot Pairwise RElative Criteria Importance Assessment) and RAWEC (Ranking Alternatives with WEights of Criterion) methods was used. These methods utilised experts' ratings based on linguistic values. The results of this approach showed that the criteria return on investment, environmental impact, and investment costs are more important than the other seven criteria according to the experts' ratings. The results also showed that the RES systems Wind Farms is the best among the five alternatives used in this research according to experts' ratings. The obtained results were confirmed by comparative analysis and sensitivity analysis. This research provides guidelines for improving the application of RES systems in the territory of the Brčko District to make it competitive with other local communities and entities in terms of electricity generation from RES systems.*

Keywords: *renewable energy source, interval fuzzy 2 logic, wind farms.*

JEL Classification: Q20, Q40, Q50, C44.

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1. Introduction

The growing concern of countries in the world to solve pollution issues has spurred the development of strategic documents for the advancement of renewable energy sources (RES). RES is progressively gaining ground in total electricity generation. In addition, there is a growing demand for electricity, while fossil fuel reserves are diminishing. However, fossil fuels cause environmental problems (Li et al., 2020). There is a significant difference between electricity generation from fossil fuels and renewable sources. Fossil fuels generate substantial carbon emissions, contributing to climate problems. Thus, coal consumption exceeded 10 billion tons annually for electricity generation (Li et al., 2021). To address this issue, there is a growing trend towards transitioning to RES. Bosnia and Herzegovina (BiH) is a developing country (Štilić et al., 2022). When it comes to electricity generation, hydroelectric power was the predominant method of electricity generation in BiH. Other modes of RES were not represented. Only in the last few years has wind energy begun to be utilised by constructing wind farms and solar energy by using solar power plants. In BiH, as for data from 2022, electricity was primarily generated using coal and lignite (62.30%), hydropower (35.03%) and wind power (2.04%) (Sher et al., 2024). The enacted laws and regulations in BiH aim to increase electricity generation from renewable sources. Due to the constitutional arrangement of BiH, RES is not equally represented. It is least represented in the territory of the Brčko District of BiH. Based on that, the motivation for this research is as follows:

- Improving the utilisation of RES in the Brčko District of BiH to achieve sustainability goals within this local community.
- Reducing dependence on electricity produced in the entities of BiH, thus gradually diminishing this dependency.
- Determining which sustainable energy sources would yield the best results in this local community.

The Government of the Brčko District of BiH has initiated procedures to enable the generation and distribution of electricity obtained from renewable sources, and it is expected to be resolved soon through the enactment of laws and regulations on this matter. Therefore, this research aims to examine which combination of RES would be best for the Brčko District of BiH, i.e., which of them would yield the best results and be most suitable for future investors. To achieve this, the following objectives are set:

- Conduct the evaluation of various RES alternatives.
- Influence the increase in the application of RES in practice.
- Apply interval type-2 fuzzy methods in the evaluation of RES alternatives.
- Based on these research objectives, this paper has the following contributions:
- Promote RES in the Brčko District of BiH and throughout the entire BiH.
- Examine which RES systems can be used in the Brčko District of BiH.
- Provide guidance for future investors on which RES systems have the best indicators.

- Develop a methodology based on the interval type-2 fuzzy methods - PIPRECIA and RAWEC.

2. Literature review

During the literature review, papers related to sustainable energy sources and those utilising Multi-Criteria Decision Analysis (MCDA) will be presented. Şahin, (2021) used two subjective methods and four objective methods to determine the weights of criteria while ranking RES alternatives using the ORESTE (organisation, rangement et synthese de donnes relationnelles) method. The results of this research showed that the best RES alternative was hydropower. Krishankumar et al. (2021) addressed the selection problem of which RES best satisfies the development goals of Karnataka in India, utilising the q-rung orthopair fuzzy TODIM (an acronym in Portuguese for Interactive Multi-Criteria Decision Making) method. Their results showed that biomass and solar energy gave the best results. Wang et al. (2020), in their research, selected a strategy for evaluating RES using the SWOT matrix and the AHP method. Using the example of the Sindh and Baluchistan provinces in Pakistan, they stated that wind power generation has the highest potential. Saraswat and Digalwar (2021) investigated the combination of conventional and RES energy sources. They used the Entropy method for objective weight calculation, the AHP method for subjective weight calculation, and six other fuzzy methods. The results have demonstrated that in India it is most advantageous to use solar energy. Akçaba and Eminer (2022) aimed to provide strategic guidelines for Northern Cyprus to transition from fossil to RES, using SWOT analysis. In addition to selecting a specific RES alternative for certain regions and countries, this selection was also made for certain industries. Ulewicz et al. (2021), on the example of Polish industry, selected RES alternatives that could be used in these industries, using fuzzy AHP and TOPSIS methods. Manirathinam et al. (2023) addressed the issue of RES in smart homes, utilising the AHP and MARCOS (Measurement of Alternatives and Ranking according to Compromise Solution) methods. Liu et al. (2021) considered the application of RES in blockchain technology and, using DAMATEL (decision making trial and evaluation laboratory) and ANP (analytical hierarchy process), found that wind and solar energy alternatives obtained the best results as RES. Sun et al. (2022) considered the application of a hybrid system combining RES alternatives with conventional electricity to reduce energy consumption and electricity bills. They used a combination of q-rung orthopair fuzzy DEMATEL with golden cut and M-SWARA (multi-stepwise weight assessment ratio analysis) methods, showing that solar energy is the best alternative.

3. Preliminaries and methods

The fuzzy set was first defined by the author Zadeh (1965), while the fuzzy 2 set represents an extension of the classical fuzzy set. It is used when it is not possible to define an exact membership function and is used in conditions where decision uncertainty prevails (Radulescu et al., 2023; Chen et al., 2024). The reason for using the fuzzy 2 set can be found in the fact that when using qualitative criteria, it is difficult to obtain an objective value of a specific alternative, so linguistic values are used. The basic concepts and arithmetic processes of interval fuzzy 2 sets have been developed in previous paper (Dorfeshan et al., 2021), so only the basic arithmetic operations with fuzzy 2 sets will be provided here (Figure 1).

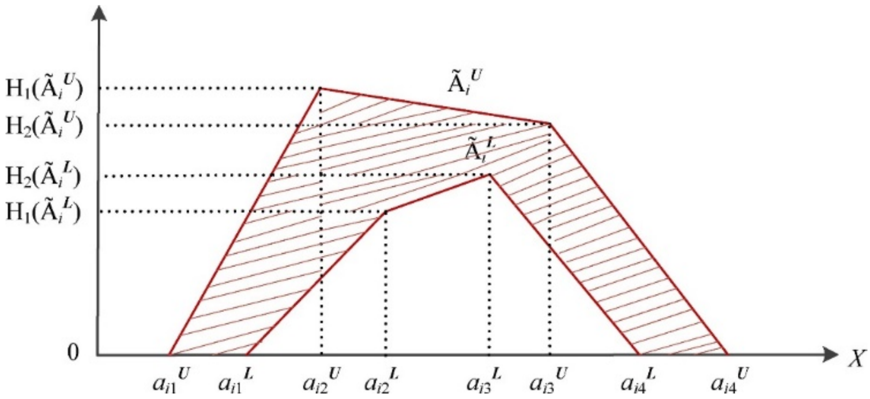

Figure 1. Asymmetric interval fuzzy 2 set
Source: Dorfeshan et al. 2021.

3.1 Interval fuzzy 2 set PIPRECIA method

When determining the importance of the criteria used to evaluate alternatives, two approaches are used: objective and subjective determination of the importance of criteria. The PIPRECIA method also belongs to the group of methods for subjectively determining the importance of criteria (Korucuk & Aytekin, 2023). This method is formed by adapting the SWARA method for group decision-making (Stanujkic et al., 2017). In addition, through its previous application, it has shown very good results, which is why it is selected in this research. In order to be used with an interval fuzzy 2 set, the PIPRECIA method has been adjusted and has the following steps (Xu et al., 2023):

Step 1. Sorting by the importance of criteria from the most important to the least important.

Step 2. Evaluating the importance of criteria according to the defined scale (Table 1).

Table 1. Criterion importance scale

Linguistic values	Interval fuzzy 2 set values ($\tilde{\tau}_j$)
Extremely low importance (ELI)	(0, 0.1, 0.1, 0.2; 1, 1), (0, 0.1, 0.1, 0.15; 0.9, 0.9)
Very low importance (VLI)	(0.1, 0.2, 0.2, 0.3; 1, 1), (0.15, 0.2, 0.2, 0.25; 0.9, 0.9)
Low importance (LI)	(0.2, 0.3, 0.3, 0.4; 1, 1), (0.25, 0.3, 0.3, 0.35; 0.9, 0.9)
Medium low importance (MLI)	(0.3, 0.4, 0.4, 0.5; 1, 1), (0.35, 0.4, 0.4, 0.45; 0.9, 0.9)
Medium importance (MI)	(0.4, 0.5, 0.5, 0.6; 1, 1), (0.45, 0.5, 0.5, 0.55; 0.9, 0.9)
Medium high importance (MHI)	(0.5, 0.6, 0.6, 0.7; 1, 1), (0.55, 0.6, 0.6, 0.65; 0.9, 0.9)

Linguistic values	Interval fuzzy 2 set values ($\tilde{\boldsymbol{\tau}}_j$)
High importance (HI)	(0.6, 0.7, 0.7, 0.8; 1, 1), (0.65, 0.7, 0.7, 0.75; 0.9, 0.9)
Very high importance (VHI)	(0.7, 0.8, 0.8, 0.9; 1, 1), (0.75, 0.8, 0.8, 0.85; 0.9, 0.9)
Extremely high importance (EHI)	(0.8, 0.9, 0.9, 1; 1, 1), (0.85, 0.90, 0.90, 1; 0.9, 0.9)

Source: Xu et al. (2023).

It is necessary to note that the most important criterion is assigned the value (1, 1, 1, 1, 1, 1), (1, 1, 1, 1, 1, 1), while values for other criteria are assigned based on experts' ratings.

Step 3. Calculating the values of the coefficient $\tilde{\varsigma}_j$:

$$\tilde{\varsigma}_j = \begin{cases} = \tilde{1}\ if\ j = 1 \\ 2 - \tilde{\tau}_j\ if\ j > 1 \end{cases} \Rightarrow \tilde{\varsigma}_j = \begin{cases} (1,1,1,1,1,1),(1,1,1,1,1,1) \\ 2 - \tilde{\tau}_j \end{cases}$$

Step 4. Determining fuzzy weights:

$$\tilde{\gamma}_j = \begin{cases} = \tilde{1}\ if\ j = 1 \\ \dfrac{\tilde{\gamma}_j - 1}{\tilde{\varsigma}_j}\ if\ j > 1 \end{cases} \Rightarrow \tilde{\gamma}_j = \begin{cases} (1,1,1,1,1,1),(1,1,1,1,1,1) \\ \dfrac{\tilde{\gamma}_j - 1}{\tilde{\varsigma}_j} \end{cases}$$

Step 5. Determining the weights of criteria:

$$\widetilde{\omega}_j = \frac{\tilde{\gamma}_j}{\sum_{j=1}^{n} \tilde{\gamma}_j}$$

Then, the reverse steps of this method are applied. The least important criterion is assigned (1, 1, 1, 1, 1, 1), (1, 1, 1, 1, 1, 1), while values for other criteria are assigned based on experts' ratings.

Step 6. Calculating the values of the coefficient$\tilde{\varsigma}'_j$:

$$\tilde{\varsigma}'_j = \begin{cases} = \tilde{1}\ if\ j = 1 \\ 2 - \tilde{\tau}'_j\ if\ j > 1 \end{cases} \Rightarrow \tilde{\varsigma}'_j = \begin{cases} (1,1,1,1,1,1),(1,1,1,1,1,1) \\ 2 - \tilde{\tau}'_j \end{cases}$$

Step 7. Determining fuzzy weights:

$$\tilde{\gamma}_j = \begin{cases} = \tilde{1}\ if\ j = 1 \\ \dfrac{\tilde{\gamma}'_j - 1}{\tilde{\varsigma}'_j}\ if\ j > 1 \end{cases} \Rightarrow \tilde{\gamma}_j = \begin{cases} (1,1,1,1,1,1),(1,1,1,1,1,1) \\ \dfrac{\tilde{\gamma}'_j - 1}{\tilde{\varsigma}_j} \end{cases}$$

Step 8. Determining the weights of criteria:

$$\widetilde{\omega}'_j = \frac{\tilde{\gamma}'_j}{\sum_{j=1}^{n} \tilde{\gamma}'_j}$$

The final weight according to this method is obtained by finding the average weight for each criterion.

3.2 Interval fuzzy 2 set RAWEC method

The RAWEC method is a newer MCDM method that ranks alternatives based on the deviation from the value of the weights of criteria (Puška et al., 2024). To apply this method with an interval fuzzy 2 set, it is necessary to apply the following steps of the method.

Step 1. Formation of an initial decision matrix. This step is formed by experts assigning linguistic values to evaluate alternatives according to the criteria used (Table 2).

Table 2. Linguistic values for the evaluation of alternatives

Linguistic values	Interval fuzzy 2 set values
Very bad (VB)	(0, 0, 0, 0.1; 1, 1), (0, 0, 0, 0.05; 0.9, 0.9)
Bad (B)	(0, 0.1, 0.1, 0.3; 1, 1), (0.05, 0.1, 0.1, 0.2; 0.9, 0.9)
Medium bad (MB)	(0.1, 0.3, 0.3, 0.5; 1, 1), (0.2, 0.3, 0.3, 0.4; 0.9, 0.9)
Equal (E)	(0.3, 0.5, 0.5, 0.7; 1, 1), (0.4, 0.5, 0.5, 0.6; 0.9, 0.9)
Medium good (MG)	(0.5, 0.7, 0.7, 0.9; 1, 1), (0.6, 0.7, 0.7, 0.8; 0.9, 0.9)
Good (G)	(0.7, 0.9, 0.9, 1; 1, 1), (0.8, 0.9, 0.9, 0.95; 0.9, 0.9)
Very good (VG)	(0.9, 1, 1, 1; 1, 1), (0.95, 1, 1, 1; 0.9, 0.9)

Source: Xu et al. (2023).

Step 2. Conversion of linguistic values into interval fuzzy 2 set values (Table 2).

Step 3. Normalisation of the initial decision matrix. The specificity of this method lies in computing two normalisations $\tilde{n}_{ij}$ and $\tilde{n}'_{ij}$. First, all values are normalised to maximum values ($\tilde{n}_{ij}$), then all values are normalised to minimum values ($\tilde{n}'_{ij}$).

$$\tilde{n}_{ij} = \left(\frac{x_{ij}^{L1}}{max\ x_j^{L4}}, \frac{x_{ij}^{L2}}{max\ x_j^{L4}}, \frac{x_{ij}^{L3}}{max\ x_j^{L4}}, \frac{x_{ij}^{L4}}{max\ x_j^{L4}}, x_{ij}^{\delta}, x_{ij}^{\delta}\right), \left(\frac{x_{ij}^{U1}}{max\ x_j^{U4}}, \frac{x_{ij}^{U2}}{max\ x_j^{U4}}, \frac{x_{ij}^{U3}}{max\ x_j^{U4}}, \frac{x_{ij}^{U4}}{max\ x_j^{U4}}, x_{ij}^{\rho}, x_{ij}^{\rho}\right)\ if\ j \in B$$

$$\tilde{n}'_{ij} = \left(\frac{minx_j^{L1}}{x_{ij}^{L4}}, \frac{minx_j^{L1}}{x_{ij}^{L3}}, \frac{minx_j^{L1}}{x_{ij}^{L2}}, \frac{minx_j^{L1}}{x_{ij}^{L1}}, x_{ij}^{\delta}, x_{ij}^{\delta}\right), \left(\frac{minx_j^{U1}}{x_{ij}^{U4}}, \frac{minx_j^{U1}}{x_{ij}^{U3}}, \frac{minx_j^{U1}}{x_{ij}^{U2}}, \frac{minx_j^{U1}}{x_{ij}^{U1}}, x_{ij}^{\rho}, x_{ij}^{\rho}\right)\ if\ j \in B$$

$$\tilde{n}_{ij} = \left(\frac{minx_j^{L1}}{x_{ij}^{L4}}, \frac{minx_j^{L1}}{x_{ij}^{L3}}, \frac{minx_j^{L1}}{x_{ij}^{L2}}, \frac{minx_j^{L1}}{x_{ij}^{L1}}, x_{ij}^{\delta}, x_{ij}^{\delta}\right), \left(\frac{minx_j^{U1}}{x_{ij}^{U4}}, \frac{minx_j^{U1}}{x_{ij}^{U3}}, \frac{minx_j^{U1}}{x_{ij}^{U2}}, \frac{minx_j^{U1}}{x_{ij}^{U1}}, x_{ij}^{\rho}, x_{ij}^{\rho}\right)\ if\ j \in C$$

$$\tilde{n}'_{ij} = \left(\frac{x_{ij}^{L1}}{max\ x_j^{L4}}, \frac{x_{ij}^{L2}}{max\ x_j^{L4}}, \frac{x_{ij}^{L3}}{max\ x_j^{L4}}, \frac{x_{ij}^{L4}}{max\ x_j^{L4}}, x_{ij}^{\delta}, x_{ij}^{\delta}\right), \left(\frac{x_{ij}^{U1}}{max\ x_j^{U4}}, \frac{x_{ij}^{U2}}{max\ x_j^{U4}}, \frac{x_{ij}^{U3}}{max\ x_j^{U4}}, \frac{x_{ij}^{U4}}{max\ x_j^{U4}}, x_{ij}^{\rho}, x_{ij}^{\rho}\right)\ if\ j \in C$$

Through such normalisation, all normalised values will be between 0 and 1, which is the goal of every normalisation. Using this normalisation setup, it is possible to perform a classical deviation from the weight of criteria as defined by the RAWEC method.

Step 4. Calculating the sum of deviations from the criterion weight

$$\tilde{v}_{ij} = \sum_{i=1}^{n} \tilde{w}_j \cdot (1 - \tilde{n}_{ij})$$

$$\tilde{v}'_{ij} = \sum_{i=1}^{n} \tilde{w}_j \cdot \left(1 - \tilde{n}'_{ij}\right)$$

Then the defuzzification of these values is performed using the centroid method.
Step 5. Calculating the value of the RAWEC method.

$$Q_i = \frac{v'_{ij} - v_{ij}}{v'_{ij} + v_{ij}}$$

4. Case study

The Brčko District of BiH is located in the northeast of BiH (Figure 2) and is situated between the mountain of Majevica in the south and the Sava River in the north. The area of this local community is suitable for RES production due to several reasons: it has many sunny days, four rivers flow through this local community, there is sufficient wind flow, it possesses abundant biomass, and there are possibilities for using geothermal sources. Based on this, it can be said that there are several RES alternatives that can be used in the Brčko District of BiH, with these five alternatives aforementioned being usable in this area. Therefore, in collaboration with the Brčko District Government, this research has been conducted to investigate which of the RES alternatives has the greatest potential in this area.

Figure 2. Geographical location of the Brčko District of BiH
Source: Author creation.

In order to conduct this research, experts who participated in the research were first selected. The experts were selected from among the employees of the Government of the Brčko District of BiH and public enterprises established by the Government of the Brčko District of BiH. First, a list of potential experts who could contribute their expertise to the research was formed. A total of 25 experts were identified to participate in the research. Those experts were contacted, and 14 experts decided to participate in the research; however, due to personal and business commitments, the total number of experts who participated in the research ultimately amounted to nine. A meeting was first organised with these experts during which a panel of research was conducted regarding the selection of possible alternatives and criteria to conduct the research. It was decided that the focus of the research would be on the financial projections of these alternatives and their sustainability related to RES. The focus on financial aspects is because it is necessary to provide possible implications for investing in RES for both the Government of the Brčko District of BiH and potential investors. The focus on sustainability is because investing in RES should be in line with sustainability goals. Of all the possible criteria by which these RES systems would be examined, a total of 10 criteria were selected (Table 3). These criteria are arranged so that the first four criteria are related to the financial aspect, while the remaining criteria are related to the sustainability aspect.

Table 3. Criteria for evaluating RES alternatives

ID	Criterion	Description
C1	Investment Costs	It refers to the initial financial expenses required to put the RES alternative into operation.
C2	Return on Investment	It refers to the period of time required for the initial investment costs to be recovered.
C3	Costs of Generated Electricity	It refers to the total costs of electricity generation from the RES alternative.
C4	Project Revenue Uncertainty	It refers to the variability and unpredictability of future revenues from the RES alternative.
C5	Maintenance Costs	It refers to the regular financial expenses required for maintenance, repair and servicing during use.
C6	Reliability	It refers to the continuous and stable supplying of electricity by the RES alternative.
C7	Job Creation	It refers to the number of new jobs during the construction and maintenance of RES alternative.
C8	Public Acceptance	It refers to the level of support and acceptance from the local community and broader public.
C9	Environmental Impact	It refers to the assessment of negative and positive effects on the environment.
C10	Land Requirement	It refers to the amount and type of land required for the construction of the RES alternative.

Source: Authors of the research.

By selecting all potential RES systems that can be used in the Brčko District of Bosnia and Herzegovina, five alternatives with the greatest potential according to experts' opinions have been selected. Those systems are:

- Hydroelectric Power Plant (R1). Four rivers flow through the territory of the Brčko District, and the potential of these rivers can be utilised for electricity generation.
- Solar Power Plant (R2). The territory of the Brčko District is among the warmest areas in Bosnia and Herzegovina, with many sunny days that need to be utilised.
- Wind Farms (R3). The territory of the Brčko District is located between the mountain of Majevica in the south and the Sava River in the north, thus experiencing constant winds that should be utilised.

- Biomass (R4). The territory of the Brčko District is largely situated in the Pannonian Plain and is characterised by significant agricultural production, making it necessary to utilise biomass for electricity generation.
- Geothermal Sources (R5). Surrounding settlements utilise geothermal sources, which are not extensively explored in the Brčko District area. According to the conducted research, there is potential to utilise these sources as RES alternatives.

After the criteria and alternatives were selected, the questionnaires were distributed to experts who filled them out and returned them in order to form the results of the research.

5. Results

In this research, a survey using a questionnaire consisting of two parts was employed. In the first part of the questionnaire, experts determined the significance of the criteria used for the selection of RES alternatives. In the second part of the questionnaire, experts evaluated the used alternatives according to the selected criteria. In order to obtain criteria weights that can be implemented in the method for ranking alternatives, it is necessary to form nine models that include computation with the TrIT2F PI-PRECIA method. This means that a separate model was formed for each DM, and then the TrIT2F Bonferroni operator was applied to average the criteria and obtain unique values. Below is an example of computation for the first DM. First, the evaluation matrix is formed as shown:

$$\tilde{\tau}_j = \begin{array}{c} C_8 \\ C_9 \\ C_1 \\ C_2 \\ C_6 \\ C_7 \\ C_{10} \\ C_3 \\ C_4 \\ C_5 \\ \\ \end{array} \begin{bmatrix} (1,1,1,1,1,1),(1,1,1,1,1) \\ (0,0.7,0.8,0.8,0.9,1,1),(0.75,0.8,0.8,0.85,0.9) \\ (0,0.6,0.7,0.7,0.8,1,1),(0.65,0.7,0.7,0.75,0.9) \\ (0,0.6,0.7,0.7,0.8,1,1),(0.65,0.7,0.7,0.75,0.9) \\ (0,0.5,0.6,0.6,0.7,1,1),(0.55,0.6,0.6,0.65,0.9) \\ (0,0.5,0.6,0.6,0.7,1,1),(0.55,0.6,0.6,0.65,0.9) \\ (0,0.5,0.6,0.6,0.7,1,1),(0.55,0.6,0.6,0.65,0.9) \\ (0,0.4,0.5,0.5,0.6,1,1),(0.45,0.5,0.5,0.55,0.9) \\ (0,0.4,0.5,0.5,0.6,1,1),(0.45,0.5,0.5,0.55,0.9) \\ (0,0.4,0.5,0.5,0.6,1,1),(0.45,0.5,0.5,0.55,0.9) \end{bmatrix}$$

Then, the matrix $\tilde{\varsigma}_j$:

$$\tilde{\varsigma}_j = \begin{bmatrix} (1,1,1,1,1,1),(1,1,1,1,1,1) \\ (1,1,1,1,1,1),(1,1,1,1,1,1) \\ (1.2,1.3,1.3,1.4,1,1),(1.25,1.3,1.3,1.35,0.9,0.9) \\ (1,1,1,1,1,1),(1,1,1,1,0.9,0.9) \\ (1.3,1.4,1.4,1.5,1,1),(1.35,1.4,1.4,1.45,0.9,0.9) \\ (1,1,1,1,1,1),(1,1,1,1,0.9,0.9) \\ (1,1,1,1,1,1),(1,1,1,1,0.9,0.9) \\ (1.4,1.5,1.5,1.6,1,1),(1.45,1.5,1.5,1.55,0.9,0.9) \\ (1,1,1,1,1,1),(1,1,1,1,0.9,0.9) \\ (1,1,1,1,1,1),(1,1,1,1,0.9,0.9) \end{bmatrix}$$

is obtained in the following way:

$$\tilde{\varsigma}_1 = (2-0.8, 2-0.7, 2-0.7, 2-0.6, 1, 1), (2-0.75, 2-0.7, 2-0.7, 2-0.65, 0.9, 0.9)$$

It is important to note that if the first two criteria, marked as the most important, have equal importance, then TrIT2F (1) is assigned; and if in the further structure the criteria have significance, it is assigned (1,1,1,1,1,1), (1,1,1,1,0.9,0.9).

After that, the matrix $\tilde{\gamma}_j$ is computed:

$$\tilde{\gamma}_j = \begin{bmatrix} (1,1,1,1,1,1),(1,1,1,1,1,1) \\ (1,1,1,1,1,1),(1,1,1,1,1,1) \\ (0.714,0.769,0.769,0.833,1,1),(0.741,0.769,0.769,0.8,0.9,0.9) \\ (0.714,0.769,0.769,0.833,1,1),(0.741,0.769,0.769,0.8,0.9,0.9) \\ (0.476,0.549,0.549,0.641,1,1),(0.511,0.549,0.549,0.593,0.9,0.9) \\ (0.476,0.549,0.549,0.641,1,1),(0.511,0.549,0.549,0.593,0.9,0.9) \\ (0.476,0.549,0.549,0.641,1,1),(0.511,0.549,0.549,0.593,0.9,0.9) \\ (0.298,0.366,0.366,0.458,1,1),(0.33,0.366,0.366,0.409,0.9,0.9) \\ (0.298,0.366,0.366,0.458,1,1),(0.33,0.366,0.366,0.409,0.9,0.9) \\ (0.298,0.366,0.366,0.458,1,1),(0.33,0.366,0.366,0.409,0.9,0.9) \end{bmatrix}$$

$$\tilde{\gamma}_1 = \left(\frac{1}{1.4}, \frac{1}{1.3}, \frac{1}{1.3}, \frac{1}{1.2}, 1, 1\right), \left(\frac{1}{1.35}, \frac{1}{1.3}, \frac{1}{1.3}, \frac{1}{1.25}, 0.9, 0.9\right)$$

The weights of the criteria $\tilde{w}_j$ are obtained by applying Eq. (12) and are as follows:

$$\tilde{w}_8 = (0.144, 0.159, 0.159, 0.174, 1, 1), (0.151, 0.159, 0.159, 0.167, 1, 1)$$
$$\tilde{w}_9 = (0.144, 0.159, 0.159, 0.174, 1, 1), (0.151, 0.159, 0.159, 0.167, 1, 1)$$

……………………………………………………………………

By applying the inverse TrIT2F PIPRECIA step, the following values are obtained:

$$\tilde{w}_8 = (0.155, 0.171, 0.171, 0.185, 1, 1), (0.163, 0.171, 0.171, 0.178, 1, 1)$$
$$\tilde{w}_9 = (0.155, 0.171, 0.171, 0.185, 1, 1), (0.163, 0.171, 0.171, 0.178, 1, 1)$$

……………………………………………………………………

Subsequently, the final values are obtained by applying the TrIT2F PIPRECIA method for all DMs and averaging them with the TrIT2F Bonferroni operator, and they are presented in Table 4.

Table 4. Values of the criteria obtained by applying the TrIT2F PIPRECIA method

criterion	weights
C1	(0.11,0.128,0.128,0.146,1,1), (0.119,0.128,0.128,0.137,0.9,0.9)
C2	(0.112,0.13,0.13,0.148,1,1), (0.121,0.13,0.13,0.139,0.9,0.9)
C3	(0.086,0.103,0.103,0.123,1,1), (0.094,0.103,0.103,0.113,0.9,0.9)
C4	(0.068,0.086,0.086,0.107,1,1), (0.077,0.086,0.086,0.096,0.9,0.9)
C5	(0.063,0.08,0.08,0.103,1,1), (0.071,0.08,0.08,0.091,0.9,0.9)
C6	(0.081,0.099,0.099,0.12,1,1), (0.09,0.099,0.099,0.109,0.9,0.9)
C7	(0.049,0.065,0.065,0.088,1,1), (0.056,0.065,0.065,0.076,0.9,0.9)
C8	(0.076,0.093,0.093,0.115,1,1), (0.084,0.093,0.093,0.104,0.9,0.9)
C9	(0.112,0.129,0.129,0.148,1,1), (0.12,0.129,0.129,0.138,0.9,0.9)
C10	(0.058,0.076,0.076,0.099,1,1), (0.066,0.076,0.076,0.086,0.9,0.9)

Source: Authors of the research.

After the weights of the criteria are determined by experts, the importance of the selected RES systems will be determined using their ranking through the TrIT2F RAWEC method. The first step of this method is the evaluation of alternatives according to defined criteria by experts. The experts provide the appropriate values of the alternatives for the observed criteria using linguistic ratings (Table 5).

Table 5. Initial Linguistic Decision Matrix

E1	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
R1	MB	E	MB	MB	E	E	MB	E	MB	B
R2	G	G	E	E	E	MB	MB	VG	G	MG
R3	VG	VG	E	E	E	E	MB	G	G	MG
R4	G	G	MB	E	MB	MB	MB	MG	MG	MG
R5	MG	E	E	MB	MB	MB	MB	E	E	MB
E2	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
R1	VG	VG	G	MB	E	VG	VG	VG	VG	MG
R2	VG	VG	MG	B	MB	VG	VG	VG	VB	E
R3	VG	VG	VG	MB	G	VG	VG	VG	VB	MB
R4	MB	MG	G	VG	VG	MB	MB	B	G	G
R5	MB	E	MB	VG	VG	E	E	MB	E	VG
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
E9	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
R1	VG	MG	G	MG	MG	MG	G	MG	B	VB
R2	G	VG	G	G	MG	G	MG	G	VG	MG
R3	G	MG	MG	G	G	MG	MG	G	MG	G
R4	MG	MG	E	MG	G	MG	MG	MG	E	E
R5	MG	MG	MG	G	MG	E	E	G	MG	MG

Source: Authors of the research.

The next step is to transform this linguistic decision matrix using the membership function into corresponding interval fuzzy 2 numbers (Table 2). In order to proceed further, it is necessary to form an aggregate decision matrix. The formation of the decision matrix is done by giving equal importance to each expert, thereby influencing the final decision equally. The first step of the TrIT2F RAWEC method is to normalise this aggregate decision matrix. For the first normalisation, the highest value of the fuzzy number for individual criteria is sought, and the individual values of alternatives are divided by this value. In cost normalisation, the lowest value for individual criteria is found, and that value is divided by the individual values of alternatives. For criterion C1 and alternative A2, it looks like:

$$\tilde{n}_{21} = \left(\frac{0.61}{0.97} = 0.63, \frac{0.79}{0.97} = 0.82, \frac{0.79}{0.97} = 0.82, \frac{0.93}{0.97} = 0.96, 1, 1\right)$$
$$\left(\frac{0.70}{0.93} = 0.75, \frac{0.79}{0.93} = 0.85, \frac{0.79}{0.93} = 0.85, \frac{0.85}{0.93} = 0.91\ , 0.9, 0.9\right)$$
$$\tilde{n}'_{21} = \left(\frac{0.33}{0.93} = 0.36, \frac{0.33}{0.79} = 0.42, \frac{0.33}{0.79} = 0.42, \frac{0.33}{0.61} = 0.55, 1, 1\right)$$
$$\left(\frac{0.43}{0.85} = 0.50, \frac{0.43}{0.79} = 0.54, \frac{0.43}{0.79} 0.54, \frac{0.43}{0.70} = 0.61, 0.9, 0.9\right)$$

This way, normalised values are calculated and two normalised decision matrices are formed. Then, the calculation of the cumulative deviation relative to the weights of the criteria follows. This step will be explained by first describing how the deviation from the criterion weight is calculated, and then how the sum of those deviations is performed. It will be explained using the same criterion and alternative.

$$\begin{aligned} d_{21} = \{&0.11 \cdot (1 - 0.96) = 0.00, 0.13 \cdot (1 - 0.82) = 0.02, 0.13 \cdot (1 - 0.82) \\ &= 0.02, 0.15 \cdot (1 - 0.63) = 0.05, 1, 1\}, \{0.12 \cdot (1 - 0.91) \\ &= 0.01, 0.13 \cdot (1 - 0.85) = 0.02, 0.13 \cdot (1 - 0.85) = 0.02, 0.14 \cdot (1 - 0.75) \\ &= 0.03, 0.9, 0.9\} \end{aligned}$$
$$\begin{aligned} d'_{21} = \{&0.11 \cdot (1 - 0.55) = 0.05, 0.13 \cdot (1 - 0.42) = 0.07, 0.13 \cdot (1 - 0.42) \\ &= 0.07, 0.15 \cdot (1 - 0.36) = 0.09, 1, 1\}, \{0.12 \cdot (1 - 0.61) \\ &= 0.05, 0.13 \cdot (1 - 0.54) = 0.06, 0.13 \cdot (1 - 0.54) = 0.06, 0.14 \cdot (1 - 0.50) \\ &= 0.07, 0.9, 0.9\} \end{aligned}$$

By following this approach, all deviations are calculated, then the deviations are summed up, forming a cumulative deviation from the weights of the criteria. After this step, the defuzzification is calculated using the centroid method. Using alternative A1 as an example, the calculation of the final step of the RAWEC method will be explained.

$$Q_1 = \frac{1.124 - 0.942}{1.124 + 0.942} = 0.088$$

Based on the obtained results (Table 6), it can be seen that alternative R3 (Wind Farms) is the best-ranked followed by alternative R2 (Solar Power Plants), while alternative R5 (Geothermal Sources) yielded the poorest results.

Table 6. Final ranking of RES systems

Id	v_j	v'_j	Q_j	Rank
R1	0.942	1.124	0.088	3
R2	0.504	1.498	0.497	2
R3	0.436	1.549	0.561	1
R4	1.054	1.082	0.013	4
R5	1.063	1.041	-0.010	5

Source: Authors of the research.

In order to confirm or refute these results, a comparison will be made with the results of other MCDM methods (Więckowski et al., 2023). In this case, four other methods will be used: SAW (Simple Additive Weighting), ARAS (Additive Ratio Assessment), MABAC (Multi-Attributive Border Approximation area Comparison) and CRADIS (Compromise Ranking of Alternatives from Distance to Ideal Solution). The results of this analysis indicate that all methods yield the same ranking order. The only exception is with the ARAS method, where alternatives R2 and R3 obtained the same ranking order. On the basis of the results obtained by the comparative analysis, it can be concluded that the results of the RAWEC method are confirmed.

Table 7. Results of comparative analysis

Id	IF2RAWEC	IF2SAW	IF2ARAS	IF2MABAC	IF2CRADIS
R1	3	3	3	3	3
R2	2	2	1	2	2
R3	1	1	1	1	1
R4	4	4	4	4	4
R5	5	5	5	5	5

Source: Authors of the research.

After conducting a comparative analysis and confirming the results of the RAWEC method, a sensitivity analysis is performed. The aim of this analysis is to examine how changes in the importance of criteria affect the final ranking (Badi & Elghoul, 2023). This analysis is conducted by changing the weights assigned to the criteria (Petrovic et al., 2024). In this research, the obtained weights will be used and then altered. The weights of each individual criterion will be changed by reducing them by 30%, 60%, and 90%, while the weights for the other criteria will be proportionally increased to maintain the same total weight value. Since one criterion is changed three times and there are 10 criteria in this research, it means that 30 scenarios will be conducted within this sensitivity analysis.

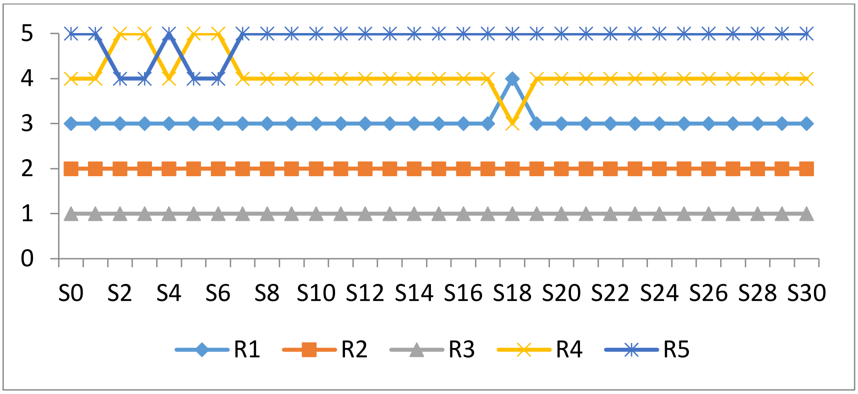

Figure 3. Sensitivity analysis results

Source: Authors of the research.

The results of this analysis (Figure 3) show that the ranking order changed for three alternatives. When changing the weights of criteria C1 and C2, there was a change in the ranking order for alternatives R4 and R5, with alternative R5 improving its ranking compared to R4. This means that alternative R5 has poorer indicators for criteria C1 and C2 compared to alternative R4, so with a decrease in the weight values for these criteria, R5 occupied a better position in the ranking order in those scenarios. In order to improve the ranking of alternative R5, it is necessary to primarily improve the ratings for these two criteria. The same is the case with scenario 18, where the weight of criterion C6 was reduced by 90%. Then, alternatives R4 had a better ranking compared to alternatives R1. This indicates that the ratings for criterion C6 are lower for alternative R4 compared to alternative R1. The results of this analysis also showed that alternatives R3 and R2 did not change their ranking compared to the scenarios conducted.

6. Discussion

Due to the specificity of the constitutional arrangement of BiH, the entities and the Brčko District must have laws on electricity generation from RES. Entities have enacted the laws on RES, but the Brčko District does not have one. Therefore, it was significant to investigate which RES alternatives would be most desirable for the territory of the Brčko District of BiH so that investments could begin immediately after the enactment of the law. Based on this research, recommendations are provided to future investors on which alternatives to invest in. The research was conducted to provide these recommendations.

A total of five RES systems were considered, with a total of 10 criteria. The specificity of this research lies in selecting these criteria to examine both financial and sustainability aspects. The first four criteria were chosen to assess financial aspects, while the remaining six were chosen to assess sustainability aspects. The reasons for selecting these criteria are as follows: firstly, it is necessary to present investors with the costs/benefits of investing in RES, hence financial criteria are taken; secondly, it is necessary to ensure that RES investments do not have a negative impact on the environment; thirdly, it is important to ensure that future generations can also utilise RES resources, hence sustainability criteria were chosen. The selection of the five RES systems was based on the availability of specific resources in the territory of the Brčko District.

The research involved employees of the Brčko District Government and public enterprises. One reason they have been chosen as experts is that several of them will be involved in drafting legislation on the implementation of RES in the Brčko District. Additionally, these experts possess both practical and theoretical knowledge about these alternatives, making them competent for this research. The reason experts from the industry have not been included is that they might subjectively advocate for certain alternatives that are in the interest of the businesses they represent. A total of 14 experts were contacted, out of which 9 participated in the research. These experts had to first determine the importance of the weights of the criteria and then evaluate the selected RES alternatives. In this research, the approach of using an interval fuzzy 2 set was chosen. The fuzzy set was used to reduce decision-making uncertainty and to avoid the possibility of poorly defined membership function.

In order to determine the importance of criteria for decision-makers, the TrIT2F PIPRECIA method was used. The results obtained by this method show that the most important criteria for the experts are C2 and C9, followed by criterion C1. These criteria received higher weights than other criteria. Based on this, the criteria Return on Investment, Environmental Impact and Investment Costs are more significant for experts compared to other criteria.

The TrIT2F RAWEC method was used to rank the RES systems. The application of this method has shown that the construction of wind farms is the best RES alternative for the territory of the Brčko District, followed by solar power plants, while geothermal sources have the worst indicators. These results are due to the fact that, although there are many sunny days in the region, all four seasons are expressed, which can reduce electricity generation from solar power plants. The proximity of the mountain of Majevica and the constant winds along the Sava River, which forms the northern border of the Brčko District, provide significant potential for using this RES systems. The only thing is that, during the construction of wind farms, it is necessary to determine specific areas within the Brčko District where winds are more present compared to other areas to make investments more profitable and utilise this potential to a greater extent. The results of this research have shown that there are conditions for implementing various RES systems in the territory of the Brčko District.

6.1 Theoretical and managerial implications of the research

This paper contributes to the research on RES systems for electricity generation. These systems are imperative and efforts are made to utilise them as much as possible in practice. The aim of these alternatives is to utilise sustainable resources to produce electricity for future generations. Therefore, this research provides certain theoretical contributions, which are reflected in the following aspects. A theoretical review of previous research is carried out, and RES systems are explained. Then, theoretical foundations for the evaluation of these alternatives, including criteria, are established. The role these criteria play in the selection of RES systems is explained. Understanding the importance of these criteria is important for preparing future research. These criteria have already been used in existing studies, and this paper provides theoretical foundations that it further enhances.

The contribution of this research is the development of a new form of the RAWEC method in practice. This provides guidelines on how other new methods can also be used in the interval fuzzy 2 form. This method is designed to simplify a decision-making process in practice by consolidating certain steps and requiring fewer steps to achieve the final result. In addition to the methods themselves, the criteria and alternatives used represent new practical implications of this research.

However, the most important implication of this research lies in providing guidelines to investors on which RES systems to apply in order to achieve the best results in the territory of the Brčko District.

6.2 Research limitations and future research directions

In every conducted study using MCDM methods, the same limitations of that research can always be identified. These limitations manifest in terms of the use of criteria, alternatives, and MCDM methods. These studies aim to demonstrate how different aspects and criteria can be utilised, which need to be further developed in future research. Future research must assess the criteria used and provide recommendations on which criteria could be used in further studies. Furthermore, the used RES alternatives can be characterised as a limitation of the research. The absence of a certain alternative is due to the fact that the territory of the Brčko District lacks resources for that alternative, and it was considered unnecessary for this research. Therefore, it is necessary to include new alternatives in future research in order to obtain new data necessary for investors to reduce uncertainty in decision-making and risk in its implementation.

7. Conclusions

The research was conducted to promote the use of RES alternatives in the territory of the Brčko District of BiH. In addition, this research aimed to provide guidelines to investors on which alternatives to use in this local community. To achieve this, the research was based on expert decision-making and the use of interval fuzzy 2 logic. Based on that, a methodology based on the PIPRECIA and RAWEC methods was developed. The results of the approach showed that alternative R3 (Wind Farms) is the most suitable for the territory of the Brčko District of BiH. By developing the application of the RES system on the territory of the Brčko District, it provides the opportunity for this local community to be self-sustainable in terms of electricity and not to depend on the public company Elektroprivreda BiH, which aims to distribute electricity on the territory of BiH.

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