Applied Energy 324 (2022) 119597

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Floating photovoltaic site selection using fuzzy rough numbers based LAAW and RAFSI model

Muhammet Deveci [a,e,*], Dragan Pamucar [b], Elif Oguz [c,d]

[a] Royal School of Mines, Imperial College London, London SW7 2AZ, UK
[b] Department of Operations Research and Statistics, Faculty of Organizational Sciences, University of Belgrade, 11000 Belgrade, Serbia
[c] Hydraulics Laboratory, Civil Engineering Department, Middle East Technical University, 06800, Turkey
[d] METU Center For Wind Energy Research (RÜZGEM), Middle East Technical University, 06800 Ankara, Turkey
[e] Department of Industrial Engineering, Turkish Naval Academy, National Defence University, 34940 Tuzla, Istanbul, Turkey

HIGHLIGHTS

- Site selection for floating PV systems is performed.
- Fuzzy sets and Geographic Information Systems are utilized.
- A novel hybrid decision-making model is proposed.
- Logarithmic additive assessment of the weight coefficients (LAAW) is used.
- Manavgat (Antalya) and Göksun (Karaman) sites are found to be the best two alternatives.

ARTICLE INFO

Keywords:
Renewable energy
Floating Photovoltaic
Site selection
Fuzzy rough numbers
Multi-criteria decision making

ABSTRACT

This study presents a quantitative methodology for Floating Photovoltaic (FPV) power plant site selection in Turkey using Geographical Information Systems (GIS) and fuzzy sets, which is one of the Multi-Criteria Decision Making (MCDM) methods. In this study, we propose a new hybrid framework which combines fuzzy rough number (FRN) based decision making model including LAAW (Logarithmic Additive Assessment of the Weight coefficients) and RAFSI (Ranking of Alternatives through Functional mapping of criterion subintervals into a Single Interval). The fuzzy rough number is applied for handling the uncertainty and inaccuracy of experts' opinions in the evaluation process. Firstly, FRN based LAAW method is used to determine the weighting coefficients of the criteria. Secondly, FRN based RAFSI method is used to rank the alternatives. The proposed decision making model is applied to determine feasible site for Floating Photovoltaic (FPV) system in Southern part of Turkey. Out of the five alternative sites, Manavgat - Antalya is concluded to be the most suitable site, and the second-best alternative is Göksun - Karaman. The results show the rationality and applicability of the proposed model.

1. Introduction

As the focus on the reduction of CO2 increases, researchers are seeking ways to design more environmentally friendly buildings together with green monitoring solutions [1], Wu et al. [2,1]. Over the last few years, floating solar power plants have been attracting attention worldwide. They may be located inland on lakes or dam reservoirs, nearshore or offshore with no land requirement. Floating PVs have over 11% higher efficiency compared to conventional land-based PVs due to the increased cooling effect of water. They can simultaneously reduce the water evaporation up to 70% [3]. The other advantages of FPVs include improvement of water quality with reduced algae growth, less prominent dust effect and maintenance cost, land saving and simple construction with no foundation work. When used on dam reservoirs, the cost even decreases further by shared substation and transmission.

Floating solar power plants is a new concept and trend in the world and despite some recent projects in Europe and China, it is an evolving technology and yet there exists some challenges like uncertainty about environmental impacts, the complexity of designing, building and

* Corresponding author.
E-mail addresses: muhammetdeveci@gmail.com (M. Deveci), elifoguz@metu.edu.tr (E. Oguz).

https://doi.org/10.1016/j.apenergy.2022.119597
Received 16 March 2022; Received in revised form 15 June 2022; Accepted 29 June 2022
Available online 1 August 2022

Nomenclature

FPV	Floating Photovoltaic
GIS	Geographical Information Systems
MCDM	Multi-Criteria Decision Making
FRN	Fuzzy Rough Number
LAAW	Logarithmic Additive Assessment of the Weight coefficients
RAFSI	Ranking of Alternatives through Functional mapping of criterion subintervals into a Single Interval
IEA	International Energy Agency
SERIS	Solar Energy Research Institute of Singapore
GHI	Global Horizontal Irradiation
DHI	Diffuse Horizontal Irradiation
DNI	Direct Normal Irradiation
DM	Decision-Maker
e	Number of experts
$\underline{Apr}\left(\widetilde{\tau}_i\right)$	lower approximation of class $\widetilde{\tau}_i$
$\overline{Apr}\left(\widetilde{\tau}_i\right)$	upper approximation of class $\widetilde{\tau}_i$
$\underline{Lim}\left(\widetilde{\tau}_i\right)$	lower limit of $\widetilde{\tau}_i$
$\overline{Lim}\left(\widetilde{\tau}_i\right)$	upper limit of $\widetilde{\tau}_i$
μ_1, μ_2	Stabilization parameters
Υ	Priority vector
$\overline{\Upsilon}$	Aggregated FRN priority vector
$\overline{\delta}_{AIP}$	The absolute anti-ideal point
X	Fuzzy rough ratio vector
$\overline{w}_j$	FRN vector of weight coefficients of the criteria
C_j	The set of criteria
A_i	The set of alternatives
$\aleph$	Fuzzy rough initial decision matrix
$\widetilde{\chi}$	Fuzzy sequences
$\overline{\varphi}_{ij}$	Fuzzy rough function
$\aleph_s$	Fuzzy rough standardized fuzzy rough matrix
$\aleph_N$	Fuzzy rough normalized decision matrix
A	Arithmetic mean
H	Harmonic mean
$Q(A_i)$	FRN criterion functions

operating on water especially for the mooring/anchoring issues and electrical safety. Turkey has high solar potential and government policies highly supporting the use of renewable energy resources [4]. This technology is quite new to Turkey and except a lab scale test in Turkey, it has not been developed yet.

Renewable energy systems are site specific and site selection is one of the first step prior to design and/or develop those systems for a specific region. To the best of the authors' knowledge, no specific MCDM study (combined with GIS) exists at present to determine suitable sites for FPVs in Turkey. The aim of the present paper is therefore to fill this gap by employing the proposed fuzzy model for site selection of FPV in Southern part of Turkey. This study may therefore be considered as a benchmark. Proposed method enables the selection of the suitable sites for FPV.

The aim of this research is to evaluate the site selection criteria for Southern part of Turkey and determine the suitable sites for Floating Photovoltaic (FPV) power plant using Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) method. The novelty of this study is to carry out a comprehensive study for Southern part of Turkey considering i) necessary criteria for site selection, ii) relative weights of fuzzy sets based on a questionnaire collected from both Turkish and international experts, iii) application of the proposed MCDM method.

This study divided into three main stages. The first stage includes a literature review on the site selection process. By doing that the necessary criteria are determined for potential sites. The needed GIS data are collected for Southern part of Turkey. Classification and evaluation of the criteria are performed in the second stage. GIS data is used to determine the alternatives. The third and last step of the study is that the criteria that are the subject of the proposed hybrid MCDM model including fuzzy rough numbers based LAAW and RAFSI are evaluated by the participants and scored in order of importance, and finally, the most suitable area is determined for a FPV power plants as a result of these evaluations.

The main contributions of this paper are summarized in the following.

- In this paper, a new approach for defining fuzzy rough numbers is proposed, which is based on an improved methodology for defining lower and upper limit of rough numbers. The concept of fuzzy rough numbers based on the Bonferroni functions used to define the lower and upper limit of rough numbers is proposed.
- The new concept for defining the limit values of fuzzy rough numbers allows us to consider the relationships between the elements of the fuzzy set.
- The application of the proposed methodology enables flexible representation of rough boundary interval and definition of the degree of risk depending on the dynamic environmental conditions.
- A flexible nonlinear function for the fusion of criteria weights has been proposed in the multi-criteria methodology. The proposed function allows simulation of different levels of significance of criteria weights and analysis of their impact on the final prioritization of alternatives.
- The relationships between evaluation criteria are tackled in a more realistic manner through the fuzzy rough LMAAW RAFSI methodology.
- Imprecisions and uncertainties arising from expert evaluations can be eliminated with the fuzzy & rough-driven LMAAW RAFSI methodology. The proposed integrated approach not only allows decision-makers to more easily understand the relationships between criteria but also aids in better analysis of raw data when evaluating alternatives.
- The proposed method was applied to find feasible site for FPV power plant in Turkey.

This paper is organized as follows. Section 2 presents a brief background on floating photovoltaic systems and MCDM studies. The problem definition together with criteria and the alternatives are given in Section 3. Following this, Section 4 presents the proposed methodology illustrating how the proposed method can be applied to site selection of FPV systems. The experimental results are discussed in Section 5. Finally, a brief summary of the main results from this work are provided in Section 6 and suggestions are made for future study.

2. Literature review

According to the WorldBank Floating Solar Market Report [5], the available peak capacity and energy generation potential is very high especially in Middle East and Asia, Africa and North America. When the installed capacity of 1.3 GWp by the end of 2018 and the overall potential are considered, it is clearly observed that just a little portion of the available potential has been materialised.

The highest energy production from renewable resources is provided by hydropower plants in Turkey. However, there is a capacity to implement such plants and the large part of the capacity is already in use or under construction. Although the hydropower and solar capacity is not similar in terms of the power production type (solar has a lower capacity factor and variable power generation). For instance, only 3% of the Atatürk Dam Lake's area is enough for FPV to match the peak capacity of the hydropower plant. When the global capacity of the hydropower plants and FPV potentials are considered, only 25% coverage area of hydropower reservoirs is enough for FPV to provide more electricity by the intermittent operation (6270 TWh in total) than the electricity generated by hydropower alone (2510 TWh in total). The same coverage area leads to 6.3% reduction in evaporation from reservoirs which results in an increase of water supply as well as energy production from hydropower plant. Hence the FPVs can be considered complementary to hydropower plants [6].

According to the EPDK Report, in 2021 the renewable energy generated in Turkey was 74.5% of the total. The breakdown of the generated energy is as follows: hydropower 25.6%, wind power 8.1%, geothermal 3.3% (biogas), and solar power 3.7%.

The floating power plant is a recent technology with completed pilot studies in 2007 and the first floating photovoltaics plant was built in California in 2008 [7]. In 2018, The World Bank published a report about floating solar market and it is stated that the installed capacity of floating solar photovoltaic systems (FPV) is increased from 10 MW to 1.3 GW (see Fig. 1) by growing more than 100-fold between the 2014 and 2018 [8]. According to the report, the technology is especially seemed promising for the growing Asian economies. China, India and Southeast Asia have already large floating solar power plants being installed or planned. By the end of 2019, there is at least 2.4 GW installed capacity of floating solar PV and it is expected to grow by an average of 22% annually from 2019 through 2024. Although floating systems generate 1 percent of the global solar installation in 2019, it is expected to double by 2022 [9].

According to the Float Solar Market Report published by The World Bank Group (2019), China installed a plant with 150 MW peak capacity, which has the largest capacity up to now, on the flooded coal mines in the same region with 40 MW and 77.7 MW projects. China started to turn the challenges of the flooded mines into its advantage by installing FPV on them. As indicated in the same report, China became the market leader by installation of these large FPV systems over the past two years, with a market share of 73% and installed capacity of 950MWp. Due to lack of land accessibility and the encouragement of the government about use of renewable energy, Japan had the second largest share in the market in 2019 with a share of 16% [8]. In addition to that, over populated countries like Bangladesh [10], India Mittal et al. [11] have

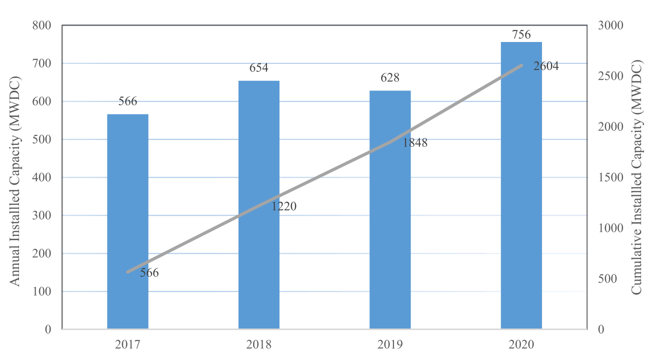


Fig. 1. Annual global FPV capacity, 2017–2020 (modified from Cox 2021, Ramasamy V. & Margolis, R 2021). Ref for Fig. 1. Ramasamy, V., & Margolis, R. (2021). Floating Photovoltaic System Cost Benchmark: Q1 2021 Installations on Artificial Water Bodies. *National Renewable Energy Laboratory*, (October).

important studies and investments on FPV systems due to inaccessibility of huge land for establishing solar PV. Especially the countries located at low latitudes with higher irradiation amount (see Fig. 2) benefits from solar energy. When the requirement of the land use to install the solar systems considered, floating solar photovoltaic systems can be seen as an appropriate solution. Although the levelized cost of energy of floating PV systems (44–248 €/MWh depending on the site) is higher than the land-based PV systems (35–40 €/MWh depending on the site), it is expected that the cost of floating PV systems will decrease with the increasing number of the studies and attention to floating PV systems by industry players [12].

Turkey provided 42.5% of the required energy from renewable resources while the remaining 57.5% of the electricity was produced using fossil fuels in 2020. The share of the electricity production by solar energy is only 3.7% and it is very low comparing to the high solar energy potential of Turkey. The Republic of Turkey Ministry of Energy and Natural Resources stated that average annual sunshine duration is 2766.5 h/year (7.58 h/day) and average annual radiation intensity is 1527.1 kWh/m^2/year (4.17 kWh/m^2/day) according to solar energy potential map of Turkey.[2]

Although Turkey has high solar potential and it is a rich country in terms of seas, lakes and reservoirs, FPV is a recent technology and there is no application apart from the pilot study carried out in Büyükçekmece Lake. This project constructed with 960 polycristaline panels each having 260 W, with a total power generation capacity of 249.6 KW [13]. It is planning to decrease the evaporation in a considerable amount and decrease the carbon dioxide emission by 210 tons per year with the implementation of this project.

Turkey's solar radiation and its energy potential have been evaluated by a number of researchers (Toğrul and Toğrul [14], Sözen et al. [15], Sözen et al. [16–18], Bulut and Büyükalaca [19], Şenkal [20,21], Kaygusuz [22], Bakirci [23,24], Ozgoren et al. [25], Uyan [26]). Turkey's solar resource map was published in 2019 by The World Bank (see Fig. 3). However, there is no specific study focusing on the site selection of FPV using ARCGIS and MCDM method for Turkey's lakes and reservoirs. Hence, in this paper, considering the high solar energy potential of Turkey's lakes and reservoirs potential sites were determined in Southern part of Turkey using MCDM method. Relevant technical data such as sun potential were used in a GIS environment for all alternative sites. Then, MCDM method was applied to select the most feasible site for floating PV system.

Although there is no specific study on site selection of FPV in Turkey, few studies around the World are summarized within the scope of the literature review. Different studies in different regions have been discussed and presented in Table 1.

Wu et al. [27] studied on developing a two-stage framework for site selection of the offshore hybrid wind-photovoltaic-seawater pumped storage based on a hybrid MCDM approach. At the first stage of proposed framework, veto criteria are defined to ensure that the natural resources of the evaluated site meet the minimum requirements of the units of the offshore hybrid wind-PV-SPS system. A second evaluation criteria for the second stage is established based on natural aspect, environmental aspect, economic aspect and social aspect to achieve the sustainable development of the project. The criteria values are determined by triangular intuitionistic fuzzy numbers (TIFNS) and the entropy weight method is used to evaluate the criteria weights to evaluate uncertainties of decision-making process. Then, TODIM method is utilized to rank the dominance of the alternative sites. Guo et al. [28] proposed a large-scale group decision making framework for the site selection of floating PV-pumped storage power system based on probabilistic linguistic term set and fuzzy PROMETHEE method (Preference Ranking Organization Method for Enrichment Evaluation). The evaluation criteria are

[1] https://globalsolaratlas.info/map, 2020.

[2] https://enerji.gov.tr/homepage.

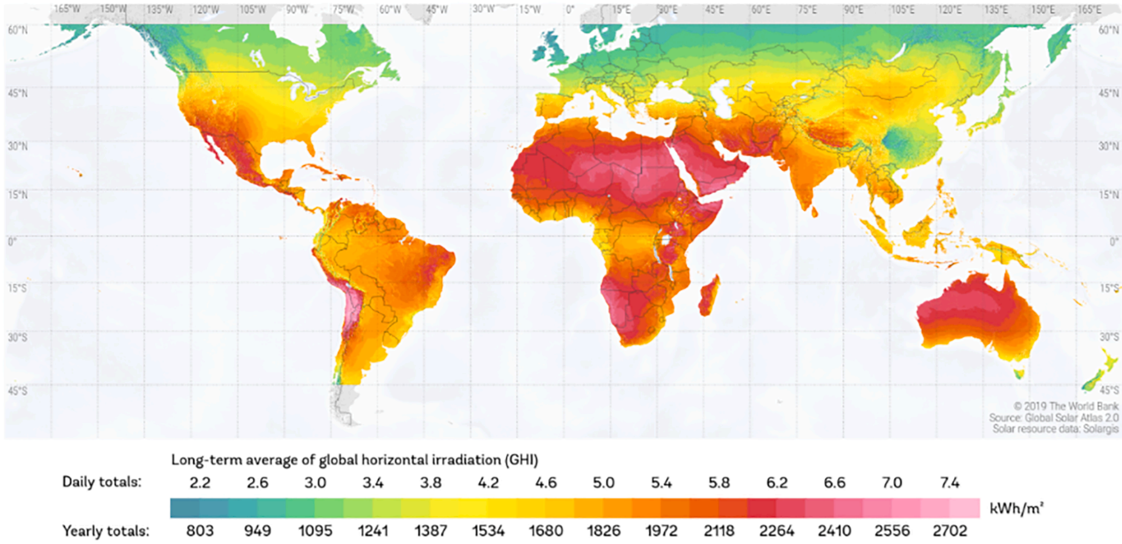


Fig. 2. Long-term average of global horizontal irradiation.[1]

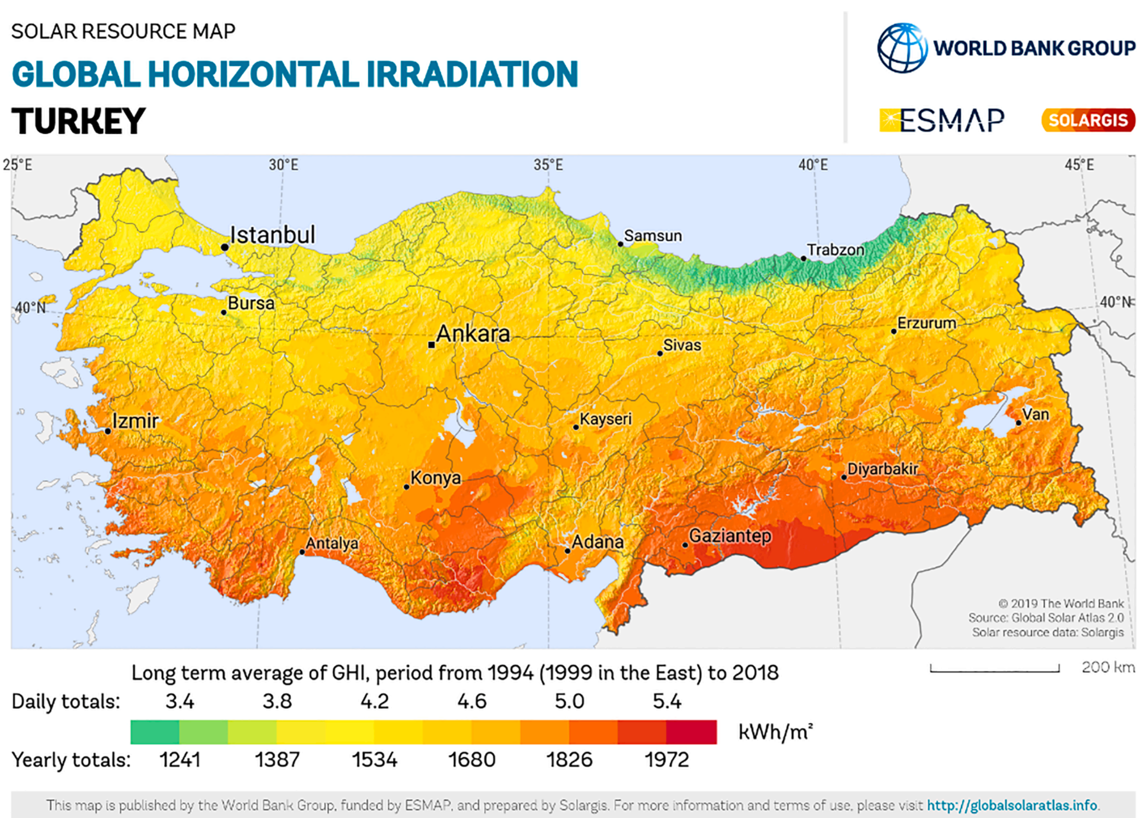


Fig. 3. Long-term average horizontal irradiation of Turkey. https://globalsolaratlas.info/map, 2020.

established based two stage approach. Literature review of the past site selection studies on FPV and PSP is used to identify the decision-making indicators at the first stage. In the second stage, experts from various backgrounds finalized the criteria system. The researchers incorporated concept of probabilistic linguistic term set in PROMETHEE method to consider the subjectivity of the gathered criteria weights and psychological orientation of the decision makers. The proposed framework applied on a case study in China. Guo et al. [29] studied on a site selection framework for the floating photovoltaic power plants. The researchers defined two stage criteria system for the site selection of FPV power plant which is composed of veto indicators and evaluation indicators. In order to evaluate the importance of the subjective expert opinions, a weighting model based on the hesitant fuzzy linguistic relative entropy is adopted. The modified hesitant fuzzy linguistic-DEMATEL (Decision Making Trial and Evaluation Laboratory) method and PROMETHEE (Preference Ranking Organization Methods for Enrichment Evaluation) method are utilized to compute criteria weights and ranking of the proposed sites. Nebey et al. [30] carried out a study on assessment of the Floating PV potential of the irrigation dams in the Amhara region of Ethiopia. The researchers employed geographic

Table 1
Summary of existing FPV site selection studies.

Reference	Renewable Energy source	Main Criteria	Sub Criteria	Area of Study	Used Methods	Fuzzy sets
Wu et al., [27]	FPV-Wind + SPS	4	19	China	TODIM- entropy weight method	triangular intuitionistic fuzzy numbers
Guo, Gao, Men, Fan, & Liu, [28,29]	Floating PV	4	16	China	DEMATEL-PROMETHEE	hesitant linguistic fuzzy numbers
Guo, Gao, Men, Fan, & Liu, [28,29]	Floating PV + pumped storage	4	19	China	PROMETHEE	probabilistic linguistic fuzzy numbers
[30]	Floating PV	–	5	Ethiopia	GIS-AHP	–

information system (GIS) and Analytical Hierarchy Processes (AHP) to identify and evaluate the usable water surfaces of the irrigation dams.

The following factors are considered in this study: global horizontal irradiation potential, annual sunshine hours, grid proximity, average temperature, topographic elevation, distance to substations, wind speed, local government subsidies, impacts on regional development and local economies, impact on the surrounding environment, population density and policy support.

2.1. The motivation of the proposed methodology

The processing of uncertainties in information and subjective assessments are essential characteristics that conventional decision-making models should possess. To meet these characteristics, researchers often extend traditional multi-criteria models by applying uncertainty theories such as fuzzy theory Zadeh [31], rough theory [32], neutrosophic approach [33], etc. The application of uncertainty theories significantly improves the performance of classical multi-criteria techniques, so researchers in recent years are increasingly opting for the application of fuzzy and rough theories in multi-criteria models for decision making [34–42]. In this study, we present an innovative hybrid model that allows taking advantage of fuzzy and rough theories by representing uncertainty and inaccuracy using fuzzy rough numbers (FRN). The multi-criteria framework presented in this paper is based on transforming conventional fuzzy numbers into fuzzy rough numbers using basic rough number settings. The efficiency and effectiveness of the FRN methodology was tested to address uncertainty and inaccuracy in a real-world case study. The FRN based multi-criteria framework consisting of two modules. The first module presents the LAAW (Logarithmic Additive Assessment of the Weight coefficients) methodology [43] for determining the weighting coefficients of the criteria. The second module presents the application of the RAFSI (Ranking of Alternatives through Functional mapping of criterion subintervals into a Single Interval) methodology Zizovic et al. [44] for the evaluation of alternatives. Fuzzy rough numbers were used to process the information in both modules. The developed multi-criteria framework based on FRNs defines the degree of agreement in expert assessments using rough boundary intervals. If there is a complete consensus in expert assessments, the presented methodology enables the transformation of fuzzy rough numbers into classic fuzzy numbers. However, the increase in discrepancies in expert estimates leads to a rise in the uncertainty footprint in fuzzy rough numbers, i.e., to an increase in the rough boundary interval.

3. Problem definition

Floating photovoltaic (FPV) systems are the placement of solar PV systems on a water body instead of on a building or land. Due to difficult terrain conditions or land constraints which make land based systems impractical, FPVs are becoming popular over the last years especially important in terms of reducing land-constraint problems. In addition, FPVs have been shown to minimize evaporation and reduce algae growth, which is often desirable Spencer et al. [45]. The water volume also has a cooling effect on the system, resulting in an increment in the panels' performance [46]. FPVs provide easy installation and deployment in sites with low anchoring and mooring requirements, with a high degree of modularity, resulting in faster installations [5]. Fig. 4 shows a typical large-scaled FPV system and its components.

In this study, characteristics of suitable sites for floating solar system based on the engineering requirements and previous experiences are identified and then location of potential sites in Turkey are determined accordingly. Major parameters may include global horizontal irradiation, annual sunshine hours, grid proximity, average temperature, topographic elevation, distance to substations and wind speed. A GIS based software was used to nominate the suitable sites. The existing floating PV systems in Europe and across the world investigated with an aim to determine the required properties.

Following this, a map produced demonstrating the locations of floating PV system using a MCDM method. The site selection provides the necessary information for a future design and optimisation of the floating system. Hence, it serves as an initial point to deliver solar potential, reservoir, and grid connectivity data. The outputs from this paper may feed into the future FPV developments in Turkey.

The renewable energy potential of the lakes, dam reservoirs and ponds identified using irradiation map obtained from PVGIS database[3] in the first stage. Considering the irradiation amount, possible regions having a higher irradiation selected, because a PV system which receives higher yearly irradiation will produce higher electrical output [47]. Then, for the suitable regions, economic, environmental and social data were also considered together with technical data. Global Wind Atlas[4] used to obtain the wind data and spectral wave modelling used to generate wave data. The bathymetry data achieved using GEBCO[5] software. After obtaining all of the relevant data, they integrated in a GIS based software (ArcGIS) layer by layer to determine the suitable region to implement a FPV system. Also, the grid connection availability included for possible regions. In addition to these, the evaporation amount could be used as a decisive parameter for the site selection. The advantage of the FPV system compared to other PV systems is to reduce evaporation which could be used for the regions having high evaporative conditions in order to limit the evaporation amount and save water. Considering the outputs of the GIS analysis and the other concerns like environmental aspects, the most suitable region discussed.

3.1. Definition of alternatives

In this study, Southern part of Turkey is investigated due to having higher amount of annual sunshine hours, global horizontal irradiation and so on. Table 2 presents alternative sites and their coordinates, which are discussed in this study. The selected alternative sites for FPV in Turkey are shown in Fig. 5.

[3] https://ec.europa.eu/jrc/en/pvgis.
[4] https://globalwindatlas.info/.
[5] https://www.gebco.net/.

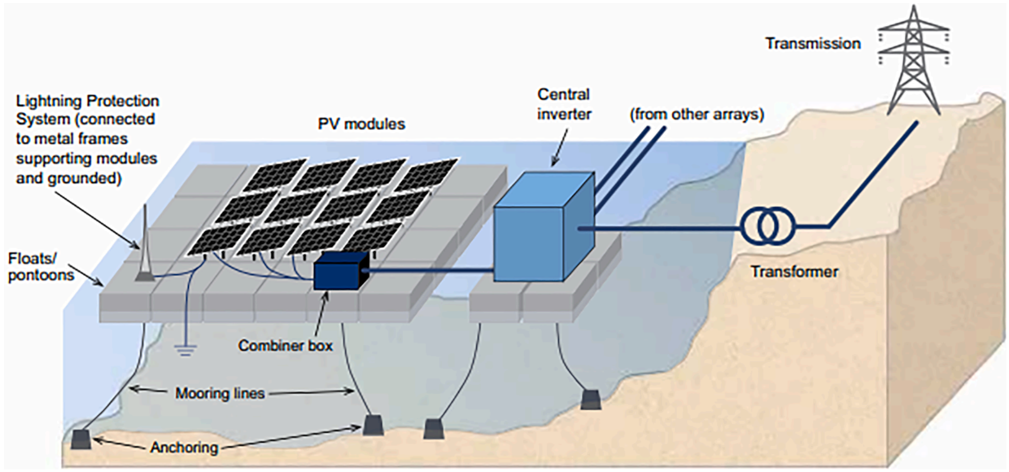


Fig. 4. A typical large-scale FPV system and its components (Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS)). World Bank Group; Energy Sector Management Assistance Program; Solar Energy Research Institute of Singapore. 2019. Where Sun Meets Water: Floating Solar Market Report. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/31880 License: CC BY 3.0 IGO.

Table 2
Alternative sites for a potential FPV in Turkey.

Alternative	Potential Site	Coordinates
A_1	Göksun, Kahramanmaraş	38°06′29″, 36°44′25″
A_2	Bucak, Burdur	37.36874, 30.8294
A_3	Manavgat, Antalya	36°52′16″, 31°32′49″
A_4	Güney, Denizli	38°09′31″, 29°12′21″
A_5	Dalaman, Muğla	36°53′55″, 28°54′05″
A_6	Çine, Aydın	37°28′26″, 28°09′25″

3.2. Definition of criteria

While selecting a suitable site for a potential FPV, a variety of criteria are considered in this study. Table 3 presents a list of main criteria and sub-criteria used in this study. Main criteria are classified as technical, economic, environmental and social criteria. Global horizontal irradiation, annual sunshine hours, grid proximity, average temperature, topographic elevation, distance to substations, and wind speed are considered as technical criteria in this study. Also, while local government subsidies, impacts on regional development and local economies are classified as economic criteria; impact on the surrounding environment, population density and policy support are classified as environmental and social criteria. Fig. 6 illustrates GIS based map layers for evaluation criteria of alternative A_3.

All criteria considered in this study are given in the following.

(1) <u>*Technical Concerns:*</u>

C_1: Global Horizontal Irradiation: Global horizontal irradiation (GHI) is the sum of diffuse horizontal irradiation (DHI) and direct normal irradiation (DNI). Fig. 7(a) shows the yearly GHI values of Turkey. It is clear from the figure that the south of Turkey has higher GHI values. During suitable FPV site selection, higher GHI values are desirable. For solar PVs, generally, areas having annual 1300 kWh/m^2 values are recommended as a minimum for economic operation [48].

C_2: Annual Sunshine Hours: Another important factor for suitable FPV site selection is annual sunshine hours. Since solar energy is an intermittent source, energy production is related to the sunshine duration. For a suitable site, high annual sunshine hours are desirable[6]. The annual sunshine hours of Turkey are shown in Fig. 7(b).

C_3: Grid Proximity: Grid proximity is another important factor for

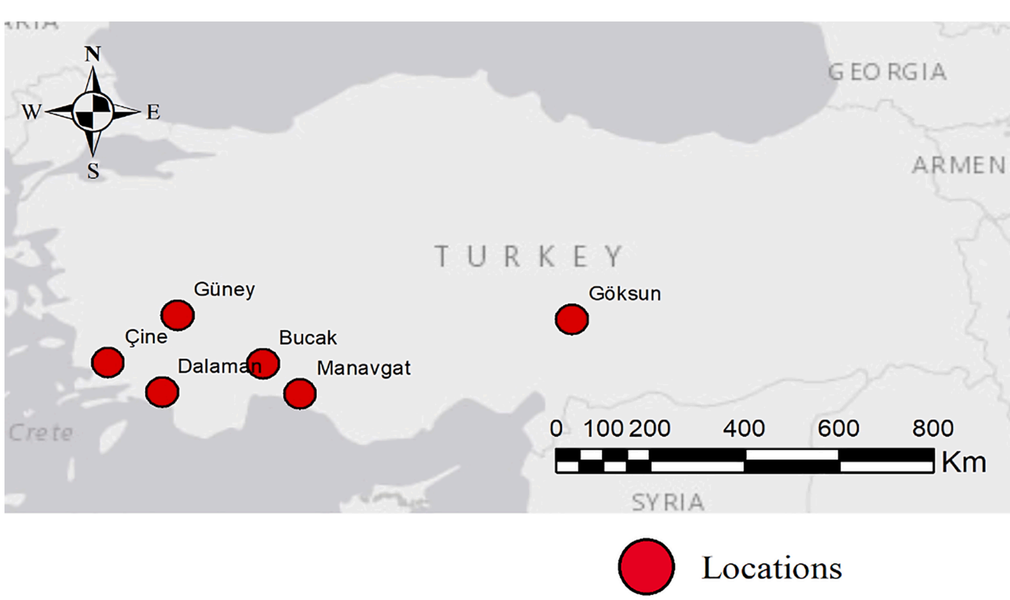


Fig. 5. Alternative sites discussed in this study.

Table 3
Main evaluation criteria and sub-criteria used in this study.

Main-criteria	Symbol	Sub-criteria	Type
	C_1	Global horizontal irradiation (kWh/m^2/y)	Benefit
	C_2	Annual sunshine hours (h/year)	Benefit
	C_3	Grid proximity	Benefit
Technical	C_4	Average temperature (°C)	Benefit
	C_5	Topographic elevation (m)	Benefit
	C_6	Distance to substations	Benefit
	C_7	Wind speed	Cost
Economic	C_8	Local government subsidies	Benefit
	C_9	Impacts on regional development and local economies	Benefit
	C_{10}	Impact on the surrounding environment	Cost
Environmental and Social	C_{11}	Population density	Benefit
	C_{12}	Policy support	Benefit

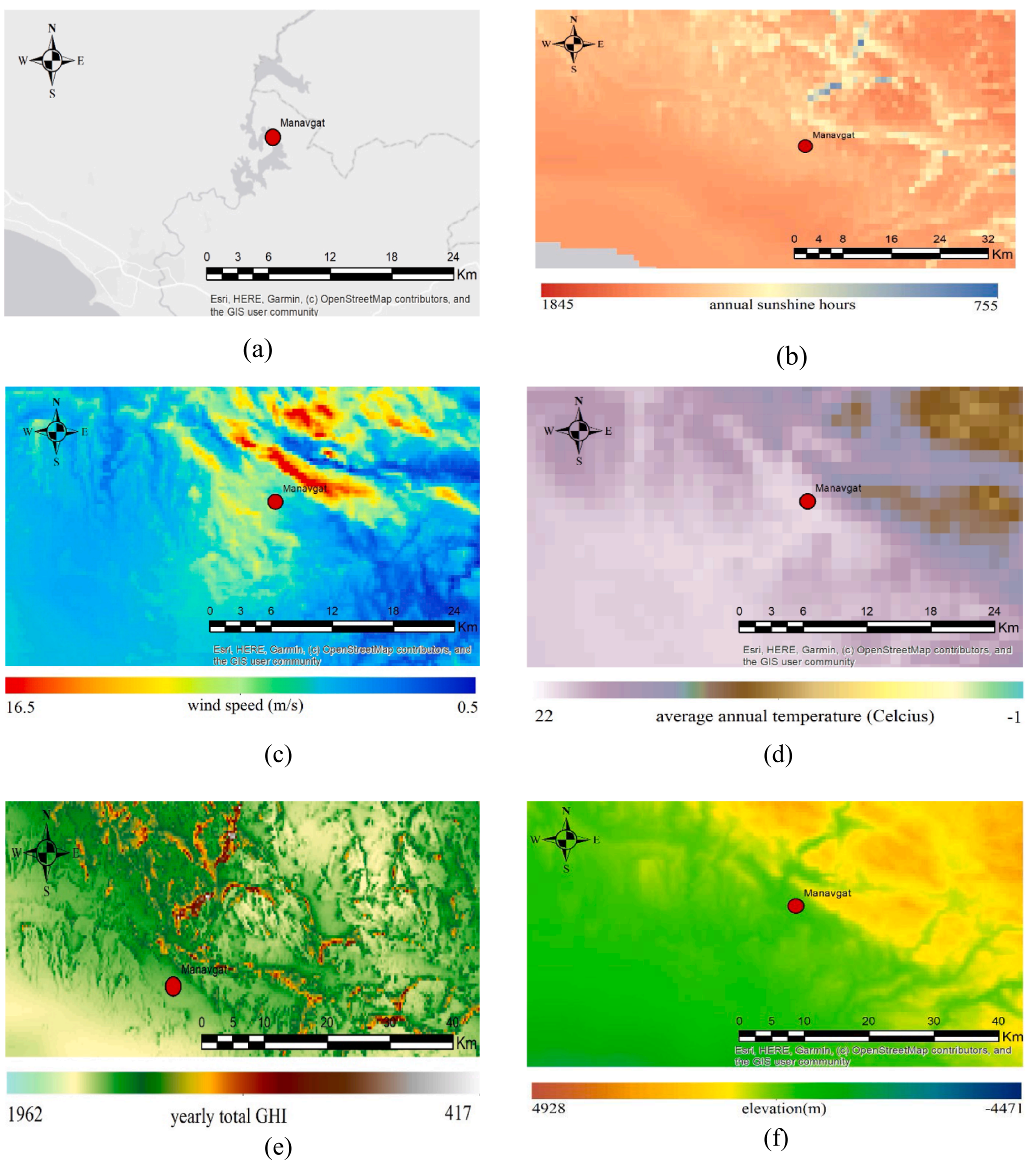
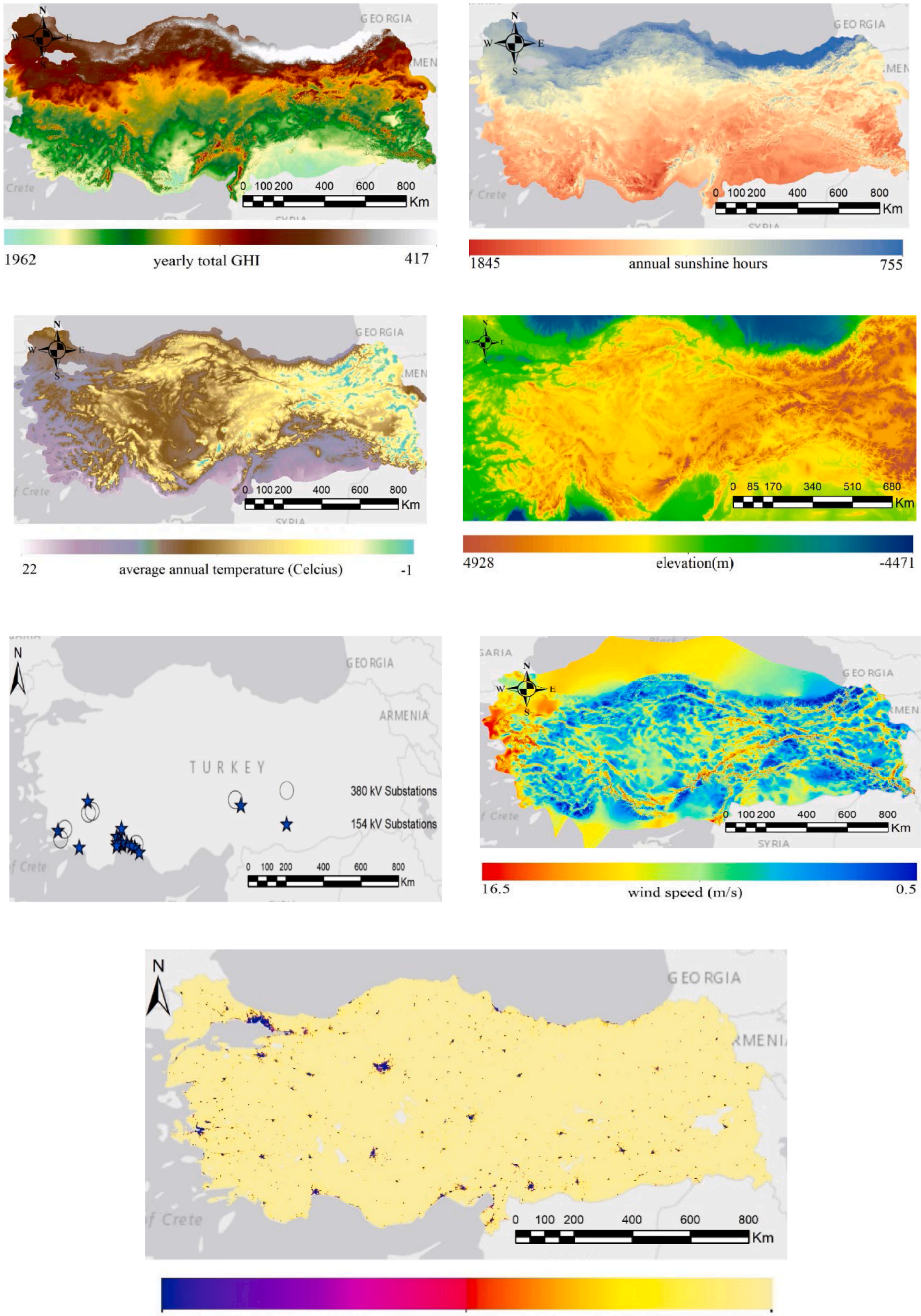


Fig. 6. GIS based map layers for evaluation criteria of alternative A_3 (Manavgat), a) location, b) annual sunshine hours, c) wind speed, d) average annual temperature, e) yearly total GHI, f) elevation.



(g) Population density in Turkey

Fig. 7. GIS based map layers for evaluation criteria.

suitable FPV site selection. This factor affects the easiness or difficulty of cable connection and energy transmission. Sometimes, electricity transmission systems work with full capacity. Therefore, it is important to identify cable lines clearly based on their capacity and availability.

C_4: Average Temperature: With the increasing air temperature, panel efficiency decreases. Noorollahi et al. [48] stated that the produced amount of energy decreases 0.4%-0.5% for every 1 °C rise in the cell temperature at temperatures above 25 ℃. Therefore, areas having high temperatures are not desirable for a potential FPV. The annual temperature of Turkey is shown in Fig. 7(c).

C_5: Topographic Elevation: The atmosphere affects the entrance of both the sun's shortwave energy and the earth's longwave energy due to its thickness and compounds. Thus, elevated areas have a more significant solar radiation potential than lower regions because they receive a great amount of energy Noorollahi et al. [48]. Fig. 7(d) shows topographic elevation map of Turkey based on GEBCO (2021).[6]

C_6: Distance to Substation: Having close transmission lines and substations is important to reduce high cable installation costs and minimize the loss of power in the transmission [7]. Some of 380 kV and 154 kV capacity substations of Turkey is shown in Fig. 7(e).

C_7: Wind Speed: Wind speed has also affected FPV systems in either negative or positive ways. It is a fact that wind is a primary source of wave generation. Areas having high wind speed might be at the risk of high waving. This situation might affect the FPV system design or substructure system. On the other hand, wind reduces the heat of the FPV system, which increases the energy efficiency of FPV systems. According to data from Global Wind Atlas, annual mean wind speed map at 100 m is shown in Fig. 7(f).

(2) Economic Concerns

C_8: Local Government Subsidies: The acceptance and support of the regional local government play a vital role in the installation of FPVs. Local government support and subsidies are also significant to solve the difficulties and problems faced during the installation phase of FPVs.

C_9: Impact on regional development and local economies: The FPVs will also increase job opportunities in the local region and contribute to local development in terms of the economy.

(3) Environmental-Social Concerns:

C_{10}: Impact on Surrounding Environment: The impact of FPV systems on the environment is one of the important criteria that should be considered in suitable site selection processes. Like other renewable energy sources, FPVs have very little negative impact on the environment. As an example, these systems have the possibility to affect underwater life, albeit to a very small degree. Underwater cables can also affect marine life and the environment. This criterion should also be taken into account in the suitable site selection in detail.

C_{11}: Population Density: In regions with high population density, the amount of energy needed is also high. The population density in Turkey is shown in Fig. 7(g). Population density is considered as one of the criteria since it is important to used yielded energy nearby the plant.

C_{12}: Policy Support: Energy-dependent countries, like Turkey, generally put ambitious renewable energy targets. It is important to achieve these targets in terms of government policies and relevant regulations.

4. Proposed methodology

In this section, we introduce the preliminaries on fuzzy rough numbers and the proposed model.

4.1. Preliminaries on fuzzy rough numbers

Fuzzy numbers are expected to represent the uncertainties that exist in human perceptions. To better capture uncertainties in perceptions, the concept of fuzzy numbers involves defining a boundary interval that encompasses a set of uncertain elements. One of the disadvantages of fuzzy numbers is the small flexibility of the boundary interval, which was improved in this study through the presentation of fuzzy rough numbers with adaptive boundary intervals. The concept of rough numbers and rough Bonferroni functions was used to create an adaptive boundary interval. The Bonferroni function [49] was chosen because of its two key advantages: (1) It can be provide a flexible decision making due to experts' risk attitude, and (2) It enables respect for mutual connections between fuzzy sequences.

The following section presents an original new approach to generating hybrid fuzzy rough numbers.

Let us denote by $\Im$ the universe in which the preferences of the decision-maker (DM) are contained, which are represented by the triangular fuzzy numbers $\widetilde{\tau}_i = \left(\tau_i^{(l)}, \tau_i^{(m)}, \tau_i^{(u)}\right)$, with the mode, left endpoint, and right endpoint denoted by $\tau_i^{(l)}, \tau_i^{(m)}$, and $\tau_i^{(u)}$, respectively. Then, the condition that $\widetilde{\tau}_1 \leqslant \widetilde{\tau}_2 \leqslant, \ldots, \leqslant \widetilde{\tau}_x$. Moreover, if we assume that Ω is a collection of $\left(\widetilde{\tau}_1, \widetilde{\tau}_2, \ldots, \widetilde{\tau}_x\right)$ and ς is an arbitrary element of $\Im$, then the lower and upper approximation of class $\widetilde{\tau}_i$ can be defined as follows:

$$\begin{aligned} \underline{Apr}\left(\tau_i^{(l)}\right) &= \bigcup_{1 \leqslant i \leqslant x} \left\{\varsigma \in \Im / \Omega(\varsigma) \leqslant \tau_i^{(l)}\right\} \\ \underline{Apr}\left(\tau_i^{(m)}\right) &= \bigcup_{1 \leqslant i \leqslant x} \left\{\varsigma \in \Im / \Omega(\varsigma) \leqslant \tau_i^{(m)}\right\} \\ \underline{Apr}\left(\tau_i^{(u)}\right) &= \bigcup_{1 \leqslant i \leqslant x} \left\{\varsigma \in \Im / \Omega(\varsigma) \leqslant \tau_i^{(u)}\right\} \end{aligned} \tag{1}$$

$$\begin{aligned} \overline{Apr}\left(\tau_i^{(l)}\right) &= \bigcup_{1 \leqslant i \leqslant x} \left\{\varsigma \in \Im / \Omega(\varsigma) \geqslant \tau_i^{(l)}\right\} \\ \overline{Apr}\left(\tau_i^{(m)}\right) &= \bigcup_{1 \leqslant i \leqslant x} \left\{\varsigma \in \Im / \Omega(\varsigma) \geqslant \tau_i^{(m)}\right\} \\ \overline{Apr}\left(\tau_i^{(u)}\right) &= \bigcup_{1 \leqslant i \leqslant x} \left\{\varsigma \in \Im / \Omega(\varsigma) \geqslant \tau_i^{(u)}\right\} \end{aligned} \tag{2}$$

The lower limit of $\widetilde{\tau}_i$ can be defined as follows:

$$\underline{Lim}\left(\tau_i^{(l)}\right) = \left(\frac{1}{N_{Ll}} \sum_{i,j=1}^{N_{Ll}} \tau_i^{(l)\mu_1} \left(\prod_{j=1}^{N_{Ll}} \tau_j^{(l)\mu_2}\right)^{\frac{1}{N_{Ll}-1}}\right)^{\frac{1}{\mu_1+\mu_2}} \left| \tau_i^{(l)\mu_1}, \tau_j^{(l)\mu_2} \in \underline{Apr}\left(\tau_i^{(l)}\right)\right. \tag{3}$$

$$\underline{Lim}\left(\tau_i^{(m)}\right) = \left(\frac{1}{N_{Lm}} \sum_{i,j=1}^{N_{Lm}} \tau_i^{(m)\mu_1} \left(\prod_{j=1}^{N_{Lm}} \tau_j^{(m)\mu_2}\right)^{\frac{1}{N_{Lm}-1}}\right)^{\frac{1}{\mu_1+\mu_2}} \left| \tau_i^{(m)\mu_1}, \tau_i^{(m)\mu_2} \in \underline{Apr}\left(\tau_i^{(m)}\right)\right. \tag{4}$$

$$\underline{Lim}\left(\tau_i^{(u)}\right) = \left(\frac{1}{N_{Lu}} \sum_{i,j=1}^{N_{Lu}} \tau_i^{(u)\mu_1} \left(\prod_{j=1}^{N_{Lu}} \tau_j^{(u)\mu_2}\right)^{\frac{1}{N_{Lu}-1}}\right)^{\frac{1}{\mu_1+\mu_2}} \left| \tau_i^{(u)\mu_1}, \tau_i^{(u)\mu_2} \in \underline{Apr}\left(\tau_i^{(u)}\right)\right. \tag{5}$$

where N_{Ll}, N_{Lm} and N_{Lu} represents a number of elements in $\underline{Apr}(\tau_i^{(l)})$, $\underline{Apr}(\tau_i^{(m)})$ and $\underline{Apr}(\tau_i^{(u)})$ respectively; $\mu_1, \mu_2 \geqslant 0$ and $\mu_1, \mu_2 \in \Re$, where $\Re$ represents a set of real numbers.

We can also define an upper limit of $\widetilde{\tau}_i$ as follows:

$$\overline{Lim}\left(\tau_i^{(l)}\right) = \left(\frac{1}{N_{Ul}} \sum_{i,j=1}^{N_{Ul}} \tau_i^{(l)\mu_1} \left(\prod_{j=1}^{N_{Ul}} \tau_j^{(l)\mu_2}\right)^{\frac{1}{N_{Ul}-1}}\right)^{\frac{1}{\mu_1+\mu_2}} \left| \tau_i^{(l)\mu_1}, \tau_j^{(l)\mu_2} \in \overline{Apr}\left(\tau_i^{(l)}\right)\right. \tag{6}$$

[6] https://www.gebco.net/.

$$\overline{Lim}\left(\tau_i^{(m)}\right) = \left(\frac{1}{N_{Um}}\sum_{i,j=1}^{N_{Um}}\tau_i^{(m)\mu_1}\left(\prod_{j=1}^{N_{Um}}\tau_j^{(m)\mu_2}\right)^{\frac{1}{N_{Um}-1}}\right)^{\frac{1}{\mu_1+\mu_2}}\Big|\tau_i^{(m)\mu_1},\tau_j^{(m)\mu_2} \in \overline{Apr}\left(\tau_i^{(m)}\right) \tag{7}$$

$$\overline{Lim}\left(\tau_i^{(u)}\right) = \left(\frac{1}{N_{Uu}}\sum_{i,j=1}^{N_{Uu}}\tau_i^{(u)\mu_1}\left(\prod_{j=1}^{N_{Uu}}\tau_j^{(u)\mu_2}\right)^{\frac{1}{N_{Uu}-1}}\right)^{\frac{1}{\mu_1+\mu_2}}\Big|\tau_i^{(u)\mu_1},\tau_j^{(u)\mu_2} \in \overline{Apr}\left(\tau_i^{(u)}\right) \tag{8}$$

$$FRN\left(\widetilde{\tau}_i\right) = \left(\left[\underline{Lim}\left(\tau_i^{(l)}\right),\overline{Lim}\left(\tau_i^{(l)}\right)\right],\left[\underline{Lim}\left(\tau_i^{(m)}\right),\overline{Lim}\left(\tau_i^{(m)}\right)\right],\left[\underline{Lim}\left(\tau_i^{(u)}\right),\overline{Lim}\left(\tau_i^{(u)}\right)\right]\right) = \left(\left[\tau_i^{(l)-},\tau_i^{(l)+}\right],\left[\tau_i^{(m)-},\tau_i^{(m)+}\right],\left[\tau_i^{(u)-},\tau_i^{(u)+}\right]\right) \tag{9}$$

where N_{Ul}, N_{Um} and N_{Uu} represents a number of elements in $\overline{Apr}(\tau_i^{(l)})$, $\overline{Apr}(\tau_i^{(m)})$ and $\overline{Apr}(\tau_i^{(u)})$ respectively.

Then, based on the previously defined (Eqs. (1)–(8)) we can represent the FRN $\widetilde{\tau}_i$ as follows:

In the following section, the operations between the two FRNs $FRN\left(\widetilde{v}_1\right) = \left(\left[v_1^{(l)-},v_1^{(l)+}\right],\left[v_1^{(m)-},v_1^{(m)+}\right],\left[v_1^{(u)-},v_1^{(u)+}\right]\right)$ and $FRN\left(\widetilde{v}_2\right) = \left(\left[v_2^{(l)-},v_2^{(l)+}\right],\left[v_2^{(m)-},v_2^{(m)+}\right],\left[v_2^{(u)-},v_2^{(u)+}\right]\right)$ are presented, $\theta > 0$:

$$FRN\left(\widetilde{v}_1\right) + FRN\left(\widetilde{v}_2\right) = \left[\left(v_1^{(l)-}+v_2^{(l)-},v_1^{(l)+}+v_2^{(l)+}\right),\left(v_1^{(m)-}+v_2^{(m)-},v_1^{(m)+}+v_2^{(m)+}\right),\left(v_1^{(u)-}+v_2^{(u)-},v_1^{(u)+}+v_2^{(u)+}\right)\right] \tag{10}$$

$$FRN\left(\widetilde{v}_1\right) \times FRN\left(\widetilde{v}_2\right) = \left[\left(v_1^{(l)-}\times v_2^{(l)-},v_1^{(l)+}\times v_2^{(l)+}\right),\left(v_1^{(m)-}\times v_2^{(m)-},v_1^{(m)+}\times v_2^{(m)+}\right),\left(v_1^{(u)-}\times v_2^{(u)-},v_1^{(u)+}\times v_2^{(u)+}\right)\right] \tag{11}$$

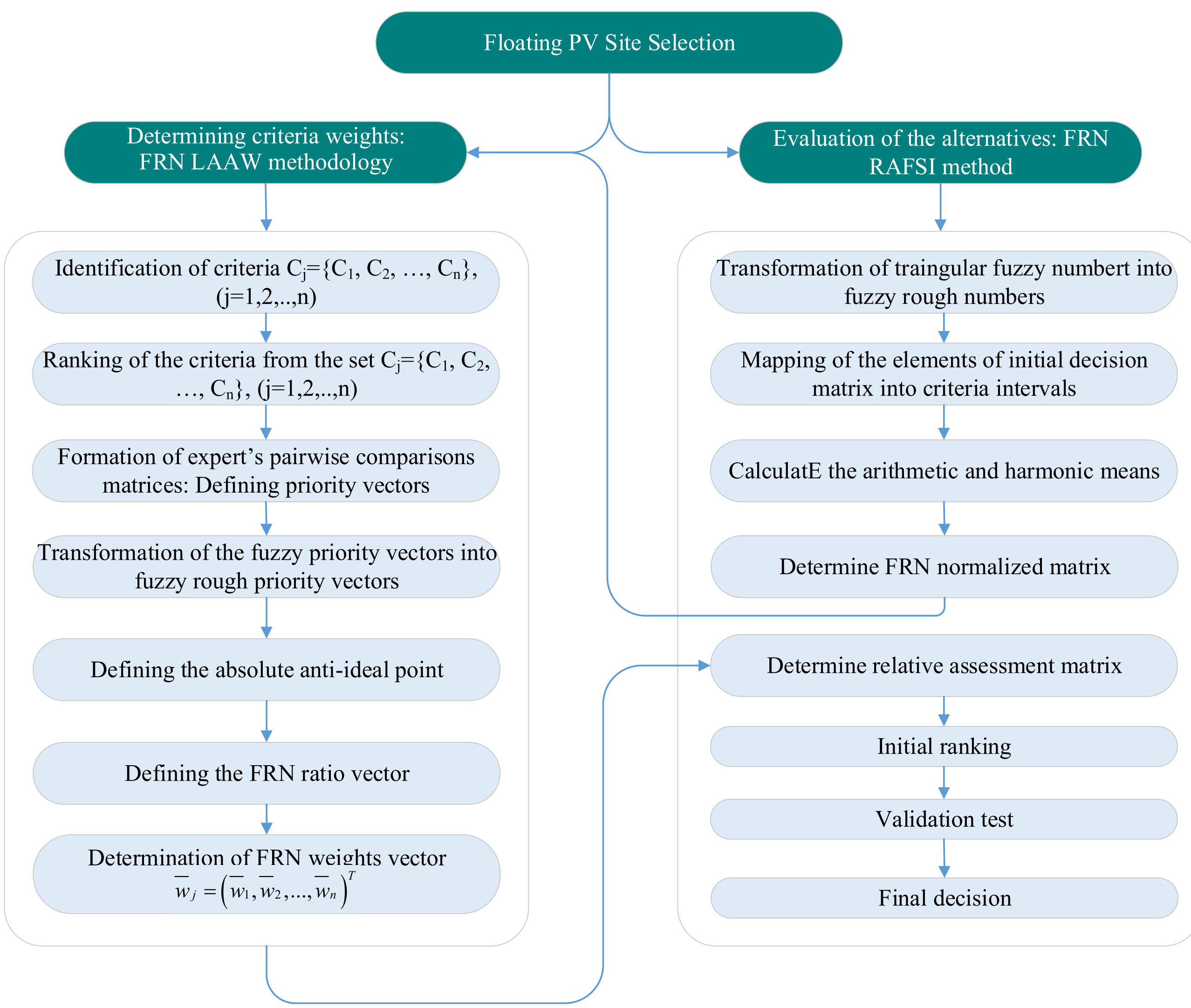


Fig. 8. FRN based LAAW-RAFSI framework.

$$\theta \times FRN\left(\widetilde{\upsilon}_2\right) = \left[\left(\theta \times \upsilon_2^{(l)-}, \theta \times \upsilon_2^{(l)+}\right), \left(\theta \times \upsilon_2^{(m)-}, \theta \times \upsilon_2^{(m)+}\right), \left(\theta \times \upsilon_2^{(u)-}, \theta \times \upsilon_2^{(u)+}\right)\right] \tag{12}$$

4.2. Integration of LAAW in RAFSI model based on fuzzy rough numbers

The following section presents a multi-criteria framework based on the integration of LAAW in the RAFSI model Zizovic et al. [44]. In addition, the concept of FRN was used to deal with uncertainty and inaccuracy in the presented multi-criteria methodology as shown in Fig. 8.

The FRN RAFSI methodology was used to evaluate alternatives based on defining ideal and anti-ideal criteria values and determining the relationship between alternatives concerning the defined ideal/anti-ideal values. Based on the defined relationships, fuzzy rough criterion functions have created that map the criterion sub-intervals into a unique criterion interval. The FRN RAFSI method has the following advantages due to which it was chosen for application in this study and which contribute to objective and rational decision-making [50]: *i)* The algorithm of the RAFSI methodis a simple; *ii)* The RAFSI method has a new decision making model for standardization of criteria that allows objective translation of data from the initial decision matrix into an interval that is suitable for rational decision making; *iii)* The RAFSI method is resistant to the rank reversal problem, as one of the significant drawbacks of many MCDM methods. Detailed steps of the integrated FRN LAAW - RAFSI methodology are presented in the next section.

(a) *Defining weighting coefficients: The FRN based LAAW methodology*

Suppose that in the FRN LAAW - RAFSI model for the evaluation of l alternatives A_i={A_1, A_2, …, A_l}, (i = 1,2,..,l) are involved n criteria C_j={C_1, C_2, …, C_n}, (j = 1,2,..,n). Also, suppose that there are qualitative criteria in the multi-criteria decision making (MCDM) model and that the experts E_h={E_1, E_2, …, E_n}, (h = 1,2,..,e) define the values of the qualitative criteria based on a predefined fuzzy scale.

In the following section, the fuzzy rough LAAW model for determining the weight coefficients of the criteria is presented.

Step 1. Determining the fuzzy rough priority vector. Based on the defined fuzzy scale, experts evaluate the criteria by assigning a higher value to the criterion with more significance than the fuzzy scale, while assigning lower values to criteria with less significance. Thus we get the fuzzy priority vector $\Upsilon^t = \left(\widetilde{\theta}_1^t, \widetilde{\theta}_2^t, .., \widetilde{\theta}_n^t\right)$, where $\widetilde{\theta}_j^t = \left(\theta_j^{(l)t}, \theta_j^{(m)t}, \theta_j^{(u)t}\right)$ represents the triangular fuzzy number (TFN) from the fuzzy scale assigned by the expert t (1⩽t⩽e) to the criterion n. By applying Eqs. (1)–(8) the fuzzy sequences $\theta_j^{t(l)} = \left\{\theta_j^{1(l)}, \theta_j^{2(l)}, ..., \theta_j^{e(l)}\right\}$, $\theta_j^{t(m)} = \left\{\theta_j^{1(m)}, \theta_j^{2(m)}, ..., \theta_j^{e(m)}\right\}$ and $\theta_j^{t(m)} = \left\{\theta_j^{1(u)}, \theta_j^{2(u)}, ..., \theta_j^{e(u)}\right\}$ (1⩽t⩽e) were transformed into rough sequences and a fuzzy rough priority vector was formed for each expert $\overline{\Upsilon}^t = \left(\overline{\theta}_1^t, \overline{\theta}_2^t, .., \overline{\theta}_n^t\right)$ (1⩽t⩽e), where $\overline{\theta}_j^t = \left(\left[\theta_j^{t(l)-}, \theta_j^{t(l)+}\right], \left[\theta_j^{t(m)-}, \theta_j^{t(m)+}\right], \left[\theta_j^{t(u)-}, \theta_j^{t(u)+}\right]\right)$. Aggregated FRN priority vector $\overline{\Upsilon} = (\overline{\theta}_1, \overline{\theta}_2, .., \overline{\theta}_n)$ we obtain by applying a fuzzy rough weighted geometric Bonferroni function, Eq. (13).

$$\overline{\theta}_j = \left(\frac{1}{e(e-1)}\sum_{\substack{x,y=1\\ x\neq y}}^{e} \overline{\theta}_{j(x)}^{\mu_1} \otimes \overline{\theta}_{j(y)}^{\theta_2}\right)^{\frac{1}{\mu_1+\mu_2}}$$

$$= \left(\begin{array}{l} \left[\left(\frac{1}{e(e-1)}\sum_{\substack{x,x=1\\ x\neq y}}^{e} \theta_{j(x)}^{(l)-\,\mu_1} \otimes \theta_{j(y)}^{(l)-\,\mu_2}\right)^{\frac{1}{\mu_1+\mu_2}}, \left(\frac{1}{e(e-1)}\sum_{\substack{x,x=1\\ x\neq y}}^{e} \theta_{j(x)}^{(l)+\,\mu_1} \otimes \theta_{j(y)}^{(l)+\,\mu_2}\right)^{\frac{1}{\mu_1+\mu_2}}\right], \\ \left[\left(\frac{1}{e(e-1)}\sum_{\substack{x,x=1\\ x\neq y}}^{e} \theta_{j(x)}^{(m)-\,\mu_1} \otimes \theta_{j(y)}^{(m)-\,\mu_2}\right)^{\frac{1}{\mu_1+\mu_2}}, \left(\frac{1}{e(e-1)}\sum_{\substack{x,x=1\\ x\neq y}}^{e} \theta_{j(x)}^{(m)+\,\mu_1} \otimes \theta_{j(y)}^{(m)+\,\mu_2}\right)^{\frac{1}{\mu_1+\mu_2}}\right], \\ \left[\left(\frac{1}{e(e-1)}\sum_{\substack{x,x=1\\ x\neq y}}^{e} \theta_{j(x)}^{(u)-\,\mu_1} \otimes \theta_{j(y)}^{(u)-\,\mu_2}\right)^{\frac{1}{\mu_1+\mu_2}}, \left(\frac{1}{e(e-1)}\sum_{\substack{x,x=1\\ x\neq y}}^{e} \theta_{j(x)}^{(u)+\,\mu_1} \otimes \theta_{j(y)}^{(u)+\,\mu_2}\right)^{\frac{1}{\mu_1+\mu_2}}\right] \end{array}\right) \tag{13}$$

where e denotes the number of experts, while μ_1, $\mu_2 \geq 0$ are set of non-negative numbers.

Step 2. Defining the absolute anti-ideal point ($\overline{\delta}_{AIP}$). The absolute anti-ideal point is defined by applying the condition that it is

$\overline{\delta}_{AIP} < \min(\overline{\theta}_1, \overline{\theta}_2, .., \overline{\theta}_n)$.

Step 3. Defining a fuzzy rough ratio vector X. Using Eq. (14), the relationship between the fuzzy rough priority vector elements and the absolute anti-ideal point ($\overline{\delta}_{AIP}$) is determined.

$$\overline{\gamma}_j = \frac{\overline{\theta}_j}{\overline{\delta}_{AIP}} = \left(\left[\frac{\theta_j^{(l)-}}{\delta_j^{(u)+}}, \frac{\theta_j^{(l)+}}{\delta_j^{(u)-}}\right], \left[\frac{\theta_j^{(m)-}}{\delta_j^{(m)+}}, \frac{\theta_j^{(m)+}}{\delta_j^{(m)-}}\right], \left[\frac{\theta_j^{(u)-}}{\delta_j^{(l)+}}, \frac{\theta_j^{(u)+}}{\delta_j^{(l)-}}\right]\right) \tag{14}$$

where $\overline{\theta}_j = \left(\left[\theta_j^{(l)-}, \theta_j^{(l)+}\right], \left[\theta_j^{(m)-}, \theta_j^{(m)+}\right], \left[\theta_j^{(u)-}, \theta_j^{(u)+}\right]\right)$ represents an element of the priority vector $\overline{\Upsilon}$, while $\overline{\gamma}_j$ represents an element of the fuzzy rough ratio vector $X = (\overline{\gamma}_1, \overline{\gamma}_2, .., \overline{\gamma}_n)$.

$$\overline{w}_j = \frac{\ln(\overline{\gamma}_j)}{\ln(\overline{b})} = \left(\left[\frac{\ln\left(\gamma_j^{(l)-}\right)}{\ln\left(b_j^{(u)+}\right)}, \frac{\ln\left(\gamma_j^{(l)+}\right)}{\ln\left(b_j^{(u)-}\right)}\right], \left[\frac{\ln\left(\gamma_j^{(m)-}\right)}{\ln\left(b_j^{(m)+}\right)}, \frac{\ln\left(\gamma_j^{(m)+}\right)}{\ln\left(b_j^{(m)-}\right)}\right], \left[\frac{\ln\left(\gamma_j^{(u)-}\right)}{\ln\left(b_j^{(l)+}\right)}, \frac{\ln\left(\gamma_j^{(u)+}\right)}{\ln\left(b_j^{(l)-}\right)}\right]\right) \tag{15}$$

Step 4. Determination of FRN vectors of weight coefficients $\overline{w}_j = (\overline{w}_1, \overline{w}_2, ..., \overline{w}_n)^T$. By applying Eq. (15), we obtain a vector of weight coefficients of the criteria:

where $\overline{\gamma}_j = \left(\left[\gamma_j^{(l)-}, \gamma_j^{(l)+}\right], \left[\gamma_j^{(m)-}, \gamma_j^{(m)+}\right], \left[\gamma_j^{(u)-}, \gamma_j^{(u)+}\right]\right)$ represents an element of the fuzzy rough ratio vector X, where $\overline{b} = \prod_{j=1}^{n}\overline{\gamma}_j = \left(\left[\prod_{j=1}^{n}\gamma_j^{(l)-}, \prod_{j=1}^{n}\gamma_j^{(l)+}\right], \left[\prod_{j=1}^{n}\gamma_j^{(m)-}, \prod_{j=1}^{n}\gamma_j^{(m)+}\right], \left[\prod_{j=1}^{n}\gamma_j^{(u)-}, \prod_{j=1}^{n}\gamma_j^{(u)+}\right]\right)$.

(b) *The FRN based RAFSI method for the evaluation of alternatives*

Step 1: *Creating a fuzzy rough initial decision matrix*. Assume that the experts evaluated the alternatives A_i={A_1, A_2, …, A_l} in relation to the set C_j={C_1, C_2, …, C_n} criteria. Expert preferences in the initial matrix are represented by a predefined fuzzy scale in which triangular fuzzy numbers represent linguistic expressions $\widetilde{\chi} = (\chi^l, \chi^m, \chi^u)$. Based on the expert response matrices $\widetilde{\chi} = (\chi^l, \chi^m, \chi^u)$, three matrices $\aleph^l$ are formed, containing aggregated expert sequences.

$$\aleph^l = \begin{bmatrix} \chi_{11}^{1l}, \chi_{11}^{2l}, \ldots, \chi_{11}^{el} & \chi_{12}^{1l}, \chi_{12}^{2l}, \ldots, \chi_{12}^{el} & , \ldots, & \chi_{1n}^{1l}, \chi_{1n}^{2l}, \ldots, \chi_{1n}^{el} \\ \chi_{21}^{1l}, \chi_{21}^{2l}, \ldots, \chi_{1}^{el} & \chi_{22}^{1l}, \chi_{22}^{2l}, \ldots, \chi_{22}^{el} & , \ldots, & \chi_{2n}^{1l}, \chi_{2n}^{2l}, \ldots, \chi_{2n}^{el} \\ \ldots & \ldots & , \ldots, & \ldots \\ \chi_{m1}^{1l}, \chi_{m1}^{2l}, \ldots, \chi_{m1}^{el} & \chi_{m2}^{1l}, \chi_{m2}^{2l}, \ldots, \chi_{m2}^{el} & , \ldots, & \chi_{mn}^{1l}, \chi_{mn}^{2l}, \ldots, \chi_{mn}^{el} \end{bmatrix} \tag{16}$$

$$\aleph^m = \begin{bmatrix} \chi_{11}^{1m}, \chi_{11}^{2m}, \ldots, \chi_{11}^{em} & \chi_{12}^{1m}, \chi_{12}^{2m}, \ldots, \chi_{12}^{em} & , \ldots, & \chi_{1n}^{1m}, \chi_{1n}^{2m}, \ldots, \chi_{1n}^{em} \\ \chi_{21}^{1m}, \chi_{21}^{2m}, \ldots, \chi_{1}^{em} & \chi_{22}^{1m}, \chi_{22}^{2m}, \ldots, \chi_{22}^{em} & , \ldots, & \chi_{2n}^{1m}, \chi_{2n}^{2m}, \ldots, \chi_{2n}^{em} \\ \ldots & \ldots & , \ldots, & \ldots \\ \chi_{m1}^{1m}, \chi_{m1}^{2m}, \ldots, \chi_{m1}^{em} & \chi_{m2}^{1m}, \chi_{m2}^{2m}, \ldots, \chi_{m2}^{em} & , \ldots, & \chi_{mn}^{1m}, \chi_{mn}^{2m}, \ldots, \chi_{mn}^{em} \end{bmatrix} \tag{17}$$

$$\aleph^u = \begin{bmatrix} \chi_{11}^{1u}, \chi_{11}^{2u}, \ldots, \chi_{11}^{eu} & \chi_{12}^{1u}, \chi_{12}^{2u}, \ldots, \chi_{12}^{eu} & , \ldots, & \chi_{1n}^{1u}, \chi_{1n}^{2u}, \ldots, \chi_{1n}^{eu} \\ \chi_{21}^{1u}, \chi_{21}^{2u}, \ldots, \chi_{1}^{eu} & \chi_{22}^{1u}, \chi_{22}^{2u}, \ldots, \chi_{22}^{eu} & , \ldots, & \chi_{2n}^{1u}, \chi_{2n}^{2u}, \ldots, \chi_{2n}^{eu} \\ \ldots & \ldots & , \ldots, & \ldots \\ \chi_{m1}^{1u}, \chi_{m1}^{2u}, \ldots, \chi_{m1}^{eu} & \chi_{m2}^{1u}, \chi_{m2}^{2u}, \ldots, \chi_{m2}^{eu} & , \ldots, & \chi_{mn}^{1u}, \chi_{mn}^{2u}, \ldots, \chi_{mn}^{eu} \end{bmatrix} \tag{18}$$

where $\chi_{ij}^{l} = \left\{\chi_{ij}^{1l}, \chi_{ij}^{2l}, \ldots, \chi_{ij}^{el}\right\}$, $\chi_{ij}^{m} = \left\{\chi_{ij}^{m1}, \chi_{ij}^{2m}, \ldots, \chi_{ij}^{em}\right\}$ and $\chi_{ij}^{u} = \left\{\chi_{ij}^{1u}, \chi_{ij}^{2u}, \ldots, \chi_{ij}^{eu}\right\}$ represent fuzzy sequences. By applying Eqs. (1)–(8) the fuzzy sequences χ_{ij}^{tl}, χ_{ij}^{tm} and χ_{ij}^{tu} ($1 \leqslant t \leqslant e$) transform into fuzzy rough sequences. Using the FRN Bonferroni function, the experts' fuzzy rough sequences are averaged into unique fuzzy rough sequences $\overline{\chi}_{ij} = \left(\left[\chi_{ij}^{(l)-}, \chi_{ij}^{(l)+}\right], \left[\chi_{ij}^{(m)-}, \chi_{ij}^{(m)+}\right], \left[\chi_{ij}^{(u)-}, \chi_{ij}^{(u)+}\right]\right)$. So we get a fuzzy rough initial decision matrix:

$$\aleph = \begin{matrix} \\ A_1 \\ A_2 \\ \ldots \\ A_m \end{matrix} \begin{matrix} C_1 & C_2 & \ldots & C_n \\ \end{matrix} \begin{bmatrix} \overline{\chi}_{11} & \overline{\chi}_{12} & \cdots & \overline{\chi}_{1n} \\ \overline{\chi}_{21} & \overline{\chi}_{22} & \cdots & \overline{\chi}_{2n} \\ \cdots & \cdots & \ddots & \cdots \\ \overline{\chi}_{m1} & \overline{\chi}_{m2} & \cdots & \overline{\chi}_{mn} \end{bmatrix}_{m \times n} \tag{19}$$

Step 2: *Mapping of FRN matrix* $\aleph = \left[\widetilde{\chi}_{ij}\right]_{m \times n}$ *elements into criterion intervals*. For each criterion $C_j (j = 1, 2, .., n)$, the ideal and anti-ideal values $\overline{\chi}_{I_j}$ and $\overline{\chi}_{N_j}$ are defined, where $\overline{\chi}_{I_j}$ represents the ideal value, while $\overline{\chi}_{N_j}$ represents the anti-ideal value according to the criterion C_j.

Based on the defined ideal and anti-ideal values, fuzzy rough functions $\overline{\varphi}_{ij}$ are defined, which transform the criterion intervals from the matrix (19) into the criterion interval $[\psi_1, \psi_b]$. Fuzzy rough criterion functions are defined for each criterion from the set C_j $(j = 1, 2, \ldots, n)$, Eq. (20).

$$\overline{\varphi}_{ij} = \begin{cases} \dfrac{\psi_b - \psi_1}{\gamma_{I_j} - \overline{\chi}_{N_j}}\overline{\chi}_{ij} + \dfrac{\overline{\chi}_{I_j} \cdot \psi_1 - \overline{\chi}_{N_j} \cdot \psi_b}{\overline{\chi}_{I_j} - \overline{\chi}_{N_j}}, \textit{for } \max \textit{ criteria} \\ \dfrac{\psi_b - \psi_1}{\gamma_{N_j} - \overline{\chi}_{I_j}}\overline{\chi}_{ij} + \dfrac{\overline{\chi}_{N_j} \cdot \psi_1 - \overline{\chi}_{I_j} \cdot \psi_b}{\overline{\chi}_{N_j} - \overline{\chi}_{I_j}}, \textit{for } \min \textit{ criteria} \end{cases} \tag{20}$$

where ψ_b and ψ_1 represent a relationship that shows how much the ideal value is better than the anti-ideal value, while $\overline{\chi}_{ij}$ represents the element of the matrix (19). The recommendation is that the ideal value is at least six times better than the anti-ideal, i.e. $\psi_b \geqslant 6$.

Thus we obtain a standardized fuzzy rough matrix $\aleph_s = \left[\overline{\varphi}_{ij}\right]_{m \times n}$ in which all matrix elements are translated into the criterion interval $[\psi_1, \psi_b]$.

Step 3: *Formation of FRN normalized decision matrix* $\aleph_N = \left[\widehat{\varphi}_{ij}\right]_{m \times n}$. By applying Eq. (21), we obtain normalized elements.

$$\widehat{\varphi}_{ij} = \begin{cases} \dfrac{\overline{\varphi}_{ij}}{2A}, \textit{ for } \max \textit{ criteria} \\ \dfrac{H}{2\overline{\varphi}_{ij}}, \textit{for } \min \textit{ criteria} \end{cases} \tag{21}$$

$$Q(A_i) = \sum_{j=1}^{n}\overline{w}_j\widehat{\varphi}_{ij} = \left(\left[\sum_{j=1}^{n} w_j^{(l)-}\widehat{\varphi}_j^{(l)-}, \sum_{j=1}^{n} w_j^{(l)+}\widehat{\varphi}_j^{(l)+}\right], \left[\sum_{j=1}^{n} w_j^{(m)-}\widehat{\varphi}_j^{(m)-}, \sum_{j=1}^{n} w_j^{(m)+}\widehat{\varphi}_j^{(m)+}\right], \left[\sum_{j=1}^{n} w_j^{(u)-}\widehat{\varphi}_j^{(u)-}, \sum_{j=1}^{n} w_j^{(u)+}\widehat{\varphi}_j^{(u)+}\right]\right) \tag{22}$$

Table 4
Fuzzy linguistic scale.

Linguistic terms	Membership function
Very low (VL)	(1,1,1)
Low (L)	(1,2,3)
Medium low (ML)	(1,3,5)
Medium (M)	(3,5,7)
Medium high (MH)	(5,7,9)
High (H)	(7,9,10)
Very high (VH)	(9,10,10)

Table 5
Priority vectors.

Criteria	E1	E2	E3	E4	E5
Technical (MC_1)	VH	VH	VH	VH	VH
C_1	VH	VH	VH	VH	VH
C_2	H	MH	H	VH	VH
C_3	H	H	H	MH	VH
C_4	M	MH	MH	M	MH
C_5	ML	ML	M	M	M
C_6	MH	MH	H	H	H
C_7	M	L	M	M	M
Economic (MC_2)	H	MH	MH	M	H
C_8	M	M	M	L	M
C_9	MH	H	M	M	M
Environmental and Social (MC3)	MH	MH	H	M	MH
C_{10}	H	MH	MH	MH	H
C_{11}	MH	H	M	M	M
C_{12}	MH	MH	M	H	M

Table 6
Aggregated FRN priority vector.

Criteria	FRN priority vector
Technical (MC_1)	([9.00,9.00],[10.0,10.0],[10.0,10.0])
C_1	([9.00,9.00],[10.0,10.0],[10.0,10.0])
C_2	([6.43,8.24],[8.30,9.59],[9.63,9.96])
C_3	([6.24,7.65],[8.22,9.29],[9.63,9.96])
C_4	([3.66,4.64],[5.68,6.65],[7.69,8.66])
C_5	([1.59,2.59],[3.66,4.64],[5.68,6.65])
C_6	([5.68,6.65],[7.69,8.66],[9.35,9.84])
C_7	([2.15,2.89],[3.76,4.84],[5.36,6.80])
Economic (MC_2)	([4.39,6.22],[6.43,8.24],[8.30,9.59])
C_8	([2.15,2.89],[3.76,4.84],[5.36,6.80])
C_9	([3.30,5.00],[5.31,7.04],[7.29,8.68])
Environmental and Social (MC_3)	([4.22,5.64],[6.24,7.65],[8.22,9.29])
C_{10}	([5.32,6.27],[7.32,8.28],[9.17,9.65])
C_{11}	([3.30,5.00],[5.31,7.04],[7.29,8.68])
C_{12}	([3.63,5.39],[5.66,7.42],[7.64,9.06])

Table 7
Ratio vectors.

Criteria	FRN priority vector
Technical (MC_1)	([15.00,15.00],[16.67,16.67],[16.67,16.67])
C_1	([15.00,15.00],[16.67,16.67],[16.67,16.67])
C_2	([10.71,13.74],[13.83,15.98],[16.06,16.60])
C_3	([10.41,12.76],[13.71,15.49],[16.06,16.60])
C_4	([6.09,7.73],[9.46,11.09],[12.81,14.43])
C_5	([2.64,4.32],[6.09,7.73],[9.46,11.09])
C_6	([9.46,11.09],[12.81,14.43],[15.59,16.39])
C_7	([3.59,4.82],[6.26,8.07],[8.94,11.33])
Economic (MC_2)	([7.31,10.37],[10.71,13.74],[13.83,15.98])
C_8	([3.59,4.82],[6.26,8.07],[8.94,11.33])
C_9	([5.49,8.33],[8.86,11.74],[12.15,14.47])
Environmental and Social (MC_3)	([7.03,9.39],[10.41,12.76],[13.71,15.49])
C_{10}	([8.86,10.46],[12.2,13.8],[15.28,16.08])
C_{11}	([5.49,8.33],[8.86,11.74],[12.15,14.47])
C_{12}	([6.06,8.98],[9.44,12.37],[12.74,15.1])

Table 8
FRN vector of weighting coefficients criteria.

Criteria	Local FRN criteria weights	Global FRN criteria weights
Technical (MC_1)	([0.325,0.336], [0.353,0.374], [0.386,0.423])	–
C_1	([0.145,0.150], [0.160,0.171], [0.183,0.205])	([0.047,0.050], [0.057,0.064], [0.071,0.087])
C_2	([0.127,0.145], [0.150,0.168], [0.181,0.205])	([0.041,0.049], [0.053,0.063], [0.070,0.087])
C_3	([0.125,0.141], [0.149,0.166], [0.181,0.205])	([0.041,0.047], [0.053,0.062], [0.070,0.087])
C_4	([0.096,0.113], [0.128,0.146], [0.166,0.195])	([0.031,0.038], [0.045,0.055], [0.064,0.082])
C_5	([0.052,0.081], [0.103,0.124], [0.146,0.175])	([0.017,0.027], [0.036,0.046], [0.056,0.074])
C_6	([0.120,0.133], [0.145,0.162], [0.179,0.204])	([0.039,0.045], [0.051,0.060], [0.069,0.086])
C_7	([0.068,0.087], [0.105,0.127], [0.143,0.177])	([0.022,0.029], [0.037,0.047], [0.055,0.075])
Economic (MC_2)	([0.239,0.290], [0.297,0.348], [0.360,0.417])	–
C_8	([0.250,0.335], [0.403,0.520], [0.593,0.814])	([0.060,0.097], [0.120,0.181], [0.214,0.339])
C_9	([0.334,0.452], [0.479,0.613], [0.676,0.896])	([0.080,0.131], [0.142,0.213], [0.244,0.374])
Environmental and Social (MC_3)	([0.234,0.278], [0.294,0.338], [0.359,0.412])	–
C_{10}	([0.209,0.273], [0.287,0.356], [0.375,0.470])	([0.063,0.084], [0.097,0.128], [0.147,0.201])
C_{11}	([0.221,0.283], [0.295,0.363], [0.382,0.477])	([0.049,0.076], [0.084,0.120], [0.135,0.194])
C_{12}	([0.325,0.336], [0.353,0.374], [0.386,0.423])	([0.052,0.079], [0.087,0.123], [0.137,0.197])

where A and H respectively represent the arithmetic and harmonic mean of the elements ψ_b and ψ_1.

Step 4: *Calculation of criterion functions $Q(A_i)$ and ranking of alternatives*. Using Eq. (22), the fuzzy rough criterion functions of the alternatives ($Q(A_i)$) are calculated, and the alternatives are ranked.

From the considered set of alternatives, the alternative with a higher value of the fuzzy rough criterion function $Q(A_i)$ is chosen. If the two alternatives A_1 and A_2 have the values of the criterion functions $Q(A_1)$ and $Q(A_2)$ then $Q(A_1)\rangle Q(A_2)$ if$h(Q(A_1))\rangle h(Q(A_2))$, where.

$$h(Q(A_1)) = \frac{Q_1^{(l)-} + Q_1^{(l)+} + Q_1^{(m)-} + Q_1^{(m)+} + Q_1^{(u)-} + Q_1^{(u)+}}{6} \quad (23)$$

$$h(Q(A_2)) = \frac{Q_2^{(l)-} + Q_2^{(l)+} + Q_2^{(m)-} + Q_2^{(m)+} + Q_2^{(u)-} + Q_2^{(u)+}}{6} \quad (24)$$

5. Application of FRN LAAW-RAFSI methodology

5.1. The results of proposed model

As shown in Fig. 8, the integrated FRN LAAW-RAFSI methodology is

Table 9
Experts correspondence matrices.

Criteria	A_1	A_2	A_3
C_1	–	–	–
C_2	MH; H; M; MH; M	H; M; MH; MH; MH	VH; H; VH; VH; VH
C_3	H; MH; MH; M; MH	M; ML; ML; M; ML	MH; H; VH; H; VH
C_4	–	–	–
C_5	–	–	–
C_6	H; MH; MH; MH; MH	M; ML; ML; ML; ML	H; VH; VH; VH; VH
C_7	VH; H; H; VH; H	H; M; M; MH; M	M; L; ML; L; ML
C_8	M; M; MH; MH; MH	M; M; MH; M; ML	H; H; MH; VH; MH
C_9	MH; H; MH; VH; MH	VH; MH; MH; H; MH	ML; L; ML; L; M
C_{10}	M; L; ML; L; ML	M; M; MH; ML; MH	L; ML; L; ML; L
C_{11}	M; H; M; MH; M	L; L; L; L; L	H; VH; H; VH; MH
C_{12}	MH; VH; MH; H; H	VH; H; MH; MH; H	MH; MH; MH; VH; H
Criteria	A_4	A_5	A_6
C_1	–	–	–
C_2	L; ML; M; ML; M	VH; VH; VH; H; VH	H; MH; VH; MH; H
C_3	MH; M; M; MH; M	ML; ML; L; L; L	VH; VH; H; VH; H
C_4	–	–	–
C_5	–	–	–
C_6	MH; M; M; M; M	ML; ML; M; ML; M	VH; H; H; H; H
C_7	MH; VH; MH; H; MH	ML; L; M; M; M	MH; H; H; H; VH
C_8	M; M; MH; H; MH	M; H; MH; M; MH	ML; MH; MH; ML; MH
C_9	MH; M; MH; M; MH	ML; VL; ML; ML; ML	H; VH; MH; MH; MH
C_{10}	MH; M; ML; M; ML	MH; H; MH; VH; H	ML; MH; M; MH; M
C_{11}	M; MH; M; H; M	L; ML; ML; M; ML	ML; M; ML; ML; ML
C_{12}	MH; M; MH; MH; M	ML; ML; MH; ML; M	H; M; MH; M; M

Table 10
FRN criterion functions and the final ranking of alternatives.

Alt.	$Q(A_i)$	Rank
A_1	([0.2068,0.3460],[0.4318,0.6749],[0.8629,1.3340])	2
A_2	([0.1696,0.2829],[0.3584,0.5625],[0.7191,1.1389])	5
A_3	([0.2440,0.3754],[0.4671,0.6993],[0.8807,1.3206])	1
A_4	([0.1710,0.2826],[0.3668,0.5833],[0.7479,1.2319])	4
A_5	([0.1636,0.2449],[0.3218,0.4971],[0.6197,1.0300])	6
A_6	([0.2072,0.3293],[0.4095,0.6301],[0.7855,1.2387])	3

implemented through two phases. In the first phase, the weight coefficients of the criteria are calculated using the FRN LAAW model. In contrast, in the second phase, the evaluation of alternatives is performed using the FRN RAFSI model and the validation of the obtained solutions. The following section presents the application of the integrated FRN LAAW-RAFSI model for the evaluation of six alternatives. For the assessment of alternatives, twelve criteria are identified and grouped within three clusters (see Table 5).

The participants have experience in the sector and been chosen from the networks of the Multi-Purpose Floating Solar Power Plant (FloSoWer) project participants (see Acknowledgements). There are also participants from Turkey, Iran, United Kingdom and Portugal so that experience of countries with installed renewable energy systems and local conditions of Turkey have been combined. The participants have different backgrounds including civil engineers, electrical engineers, mechanical engineering, biologists, solar PV project managers and renewable energy project financers.

(a) *Defining the weight coefficients of the criteria using the FRN based LAAW method*

Step 1: The study involved five experts who evaluated the criteria using the fuzzy scale given in Table 4.

Based on the expert assessments, a priority vector was defined for each expert as given in Table 5.

Using Eqs. (1)–(8), the fuzzy priority vectors (see Table 5) coefficients were transformed into FRN priority vectors (see Table 6). The Eq. (13) is used for the fusion of the FRN priority vector. In Appendix B we have given the transformation of expert assessments in the priority

Table A1
Aggregated FRN initial matrix.

Crit.	A_1	A_2	A_3
C_1	([1781,1781],[1781,1781],[1781,1781])	([1724,1724],[1724,1724],[1724,1724])	([1822,1822],[1822,1822],[1822,1822])
C_2	([3.63,5.39],[5.66,7.42],[7.64,9.06])	([4.22,5.64],[6.24,7.65],[8.22,9.29])	([8.25,8.91],[9.63,9.96],[10.0,10.0])
C_3	([4.22,5.64],[6.24,7.65],[8.22,9.29])	([1.27,2.19],[3.30,4.25],[5.32,6.27])	([6.43,8.24],[8.30,9.59],[9.63,9.96])
C_4	([10.3,10.3],[10.3,10.3],[10.3,10.3])	([18.3,18.3],[18.3,18.3],[18.3,18.3])	([21.1,21.1],[21.1,21.1],[21.1,21.1])
C_5	([1315,1315],[1315,1315],[1315,1315])	([277,277],[277,277],[277,277])	[32,32],[32,32];[32,32])
C_6	([5.07,5.68],[7.07,7.69],[9.04,9.35])	([1.06,1.59],[3.07,3.66],[5.07,5.68])	([8.25,8.91],[9.63,9.96],[10.0,10.0])
C_7	([7.32,8.28],[9.17,9.65],[10.0,10.0])	([3.30,5.00],[5.31,7.04],[7.29,8.68])	([1.06,1.59],[2.35,3.56],[3.63,5.39])
C_8	([3.66,4.64],[5.68,6.65],[7.69,8.66])	([2.13,3.59],[4.22,5.64],[6.24,7.65])	([5.66,7.42],[7.64,9.06],[9.35,9.84])
C_9	([5.31,7.04],[7.29,8.68],[9.17,9.65])	([5.31,7.04],[7.29,8.68],[9.17,9.65])	([1.06,1.59],[2.35,3.56],[3.63,5.39])
C_{10}	([1.06,1.59],[2.35,3.56],[3.63,5.39])	([2.27,4.17],[4.39,6.22],[6.43,8.24])	([1.00,1.00],[2.16,2.63],[3.30,4.25])
C_{11}	([3.30,5.0],[5.31,7.04],[7.29,8.68])	([1.00,1.00],[2.00,2.00],[3.00,3.00])	([6.43,8.24],[8.3,9.59],[9.63,9.96])
C_{12}	([5.66,7.42],[7.64,9.06],[9.35,9.84])	([5.66,7.42],[7.64,9.06],[9.35,9.84])	([5.31,7.04],[7.29,8.68],[9.17,9.65])
Crit.	A_4	A_5	A_6
C_1	([1726,1726],[1726,1726],[1726,1726])	([1822,1822],[1822,1822],[1822,1822])	([1794,1794],[1794,1794],[1794,1794])
C_2	([1.27,2.19],[2.84,4.25],[4.39,6.22])	([8.25,8.91],[9.63,9.96],[10.0,10.0])	([5.66,7.42],[7.64,9.06],[9.35,9.84])
C_3	([3.30,4.25],[5.32,6.27],[7.32,8.28])	([1.00,1.00],[2.16,2.63],[3.30,4.25])	([7.69,8.66],[9.35,9.84],[10.0,10.0])
C_4	([17.3,17.3],[17.3,17.3],[17.3,17.3])	([19.9,19.9],[19.9,19.9],[19.9,19.9])	([19.1,19.1],[19.1,19.1],[19.1,19.1])
C_5	([457,457],[457,457],[457,457])	([162,162],[162,162],[162,162])	([250,250],[250,250],[250,250])
C_6	([3.07,3.66],[5.07,5.68],[7.07,7.69])	([1.27,2.19],[3.30,4.25],[5.32,6.27])	([7.07,7.69],[9.04,9.35],[10.0,10.0])
C_7	([5.31,7.04],[7.29,8.68],[9.17,9.65])	([1.59,2.59],[3.16,4.64],[4.70,6.60])	([6.24,7.65],[8.22,9.29],[9.63,9.96])
C_8	([3.63,5.39],[5.66,7.42],[7.64,9.06])	([3.63,5.39],[5.66,7.42],[7.64,9.06])	([2.05,4.10],[4.23,6.22],[6.29,8.27])
C_9	([3.66,4.64],[5.68,6.65],[7.69,8.66])	[1,1],[2.15,2.89],[3.18,4.75])	([5.31,7.04],[7.29,8.68],[9.17,9.65])
C_{10}	([1.55,3.29],[3.63,5.39],[5.66,7.42])	([5.66,7.42],[7.64,9.06],[9.35,9.84])	([2.27,4.17],[4.39,6.22],[6.43,8.24])
C_{11}	([3.30,5.00,[5.31,7.04],[7.29,8.68])	([1.06,1.59],[2.65,3.66],[4.22,5.64])	([1.06,1.59],[3.07,3.66],[5.07,5.68])
C_{12}	([3.66,4.64],[5.68,6.65],[7.69,8.66])	([1.25,2.88],[3.3,5],[5.31,7.04])	([3.3,5],[5.31,7.04],[7.29,8.68])

Table A2
Standardized FRN matrix.

Crit.	A_1	A_2	A_3
C_1	([3.62,3.62], [3.62,3.62], [3.62,3.62])	([2.48,2.48], [2.48,2.48], [2.48,2.48])	([4.44,4.44], [4.44,4.44], [4.44,4.44])
C_2	([2.41,3.19], [3.46,4.3], [4.63,5.36])	([2.67,3.3], [3.74,4.41], [4.93,5.48])	([4.47,4.77], [5.35,5.5], [5.84,5.84])
C_3	([2.67,3.3], [3.74,4.41], [4.93,5.48])	([1.35,1.76], [2.34,2.79], [3.45,3.94])	([3.66,4.46], [4.71,5.33], [5.65,5.82])
C_4	([1.46,1.46], [1.46,1.46], [1.46,1.46])	([4.32,4.32], [4.32,4.32], [4.32,4.32])	([5.32,5.32], [5.32,5.32], [5.32,5.32])
C_5	([5.69,5.69], [5.69,5.69], [5.69,5.69])	([1.9,1.9],[1.9,1.9], [1.9,1.9])	([1.01,1.01], [1.01,1.01], [1.01,1.01])
C_6	([3.05,3.32], [4.13,4.42], [5.35,5.51])	([1.26,1.5],[2.22,2.5], [3.32,3.63])	([4.47,4.77], [5.35,5.5], [5.84,5.84])
C_7	([4.05,4.48], [5.13,5.36], [5.84,5.84])	([2.26,3.02], [3.29,4.12], [4.45,5.16])	([1.26,1.5], [1.88,2.46], [2.59,3.48])
C_8	([2.42,2.86], [3.47,3.93], [4.66,5.15])	([1.74,2.39], [2.77,3.45], [3.92,4.64])	([3.31,4.1],[4.4,5.08], [5.51,5.75])
C_9	([3.16,3.93], [4.23,4.9], [5.41,5.66])	([3.16,3.93], [4.23,4.9], [5.41,5.66])	([1.26,1.5], [1.88,2.46], [2.59,3.48])
C_{10}	([1.26,1.5], [1.88,2.46], [2.59,3.48])	([1.8,2.65], [2.85,3.72], [4.01,4.94])	([1.23,1.23], [1.79,2.02], [2.42,2.91])
C_{11}	([2.26,3.02], [3.29,4.12], [4.45,5.16])	([1.23,1.23], [1.71,1.71], [2.27,2.27])	([3.66,4.46], [4.71,5.33], [5.65,5.82])
C_{12}	([3.31,4.1],[4.4,5.08], [5.51,5.75])	([3.31,4.1],[4.4,5.08], [5.51,5.75])	([3.16,3.93], [4.23,4.9], [5.41,5.66])
Crit.	A_4	A_5	A_6
C_1	([2.52,2.52], [2.52,2.52], [2.52,2.52])	([4.44,4.44], [4.44,4.44], [4.44,4.44])	([3.88,3.88], [3.88,3.88], [3.88,3.88])
C_2	([1.35,1.76], [2.11,2.79], [2.97,3.91])	([4.47,4.77], [5.35,5.5], [5.84,5.84])	([3.31,4.1],[4.4,5.08], [5.51,5.75])
C_3	([2.26,2.69], [3.29,3.75], [4.47,4.96])	([1.23,1.23], [1.79,2.02], [2.42,2.91])	([4.22,4.65], [5.22,5.45], [5.84,5.84])
C_4	([3.96,3.96], [3.96,3.96], [3.96,3.96])	([4.89,4.89], [4.89,4.89], [4.89,4.89])	([4.61,4.61], [4.61,4.61], [4.61,4.61])
C_5	([2.56,2.56], [2.56,2.56], [2.56,2.56])	([1.48,1.48], [1.48,1.48], [1.48,1.48])	([1.8,1.8],[1.8,1.8], [1.8,1.8])
C_6	([2.16,2.42], [3.18,3.47], [4.34,4.66])	([1.35,1.76], [2.34,2.79], [3.45,3.94])	([3.94,4.22], [5.07,5.22], [5.84,5.84])
C_7	([3.16,3.93], [4.23,4.9], [5.41,5.66])	([1.49,1.94], [2.27,2.97], [3.13,4.1])	([3.57,4.2], [4.68,5.19], [5.65,5.82])
C_8	([2.41,3.19], [3.46,4.3], [4.63,5.36])	([2.41,3.19], [3.46,4.3], [4.63,5.36])	([1.7,2.62], [2.78,3.73], [3.95,4.95])
C_9	([2.42,2.86], [3.47,3.93], [4.66,5.15])	([1.23,1.23], [1.79,2.14], [2.36,3.16])	([3.16,3.93], [4.23,4.9], [5.41,5.66])
C_{10}	([1.48,2.26], [2.49,3.33], [3.62,4.52])	([3.31,4.1],[4.4,5.08], [5.51,5.75])	([1.8,2.65], [2.85,3.72], [4.01,4.94])
C_{11}	([2.26,3.02], [3.29,4.12], [4.45,5.16])	([1.26,1.5], [2.02,2.51], [2.89,3.61])	([1.26,1.5],[2.22,2.5], [3.32,3.63])
C_{12}	([2.42,2.86], [3.47,3.93], [4.66,5.15])	([1.34,2.07], [2.33,3.14], [3.45,4.33])	([2.26,3.02], [3.29,4.12], [4.45,5.16])

vector for the main criteria group from Table 5 at the position of the C_4 group of criteria.

Step 2: The absolute anti-ideal point $\overline{\delta}_{AIP}$ is defined based on the condition $\overline{\delta}_{AIP} < \min(\overline{\theta}_1, \overline{\theta}_2, .., \overline{\theta}_n)$. The value $\overline{\delta}_{AIP} = ([0.6, 0.6], [0.6, 0.6], [0.6, 0.6])$ is arbitrarily adopted. Since the final values of the weighting coefficients depend on the value of $\overline{\delta}_{AIP}$, an analysis of the influence of different values of $\overline{\delta}_{AIP}$ on the final results of the FRN LAAW-RAFSI model was performed. A detailed analysis is shown in the next section of the paper.

Step 3: Using Eq. (14), the ratio vectors are defined $X = (\overline{\gamma}_1, \overline{\gamma}_2, .., \overline{\gamma}_n)$, Table 7.

Step 4: By applying Eq. (15), FRN vectors of weight coefficients of the criteria are obtained in Table 8.

The global values of the criteria were obtained by multiplying the local values of the main group of criteria with the values of the weight coefficients within the corresponding group. Global criterion values are used to assess the alternatives using the FRN RAFSI model.

(b) *Alternative ranking – Application of the FRN RAFSI model*

Step 1: The evaluation of alternatives was performed concerning twelve criteria. Criteria C_2, C_3, and C_6-C_{12} are qualitative, and the experts evaluated the alternatives concerning the above criteria using the fuzzy linguistic terms presented in Table 4. Criteria C_1, C_4, and C_5 are quantitative, and values are defined based on measured values. The following section presents expert correspondence matrices that contain quality-type criteria as given in Table 9.

Based on the presented expert preferences, it is evident that there are deviations in expert assessments. To consider and exploit the presented uncertainties and inaccuracies (see Table 9), expert preferences were transformed into fuzzy rough numbers. Using Eqs. (1)–(8) fuzzy expert estimates were transformed into FRN values. The fusion of expert correspondent matrices into aggregated into FRN initial decision matrices (see Table A.1 in Appendix A) was performed using the Bonferroni function.

Step 2: In the following section, the elements of the FRN matrix (see Table A.1) were mapped into the criterion intervals. Then, based on consensus, the experts defined values $\overline{\chi}_{I_j}$ and $\overline{\chi}_{N_j}$ for each criterion:

(a) Ideal values:

$\overline{\chi}_{I_{C1}} = ([1900, 1900], [1900, 1900], [1900, 1900]);$

$\overline{\chi}_{I_{C2}} = \overline{\chi}_{I_{C3}} = \overline{\chi}_{I_{C6}} = \overline{\chi}_{I_{C8}} = \overline{\chi}_{I_{C9}} = \overline{\chi}_{I_{C11}} = \overline{\chi}_{I_{C12}} = ([10, 10], [11, 11], [12, 12]);$

$\overline{\chi}_{I_{C4}} = ([23, 23], [23, 23], [23, 23]);$

$\overline{\chi}_{I_{C5}} = ([1400, 1400], [1400, 1400], [1400, 1400]);$

$\overline{\chi}_{I_{C7}} = \overline{\chi}_{I_{C10}} = ([0.2, 0.2], [0.5, 0.5], [0.8, 0.8]).$

(b) Anti-ideal values:

$\overline{\chi}_{N_{C1}} = ([1650, 1650], [1650, 1650], [1650, 1650]);$

$\overline{\chi}_{N_{C2}} = \overline{\chi}_{N_{C3}} = \overline{\chi}_{N_{C6}} = \overline{\chi}_{N_{C8}} = \overline{\chi}_{N_{C9}} = \overline{\chi}_{N_{C11}} = \overline{\chi}_{N_{C12}} = ([0.2, 0.2], [0.5, 0.5], [0.8, 0.8]);$

$\overline{\chi}_{N_{C4}} = ([9, 9], [9, 9], [9, 9]);$

$\overline{\chi}_{N_{C5}} = ([30, 30], [30, 30], [30, 30]);$

$\overline{\chi}_{N_{C7}} = \overline{\chi}_{N_{C10}} = ([10, 10], [11, 11], [12, 12]);$

Using Eq. (20), the FRN functions are defined, based on which the elements of the aggregated FRN initial decision matrix are mapped into the criterion interval $[\psi_1, \psi_b]$. In this study, it was adopted that the ideal value of the alternative is six times higher than the anti - ideal value, that is $\psi_1 = 1$ and $\psi_b = 6$. The procedure for obtaining the FRN criterion function for criterion C_2 is presented. Since criterion C_2 belongs to the benefit group, based on Eq. (24), the condition that $\psi_b \geq 6$, $\overline{\chi}_{I_{C2}} = ([10,$

Table A3
Normalized FRN decision matrix.

Crit.	A_1	A_2	A_3
C_1	([0.52,0.52], [0.52,0.52], [0.52,0.52])	([0.35,0.35], [0.35,0.35], [0.35,0.35])	([0.63,0.63], [0.63,0.63], [0.63,0.63])
C_2	([0.34,0.46], [0.49,0.61], [0.66,0.77])	([0.38,0.47], [0.53,0.63], [0.7,0.78])	([0.64,0.68], [0.76,0.79], [0.83,0.83])
C_3	([0.38,0.47], [0.53,0.63], [0.7,0.78])	([0.19,0.25], [0.33,0.4], [0.49,0.56])	([0.52,0.64], [0.67,0.76], [0.81,0.83])
C_4	([0.21,0.21], [0.21,0.21], [0.21,0.21])	([0.62,0.62], [0.62,0.62], [0.62,0.62])	([0.76,0.76], [0.76,0.76], [0.76,0.76])
C_5	([0.81,0.81], [0.81,0.81], [0.81,0.81])	([0.27,0.27], [0.27,0.27], [0.27,0.27])	([0.14,0.14], [0.14,0.14], [0.14,0.14])
C_6	([0.44,0.47], [0.59,0.63], [0.76,0.79])	([0.18,0.21], [0.32,0.36], [0.47,0.52])	([0.64,0.68], [0.76,0.79], [0.83,0.83])
C_7	([0.15,0.15], [0.16,0.17], [0.19,0.21])	([0.17,0.19], [0.21,0.26], [0.28,0.38])	([0.25,0.33], [0.35,0.46], [0.57,0.68])
C_8	([0.35,0.41], [0.5,0.56], [0.67,0.74])	([0.25,0.34], [0.4,0.49], [0.56,0.66])	([0.47,0.59], [0.63,0.73], [0.79,0.82])
C_9	([0.45,0.56],[0.6,0.7], [0.77,0.81])	([0.45,0.56],[0.6,0.7], [0.77,0.81])	([0.18,0.21], [0.27,0.35], [0.37,0.5])
C_{10}	([0.25,0.33], [0.35,0.46], [0.57,0.68])	([0.17,0.21], [0.23,0.3], [0.32,0.48])	([0.3,0.35], [0.43,0.48],[0.7,0.7])
C_{11}	([0.32,0.43], [0.47,0.59], [0.64,0.74])	([0.18,0.18], [0.24,0.24], [0.32,0.32])	([0.52,0.64], [0.67,0.76], [0.81,0.83])
C_{12}	([0.47,0.59], [0.63,0.73], [0.79,0.82])	([0.47,0.59], [0.63,0.73], [0.79,0.82])	([0.45,0.56],[0.6,0.7], [0.77,0.81])
	A_4	A_5	A_6
C_1	([0.36,0.36], [0.36,0.36], [0.36,0.36])	([0.63,0.63], [0.63,0.63], [0.63,0.63])	([0.55,0.55], [0.55,0.55], [0.55,0.55])
C_2	([0.19,0.25],[0.3,0.4], [0.42,0.56])	([0.64,0.68], [0.76,0.79], [0.83,0.83])	([0.47,0.59], [0.63,0.73], [0.79,0.82])
C_3	([0.32,0.38], [0.47,0.54], [0.64,0.71])	([0.18,0.18], [0.26,0.29], [0.35,0.42])	([0.6,0.66], [0.75,0.78], [0.83,0.83])
C_4	([0.57,0.57], [0.57,0.57], [0.57,0.57])	([0.7,0.7],[0.7,0.7], [0.7,0.7])	([0.66,0.66], [0.66,0.66], [0.66,0.66])
C_5	([0.37,0.37], [0.37,0.37], [0.37,0.37])	([0.21,0.21], [0.21,0.21], [0.21,0.21])	([0.26,0.26], [0.26,0.26], [0.26,0.26])
C_6	([0.31,0.35], [0.45,0.5], [0.62,0.67])	([0.19,0.25], [0.33,0.4], [0.49,0.56])	([0.56,0.6], [0.72,0.75], [0.83,0.83])
C_7	([0.15,0.16], [0.18,0.2], [0.22,0.27])	([0.21,0.27], [0.29,0.38], [0.44,0.57])	([0.15,0.15], [0.17,0.18], [0.2,0.24])
C_8	([0.34,0.46], [0.49,0.61], [0.66,0.77])	([0.34,0.46], [0.49,0.61], [0.66,0.77])	([0.24,0.37], [0.4,0.53], [0.56,0.71])
C_9	([0.35,0.41], [0.5,0.56], [0.67,0.74])	([0.18,0.18], [0.26,0.31], [0.34,0.45])	([0.45,0.56],[0.6,0.7], [0.77,0.81])
C_{10}	([0.19,0.24], [0.26,0.34], [0.38,0.58])	([0.15,0.16], [0.17,0.19], [0.21,0.26])	([0.17,0.21], [0.23,0.3], [0.32,0.48])
C_{11}	([0.32,0.43], [0.47,0.59], [0.64,0.74])	([0.18,0.21], [0.29,0.36], [0.41,0.52])	([0.18,0.21], [0.32,0.36], [0.47,0.52])
C_{12}	([0.35,0.41], [0.5,0.56], [0.67,0.74])	([0.19,0.3], [0.33,0.45], [0.49,0.62])	([0.32,0.43], [0.47,0.59], [0.64,0.74])

10], [11, 11], [12, 12]) and $\overline{\chi}_{N_{C2}} = ([0.2, 0.2], [0.5, 0.5], [0.8, 0.8])$ we get that:

$$\overline{\varphi}_{iC2} = \left(\left[\varphi^{(l)-}_{iC2}, \varphi^{(l)+}_{iC2}\right], \left[\varphi^{(m)-}_{iC2}, \varphi^{(m)+}_{iC2}\right], \left[\varphi^{(u)-}_{iC2}, \varphi^{(u)+}_{iC2}\right] \right) = \begin{cases} \varphi^{(l)-}_{iC2} = \varphi^{(l)+}_{iC2} = 0.446 \cdot \overline{\chi}_{iC2} + 0.786 \\ \varphi^{(m)-}_{iC2} = \varphi^{(m)+}_{iC2} = 0.476 \cdot \overline{\chi}_{iC2} + 0.762 \\ \varphi^{(u)-}_{iC2} = \varphi^{(u)+}_{iC2} = 0.510 \cdot \overline{\chi}_{iC2} + 0.735 \end{cases}$$

Similarly, we get the FRN criterion functions of the remaining criteria. The criterion functions were used to standardize the criterion values from the aggregated FRN initial matrix. Thus, we obtain a standardized FRN matrix by which all matrix elements are translated into an interval $1 \leqslant \overline{\varphi}_{ij} \leqslant 6$, Table A.2.

The following section shows the calculation of the element from Table A.2 at position C_2-A_1:

$$\overline{\varphi}_{A1-C2} = \left(\left[\varphi^{(l)-}_{A1-C2}, \varphi^{(l)+}_{A1-C2}\right], \left[\varphi^{(m)-}_{A1-C2}, \varphi^{(m)+}_{A1-C2}\right], \left[\varphi^{(u)-}_{A1-C2}, \varphi^{(u)+}_{A1-C2}\right] \right) = \begin{cases} \varphi^{(l)-}_{A1-C2} = 0.446 \cdot 3.63 + 0.786 = 2.41; \\ \varphi^{(l)+}_{A1-C2} = 0.446 \cdot 5.39 + 0.786 = 3.19; \\ \varphi^{(m)-}_{A1-C2} = 0.476 \cdot 6.24 + 0.762 = 3.46; \\ \varphi^{(m)+}_{A1-C2} = 0.476 \cdot 7.65 + 0.762 = 4.30; \\ \varphi^{(u)-}_{A1-C2} = 0.510 \cdot 8.22 + 0.735 = 4.63; \\ \varphi^{(u)+}_{A1-C2} = 0.510 \cdot 9.29 + 0.735 = 5.36. \end{cases}$$

$$= ([2.41, 3.19], [3.46, 4.3], [4.63, 5.36])$$

Similarly, we get the remaining elements from Table A.2.

Step 3: By using Eq. (25), we normalize the elements of the standardized decision matrix. The arithmetic and harmonic means of the elements $\psi_1 = 1$ and $\psi_b = 6$ were used to obtain the elements of the normalized matrix $\aleph_N = \left[\widehat{\varphi}_{ij}\right]_{6 \times 12}$. So we get that $A = 3.5$ and $H = 1.71$. The elements of the matrix $\aleph_N$ are reported in Table A.3.

Step 4: Using Eq. (22), the FRN criterion functions of the alternatives ($Q(A_i)$) are calculated. The FRN values of the alternatives are ranked using Eqs. (23) and (24) provided that the alternative with the higher value occupies a better rank. The ranking of alternatives is given in Table 10.

A graphical interpretation of the values of the FRN criterion functions of the alternatives is shown in Fig. 9.

Based on the obtained results, A_3 is the best solution. In the following part, the stability analysis of the obtained solution is performed. Stability analysis, i.e., checking the credibility of the initial solution, is performed through four phases, which are presented in the next section.

5.2. Validation of the results

There are parameters in decision-making models whose definition depends on the subjective assessments of the decision-maker. Furthermore, the values of subjectively defined parameters depend on the perception of the problem by the decision-maker. Therefore, it is expected that different groups of experts perceive the values of these parameters in different ways. Therefore, the question rightly arises: "Do subjectively defined values have a decisive influence on the final results?". In the following section, subjectively defined parameters in the FRN LAAW-RAFSI methodology were identified, and three experiments were performed based on the identified parameters:

– Experiment 1: When calculating the weighting coefficients using the FRN LAAW methodology, defining the absolute anti-ideal point ($\overline{\delta}_{AIP}$) is necessary. Respecting the condition that $\overline{\delta}_{AIP} < \min(\overline{\theta}_1, \overline{\theta}_2, .., \overline{\theta}_n)$. During the calculation of the initial

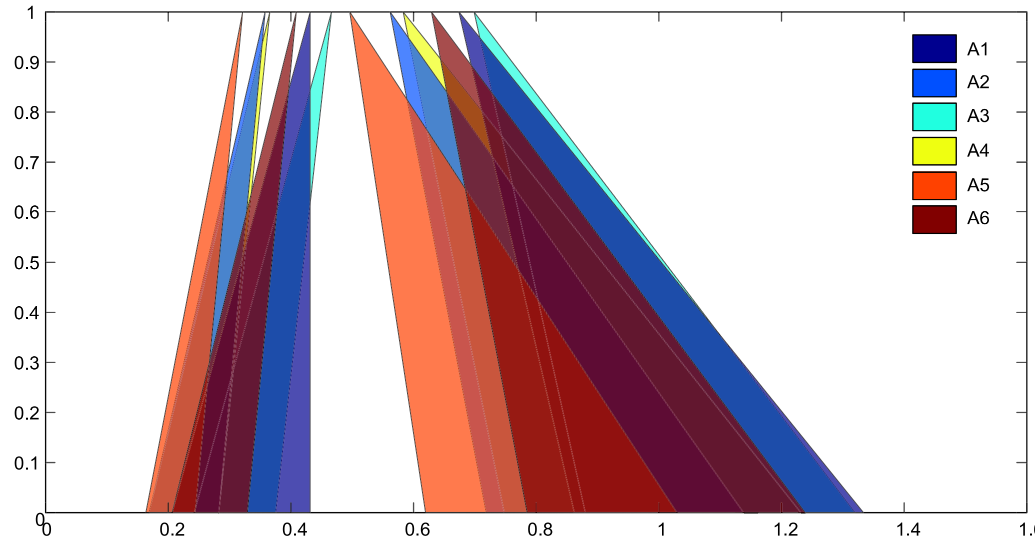


Fig. 9. FRN criterion functions $Q(A_i)$.

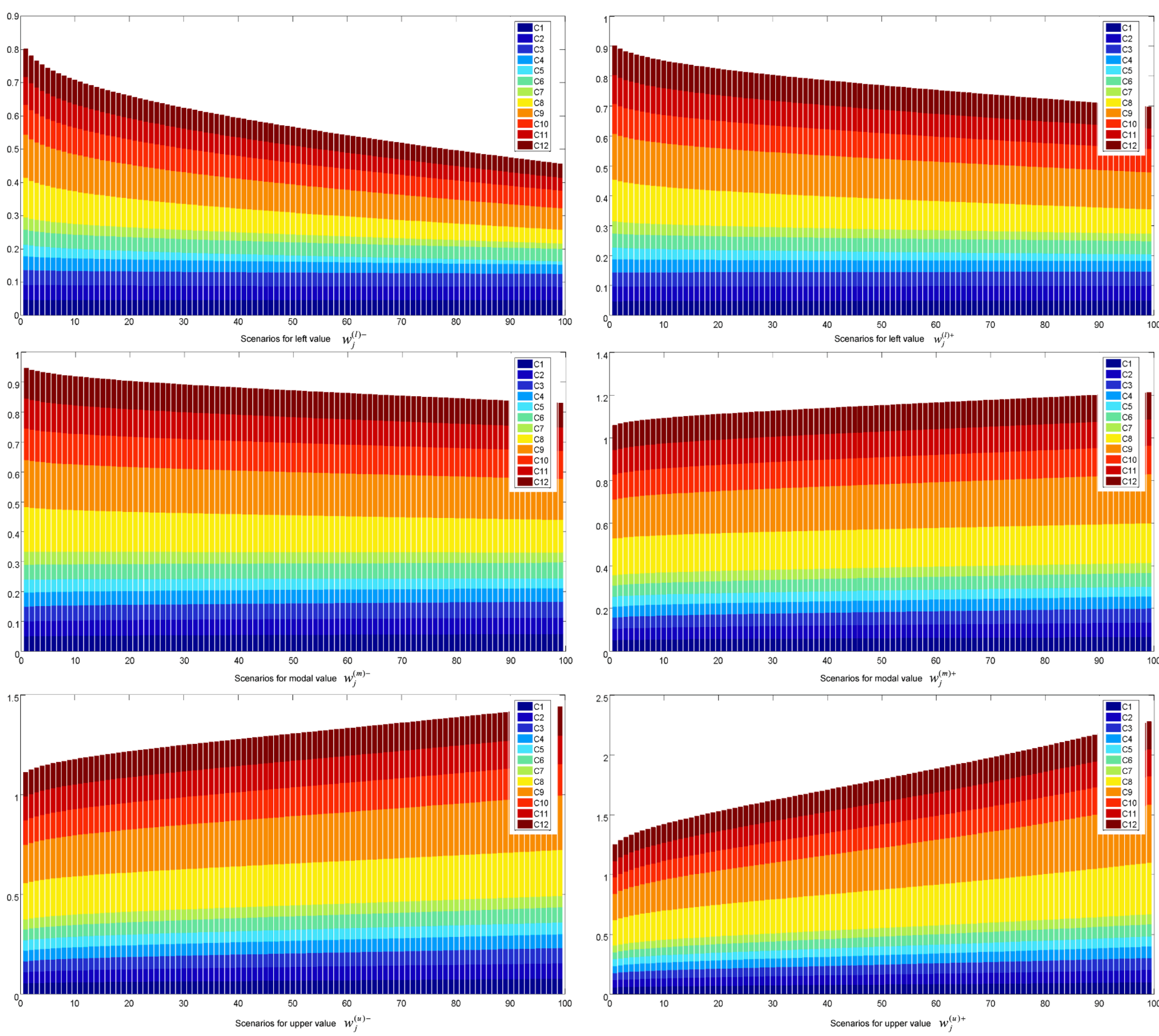


Fig. 10. Influence of AAIP on change of rough boundary interval of criteria weights.

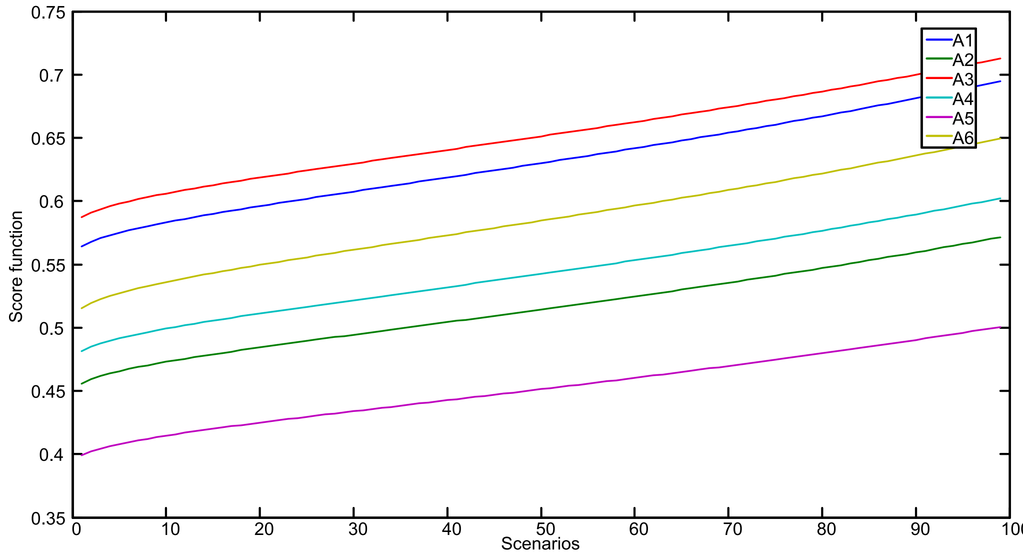


Fig. 11. Demonstration of the influence of AAIP change on the change in the value of $Q(A_i)$.

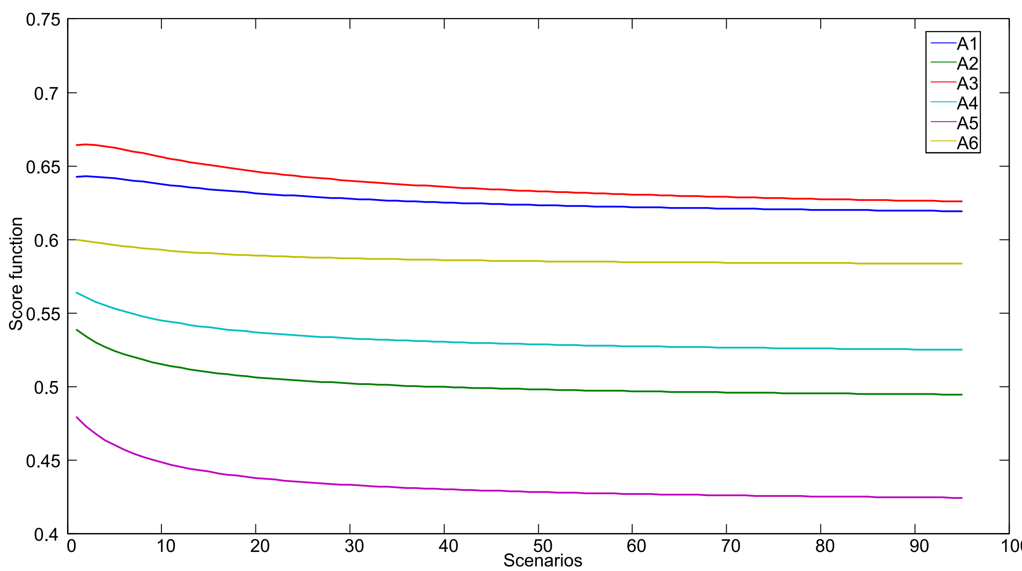


Fig. 12. Influence of change ψ_b on change of values $Q(A_i)$.

results, the value of $\overline{\delta}_{AIP} = ([0.6, 0.6], [0.6, 0.6], [0.6, 0.6])$ was adopted. The anti-ideal point directly influences the final values of the FRN weighting coefficients of the criteria and thus on the final results. Therefore, in this experiment, the change in the value of $\overline{\delta}_{AIP}$ in the interval $0.01 \leq \overline{\delta}_{AIP} \leq 1$ was simulated. Simultaneously with the change in values in this experiment, the change in the values of the FRN weighting coefficients of the criteria and their influence on the change in the initial results were monitored.

– Experiment 2: When defining the fuzzy rough function $\overline{\varphi}_{ij}$ in the FRN RAFSI model, it is necessary to define the values of ψ_b and ψ_1. The values of ψ_b and ψ_1 represent the ratio. Based on the recommendations of Pamucar et al. [51] the value of $\psi_b = 6$ is adopted, while $\psi_1 = 1$. Based on the defined parameters, the initial matrix is standardized in the interval [49,52]. In this experiment, the change in the value of ψ_b in the interval $6 \leq \psi_b \leq 100$ was simulated. At the same time, the influence of the change of the mentioned parameter on the change of the final results was analyzed.

– Experiment 3: When transforming fuzzy sets into fuzzy rough numbers, it is necessary to adopt the values of the parameters μ_1 and μ_2 in Eqs. (3)–(8). When calculating the initial results, the values of the parameters $\mu_1 = \mu_2 = 1$ were adopted. In this experiment, the change of parameters μ_1 and μ_2 in the interval $1 \leq \mu_1, \mu_2 \leq 100$ was simulated. At the same time, the influence of the change of the mentioned parameters on the change of the values of the criterion functions in the FRN RAFSI model was analyzed.

(a) *Experiment 1: Change the value of the absolute anti-ideal point ($\overline{\delta}_{AIP}$)*

The absolute-ideal point (AAIP) absolute value is defined in the FRN LAAW model to define the fuzzy rough ratio vector. The absolute anti-ideal point is defined based on the condition $\overline{\delta}_{AIP} < \min(\overline{\vartheta}_1, \overline{\vartheta}_2, .., \overline{\vartheta}_n)$. Based on the fuzzy rough priority vector, the AAIP can take any value from the interval $0.01 \leq \overline{\delta}_{AIP} \leq 1$. In this study, the value of $\overline{\delta}_{AIP} = 0.6$ was introduced to calculate the initial results. The value of $\overline{\delta}_{AIP} = 0.6$ was adopted based on expert recommendations.

In this experiment, 99 scenarios were carried out. In the first sce-

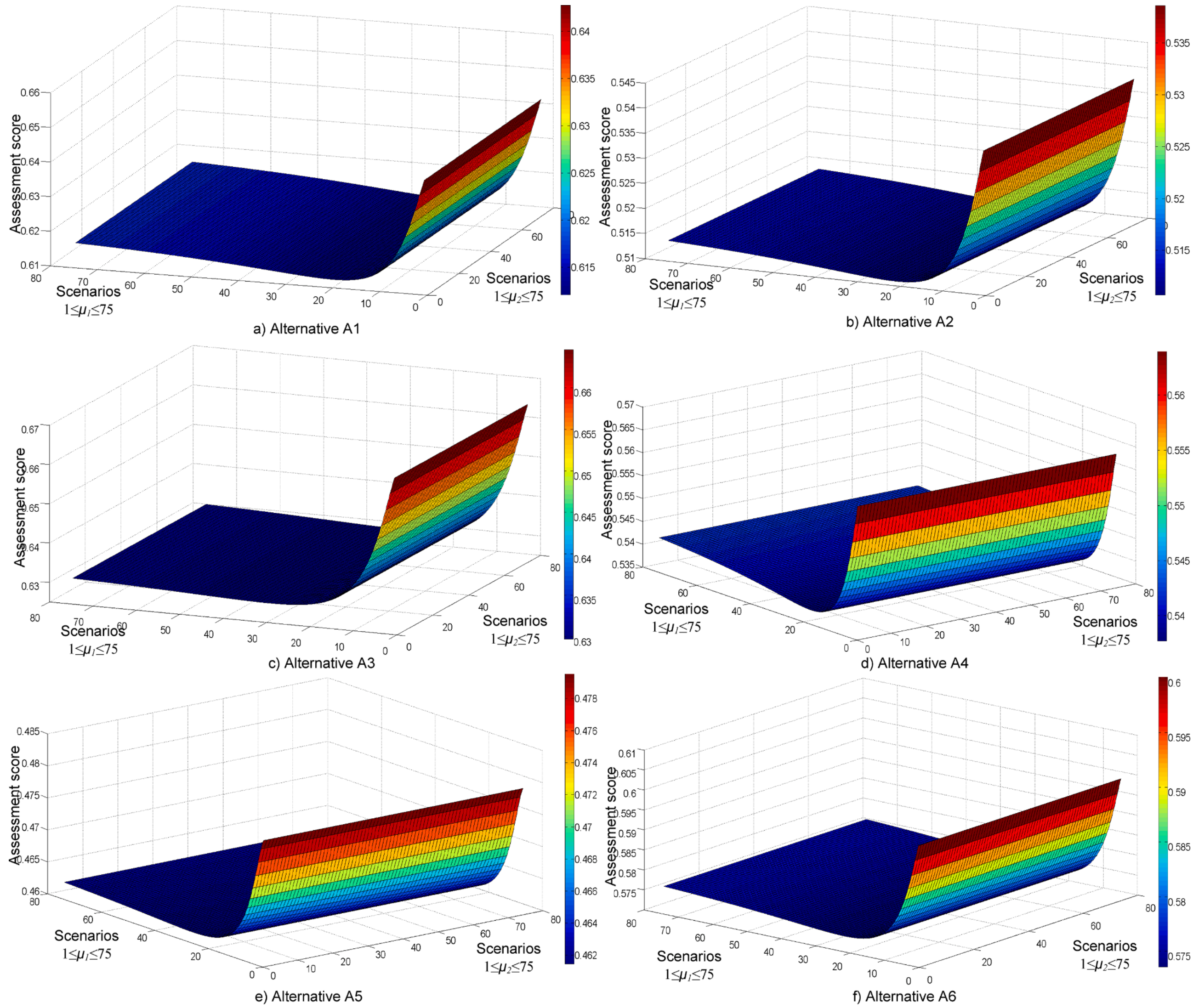


Fig. 13. Influence of change of parameters $1 \le \mu_1, \mu_2 \le 75$ on change $Q(A_i)$.

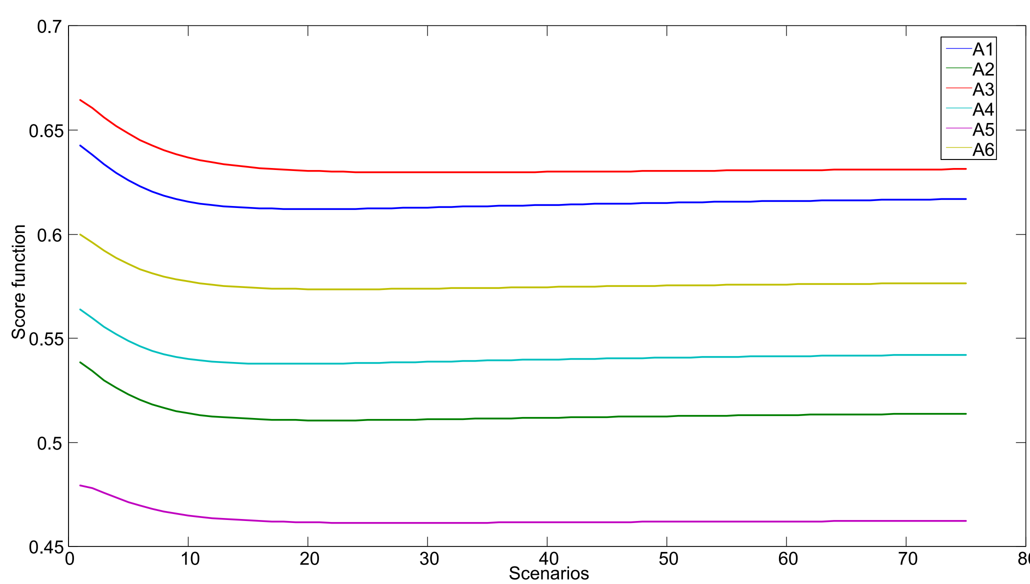


Fig. 14. Comparative presentation of the influence of the change of parameters $1 \le \mu_1, \mu_2 \le 75$ on the change $Q(A_i)$.

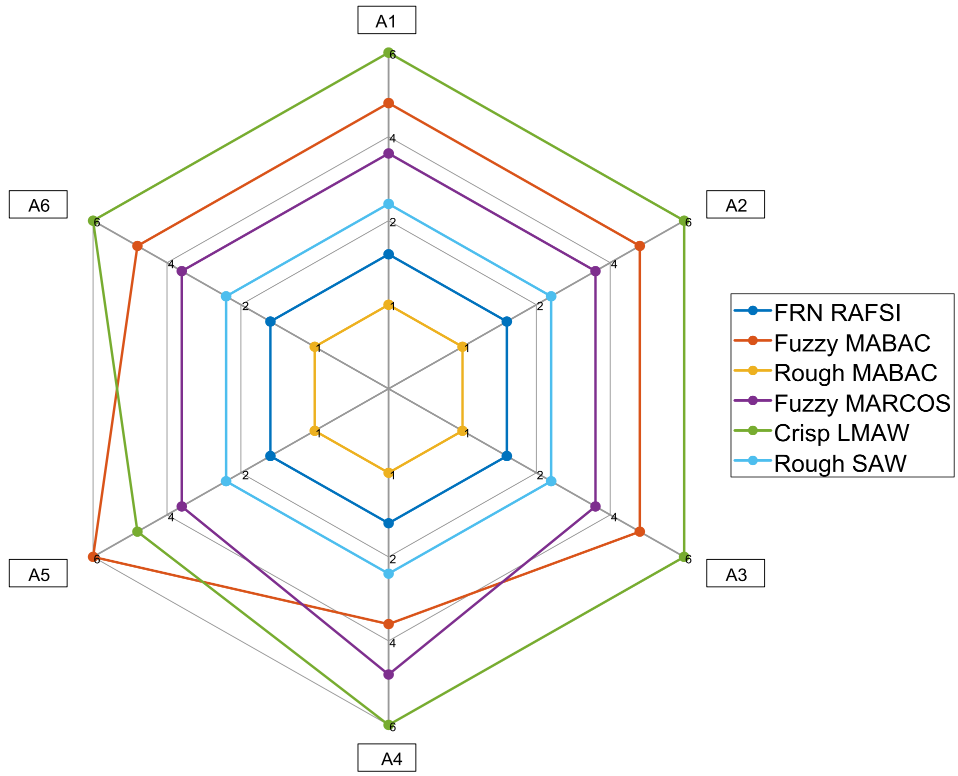


Fig. 15. Comparison of different MCDM approaches.

nario, the value of $\overline{\delta}_{AIP} = 0.01$ was adopted, while in each subsequent scenario, the value of $\overline{\delta}_{AIP}$ was increased by 0.01. Thus, 99 new vectors of weight coefficients of the criteria were generated through 99 scenarios. Changes in AAIP affect the change in the value of the rough boundary weighting interval of the criteria. Since FRN weighting coefficients were used in this study, new limits were defined for each of the six segments of the fuzzy rough number, within which the weighting of the criteria was changed. Fig. 10 shows the dependence of the rough boundary interval of the weight coefficients of the criteria on the change in the change of AAIP.

Fig. 10 clearly shows the dependence of the rough boundary weighting interval on the change in AAIP. Since the selected AAIP value directly affects the final values of the criterion weight coefficients, it is expected that a change in AAIP leads to a change in the FRN criterion function of the alternatives ($Q(A_i)$). Fig. 11 comparatively shows the changes in the value of $Q(A_i)$ depending on the change in AAIP in the interval $0.01\leq \overline{\delta}_{AIP}\leq 1$.

An increase in the value of AAIP in the interval $0.01\leq\overline{\delta}_{AIP} \leq 1$ leads to an increase in the rough boundary interval of the weight coefficients of the criteria. Increasing the rough boundary interval of the criteria simulates an increase in inaccuracy and uncertainty in the information, i.e., simulates an increase in risk decision-making progress. It can be seen from Fig. 11 that an increase in the value of AAIP leads to a proportional increase in the value of all criterion functions of the alternatives. Since there is a gradual increase in all values of $Q(A_i)$, there is no change in the initial solution, so we can conclude that the initial rank $A_3 > A_1 > A_6 > A_4 > A_2 > A_5$ is confirmed, i.e. that alternative A_3 is the dominant solution from the set.

(b) *Experiment 2: Change in value* ψ_b.

When calculating the initial solution, fuzzy rough functions ($\overline{\varphi}_{ij}$) were used to standardize the values of the initial matrix. To define the parameters of the fuzzy rough function, the value $\psi_b = 6$ was adopted, i.e., all values of the initial matrix were standardized to the interval [49,52]. In the next part, an experiment was performed in which the change in the value of ψ_b in the interval $6\leq \psi_b\leq 100$ was simulated. Fig. 12 shows the dependence of the value of ψ_b on the change in the value of $Q(A_i)$ in the interval $6\leq \psi_b\leq 100$.

The results in Fig. 12 confirm the dependence of $Q(A_i)$ on the value of the parameter ψ_b; however, changes in $Q(A_i)$ are not sufficient. An increase in the value of ψ_b in the interval $6\leq \psi_b\leq 100$ leads to a constant decrease in $Q(A_i)$. During the experiment, the limit value $\psi_b = 100$ was adopted because it was noticed through a large number of simulations that the values do not lead to significant changes $Q(A_i)$. The simulation showed the stability of the initial solution, regardless of the drastic changes in the value of ψ_b. It can be seen that the initial solution is stable.

(c) *Experiment 3: Influence of parameters* μ_1 *and* μ_2 *on ranking results*

The parameters μ_1 and μ_2 are used in Eqs. (3)–(8) to define a rough boundary interval (RBI) using Bonferroni functions. The RBI defines the degree of uncertainty present in the FRN. Higher RBI values indicate more significant uncertainty in the information, while lower values indicate less uncertainty [53]. If the RBI has a value of zero, then there is no uncertainty in the information, leading to the transformation of the FRN into a fuzzy number. For the calculation of the initial results, the values of the parameters $\mu_1 = \mu_2 = 1$ were adopted.

Since the parameters μ_1 and μ_2 define the intensity of uncertainty in the RBI, we can conclude that using μ_1 and μ_2 defines the intensity of risk in the information. An increase in the values of the parameters μ_1 and μ_2 simulates the increase in risk when making a decision, while lower values represent less uncertainty, ie lower risk intensity. It is expected that with the increase of risk intensity in expert assessments, there is a change in the value of $Q(A_i)$, which is confirmed through the results shown in Fig. 13.

It is evident from Fig. 14 that the level of risk in the information has a significant impact on the values of the criterion functions of the alternatives in making the final decision. By adopting the values $\mu_1 = \mu_2 = 1$ in the initial scenario, the optimistic scenario is simulated, since the RBI is the smallest for the values $\mu_1 = \mu_2 = 1$, so the inaccuracy and risk in the information are the lowest. Fig. 14 shows a comparative change in $Q(A_i)$ alternatives through 75 scenarios. In the initial scenario, the value of μ_1 and μ_2 was adopted, while in each subsequent scenario, the value of μ_1 and μ_2 was increased by one.

Based on their preferences, experts can define different values of the parameters μ_1 and μ_2. However, Fig. 13 indicate that the values of μ_1 and μ_2 should not be minimal. Also, from Fig. 13, we notice that the initial rank $A_3 > A_1 > A_6 > A_4 > A_2 > A_5$ is confirmed through all scenarios.

5.3. Comparison of different MCDM approaches

This section presents a comparison of the results of the fuzzy rough RAFSI methodology with the results of other multi-criteria techniques in the fuzzy and rough environment. The following MCDM techniques were used for comparison: fuzzy MABAC (Multi-Attributive Border Approximation Area Comparison) model presented by Bozanic et al. [36]; rough MABAC model [54]; fuzzy MARCOS (Measurement Alternatives and Ranking according to the COmpromise Solution) model [55]; LMAW (Logarithm Methodology of Additive Weights) method presented by Pamucar et al. [43]; and rough SAW (Simple Additive Weighting) model presented by Durmic et al. [56]. The same input parameters were used for all applied multi-criteria techniques. The results of the evaluation are shown in Fig. 15.

The results show (see Fig. 15) that the application of all multi-criteria techniques confirmed the rank of dominant alternatives. Dominant alternatives are the first three alternatives by rank. Identical rank was obtained for fuzzy rough RAFSI, fuzzy MABAC, rough MABAC, and rough SAW methods. The fuzzy MARCOS and crisp LMAW methods showed minor deviations from the initial range proposed by the FRN RAFSI technique. These results are expected as MARCOS and LMAW techniques apply different normalization techniques to the FRN RAFSI methodology. Also, differences in rankings occurred as the applied MARCOS, and LMAW techniques did not address uncertainties in the home matrix.

Although all applied multi-criteria techniques have obtained similar or identical results, it is necessary to highlight the advantages of the FRN RAFSI methodology: (1) Fuzzy rough RAFSI model allows defining lower and upper limit rough numbers based on mutual relations between sets of objects; (2) The presented methodology enables the flexible presentation of the imprint of uncertainty and definition of the degree of risk depending on the dynamic environmental conditions; (3) The presented new concept of fuzzy rough numbers has adaptive rough boundary intervals that depend on the degree of agreement in expert assessments. The adaptability of interval values in the FRN RAFSI methodology influences the realistic perception of expert preferences. Thus, higher uncertainties in the home matrix increase the uncertainty imprint for fuzzy rough numbers, while in the absence of uncertainty, the fuzzy rough number is transformed into a classic fuzzy number. In addition to the above advantages, the FRN RAFSI model can efficiently validate results through a variation of stabilization parameters. This provides the possibility of simulating a different risk attitude in the decision-maker.

On the other hand, the traditional crisp, fuzzy and rough methodologies used to compare the results do not have the possibility of flexible processing of interval values. For example, fuzzy MARCOS and MABAC methodologies apply to fuzzy numbers with predefined interval values. Also, fuzzy MARCOS and MABAC methodologies require additional operators to fuse fuzzy numbers, thus eliminating some of the uncertainty and generalizing data. The situation is similar with rough MABAC, RAFSI, SAW, and LMAW methodologies. Based on all the above, we can conclude that the FRN RAFSI method is more suitable for solving realistic decision problems.

6. Conclusion and future directions

This study aims to propose an efficient fuzzy rough number based MCDM model based on LAAW and RAFSI method for solving the site selection problem of floating PV. The proposed FRN based decision making model is composed of two main phases. In the first phase, the criteria weights are calculated using the FRN LAAW method. In the second phase, FRN RAFSI method is applied to rank the alternatives.

Determination of suitable location for floating PV power plant was carried out using the proposed decision making model. Criteria such as sun potential, grid connectivity, environmental loads and bathymetry were taken into account via GIS based software. Following this, suitable locations pointed out on a map with site suitability weighting factors and ranking. As the result of this comprehensive analysis, Manavgat-Antalya, which is already concluded as a strong alternative by other researchers before in solar potential studies, is found to be the best suitable site for a Floating PV Power Plant in Southern part of Turkey [57]. The last five alternatives in the analysis are Göksun-Karaman, Çine-Aydın, Güney-Denizli, Bucak-Burdur and Dalaman-Muğla. It should be noted that together with technical solar potential, distance to grid directly affected results. While A3 is the top one, A5 is the last one due to its long distance to existence grid lines. It should be kept in mind that the "best site" or the "most suitable site" is identified according to the site selection criteria in this study while cost and feasibility are not included.

Outputs of the research can be used by the Ministry of Energy and Natural Resources for energy development plan and it can be a road map for further investments. Better utilization of floating PV system will put forward Turkey's favorable geographic location and coastline. As the new sector develops, it will also trigger economic growth and provide employment opportunities across the countries.

The results show that the proposed model is a powerful tool for rational and objective decision-making. The generalization of the proposed methodology implies the possibility of adapting the model to different multi-criteria problems. Thus, the proposed mathematical model (fuzzy rough LMAAW RAFSI) has a high degree of generalization from the aspect of adaptability to various multi-criteria problems. Also, the transformation of expert preferences into fuzzy rough numbers consists of several iterations through which the boundary intervals of fuzzy rough numbers are defined. In general, the algorithm for reasoning and transformation of uncertainty proposed in this study should enable as much information as possible to be processed with fewer iterations. This achieves a compromise between generalization and efficiency. Thus, the degree of a generalization depends on the degree of knowledge of the problem by the decision-maker. However, it is assumed that group decision-making involves experts who have sufficient experience and knowledge based on which they can provide relevant information to solve the problem, which in turn affects the degree of generalization.

However, in addition to the apparent advantages of the presented method, there are certain limitations. One of the limitations of the fuzzy rough LAAW RAFSI methodology is the inability to represent the interrelationships between the criteria. Therefore, it is necessary to focus further research towards implementing classical and hybrid Bonferroni and Heronian functions in the RAFSI methodology. The application of Bonferroni and Heronian functions for the fusion of elements of the weighted matrix in the fuzzy rough RAFSI model would enable the representation of mutual connections between criteria. Thus, it would further improve the flexibility of the RAFSI model. In addition, further research should focus on enhancing the adaptability of the fuzzy rough RAFSI methodology by implementing Dombi, Einstein, and Hamacher norms. Also, an exciting direction for further research is the implementation of neutrosophic and gray sets in the LAAW RAFSI methodology.

Site selection studies carried out using MCDM methods play an important role as a first step of preliminary analysis for all types of renewable energy systems. They can serve as a basis for detailed feasibility analysis, help guidelines for policy and regulation, have the capacity to engender new directions for a particular renewable energy system. By doing this, they serve as the grounds for future research.

CRediT authorship contribution statement

Muhammet Deveci: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Dragan Pamucar:** Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Elif Oguz:** Conceptualization, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

This work was supported by the Scientific and Technological Research Council of Turkey (TUBITAK) and Iranian Ministry of Science, Research and Technology (MSRT) Bilateral Cooperation Program [grant no: 121N037], project title “Multi-Purpose Floating Solar Power Plant (FloSoWer)”. The authors would like to thank Miss Hatice Kübra Yıldız for her help with the GIS figures.

Appendix A

See Tables A1–A3.

Appendix B

At the position of criterion C$_4$ in Table 4, fuzzy values were obtained $\widetilde{\theta}_{C4}^{(1)} = \widetilde{\theta}_{C4}^{(4)} = (3,5,7)$ and$\widetilde{\theta}_{C4}^{(2)} = \widetilde{\theta}_{C4}^{(3)} = \widetilde{\theta}_{C4}^{(5)} = (5,7,9)$. Based on the fuzzy values, three sequences were formed$\theta_{C4}^{(l)} = \{3,3,5,5,5\}$, $\theta_{MC2}^{(m)} = \{5,5,7,7,7\}$ and$\theta_{MC2}^{(u)} = \{7,7,9,9,9\}$. Using the Eqs. (1)–(8) and provided that $\mu_1 = \mu_2 = 1$, we can calculate the lower and upper limit fuzzy sequences:

(a) Lower limits:

$$\underline{Lim}(\theta_{C4}^{(1)(l)}) = \underline{Lim}(\theta_{C4}^{(4)(l)}) = 3.00;$$

$$\underline{Lim}(\theta_{C4}^{(2)(l)}) = \underline{Lim}(\theta_{C4}^{(3)(l)}) = \underline{Lim}(\theta_{C4}^{(5)(l)}) = \left(\frac{1}{5}\left\{3\cdot(3\cdot5\cdot5\cdot5)^{1/4} + 3\cdot(3\cdot5\cdot5\cdot5)^{1/4} + \ldots + 5\cdot(3\cdot3\cdot5\cdot5)^{1/4}\right\}\right)^{1/2} = 4.11;$$

$$\underline{Lim}(\theta_{C4}^{(1)(m)}) = \underline{Lim}(\theta_{C4}^{(4)(m)}) = 5.00;$$

$$\underline{Lim}(\theta_{C4}^{(2)(m)}) = \underline{Lim}(\theta_{C4}^{(3)(m)}) = \underline{Lim}(\theta_{C4}^{(5)(m)}) = \left(\frac{1}{5}\left\{5\cdot(5\cdot7\cdot7\cdot7)^{1/4} + 5\cdot(5\cdot7\cdot7\cdot7)^{1/4} + \ldots + 7\cdot(5\cdot5\cdot7\cdot7)^{1/4}\right\}\right)^{1/2} = 6.14;$$

$$\underline{Lim}(\theta_{C4}^{(1)(u)}) = \underline{Lim}(\theta_{C4}^{(4)(u)}) = 7.00;$$

$$\underline{Lim}(\theta_{C4}^{(2)(u)}) = \underline{Lim}(\theta_{C4}^{(3)(u)}) = \underline{Lim}(\theta_{C4}^{(5)(u)}) = \left(\frac{1}{5}\left\{7\cdot(7\cdot9\cdot9\cdot9)^{1/4} + 7\cdot(7\cdot9\cdot9\cdot9)^{1/4} + \ldots + 9\cdot(7\cdot7\cdot9\cdot9)^{1/4}\right\}\right)^{1/2} = 8.16.$$

(b) Upper limits:

$$\overline{Lim}(\theta_{C4}^{(1)(l)}) = \overline{Lim}(\theta_{C4}^{(4)(l)}) = \left(\frac{1}{5}\left\{3\cdot(3\cdot5\cdot5\cdot5)^{1/4} + 3\cdot(3\cdot5\cdot5\cdot5)^{1/4} + \ldots + 5\cdot(3\cdot3\cdot5\cdot5)^{1/4}\right\}\right)^{1/2} = 4.11;$$

$$\overline{Lim}(\theta_{C4}^{(2)(l)}) = \overline{Lim}(\theta_{C4}^{(3)(l)}) = \overline{Lim}(\theta_{C4}^{(5)(l)}) = 5.00;$$

$$\overline{Lim}(\theta_{C4}^{(1)(m)}) = \overline{Lim}(\theta_{C4}^{(4)(m)}) = \left(\frac{1}{5}\left\{5\cdot(5\cdot7\cdot7\cdot7)^{1/4} + 5\cdot(5\cdot7\cdot7\cdot7)^{1/4} + \ldots + 7\cdot(5\cdot5\cdot7\cdot7)^{1/4}\right\}\right)^{1/2} = 6.14;$$

$$\overline{Lim}(\theta_{C4}^{(2)(m)}) = \overline{Lim}(\theta_{C4}^{(3)(m)}) = \overline{Lim}(\theta_{C4}^{(5)(m)}) = 7.00;$$

$$\overline{Lim}(\theta_{C4}^{(1)(u)}) = \overline{Lim}(\theta_{C4}^{(4)(u)}) = \left(\frac{1}{5}\left\{7\cdot(7\cdot9\cdot9\cdot9)^{1/4} + 7\cdot(7\cdot9\cdot9\cdot9)^{1/4} + \ldots + 9\cdot(7\cdot7\cdot9\cdot9)^{1/4}\right\}\right)^{1/2} = 8.16$$

$$\overline{Lim}(\theta_{C4}^{(2)(u)}) = \overline{Lim}(\theta_{C4}^{(3)(u)}) = \overline{Lim}(\theta_{C4}^{(5)(u)}) = 9.00.$$

FRNs can be are defined:

$$\overline{\theta}_{C4}^{(1)} = \overline{\theta}_{C4}^{(4)} = ([3, 4.11], [5, 6.14], [7, 8.16]);$$

$$\overline{\theta}_{C4}^{(2)} = \overline{\theta}_{C4}^{(3)} = \overline{\theta}_{C4}^{(3)} = ([4.11, 5], [6.14, 7], [8.16, 9]).$$

Using the Eq. (13), the fusion of FRNs is applied, and an aggregate value is obtained$\overline{\theta}_{C4} = \left(\left[\overline{\theta}_{C4}^{(l)-}, \overline{\theta}_{C4}^{(l)+}\right], \left[\overline{\theta}_{C4}^{(m)-}, \overline{\theta}_{C4}^{(m)+}\right], \left[\overline{\theta}_{C4}^{(u)-}, \overline{\theta}_{C4}^{(u)+}\right]\right) = ([3.66, 4, 64], [5.68, 6.65], [7.69, 8.66])$. The application of Bonferroni function (13) for FRN sequence $(\overline{\theta}_{C4}^{(l)-})$ fusion is as follows:

$$\overline{\theta}_{C4}^{(l)-} = \left(\frac{1}{5(5-1)}(3\cdot3 + 3\cdot4.11 + 3\cdot4.11 + \ldots + 4.11\cdot4.11)\right)^{\frac{1}{1+1}} = 3.66$$

The remaining sequences $\overline{\theta}_{C4}^{(l)+}$, $\overline{\theta}_{C4}^{(m)-}$, $\overline{\theta}_{C4}^{(m)+}$, $\overline{\theta}_{C4}^{(u)-}$ and $\overline{\theta}_{C4}^{(u)+}$ were obtained similarly. Therefore, the aggregated FRN priority vector is presented in Table 5.

References

[1] Han Y, Lou X, Feng M, Geng Z, Chen L, Ping W, et al. Energy consumption analysis and saving of buildings based on static and dynamic input-output models. Energy 2022;239:122240. https://doi.org/10.1016/j.energy.2021.122240.

[2] Wu H, Han Y, Geng Z, Fan J, Xu W. Production capacity assessment and carbon reduction of industrial processes based on novel radial basis function integrating multi-dimensional scaling. Sustain Energy Technol Assess 2022;49:1–9. https://doi.org/10.1016/j.seta.2021.101734.

[3] Charles Lawrence Kamuyu W, Lim J, Won C, Ahn H. Prediction model of photovoltaic module temperature for power performance of floating PVs. Energies 2018;11(2):447. https://doi.org/10.3390/en11020447.

[4] Erdin C, Ozkaya G. Turkey's 2023 energy strategies and investment opportunities for renewable energy sources: Site selection based on electre. Sustainability 2019;11(7):2136.

[5] World Bank Report. Where Sun Meets Water; 2019.

[6] Farfan J, Breyer C. Combining floating solar photovoltaic power plants and hydropower reservoirs: A virtual battery of great global potential. Energy Procedia 2018;155:403–11. https://doi.org/10.1016/j.egypro.2018.11.038.

[7] Doljak D, Stanojević G. Evaluation of natural conditions for site selection of ground-mounted photovoltaic power plants in Serbia. Energy 2017;127:291–300.

[8] World Bank Group, ESMAP and SERIS. Where Sun Meets Water: Floating Solar Market Report. Washington, DC: World Bank World Bank Group, ESMAP and SERIS; 2019.

[9] Cox M. The State of Floating Solar; 2019. Available online: https://www.greentechmedia.com/articles/read/the-state-of-floating-solar-bigger-projects-and-climbing-capacity (accessed on 7 November 2020).

[10] Rahman MW, Mahmud MS, Ahmed R, Rahman MS, Arif MZ. Solar lanes and floating solar PV: New possibilities for source of energy generation in Bangladesh. In: Innovations in Power and Advanced Computing Technologies (i-PACT), Vellore; 2017. p. 1–6. https://doi.org/10.1109/IPACT.2017.8244878.

[11] Mittal D, Saxena BK, Rao KVS. Floating solar photovoltaic systems: An overview and their feasibility at Kota in Rajasthan. In: 2017 International Conference on Circuit, Power and Computing Technologies (ICCPCT), Kollam, 2017, pp. 1-7, doi: 10.1109/ICCPCT.2017.8074182.

[12] Oliveira-Pinto S, Stokkermans J. Assessment of the potential of different floating solar technologies – Overview and analysis of different case studies. Energy Convers Manage 2020. https://doi.org/10.1016/j.enconman.2020.112747.

[13] İBB Türkiye' nin İlk Yüzer Güneş Enerjisi Santralini Kurdu (2017). Retrieved November 27, 2020, from https://www.ibb.istanbul/News/Detail/34143.

[14] Toğrul IT, Toğrul H. Global solar radiation over Turkey: Comparison of predicted and measured data. Renew Energy 2002. https://doi.org/10.1016/S0960-1481(00)00197-X.

[15] Sözen A, Arcaklioğlu E, Özalp M. Estimation of solar potential in Turkey by artificial neural networks using meteorological and geographical data. Energy Convers Manage 2004;45(18-19):3033–52.

[16] Sözen A, Arcaklioğlu E. Solar potential in Turkey. Appl Energy 2005. https://doi.org/10.1016/j.apenergy.2004.02.003.

[17] Sözen A, Arcaklioğlu E, Özalp M, Çağlar N. Forecasting based on neural network approach of solar potential in Turkey. Renew Energy 2005. https://doi.org/10.1016/j.renene.2004.09.020.

[18] Sözen A, Arcaklioğlu E, Özalp M, Kanit EG. Solar-energy potential in Turkey. Appl Energy 2005. https://doi.org/10.1016/j.apenergy.2004.06.001.

[19] Bulut H, Büyükalaca O. Simple model for the generation of daily global solar-radiation data in Turkey. Appl Energy 2007;84(5):477–91.

[20] Şenkal O, Kuleli T. Estimation of solar radiation over Turkey using artificial neural network and satellite data. Appl Energy 2009;86(7-8):1222–8.

[21] Şenkal O. Modeling of solar radiation using remote sensing and artificial neural network in Turkey. Energy 2010. https://doi.org/10.1016/j.energy.2010.09.009.

[22] Kaygusuz K. Energy for sustainable development: A case of developing countries. Renew Sustain Energy Rev 2012;16(2):1116–26.

[23] Bakirci K. Correlations for estimation of daily global solar radiation with hours of bright sunshine in Turkey. Energy 2009;34(4):485–501. https://doi.org/10.1016/j.energy.2009.02.005.

[24] Bakirci K. General models for optimum tilt angles of solar panels: Turkey case study. Renew Sustain Energy Rev 2012;16(8):6149–59. https://doi.org/10.1016/j.rser.2012.07.009.

[25] Ozgoren M, Bilgili M, Sahin B. Estimation of global solar radiation using ANN over Turkey. Exp Syst Appl 2012. https://doi.org/10.1016/j.eswa.2011.11.036.

[26] Uyan M. GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region Konya/Turkey. Renew Sustain Energy Rev 2013. https://doi.org/10.1016/j.rser.2013.07.042.

[27] Wu Y, Zhang T, Xu C, Zhang B, Li L, Ke Y, et al. Optimal location selection for offshore wind-PV-seawater pumped storage power plant using a hybrid MCDM approach: A two-stage framework. Energy Convers Manage 2019;199:112066. https://doi.org/10.1016/j.enconman.2019.112066.

[28] Guo F, Gao J, Men H, Fan Y, Liu H. Large-scale group decision-making framework for the site selection of integrated floating photovoltaic-pumped storage power system. J Energy Storage 2021a; 43(May): 103125. https://doi.org/10.1016/j.est.2021.103125.

[29] Guo F, Gao J, Liu H, He P. Locations appraisal framework for floating photovoltaic power plants based on relative-entropy measure and improved hesitant fuzzy linguistic DEMATEL-PROMETHEE method. Ocean Coastal Manage 2021b; 215 (August): 105948. https://doi.org/10.1016/j.ocecoaman.2021.105948.

[30] Nebey AH, Taye BZ, Workineh TG. Site Suitability Analysis of Solar PV Power Generation in South Gondar, Amhara Region. J Energy 2020;2020:1–15. https://doi.org/10.1155/2020/3519257.

[31] Zadeh LA. Fuzzy sets. Inf Control 1965;8(3):338–53.

[32] Pawlak Z. Rough sets. Int J Comput Inform Sci 1982;11(5):341–56.

[33] Smarandache F. A unifying field in logics. Neutrosophy: Neutrosophic probability, set and logic. Rehoboth: American Research Press; 1999.

[34] Hassanpour M, Pamucar D. Evaluation of Iranian household appliance industries using MCDM models. Oper Res Eng Sci: Theory Appl 2019;2(3). https://doi.org/10.31181/oresta190101s10.31181/oresta190203s10.31181/oresta1903001h.

[35] Zavadskas EK, Turskis Z, Stević Ž, Mardani A. Modelling procedure for the selection of steel pipes supplier by applying fuzzy AHP method. Operational Res Eng Sci: Theory Appl 2020;3(2). https://doi.org/10.31181/oresta190101s10.31181/oresta200302s10.31181/oresta2003034z.

[36] Bozanic D, Randjelovic A, Radovanovic M, Tesic D. A hybrid LBWA - IR-MAIRCA multi-criteria decision-making model for determination of constructive elements of weapons. Facta universitatis series: Mech Eng 2020;18(3):399–418.

[37] Sharma HK, Kumari K, Kar S. Forecasting Sugarcane Yield of India based on rough set combination approach. Decision Making: Appl Manage Eng 2021;4(2):163–77.

[38] Muhammad LJ, Badi I, Haruna AA, Mohammed IA. Selecting the Best Municipal Solid Waste Management Techniques in Nigeria Using Multi Criteria Decision Making Techniques. Reports Mech Eng 2021;2(1):180–9.

[39] Sahu R, Dash SR, Das S. Career selection of students using hybridized distance measure based on picture fuzzy set and rough set theory. Decision Making: Appl Manage Eng 2021;4(1):104–26.

[40] Singh S, Upadhyay SP, Powar S. Developing an integrated social, economic, environmental, and technical analysis model for sustainable development using hybrid multi-criteria decision making methods. Appl Energy 2022;308:118235. https://doi.org/10.1016/j.apenergy.2021.118235.

[41] Ziemba P. Uncertain Multi-Criteria analysis of offshore wind farms projects investments–Case study of the Polish Economic Zone of the Baltic Sea. Appl Energy 2022;309:118232. https://doi.org/10.1016/j.apenergy.2021.118232.

[42] Sánchez-Lozano JM, García-Cascales MS, Lamata MT. GIS-based onshore wind farm site selection using Fuzzy Multi-Criteria Decision Making methods. Evaluating the case of Southeastern Spain. Appl Energy 2016;171:86–102.

[43] Pamučar D, Žižović M, Biswas S, Božanić D. A new logarithm methodology of additive weights (LMAW) for multi-criteria decision-making: Application in logistics. Facta Universitatis, Series: Mech Eng 2021;19(3):361. https://doi.org/10.22190/FUME210214031P.

[44] Zizovic M, Pamucar D, Albijanic M, Chatterjee P, Pribicevic I. Eliminating Rank Reversal Problem Using a New Multi-Attribute Model—The RAFSI Method. Mathematics 2020;8(6):1015. https://doi.org/10.3390/math8061015.

[45] Spencer RS, Macknick J, Aznar A, Warren A, Reese MO. Floating photovoltaic systems: assessing the technical potential of photovoltaic systems on man-made water bodies in the continental United States. Environ Sci Technol 2018;53(3):1680–9.

[46] International Finance Corporation. Floating Solar Photovoltaic on the Rise 2020:3.

[47] Ziar H, Prudon B, Lin F, Roeffen B, Heijkoop D, Stark T, Teurlincx S, Domis L, Goma EG, Extebarria JG, Alavez IN, Daniel VT, Laar HV, Santbergen R, Isabella O. Innovative floating bifacial photovoltaic solutions for inland water areas. Prog Photovolt 2020. https://doi.org/10.1002/pip.3367.

[48] Noorollahi E, Fadai D, Akbarpour Shirazi M, Ghodsipour SH. Land suitability analysis for solar farms exploitation using GIS and fuzzy analytic hierarchy process (FAHP)—a case study of Iran. Energies 2016;9(8):643.

[49] Bonferroni C. Sulle medie multiple di potenze. Bollettino Matematica Italiana 1950;5:267–70.

[50] Alossta A, Elmansouri O, Badi I. Resolving a location selection problem by means of an integrated AHP-RAFSI approach. Reports Mech Eng 2021;2(1):135–42.

[51] Pamucar D. Normalized weighted geometric Dombi Bonferroni mean operator with interval grey numbers: Application in multicriteria decision making. Rep Mech Eng 2020;1(1):44–52.

[52] Abid M, Abid Z, Sagin J, Murtaza R, Sarbassov D, Shabbir M. Prospects of floating photovoltaic technology and its implementation in Central and South Asian Countries. Int J Environ Sci Technol 2019;16(3):1755–62. https://doi.org/10.1007/s13762-018-2080-5.

[53] Pamucar D, Petrovic I, Cirovic G. Modification of the Best-Worst and MABAC methods: A novel approach based on interval-valued fuzzy-rough numbers. Exp Syst Appl 2018:89–106. https://doi.org/10.1016/j.eswa.2017.08.042.

[54] Chattopadhyay R, Das PP, Chakraborty S. Development of a rough-MABAC-DoE-based metamodel for supplier selection in an iron and steel industry. Operat Res Eng Sci: Theory Appl 2022;5(1):20–40.

[55] Bakır M, Akan Ş, Özdemir E. Regional aircraft selection with fuzzy piprecia and fuzzy marcos: a case study of the Turkish airline industry. Facta Universitatis. Series: Mech Eng 2021;19(3):423–45.
[56] Durmic E, Stević Z, Chatterjee P, Vasiljević M, Tomašević M. Sustainable supplier selection using combined FUCOM – Rough SAW model. Rep Mech Eng 2020;1(1): 34–43. https://doi.org/10.31181/rme200101034c.
[57] Kesler S, Kivrak S, Dincer F, Rustemli S, Karaaslan M, Unal E, et al. The Analysis of PV power potential and system installation in Manavgat, Turkey – A Case Study in winter season. Renew Sustain Energy Rev 2014;31:671–80. https://doi.org/10.1016/j.rser.2013.12.027.

Further reading

[58] Baskar D. Efficiency improvement on photovoltaic water pumping system by automatic water spraying over photovoltaic cells. Middle - East J Sci Res 2014;19: 1127–31. https://doi.org/10.5829/idosi.mejsr.2014.19.8.11232.
[59] Cagle AE, Armstrong A, Exley G, Grodsky SM, Macknick J, Sherwin J, et al. The land sparing, water surface use efficiency, and water surface transformation of floating photovoltaic solar energy installations. Sustainability (Switzerland) 2020; 12(19):8154. https://doi.org/10.3390/su12198154.
[60] Cazzaniga R, Cicu M, Rosa-Clot M, Rosa-Clot P, Tina GM, Ventura C. Floating photovoltaic plants: Performance analysis and design solutions. Renew Sustain Energy Rev 2018;81:1730–41. https://doi.org/10.1016/j.rser.2017.05.269.
[61] Choi YK. A study on power generation analysis of floating PV system considering environmental impact. Int J Software Eng Appl 2014. https://doi.org/10.14257/ijseia.2014.8.1.07.
[62] Chow L. World's Largest Floating Solar Farm Now Online; 2017. Retrieved November 27, 2020, from https://www.ecowatch.com/floating-solar-farm-china-2436833091.html.
[63] Dash PK, Gupta N. Effect of Temperature on Power Output from Different Commercially available Photovoltaic Modules. Int J Eng Res Appl 2015;5:148–51.
[64] EPDK. (2021). EPDK | Enerji Piyasası Düzenleme Kurumu. Retrieved May 12, 2022, from YEK Listesi website: https://www.epdk.gov.tr/Detay/Icerik/3-0-167/resmi-istatistikler.
[65] European Commission Staff Working Document, 2020, Clean Energy Transition – Technologies and Innovations, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020SC0953&rid=1.
[66] Falkner R. The Paris Agreement and the new logic of international climate politics. Int Affairs 2016;92(5):1107–25. https://doi.org/10.1111/1468-2346.12708.
[67] Fesharaki Vahid, Dehghani Mohammad, Jafari Fesharaki, Javad, Tavasoli H. The effect of temperature on photovoltaic cell efficiency. Proceedings of the 1st international conference on emerging trends in energy conservation, Tehran, Iran; 2011.
[68] Floating Photovoltaic Systems. Retrieved November 27, 2020; n.d., from http://www.nrg-energia.it/floating-pv-systems.html.
[69] Gorjian S, Sharon H, Ebadi H, Kant K, Scavo FB, Tina GM. Recent technical advancements, economics and environmental impacts of floating photovoltaic solar energy conversion systems. J Clean Prod 2021;278:124285. https://doi.org/10.1016/j.jclepro.2020.124285.
[70] Gotmare J, Prayagi DS. Enhancing the performance of photovoltaic panels by stationary cooling. Int J Eng, Sci Technol 2014; 2(7):1465–1468.
[71] Güneş. Retrieved November 27, 2020; n.d, from https://enerji.gov.tr/bilgi-merkezi-enerji-gunes-en.
[72] Han Y, Li J, Lou X, Fan C, Geng Z. Energy saving of buildings for reducing carbon dioxide emissions using novel denrite net integrated adaptive mean square gradient. Appl Energy 2022;309:1–9. https://doi.org/10.1016/j.apenergy.2021.118409.