Energy 35 (2010) 2517–2527

Contents lists available at ScienceDirect

Energy

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

Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul

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ARTICLE INFO

Article history:
Received 17 October 2009
Received in revised form
25 February 2010
Accepted 26 February 2010
Available online 1 April 2010

Keywords:
Renewable energy
Fuzzy
Multi-criteria
VIKOR
AHP
Wind energy

ABSTRACT

The purpose of this study is twofold: first, it is aimed at determining the best renewable energy alternative for Istanbul by using an integrated VIKOR-AHP methodology. Second, a selection among alternative energy production sites in this city is made using the same approach. In the proposed VIKOR-AHP methodology, the weights of the selection criteria are determined by pairwise comparison matrices of AHP. In energy decision making problems, the judgments of decision makers are usually vague. As it is relatively difficult for decision makers to provide exact values for the criteria, the evaluation data for the alternative energy policies should be expressed in linguistic terms. In order to model this kind of uncertainty in human preferences, fuzzy logic is applied very successfully. Thus, both classical VIKOR and classical AHP procedures are performed under fuzzy environment. The originality of the paper comes from the application of the proposed integrated VIKOR-AHP methodology to the selection of the best energy policy and production site. It is found that wind energy is the most appropriate renewable energy option and Çatalca district is the best area among the alternatives for establishing wind turbines in Istanbul.

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1. Introduction

Energy planning endeavor involves finding a set of sources and conversion devices so as to meet the energy requirements/demands of all the tasks in an optimal manner [1]. Making an energy planning decision involves a process of balancing diverse ecological, social, technical, and economic aspects over space and time. This balance is critical to the survival of nature and to the prosperity of energy dependent nations.

Technical and environmental aspects are usually represented in the form of multiple criteria and indicators that are often expressed by conflicting objectives. Energy planning using multi-criteria analysis has attracted the attention of decision makers for a long time. During the 1970s, dealing with energy problems by single criterion approaches which aimed at identifying the most efficient supply options at a low cost was popular. However, in the 1980s, growing environmental awareness modified the above decision framework. The need to incorporate environmental and social considerations in energy planning resulted in the increasing usage of multi-criteria approaches [2–4].

As the complexity of decisions increases, it becomes more difficult for decision makers to identify an alternative that maximizes all decision criteria. Operationally, energy assessments must deal with attributes difficult to define and components that may involve both quantitative and qualitative factors. In terms of scope, an assessment may cover technical, economic or geographic areas whose boundaries may not be easily identifiable, and socioeconomic regions that affect various interest groups or stakeholders each with their own demands and socioeconomic needs. In view of these difficulties, methods based on fuzzy logic may be quite useful in undertaking difficult assessment procedures. The fuzzy set theory was introduced by Zadeh [5] to express the linguistic terms in decision-making process in order to resolve the vagueness, ambiguity and subjectivity of human judgment.

VIKOR (VIšekriterijumsko KOmpromisno Rangiranje) is a multi-attribute decision making technique which has a simple computation procedure that allows simultaneous consideration of the closeness to ideal and anti-ideal alternatives. In the literature, there are many studies which handle VIKOR method in a comparative manner: Opricovic and Tzeng [6] conducted a comparative analysis of VIKOR and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methods with a numerical example. Tzeng et al. [7] also compared the two methodologies to determine the best compromise solution among alternative fuel modes. Opricovic and

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doi:10.1016/j.energy.2010.02.051

Table 1
List of evaluation criteria used in MCDM studies conducted on energy issues.

Aspects	Criteria
Technical	Efficiency[a]
	Exergy (rational) efficiency[a]
	Primary energy ratio
	Safety
	Reliability
	Maturity
	Others
Economic	Investment cost[a]
	Operation and maintenance cost[a]
	Fuel cost
	Electric cost
	Net present value
	Payback period
	Service life
	Equivalent annual cost
	Others
Environmental	NO_x emission[a]
	CO_2 emission[a]
	CO emission
	SO_2 emission
	Particles emission
	Non-methane volatile compounds
	Land use[a]
	Noise
	Others
Social	Social acceptability[a]
	Job creation[a]
	Social benefits
	Others

[a] Most frequently used.

Tzeng [8] made a comparison of VIKOR with PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations), ELECTRE (ELimination and Choice Expressing REality) and TOPSIS approaches. Chu et al. [9] provided a comparative analysis of SAW (Simple Additive Weighting), TOPSIS and VIKOR, which demonstrated the similarities and differences of these methodologies in achieving group decisions.

In fuzzy VIKOR, linguistic preferences can be converted to fuzzy numbers [10]. For the determination of the relative importance of selection criteria, fuzzy Analytic Hierarchy Process (AHP) can be used since it is based on pairwise comparisons and allows the utilization of linguistic variables. Although the pairwise comparison approach is the most demanding in terms of solicited input from the experts, it offers maximum insight, particularly in terms of assessing consistency of the experts' judgments. In this context, this technique is ideal for the closer examination of a selected set of renewable energy planning and site selection criteria. The technique is also the most accurate when it comes to reflecting the relative weight of each criterion and indicator [11].

Table 2
Cavallaro and Ciraolo's list of evaluation criteria for production site selection.

Aspects	Criteria
Technical	Energy production capacity
	Technological maturity
Economic	Investment cost
	Operation and maintenance cost
	Fuel cost
	Realization times
Environmental	Impact on ecosystems
	CO_2 emission
	Visual impact
	Noise
Social	Social acceptability

Table 3
Fuzzy evaluation scores for the weights.

Linguistic terms	Fuzzy score
Absolutely strong (AS)	(2, 5/2, 3)
Very strong (VS)	(3/2, 2, 5/2)
Fairly strong (FS)	(1, 3/2, 2)
Slightly strong (SS)	(1, 1, 3/2)
Equal (E)	(1, 1, 1)
Slightly weak (SW)	(2/3, 1, 1)
Fairly weak (FW)	(1/2, 2/3, 1)
Very weak (VW)	(2/5, ½, 2/3)
Absolutely weak (AW)	(1/3, 2/5, 1/2)

Turkey, which is still extensively dependent on energy imports from foreign countries, as it was in the past, can only meet about one third of its energy demand by means of native generation. The shares depending on foreign supply of oil and natural gas are even much higher. As fossil fuel energy becomes scarcer, Turkey will most probably face energy shortages, high energy prices, and energy insecurity within the next few decades. Moreover, Turkey's reliance on fossil fuel consumption will accelerate global warming and reduce the domestic environmental quality. For these reasons, the development and usage of renewable energy sources and technologies in Istanbul, Turkey's most industrialized and energy consuming region, are increasingly becoming vital for sustainable economic development of the country [12,13].

In this study, a modified fuzzy VIKOR methodology is proposed to make a multi-criteria selection among alternative renewable energy options and production sites for Istanbul area. In the proposed methodology, the decision makers' opinions on the relative importance of the selection criteria are determined by a fuzzy AHP procedure.

The rest of the paper is organized as follows: In Section 2, a literature review on multi-criteria energy decision making is briefly given. In Section 3, a modified fuzzy VIKOR methodology is presented. In Section 4, following the determination of the selection criteria and alternatives, the proposed methodology is applied to a two step renewable energy planning problem for Istanbul. In Section 5, concluding remarks are given.

2. Literature review

An energy planning process usually consists of a study of demand and supply, forecasts of the trends of input–output items, based on economics and technological models, and a list of actions, collecting several measures voted to fulfill the main objectives of the energy plan [14]. One of the most common problems of energy planning is to choose among various alternative energy sources and technologies to be promoted. Technologies based on solar energy, wind energy, hydraulic energy, biomass, animal manure, geothermal energy,

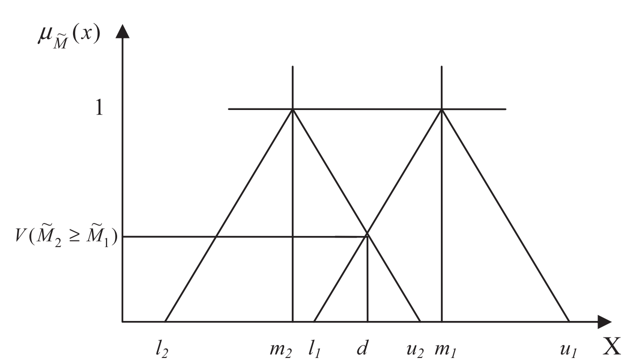


Fig. 1. The intersection between $\tilde{M}_1$ and $\tilde{M}_2$.

Table 4
Fuzzy evaluation scores for the alternatives.

Linguistic terms	Fuzzy score
Very poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)
Medium poor (MP)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Medium good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very good (VG)	(9, 10, 10)

energy saving in residential and industry sectors, wave energy are among the most popular alternatives [15–18]. Despite environmental drawbacks, nuclear and conventional energy resources like coal, oil, and natural gas may still be included in the list of alternative technologies to be promoted [17,19].

There is a vast multi-criteria decision making literature on energy issues. Keeney et al. [20] structured a hierarchical representation of criteria and then aggregated them into a combined 'value tree' in order to evaluate future energy systems of West Germany. Hamalainen and Karjalainen [21] utilized AHP to determine the relative weights of the evaluation criteria of Finland's energy policies. Mirasgedis and Diakoulaki [22] compared the external costs of power plants which used different energy sources by a multi-criteria analysis. Mavrotas et al. [23] presented a multiple objective linear programming model and applied it to the Greek electricity generation sector. Taking energy resources, environment capacity, social indicators, and economic indicators into account, Afgan and Carvalho [24] defined energy indicators which are used in the assessment of energy systems. Haralambopoulos and Polatidis [25] used PROMETHEE II to achieve group consensus in renewable energy projects and applied the decision framework to a geothermal resource usage case in the island of Chios. Beccali et al. [14] utilized ELECTRE-III under fuzzy environment to assess an action plan for the diffusion of renewable energy technologies at regional scale. Polatidis and Haralambopoulos [26] proposed a new methodological framework of multi-participatory and multi-criteria decision making to evaluate renewable energy options in Greece. Providing an integrated decision aid framework, Topcu and Ulengin [27] dealt with the problem of selecting the most suitable electricity generation alternative for Turkey. Cavallaro and Ciraolo [28] proposed a multi-criteria method in order to support the feasibility analysis of installing alternative wind energy turbine configurations in an island in Italy. Zhou et al.'s [29] literature review showed that the importance of multiple criteria decision-making methods and energy-related environmental studies have increased substantially since 1995. Begic and Afgan [30] evaluated the options of energy power systems for Bosnia Herzegovina under a multi-criteria sustainability assessment framework. Burton and Hubacek [31] compared the perceived social, economic, and environmental cost of small-scale energy technologies to larger-scale alternatives. Afgan et al. [32] evaluated the potential natural gas usage in energy sector. Önüt et al. [33] employed analytic network process (ANP) to solve an energy resource selection problem for the manufacturing industry. Patlitzianas et al. [34] developed an information decision support system, which contains an MCDM subsystem and applied to 13 accession member states of the European Union. Kahraman et al. [12] used axiomatic design (AD) and AHP for the selection of the best renewable energy alternative under fuzzy environment.

Wang et al.'s [35] literature review on the application of the MCDM techniques to the energy issues shows that evaluation criteria for energy source and site selection problems can be grouped into four main categories: Technical, economic, environmental, and social. Table 1 gives a list of the criteria utilized in energy planning oriented MCDM studies up to 2009. Table 1 also shows that efficiency, exergy (rational) efficiency, investment cost, operation and maintenance cost, NO_x emission, CO_2 emission, land use, social acceptability, and job creation are the most frequently used evaluation criteria in energy planning, energy management, and resource allocation studies.

Cavallaro and Ciraolo [28] used a smaller group of evaluation criteria for an energy production site selection case study on an Italian island. The eleven criteria used by the authors can be grouped into technical, economic, environmental, and social categories as in Table 2:

3. An integrated VIKOR & AHP methodology

A modified fuzzy approach to the classical VIKOR is proposed in this section. Some basic definitions and notations of fuzzy sets are summarized in Appendix A. The importance weight of each criterion can be obtained by either a direct-assignment based on experts' experiences or by using pairwise comparisons of criteria.

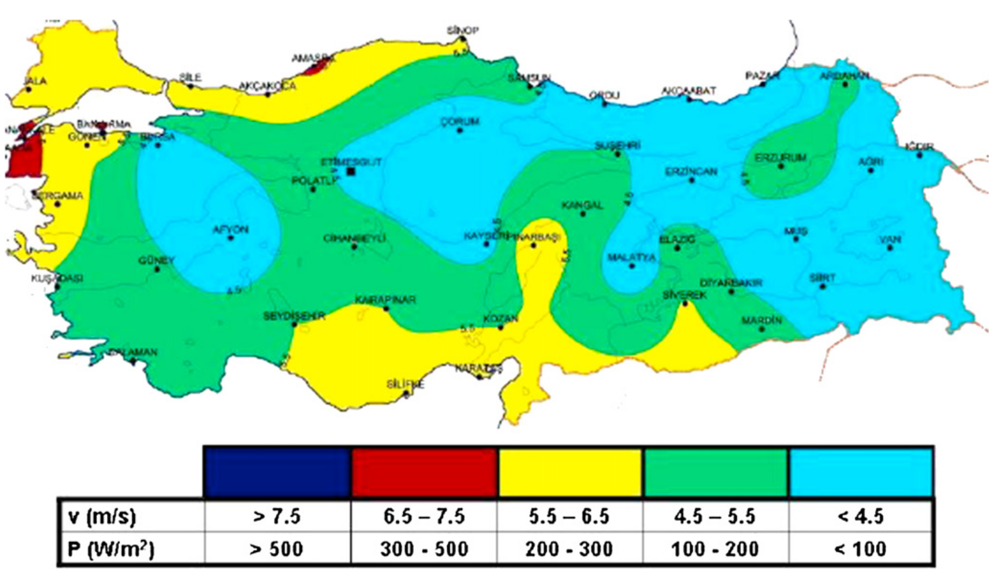


Fig. 2. Turkey's wind speed map.

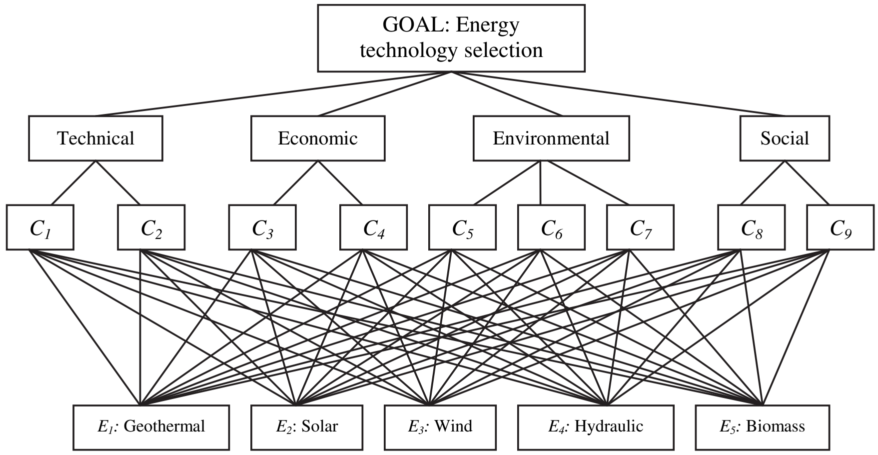


Fig. 3. The hierarchical structure for the selection of the renewable energy technology.

Here, it is suggested that the experts use the linguistic variables in Table 3 to evaluate the importance of the criteria. Wang et al. [36] calculated the weight of each criterion by summing the assigned weights by experts and then dividing the sum by the number of experts as in Eq. (1):

$$\tilde{w}_{ij} = \frac{1}{K}\left[\tilde{w}_j^1(+)\tilde{w}_j^2(+)\cdots(+)\tilde{w}_j^K\right] \quad (1)$$

where $\tilde{w}_j^K$ is the importance weight of the Kth expert.

Since a comparison matrix divides the problem into sub-problems which can be solved easier, a pairwise comparison matrix in the AHP method can be considered a good way of determining the weights of the criteria. Therefore, we propose modifying the classical weighting procedure of VIKOR methodology by using fuzzy pairwise comparison matrices. Chang's [37] extent analysis will be utilized for this purpose.

The stages of extent analysis approach can be summarized as follows: Letting $C_j = \{C_1, C_2, \ldots, C_n\}$ be a criteria set, extent analysis values for each criterion can be obtained as follows: Let $\tilde{M}_j (j = 1, 2, 3, \ldots, n)$ be TFNs.

The value of fuzzy synthetic extent for the degree of possibility of $\tilde{M}_1 \geq \tilde{M}_2$ is defined, respectively, as

$$\tilde{S}_j = \sum_{j=1}^{n} \tilde{M}_j \otimes \left[\sum_{k=1}^{m}\sum_{j=1}^{n} \tilde{M}_j\right]^{-1} \quad (2)$$

In our case, $n = m$ since a comparison matrix for criteria always has to be a square matrix.

$$V\left(\tilde{M}_1 \geq \tilde{M}_2\right) = \sup_{x \geq y}\left[\min\left(\mu_{\tilde{M}_1}(x), \mu_{\tilde{M}_2}(y)\right)\right] \quad (3)$$

When (x,y) exists such that $x \geq y$ and $\mu_{\tilde{M}_1} = \mu_{\tilde{M}_2} = 1$, $V(\tilde{M}_1 \geq \tilde{M}_2) = 1$ is obtained. Since $\tilde{M}_1$ and $\tilde{M}_2$ are convex fuzzy numbers, the following principle of the comparison of fuzzy numbers is applied:

$$V\left(\tilde{M}_1 \geq \tilde{M}_2\right) = 1 \quad \text{iff} \quad m_1 \geq m_2 \quad (4)$$

and

$$V\left(\tilde{M}_1 \geq \tilde{M}_2\right) = hgt\left(\tilde{M}_1 \cap \tilde{M}_2\right) = \mu(d) \quad (5)$$

where d is the ordinate of the highest intersection point D between $\mu_{\tilde{M}_1}$ and $\mu_{\tilde{M}_2}$. If $\tilde{M}_1 = (l_1, m_1, u_1)$ and $\tilde{M}_2 = (l_2, m_2, u_2)$, the following equation for the ordinate of the point D is given (see Fig. 1);

$$V\left(\tilde{M}_2 \geq \tilde{M}_1\right) = hgt\left(\tilde{M}_1 \cap \tilde{M}_2\right) = \begin{cases} 0, & \text{if } m_2 \geq m_1 \\ 1, & \text{if } l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise} \end{cases} \quad (6)$$

The values of $V(\tilde{M}_1 \geq \tilde{M}_2)$ and $V(\tilde{M}_2 \geq \tilde{M}_1)$ are required for comparing $\tilde{M}_1$ and $\tilde{M}_2$. The degree of possibility for a convex fuzzy number to be greater than p convex fuzzy numbers $(\tilde{M}_j, j = 1, 2, 3, \ldots, n)$ is defined as

Table 5
Pairwise comparisons of renewable energy source evaluation criteria.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	1	E_1: E E_2: E E_3: SW	E_1: SS E_2: FW E_3: E	E_1: SS E_2: FW E_3: SW	E_1: SW E_2: SW E_3: SW	E_1: FW E_2: FW E_3: E	E_1: SW E_2: SW E_3: SS	E_1: SS E_2: FW E_3: SS	E_1: SS E_2: AW E_3: E
C_2	E_1: E E_2: E E_3: SS	1	E_1: SS E_2: FW E_3: SS	E_1: SS E_2: FW E_3: E	E_1: SW E_2: SW E_3: E	E_1: FW E_2: FW E_3: SS	E_1: SW E_2: SW E_3: FS	E_1: SS E_2: FW E_3: FS	E_1: SS E_2: VW E_3: SS
C_3	E_1: SW E_2: FS E_3: E	E_1: SW E_2: FS E_3: SW	1	E_1: E E_2: E E_3: SW	E_1: FW E_2: SS E_3: SW	E_1: VW E_2: E E_3: E	E_1: FW E_2: SS E_3: SS	E_1: E E_2: E E_3: SS	E_1: E E_2: SW E_3: E
C_4	E_1: SW E_2: FS E_3: SS	E_1: SW E_2: FS E_3: E	E_1: E E_2: E E_3: SS	1	E_1: FW E_2: SS E_3: E	E_1: AW E_2: E E_3: SS	E_1: FW E_2: SS E_3: FS	E_1: E E_2: E E_3: FS	E_1: SS E_2: SW E_3: SS
C_5	E_1: SS E_2: SS E_3: SS	E_1: SS E_2: SS E_3: E	E_1: FS E_2: SW E_3: SS	E_1: FS E_2: SW E_3: E	1	E_1: SW E_2: SW E_3: SS	E_1: E E_2: E E_3: FS	E_1: FS E_2: SW E_3: FS	E_1: FS E_2: FW E_3: SS
C_6	E_1: FS E_2: FS E_3: E	E_1: FS E_2: FS E_3: SW	E_1: VS E_2: E E_3: E	E_1: AS E_2: E E_3: SW	E_1: SS E_2: SS E_3: SW	1	E_1: SS E_2: SS E_3: SS	E_1: VS E_2: E E_3: SS	E_1: VS E_2: SW E_3: E
C_7	E_1: SS E_2: SS E_3: SW	E_1: SS E_2: SS E_3: FW	E_1: FS E_2: SW E_3: SW	E_1: FS E_2: SW E_3: FW	E_1: E E_2: E E_3: FW	E_1: SW E_2: SW E_3: SW	1	E_1: FS E_2: SW E_3: SW	E_1: FS E_2: FW E_3: SS
C_8	E_1: SW E_2: FS E_3: SW	E_1: SW E_2: FS E_3: FW	E_1: E E_2: E E_3: SW	E_1: E E_2: E E_3: FW	E_1: FW E_2: SS E_3: FW	E_1: VW E_2: E E_3: SW	E_1: FW E_2: SS E_3: SS	1	E_1: E E_2: SW E_3: SW
C_9	E_1: SW E_2: AS E_3: E	E_1: SW E_2: VS E_3: SW	E_1: E E_2: SS E_3: E	E_1: SW E_2: SS E_3: SW	E_1: FW E_2: FS E_3: SW	E_1: VW E_2: SS E_3: E	E_1: FW E_2: FS E_3: SW	E_1: E E_2: SS E_3: SS	1

Table 6
Fuzzy evaluation matrix for the weights.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	(1, 1, 1)	(0.89, 1, 1)	(0.83, 0.89, 1.17)	(0.72, 0.89, 1.17)	(0.67, 1, 1)	(0.67, 0.78, 1)	(0.78, 1, 1.17)	(0.83, 0.89, 1.33)	(0.78, 0.8, 1)
C_2	(1, 1, 1.17)	(1, 1, 1)	(0.83, 0.89, 1.33)	(0.83, 0.89, 1.17)	(0.78, 1, 1)	(0.67, 0.78, 1.17)	(0.78, 1.17, 1.33)	(0.83, 1.06, 1.5)	(0.8, 0.83, 1.22)
C_3	(0.89, 1.17, 1.33)	(0.78, 1.17, 1.33)	(1, 1, 1)	(0.89, 1, 1)	(0.72, 0.89, 1.17)	(0.8, 0.83, 0.89)	(0.83, 0.89, 1.33)	(1, 1, 1.17)	(0.89, 1, 1)
C_4	(0.89, 1.17, 1.5)	(0.89, 1.17, 1.33)	(1, 1, 1.17)	(1, 1, 1)	(0.83, 0.89, 1.17)	(0.78, 0.8, 1)	(0.83, 1.06, 1.5)	(1, 1.17, 1.33)	(0.89, 1, 1.33)
C_5	(1, 1, 1.5)	(1, 1, 1.33)	(0.89, 1.17, 1.5)	(0.89, 1.17, 1.33)	(1, 1, 1)	(0.78, 1, 1.17)	(1, 1.17, 1.33)	(0.89, 1.33, 1.67)	(0.83, 1.06, 1.5)
C_6	(1, 1.33, 1.67)	(0.89, 1.33, 1.67)	(1.17, 1.33, 1.5)	(1.22, 1.5, 1.67)	(0.89, 1, 1.33)	(1, 1, 1)	(1, 1, 1.5)	(1.17, 1.33, 1.67)	(1.06, 1.33, 1.5)
C_7	(0.89, 1, 0.89)	(0.83, 0.89, 1.33)	(0.78, 1.17, 1.33)	(0.72, 1.06, 1.33)	(0.83, 0.89, 1)	(0.67, 1, 1)	(1, 1, 1)	(0.78, 1.17, 1.33)	(0.83, 1.06, 1.5)
C_8	(0.78, 1.17, 1.33)	(0.72, 1.06, 1.33)	(0.89, 1, 1)	(0.83, 0.89, 1)	(0.67, 0.78, 1.17)	(0.69, 0.83, 0.89)	(0.83, 0.89, 1.33)	(1, 1, 1)	(0.78, 1, 1)
C_9	(1.22, 1.5, 1.67)	(0.94, 1.33, 1.5)	(1, 1, 1.17)	(0.78, 1, 1.17)	(0.72, 1.06, 1.33)	(0.8, 0.83, 1.06)	(0.72, 1.06, 1.33)	(1, 1, 1.33)	(1, 1, 1)

CR for the defuzzified version of this matrix is 0.027<0.10.

$$V\left(\tilde{M}_p \geq \tilde{M}_1, \tilde{M}_2, \ldots, \tilde{M}_{p-1}, \tilde{M}_{p+1}, \ldots, \tilde{M}_n\right) = V\left[\left(\tilde{M}_p \geq \tilde{M}_1\right) \text{ and } \left(\tilde{M}_p \geq \tilde{M}_2\right) \text{ and} \ldots \text{and } \left(\tilde{M}_p \geq \tilde{M}_n\right)\right] = \min\ V\left(\tilde{M}_p \geq \tilde{M}_j\right) = d(C_j), \quad j \neq p \tag{7}$$

Consequently, the weight vector $W' = (d'(C_1), d'(C_2), \ldots, d'(C_n))^{\mathrm{T}},\ j = 1, 2, 3, \ldots, n$ is obtained. Finally, via normalization, the following normalized weight vector is obtained:

$$W = (d(C_1), d(C_2), \ldots, d(C_n))^{\mathrm{T}} \tag{8}$$

Obtaining the weight vector via the extent analysis, we can continue implementing the steps of VIKOR. VIKOR method is based on the compromise programming of MCDM. The concepts of compromise solutions were first demonstrated by Yu [38] and Zeleny [39]. The methodology simply works on the principle that each alternative can be evaluated by each criterion function; the compromise ranking will be realized by comparing the degrees of closeness to the ideal alternative. In fuzzy VIKOR, it is suggested that decision makers use linguistic variables to evaluate the ratings of alternatives with respect to criteria. Table 4 gives the linguistic scale for the evaluation of alternatives. Assuming that a decision group has K people, the ratings of alternatives with respect to each criterion can be calculated as in Eq. (9) [36];

$$\tilde{x}_{ij} = \frac{1}{K}\left[\tilde{x}_{ij}^{1}(+)\tilde{x}_{ij}^{2}(+)\cdots(+)\tilde{x}_{ij}^{K}\right] \tag{9}$$

where $\tilde{x}_{ij}^{K}$ is the rating of the Kth expert for ith alternative with respect to jth criterion.

After obtaining the weights of criteria and fuzzy ratings of alternatives with respect to each criterion, we can now express the fuzzy multi-criteria decision-making problem in matrix format as,

Table 7
Results of the fuzzy AHP extent analysis procedure for the weights.

	$\tilde{S}_j = \tilde{M}_j = (l_j, m_j, u_j)$	$W_j' = d'(C_j)^{\mathrm{T}}$	$W_j = d(C_j)^{\mathrm{T}}$
C_1	(0.072, 0.099, 0.139)	0.564	0.086
C_2	(0.075, 0.103, 0.154)	0.663	0.101
C_3	(0.078, 0.107, 0.145)	0.656	0.100
C_4	(0.081, 0.111, 0.16)	0.743	0.113
C_5	(0.083, 0.119, 0.174)	0.841	0.128
C_6	(0.094, 0.134, 0.191)	1.000	0.152
C_7	(0.074, 0.111, 0.152)	0.713	0.109
C_8	(0.072, 0.103, 0.142)	0.613	0.093
C_9	(0.082, 0.117, 0.163)	0.807	0.123

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \cdots & \tilde{x}_{2n} & \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \tag{10}$$

$$W = [w_1, w_2, \ldots, w_n],\ j = 1, 2, \ldots, n$$

where $\tilde{x}_{ij}$ is the rating of Alternative A_i with respect to Criterion j (i.e. C_j) and w_j denotes the importance weight of C_j.

Next step is to determine the fuzzy best value (FBV, $\tilde{f}_j^*$) and the fuzzy worst value (FWV, $\tilde{f}_j^-$) of each criterion function.

$$\tilde{f}_j^* = \max_i \tilde{x}_{ij},\ j \in B; \quad \tilde{f}_j^- = \min_i \tilde{x}_{ij},\ j \in C \tag{11}$$

Then, the values $\tilde{w}_j(\tilde{f}_j^* - \tilde{x}_{ij})/(\tilde{f}_j^* - \tilde{f}_j^-)$, $\tilde{S}_i$ and $\tilde{R}_i$ are computed in order to obtain

$$\tilde{S}_i = \sum_{j=1}^{n} \tilde{w}_j\left(\tilde{f}_j^* - \tilde{x}_{ij}\right) \Big/ \left(\tilde{f}_j^* - \tilde{f}_j^-\right) \tag{12}$$

$$\tilde{R}_i = \max_j \left[\tilde{w}_j\left(\tilde{f}_j^* - \tilde{x}_{ij}\right) \Big/ \left(\tilde{f}_j^* - \tilde{f}_j^-\right)\right] \tag{13}$$

where $\tilde{S}_i$ refers to the separation measure of A_i from the fuzzy best value, and $\tilde{R}_i$ to the separation measure of A_i from the fuzzy worst value.

In the next step, $\tilde{S}^*, \tilde{S}^-, \tilde{R}^*, \tilde{R}^-$, and $\tilde{Q}_i$ values are calculated:

$$\begin{aligned} \tilde{S}^* &= \min_i \tilde{S}_i, \quad \tilde{S}^- = \max_i \tilde{S}_i \\ \tilde{R}^* &= \min_i \tilde{R}_i, \quad \tilde{R}^- = \max_i \tilde{R}_i \end{aligned} \tag{14}$$

Table 8
Evaluation scores of the renewable energy alternatives.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
E_1	E_1: G E_2: MG E_3: G	E_1: F E_2: F E_3: MG	E_1: F E_2: MG E_3: MG	E_1: F E_2: MG E_3: F	E_1: MP E_2: F E_3: F	E_1: MP E_2: F E_3: MP	E_1: G E_2: MG E_3: G	E_1: F E_2: MG E_3: G	E_1: F E_2: MG E_3: G
E_2	E_1: MG E_2: F E_3: F	E_1: VG E_2: MG E_3: MG	E_1: G E_2: MG E_3: G	E_1: MG E_2: F E_3: G	E_1: VG E_2: F E_3: F	E_1: G E_2: G E_3: MG	E_1: MG E_2: MG E_3: G	E_1: MG E_2: MG E_3: VG	E_1: MP E_2: F E_3: VG
E_3	E_1: G E_2: MG E_3: G	E_1: P E_2: MP E_3: MG	E_1: G E_2: G E_3: MG	E_1: G E_2: F E_3: MG	E_1: F E_2: G E_3: G	E_1: G E_2: VG E_3: G	E_1: G E_2: VG E_3: VG	E_1: G E_2: G E_3: G	E_1: G E_2: G E_3: G
E_4	E_1: F E_2: F E_3: F	E_1: MG E_2: G E_3: MG	E_1: VP E_2: VP E_3: VG	E_1: VG E_2: VP E_3: VG	E_1: G E_2: F E_3: G	E_1: F E_2: G E_3: G	E_1: G E_2: G E_3: MP	E_1: P E_2: P E_3: VG	E_1: P E_2: VP E_3: G
E_5	E_1: MG E_2: G E_3: MG	E_1: G E_2: MG E_3: MG	E_1: G E_2: F E_3: MG	E_1: G E_2: MG E_3: MP	E_1: MP E_2: F E_3: F	E_1: F E_2: F E_3: MP	E_1: F E_2: F E_3: F	E_1: F E_2: MG E_3: MG	E_1: MG E_2: G E_3: G

Table 9
Fuzzy evaluation matrix for the alternatives.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
E_1	(6.33, 8.33, 9.67)	(3.67, 5.67, 7.67)	(4.33, 6.33, 8.33)	(3.67, 5.67, 7.67)	(2.33, 4.33, 6.33)	(1.67, 3.67, 5.67)	(6.33, 8.33, 9.67)	(5, 7, 8.67)	(5, 7, 8.67)
E_2	(3.67, 5.67, 7.67)	(6.33, 8, 9.33)	(6.33, 8.33, 9.67)	(5, 7, 8.67)	(5, 6.67, 8)	(6.33, 8.33, 9.67)	(5.67, 7.67, 9.33)	(6.33, 8, 9.33)	(4.33, 6, 7.33)
E_3	(6.33, 8.33, 9.67)	(2, 3.67, 5.67)	(6.33, 8.33, 9.67)	(5, 7, 8.67)	(5.67, 7.67, 9)	(7.67, 9.33, 10)	(8.33, 9.67, 10)	(7, 9, 10)	(7, 9, 10)
E_4	(3, 5, 7)	(5.67, 7.67, 9.33)	(3, 3.33, 4)	(6, 6.67, 7)	(5.67, 7.67, 9)	(5.67, 7.67, 9)	(5, 7, 8.33)	(3, 4, 5.33)	(2.33, 3.33, 4.67)
E_5	(5.67, 7.67, 9.33)	(5.67, 7.67, 9.33)	(5, 7, 8.67)	(4.33, 6.33, 8)	(2.33, 4.33, 6.33)	(2.33, 4.33, 6.33)	(3, 5, 7)	(4.33, 6.33, 8.33)	(6.33, 8.33, 9.67)

$$\tilde{Q}_i = v\left(\tilde{S}_i - \tilde{S}^*\right) \Big/ \left(\tilde{S}^- - \tilde{S}^*\right) + (1-v)\left(\tilde{R}_i - \tilde{R}^*\right) \Big/ \left(\tilde{R}^- - \tilde{R}^*\right) \tag{15}$$

The indices $\min_i \tilde{S}_i$ and $\min_i \tilde{R}_i$ are related to a maximum majority rule, and a minimum individual regret of an opponent strategy, respectively. As well, v is introduced as the weight of the strategy of the maximum group utility. v is usually assumed to be 0.5.

Next task is the defuzzification of the triangular fuzzy number $\tilde{Q}_i$ and ranking the alternatives by the index $\tilde{Q}_i$. Various defuzzification strategies have been suggested in the literature. In this paper, the graded mean integration approach is used [40]. According to the graded mean integration approach, for triangular fuzzy numbers, a fuzzy number $\tilde{C} = (c_1, c_2, c_3)$ can be transformed into a crisp number by employing the below equation:

$$P\left(\tilde{C}\right) = C = \frac{c_1 + 4c_2 + c_3}{6} \tag{16}$$

Finally, the best alternative with the minimum of Q_i is determined.

To summarize the methodology, the steps of the modified fuzzy VIKOR approach are given in the following:

Step 1: A group of decision-makers identifies the evaluation criteria.
Step 2: Appropriate linguistic variables for the weights of the criteria and alternatives are chosen.
Step 3: A pairwise comparison matrix for the criteria is constructed and experts' linguistic evaluations are aggregated to get a mean value for each pairwise comparison.
Step 4: Extent analysis approach is used to obtain the weights of the criteria.
Step 5: Linguistic evaluations of the experts are aggregated to get the fuzzy ratings of the alternatives with respect to each criterion.
Step 5: Fuzzy decision matrix is constructed for the implementation of VIKOR.
Step 6: Fuzzy best value (FBV, $\tilde{f}_j^*$) and fuzzy worst value (FWV, $\tilde{f}_j^-$) of each criterion function are determined.
Step 7: Separation measures ($\tilde{S}_i$ and $\tilde{R}_i$) are calculated.
Step 8: $\tilde{Q}_i$ values are calculated.
Step 9: $\tilde{Q}_i$ values are defuzzified and the alternatives are ranked by the index Q_i.
Step 10: The best alternative with the minimum of Q_i is determined.

Table 10
Separation measures of A_i from the fuzzy best and fuzzy worst values.

	$\tilde{S}_i$	$\tilde{R}_i$
E_1	(18.09, 31.15, 61.08)	(2.98, 8.23, 12.6)
E_2	(17.2, 27.19, 46.41)	(2.9, 6.66, 11.57)
E_3	(16.31, 25.95, 45.95)	(2.64, 6.66, 12.67)
E_4	(24.34, 37.2, 61.1)	(4.78, 7, 14.14)
E_5	(17.41, 29.03, 54.42)	(2.86, 7.36, 11.35)

4. An application: renewable energy planning for Istanbul

For a country, energy is one of the key indicators to show economic and social development and improved quality of life. Turkish energy consumption has risen dramatically over the past 20 years due to the combined demands of industrialization and urbanization. It has increased from 32 mtoe (million tons of oil equivalent) in 1980 to 74 mtoe in 1998. According to the planning studies, Turkey's final consumption of primary energy is estimated to be 171 mtoe in 2010 and 298 mtoe in 2020. In other words, domestic energy production will probably meet 28% of the total primary energy demand in 2010 and 24% in 2020. The level of Turkey's energy consumption is still low relative to similar sized countries [41].

As fossil fuel energy becomes scarcer, Turkey and its most populated and industrialized city, Istanbul, will face energy shortages, increasing energy prices, and energy insecurity within the next few decades. Therefore, the development and use of renewable energy sources and technologies are increasingly becoming vital for the sustainable economic development of Turkey.

In recent years some authors have made important contributions on the renewable energy literature on Turkey such as Ediger and Kentel [42], Hepbaşlı et al. [43], Demirbaş [44,45], Kaygusuz [46–48], Kaygusuz and Sarı [49], Evrendilek and Ertekin [50], Balat [51,52], Demirbaş and Bakış [53], Hepbaşlı and Ozgener [54,55]. Among the different forms of renewable energy, biomass energy is one of the major resources in Turkey. Turkey's domestic energy consumption accounts for about 37% of the total energy consumption. Of this, about 52% is from biomass-based fuels. Turkey's first biomass power project is under development in Adana province, at an installed capacity of 45 MW. Two others, at a total capacity of 30 MW, are at the feasibility study stage in Mersin and Tarsus provinces.

According to the studies on the determination of Turkey's wind energy potential, Turkey's gross wind energy potential has been estimated as 400 billion kW h/year and technical potential has been estimated as 120 billion kW h/year which is equal to the 1.2 times of the current annual electricity production of Turkey. The most attractive sites are the Marmara Sea region, Mediterranean Coast, Aegean Sea Coast and Anatolia inland. In Turkey, electricity production through wind energy for general usage purposes was first realized at the Çeşme Altınyunus Resort in 1986 by using a 55 kW nominal powered wind turbine. Fig. 2 shows Turkey's average wind speed (m/s) map.

4.1. Selection of the best energy source alternative for Istanbul

In this study, as given in Table 1, the most frequently used technical, economic, environmental and social criteria among the

Table 11
$\tilde{S}^*, \tilde{S}^-, \tilde{R}^*$, and $\tilde{R}^-$ values.

$\tilde{S}^*$	(16.31, 25.95, 45.95)
$\tilde{S}^-$	(24.34, 37.2, 61.1)
$\tilde{R}^*$	(2.64, 6.66, 11.35)
$\tilde{R}^-$	(4.78, 8.23, 14.14)

Table 12
Integrated fuzzy VIKOR-AHP analysis results.

	$\tilde{Q}_i$	Q_i	Rank order
E_1	(−2.42, 0.73, 5.11)	0.94	4
E_2	(−2.46, 0.05, 3.96)	0.29	2
E_3	(−2.54, 0, 4.19)	0.27	1
E_4	(−1.89, 0.61, 5.48)	1.00	5
E_5	(−2.47, 0.36, 4.41)	0.56	3

list of the energy technology selection criteria are utilized in evaluating renewable energy alternatives for Istanbul. The energy alternatives considered are: Geothermal energy (E_1), solar energy (E_2), wind energy (E_3), hydraulic energy (E_4), and biomass energy (E_5). The structure of the renewable energy planning decision making problem formulated in this study is presented in Fig. 3.

The criteria used in this study are briefly explained in the following [35]:

Technical efficiency (C_1): efficiency measures how much useful energy can be obtained from an energy source. The efficiency coefficient, which is one of the most frequently used measures of efficiency, is defined as the ratio of the output energy to the input energy. Efficient energy usage is essential to slowing the energy demand growth. It is the most used technical criterion to evaluate energy systems.

Exergy efficiency (C_2): exergy efficiency (rational efficiency) computes the efficiency of a process taking the second law of thermodynamics into consideration. There is always an exergy loss when a process involves a temperature change. Exergy is the net energy that is left to be used. The CHP systems are frequently evaluated with this criterion.

Investment cost efficiency (C_3): the components of investment costs are the purchase of mechanical equipment, technological installations, construction of roads and connections to the national web, engineering services, drilling and other incidental construction work. The investors must consider the costs and the benefits of investments. Investment cost is the most used economic criterion to evaluate energy systems.

Operation and maintenance cost efficiency (C_4): operation cost includes the wages and funds spent for the energy, products and services. Maintenance cost consists of the funds spent for maintenance. The operation and maintenance costs are also divided into two subcategories: fixed and variable costs.

NO_x emission (C_5): NO_x comprises a group of molecules that can contribute to air pollution, acid deposition and climate change. Reacting with organic chemicals, NO_x can also form a wide variety of toxic products which may damage health and cause mutations. Therefore, NO_x emission of an energy system is considered an important criterion according to most experts.

CO_2 emission (C_6): CO_2 is a colorless, odorless and tasteless gas that contributes to the greenhouse effect. It is mainly released through conventional energy systems. CO_2 leads to the global warming, which is focused by many governments, academicians, and researchers. Naturally, CO_2 emission of an energy system is certainly a criterion to evaluate its sustainability.

Land use (C_7): as the environment and landscape are directly affected by the energy systems, the land required by each plant is a matter of great concern for their evaluation. Different energy systems may occupy different land while the products are same. Thus, land use must be considered by energy experts.

Social acceptability (C_8): social acceptability expresses the overview of opinions related to the energy systems by the local population. It is extremely important since the opinion of the population and pressure groups may heavily influence the amount of time needed to complete an energy project. It should be noted that social acceptance is not a directly measurable figure. It is a qualitative one.

Job creation (C_9): in the decision making process of local governments, job creations of energy systems are indispensably considered and selected to evaluate their contributions.

After determining the evaluation criteria and the alternatives, the steps of the integrated fuzzy VIKOR-AHP algorithm are implemented. In order to determine the importance of each criterion, the experts employed a nine point scale given in Table 3. While evaluating the alternatives, the experts assumed that all the criteria were benefit criteria. For example, if an energy source is evaluated as 'very good' in terms of 'CO_2 emission', this means that CO_2 emission level of that renewable energy alternative is very low. On the other hand, if an energy alternative is evaluated as 'very good' in terms of 'technical efficiency', this means that technical efficiency of that energy alternative is very high. Each linguistic term is associated with a triangular fuzzy number. Table 5 gives the results of the pairwise comparisons of the evaluation criteria made by three renewable energy planning experts.

In the next step, using Table 3 and Table 5, the fuzzy evaluation matrix for the criteria weights is obtained as in Table 6. Next, in order to check the consistency ratio (CR) of the evaluation matrix, the graded mean integration approach (Eq. (16)) is utilized for defuzzification. CR for the evaluation matrix is computed as 0.027 and it is less than 0.10. Therefore, the comparison results can be considered consistent.

Next, synthetic extent values ($\tilde{S}_i$) for the evaluation criteria are produced under fuzzy environment employing Eq. (2). After obtaining the synthetic extent values, Eqs. (3–7) are utilized for calculating the vector for the criteria weights. Finally, the normalized weight vector is obtained as in Table 7.

Next step is the determination of the best renewable energy source alternative with the proposed modified fuzzy VIKOR

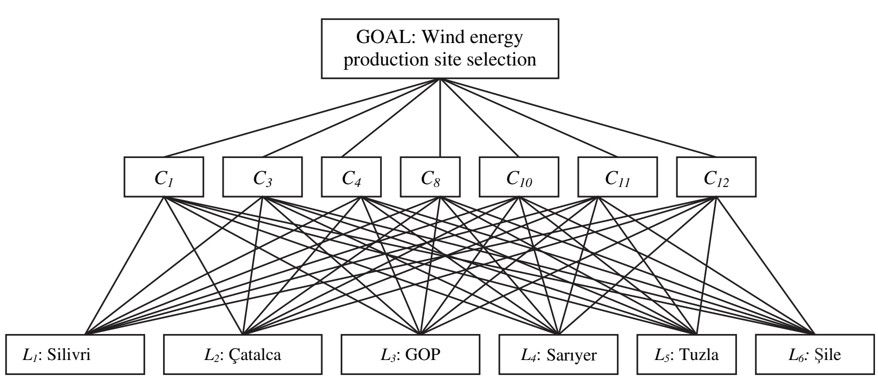


Fig. 4. The hierarchical structure for the selection of the wind energy production site.

Fig. 5. Geographical distribution of the alternative wind energy production sites in Istanbul.

procedure. To do this, three experts evaluated the five renewable energy alternatives with respect to each criterion using Table 4. Evaluation results are given in Table 8:

After calculating the arithmetic means of the associated fuzzy evaluation scores, fuzzy evaluation matrix is obtained as in Table 9:

Table 13
Pairwise comparisons of renewable energy source evaluation criteria.

	C_1	C_3	C_4	C_8	C_{10}	C_{11}	C_{12}
C_1	1	E_1: SS E_2: SW E_3: SS	E_1: FS E_2: E E_3: E	E_1: VS E_2: E E_3: SS	E_1: FS E_2: E E_3: SS	E_1: FS E_2: SS E_3: SS	E_1: SS E_2: E E_3: SW
C_3	E_1: SW E_2: SS E_3: SW	1	E_1: SS E_2: SS E_3: SW	E_1: SS E_2: SS E_3: E	E_1: SS E_2: SS E_3: E	E_1: SS E_2: FS E_3: E	E_1: E E_2: E E_3: FW
C_4	E_1: FW E_2: E E_3: E	E_1: SW E_2: SW E_3: SS	1	E_1: E E_2: E E_3: SS	E_1: E E_2: E E_3: SS	E_1: E E_2: SS E_3: SS	E_1: SW E_2: E E_3: SW
C_8	E_1: VW E_2: E E_3: SW	E_1: SW E_2: SW E_3: E	E_1: E E_2: E E_3: SW	1	E_1: E E_2: E E_3: E	E_1: E E_2: SS E_3: E	E_1: SW E_2: E E_3: FW
C_{10}	E_1: FW E_2: E E_3: SW	E_1: SW E_2: SW E_3: E	E_1: E E_2: E E_3: SW	E_1: E E_2: E E_3: E	1	E_1: E E_2: SW E_3: E	E_1: SW E_2: E E_3: FW
C_{11}	E_1: FW E_2: SW E_3: SW	E_1: SW E_2: SW E_3: E	E_1: E E_2: SW E_3: SW	E_1: E E_2: SW E_3: E	E_1: E E_2: SS E_3: E	1	E_1: SW E_2: SW E_3: FW
C_{12}	E_1: SW E_2: E E_3: SS	E_1: E E_2: E E_3: FS	E_1: SS E_2: E E_3: SS	E_1: SS E_2: E E_3: FS	E_1: SS E_2: E E_3: FS	E_1: SS E_2: SS E_3: FS	1

Then, using Eqs. (11)–(13), separation measures from the fuzzy best value $\tilde{S}_i$ and the fuzzy worst value $\tilde{R}_i$ are computed as in Table 10:

In the next step, using Eq. (14), $\tilde{S}^*, \tilde{S}^-, \tilde{R},^*$ and $\tilde{R}^-$ fuzzy values are calculated (Table 11).

Then, using Eq. (15), $\tilde{Q}_i$ values are computed. In the calculations, the weight of the strategy of the maximum group utility (v) is assumed to be 0.5. Finally, $\tilde{Q}_i$ values are defuzzified via graded mean integration method (Eq. (16)) and ranked according to Q_i index values. Table 12 gives the results of the integrated fuzzy VIKOR-AHP analysis results.

Based on the crisp Q_i index values, the ranking of the alternatives in descending order is determined as E_3,E_2, E_5, E_1 , and E_4. The best alternative is found to be E_3 (wind energy). The rank order of the rest is solar, biomass, geothermal, and hydraulic.

4.2. Selection of the best wind energy plantation site for Istanbul

In this study, in order to evaluate the alternative wind turbine plantation sites in Istanbul, a combination of the most frequently used evaluation criteria by Cavallaro and Ciraolo's [28] and Wang's [35] will be used. Other than *technical efficiency* (C_1), *investment cost efficiency* (C_3), *operational and maintenance cost efficiency* (C_4), and *social acceptability* (C_8), three new criteria which were proposed by Cavallaro and Ciraolo [28] for the evaluation of alternative wind turbine projects are employed: *Visual impact* (C_{10}), *acoustic noise* (C_{11}), and *impact on ecosystems* (C_{12}). Below are the definitions of these criteria.

Visual impact (C_{10}): this criterion reflects the visual nuisance that may be created by the establishment of a wind turbine in a specific area. The landscape of the different sites, the distance from the

Table 14
Fuzzy evaluation matrix for the site selection criteria weights.

	C_1	C_3	C_4	C_8	C_{10}	C_{11}	C_{12}
C_1	(1, 1, 1)	(0.89, 1, 1.33)	(1, 1.17, 1.33)	(1.17, 1.33, 1.67)	(1, 1.17, 1.5)	(1, 1.17, 1.67)	(0.89, 1, 1.17)
C_3	(0.78, 1, 1.17)	(1, 1, 1)	(0.89, 1, 1.33)	(1, 1, 1.33)	(1, 1, 1.33)	(1, 1.17, 1.5)	(0.83, 0.89, 1)
C_4	(0.83, 0.89, 1)	(0.78, 1, 1.17)	(1, 1, 1)	(1, 1, 1.17)	(1, 1, 1.17)	(1, 1, 1.33)	(0.78, 1, 1)
C_8	(0.69, 0.83, 0.89)	(0.78, 1, 1)	(0.89, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1.17)	(0.72, 0.89, 1)
C_{10}	(0.72, 0.89, 1)	(0.78, 1, 1)	(0.89, 1, 1)	(1, 1, 1)	(1, 1, 1)	(0.89, 1, 1)	(0.72, 0.89, 1)
C_{11}	(0.61, 0.89, 1)	(0.72, 0.89, 1)	(0.78, 1, 1)	(0.89, 1, 1)	(1, 1, 1.17)	(1, 1, 1)	(0.61, 0.89, 1)
C_{12}	(0.89, 1, 0.89)	(1, 1.17, 1.33)	(1, 1, 1.33)	(1, 1.17, 1.5)	(1, 1.17, 1.5)	(1, 1.17, 1.67)	(1, 1, 1)

CR for the defuzzified version of this matrix is $0.012 < 0.10$.

Table 15
Results of the fuzzy AHP procedure for the site selection criteria weights.

	$\tilde{S}_j = \tilde{M}_j = (l_j, m_j, u_j)$	$W'_j = d'(C_j)^T$	$W_j = d(C_j)^T$
C_1	(0.123, 0.158, 0.218)	1	0.186
C_3	(0.115, 0.142, 0.195)	0.822	0.153
C_4	(0.113, 0.139, 0.176)	0.738	0.137
C_8	(0.107, 0.135, 0.159)	0.618	0.115
C_{10}	(0.106, 0.137, 0.158)	0.622	0.115
C_{11}	(0.099, 0.134, 0.161)	0.622	0.116
C_{12}	(0.122, 0.155, 0.208)	0.962	0.179

Table 18
Separation measures of A_i from the fuzzy best and fuzzy worst values.

	$\tilde{S}_i$	$\tilde{R}_i$
L_1	(12.7, 18.08, 33.85)	(3.79, 5.2, 9.44)
L_2	(11.81, 15.79, 24.87)	(3.79, 5.2, 7.14)
L_3	(13.61, 18.54, 29.1)	(5.05, 7.05, 9.28)
L_4	(14.28, 20.97, 38.28)	(4.55, 6.58, 9.28)
L_5	(17.55, 25.81, 45.42)	(3.95, 5.2, 8.5)
L_6	(14.69, 22.29, 41.76)	(3.64, 5.2, 8.5)

nearest observer, the type and size of plants to be installed and the possibility to integrate them with their surroundings must all be considered when evaluating the alternatives. This criterion is evaluated in qualitative terms.

Acoustic noise (C_{11}): noise can generally be classified according to its two main sources: aerodynamic and mechanical. Aerodynamic noise is produced when the turbine blades interact with the atmospheric turbulence. Mechanical noise is generated by machineries such as gearboxes and generators. Noise could be reduced by better-designed turbine blade geometry and careful choice of operating conditions. This criterion takes into the noise levels generated by the turbines and the distance of residential areas into account.

Impact on ecosystems (C_{12}): this subjective criterion refers to the potential risk to ecosystems caused by production of the various projects included in the strategies and is evaluated in qualitative terms. The potential disturbance to fauna caused by wind turbines do present some problems for predatory species of migrating birds which pass from Istanbul.

It should also be noted that, when it is evaluated in a wind turbine establishment context, *efficiency* (C_1) criterion takes average wind speed and total number of turbines constructible on the site and represents the total energy which can be generated by the project.

The considered location alternatives are: Silivri (L_1), Çatalca (L_2), Gaziosmanpaşa (GOP) (L_3), Sarıyer (L_4), Tuzla (L_5), and Şile (L_6). Fig. 4 gives the hierarchical structure of the wind turbine site selection problem.

Fig. 5 gives the geographical distribution of the alternative wind energy production sites in Istanbul.

After determining the evaluation criteria and the alternatives, the steps of the AHP extent analysis are performed. In order to determine the importance of each turbine site selection criterion, the experts employed the nine point scale given in Table 3. Table 13 gives the results of the pairwise comparisons of the evaluation criteria made by three experts.

The fuzzy evaluation matrix for the weights of the turbine site selection criteria is obtained as in Table 14. CR for the evaluation matrix is computed as 0.012 and it is less than 0.10. The comparison results can be considered consistent.

Next, synthetic extent values ($\tilde{S}_i$) for the production site evaluation criteria are computed. After obtaining the synthetic extent values, the vector for the criteria weights and its normalized version are obtained as in Table 15.

Final step is the determination of the best wind energy production site with the proposed fuzzy VIKOR approach. To do this, first, three experts evaluated the six wind turbine plantation areas with respect to each site selection criterion using Table 4. Evaluation results are given in Table 16:

After calculating the arithmetic means of the associated fuzzy evaluation scores, the fuzzy evaluation matrix is obtained as in Table 17:

Then, separation measures from the fuzzy best value $\tilde{S}_i$ and the fuzzy worst value $\tilde{R}_i$ are computed as in Table 18:

In the next step, using Eq. (14) $\tilde{S}^*$, $\tilde{S}^-$, $\tilde{R}^*$ and $\tilde{R}^-$ fuzzy values are calculated (Table 19).

Then, $\tilde{Q}_i$ values are computed. In the calculations, v is assumed to be 0.5. Finally, $\tilde{Q}_i$ values are defuzzified and ranked according to Q_i index values. Table 20 gives the results of the integrated fuzzy VIKOR-AHP analysis results.

Based on the crisp Q_i index values, the ranking of the alternatives in descending order are L_2,L_1, L_6, L_3, L_5, and L_4. The best alternative is found to be L_2 (Çatalca). The second best alternative is L_1 (Silivri). The rank order of the rest is Şile, GOP, Tuzla, and Sarıyer.

Table 16
Evaluation scores of the wind energy production site alternatives.

	C_1	C_3	C_4	C_8	C_{10}	C_{11}	C_{12}
L_1	E_1: MG E_2: MG E_3: F	E_1: F E_2: F E_3: F	E_1: MG E_2: G E_3: G	E_1: G E_2: G E_3: G	E_1: G E_2: MP E_3: MG	E_1: G E_2: G E_3: F	E_1: P E_2: MP E_3: F
L_2	E_1: G E_2: MG E_3: MG	E_1: MG E_2: F E_3: G	E_1: G E_2: MG E_3: MG	E_1: M E_2: G E_3: G	E_1: F E_2: F E_3: G	E_1: MG E_2: G E_3: MG	E_1: F E_2: F E_3: G
L_3	E_1: VG E_2: VG E_3: G	E_1: G E_2: G E_3: G	E_1: F E_2: G E_3: G	E_1: F E_2: MG E_3: MG	E_1: VP E_2: G E_3: F	E_1: F E_2: MG E_3: F	E_1: F E_2: F E_3: G
L_4	E_1: P E_2: P E_3: F	E_1: F E_2: F E_3: F	E_1: MG E_2: G E_3: G	E_1: F E_2: MG E_3: G	E_1: F E_2: P E_3: G	E_1: F E_2: P E_3: G	E_1: G E_2: VG E_3: F
L_5	E_1: P E_2: VP E_3: F	E_1: MP E_2: P E_3: G	E_1: F E_2: VP E_3: VG	E_1: P E_2: P E_3: G	E_1: P E_2: G E_3: G	E_1: VP E_2: P E_3: G	E_1: VG E_2: P E_3: MG
L_6	E_1: P E_2: VP E_3: F	E_1: F E_2: MG E_3: MG	E_1: F E_2: G E_3: MG	E_1: P E_2: F E_3: G	E_1: F E_2: MG E_3: MG	E_1: MP E_2: F E_3: F	E_1: VP E_2: G E_3: MP

Table 17
Fuzzy evaluation matrix for the alternative production sites.

	C_1	C_3	C_4	C_8	C_{10}	C_{11}	C_{12}
L_1	(4.33, 6.33, 8.33)	(3, 5, 7)	(6.33, 8.33, 9.67)	(7, 9, 10)	(4.33, 6.33, 8)	(5.67, 7.67, 9)	(1.33, 3, 5)
L_2	(5.67, 7.67, 9.33)	(5, 7, 8.67)	(5.67, 7.67, 9.33)	(6.33, 8.33, 9.67)	(4.33, 6.33, 8)	(5.67, 7.67, 9.33)	(4.33, 6.33, 8)
L_3	(8.33, 9.67, 10)	(5.67, 7.67, 9)	(5.67, 7.67, 9)	(4.33, 6.33, 8.33)	(3.33, 4.67, 6)	(3.67, 5.67, 7.67)	(4.33, 6.33, 8)
L_4	(1, 2.33, 4.33)	(3, 5, 7)	(6.33, 8.33, 9.67)	(5, 7, 8.67)	(3.33, 5, 6.67)	(3.33, 5, 6.67)	(6.33, 8, 9)
L_5	(1, 2, 3.67)	(2.67, 4.33, 6)	(4, 5, 6)	(2.33, 3.67, 5.33)	(4.67, 6.33, 7.67)	(2.33, 3.33, 4.67)	(4.67, 6, 7.33)
L_6	(1, 2, 3.67)	(4.33, 6.33, 8.33)	(5, 7, 8.67)	(3.33, 5, 6.67)	(4.33, 6.33, 8.33)	(2.33, 4.33, 6.33)	(2.67, 4, 5.33)

Table 19
$\tilde{S}^*, \tilde{S}^-, \tilde{R}^*$, and $\tilde{R}^-$ values for the site selection problem

$\tilde{S}^*$	(11.81, 15.79, 24.87)
$\tilde{S}^-$	(17.55, 25.81, 45.42)
$\tilde{R}^*$	(3.64, 5.2, 7.14)
$\tilde{R}^-$	(5.05, 7.05, 9.44)

Table 20
Integrated fuzzy VIKOR-AHP analysis results for site selection.

	$\tilde{Q}_i$	Q_i	Rank order
L_1	(−0.85, 0.16, 3.92)	0.57	2
L_2	(−0.88, 0, 2.33)	0.22	1
L_3	(−0.65, 0.49, 3.3)	0.89	4
L_4	(−0.7, 0.59, 4.42)	1.00	6
L_5	(−0.66, 0.7, 5.13)	0.96	5
L_6	(−0.8, 0.45, 4.68)	0.77	3

5. Conclusions

Renewable energy is generated from natural resources such as sunlight, wind, rain, tides and geothermal heat. In many developing countries energy projects have demonstrated that renewable energy can make significant contributions to the economy by providing the energy needed for creating new businesses and employment. Moreover, renewable energy technologies make indirect contributions like providing energy for education, cooking, space heating, and lighting. Many countries and states have implemented incentives like government tax subsidies, partial payment schemes and rebates over purchase of renewables in order to encourage consumers to shift to renewable energy sources.

Turkey is a developing country which is extensively dependent on energy imports. Istanbul is the most populated and energy consuming city of Turkey. Besides, Istanbul is a rich region for the purposes of renewable energy generation. Considering the future needs of the region, our study focused on the selection of the most appropriate renewable energy investment and its location in Istanbul. A selection among the renewable energy alternatives has been made using an integrated VIKOR & AHP methodology. Then, employing the same methodology, a selection among the wind energy plantation sites has been made.

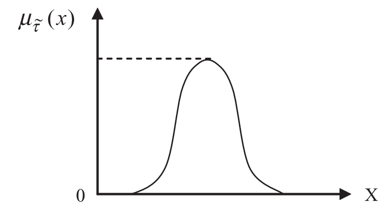
In the first step nine evaluation criteria were taken into consideration. The results of the multi-criteria decision analysis suggest that the wind energy is the best renewable energy alternative for the region. The ranking of the other alternatives in descending order is determined as solar, biomass, geothermal, and hydraulic. Secondly, using seven criteria, the site selection problem is solved for wind energy production. The rank order of alternative areas from the best to the worst is obtained as Çatalca, Şile, GOP, Tuzla, and Sarıyer. The proposed methodology has been successfully applied for both decision problems.

In the future research, similar studies can be conducted based on different multi-criteria decision-making techniques such as fuzzy PROMETHEE, fuzzy ELECTRE or fuzzy TOPSIS for comparative purposes.

Appendix A

A linguistic variable is a variable whose values are linguistic terms [56]. The concept of linguistic variable is very useful in dealing with situations which are too complex or ill-defined to be reasonably described in conventional quantitative expressions. The linguistic values can be represented by fuzzy numbers.

A fuzzy number is a fuzzy subset in the universe of discourse X that is both convex and normal. shows a fuzzy number $\tilde{\tau}$ of the universe of discourse X which is both convex and normal [57].



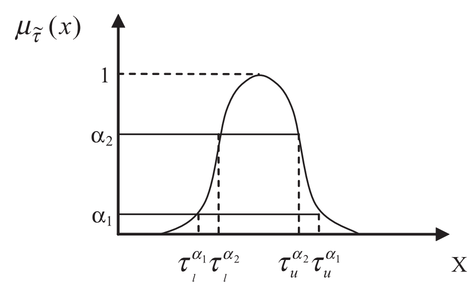
The α-cut of a fuzzy number $\tilde{\tau}$ is defined

$$\tilde{\tau}^{\alpha} = \left\{x_i : \mu_{\tilde{\tau}}(x_i) \geq \alpha, \ x_i \in X\right\} \tag{A1}$$

where $\lambda \in [0,1]$.

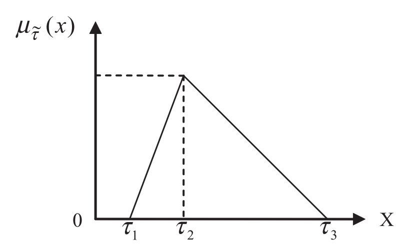
$\tilde{\tau}$ is a non-empty bounded closed interval contained in X and it can be denoted by $\tilde{\tau}^{\alpha} = [\tau_l^{\alpha}, \tau_u^{\alpha}]$, τ_l^{α} and τ_u^{α} are the lower and upper bounds of the closed interval, respectively. Fig. 2 shows a fuzzy number $\tilde{\tau}$ with α-cuts, where

$$\tilde{\tau}^{\alpha_1} = \left[\tau_l^{\alpha_1}, \tau_u^{\alpha_1}\right], \quad \tilde{\tau}^{\alpha_2} = \left[\tau_l^{\alpha_2}, \tau_u^{\alpha_2}\right]. \tag{A2}$$



From ,we can see that if $\alpha_2 \geq \alpha_1$, then $\tau_l^{\alpha_2} \geq \tau_l^{\alpha_1}$ and $\tau_u^{\alpha_1} \geq \tau_u^{\alpha_2}$.

A triangular fuzzy number (TFN) $\tilde{\tau}$ can be defined by a triplet (τ_1, τ_2, τ_3) shown in .The membership function $\mu_{\tilde{\tau}}(x)$ is defined as in Eq. (A3):



$$\mu_{\tilde{\tau}}(x) = \begin{cases} 0, & x_1 \leq \tau_1 \\ \frac{x-\tau_1}{\tau_2-\tau_1}, & \tau_1 \leq x \leq \tau_2 \\ \frac{x-\tau_3}{\tau_2-\tau_3}, & \tau_2 \leq x \leq \tau_3 \\ 0, & x \geq \tau_3 \end{cases} \tag{A3}$$

If $\tilde{\tau}$ is a fuzzy number and $\tau_l^{\alpha} > 0$ for $\alpha \in [0,1]$, then $\tilde{\tau}$ is called a positive fuzzy number. Given any two positive fuzzy numbers $\tilde{\rho}, \tilde{\tau}$ and a positive real number r, the α-cut of two fuzzy numbers are $\tilde{\rho}^{\alpha} = [\rho_l^{\alpha}, \rho_\mu^{\alpha}]$ and $\tilde{\tau}^{\alpha} = [\tau_l^{\alpha}, \tau_\mu^{\alpha}]$, $(\alpha \in [0,1])$, respectively. Some main operations of positive fuzzy numbers $\tilde{\rho}$ and $\tilde{\tau}$ can be expressed as follows [58]:

$$\left(\tilde{\rho}(+)\tilde{\tau}\right)^{\alpha} = \left[\rho_l^{\alpha} + \tau_l^{\alpha}, \rho_u^{\alpha} + \tau_u^{\alpha}\right], \tag{A4}$$

$$\left(\tilde{\rho}(-)\tilde{\tau}\right)^{\alpha} = \left[\rho_{l}^{\alpha} - \tau_{u}^{\alpha}, \rho_{u}^{\alpha} - \tau_{l}^{\alpha}\right], \tag{A5}$$

$$\left(\tilde{\rho}(\cdot)\tilde{\tau}\right)^{\alpha} = \left[\rho_{l}^{\alpha} \cdot \tau_{l}^{\alpha}, \rho_{u}^{\alpha} \cdot \tau_{u}^{\alpha}\right], \tag{A6}$$

$$\left(\tilde{\rho}(:)\tilde{\tau}\right)^{\alpha} = \left[\frac{\rho_{l}^{\alpha}}{\tau_{u}^{\alpha}}, \frac{\rho_{u}^{\alpha}}{\tau_{l}^{\alpha}}\right], \tag{A7}$$

$$\left(\tilde{\rho}^{\alpha}\right)^{-1} = \left[\frac{1}{\rho_{u}^{\alpha}}, \frac{1}{\rho_{l}^{\alpha}}\right], \tag{A8}$$

$$\left(\tilde{\rho}(\cdot)r\right)^{\alpha} = \left[\rho_{l}^{\alpha} \cdot r, \rho_{u}^{\alpha} \cdot r\right], \tag{A9}$$

$$\left(\tilde{\rho}(:)r\right)^{\alpha} = \left[\frac{\rho_{l}^{\alpha}}{r}, \frac{\rho_{u}^{\alpha}}{r}\right], \tag{A10}$$

If $\tilde{n}$ is a triangular fuzzy number and $\tau_{l}^{\alpha} > 0, \tau_{u}^{\alpha} \leq 1$ for $\alpha \in [0, 1]$, then $\tilde{\tau}$ is called a normalized positive triangular fuzzy number [59].

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