Selection of the Most Appropriate Renewable Energy Alternatives by Using a Novel Interval-Valued Neutrosophic ELECTRE I Method

Ali KARAŞAN[1,2,*], Cengiz KAHRAMAN[2]

[1] *Institute of Natural and Applied Sciences, Yildiz Technical University, 34349 Besiktas, Istanbul, Turkey*

[2] *Department of Industrial Engineering, Istanbul Technical University, 34347 Macka, Istanbul, Turkey*

e-mail: akarasan@yildiz.edu.tr

Abstract. Today energy demand in the world cannot be met based on the growing population of the countries. Exhaustible resources are not enough to supply this energy requirement. Furthermore, the pollution created by these sources is one of the most important issues for all living things. In this context, clean and sustainable energy alternatives need to be considered. In this study, a novel interval-valued neutrosophic (IVN) ELECTRE I method is conducted to select renewable energy alternative for a municipality. A new division operation and deneutrosophication method for interval-valued neutrosophic sets is proposed. A sensitivity analysis is also implemented to check the validity of the proposed method. The obtained results and the sensitivity analysis demonstrate that the given decision in the application is robust. The results of the proposed method determine that the wind power plant is the best alternative and our proposed method's decisions are consistent and reliable through the results of comparative and sensitivity analyses.

Key words: interval-valued neutrosophic sets, ELECTRE I, multi-criteria decision making, renewable energy.

1. Introduction

Selection of the most appropriate alternative of renewable energy source is one of the most important key principles for a sustainable and clean environment. This selection process focuses to choose the best location for an anticipated purpose. Since the use of exhaustible resources in cities and industries cause air pollution, safety risks, and greenhouse gas emissions in the atmosphere, the building of a renewable energy plant becomes a more important issue for a sustainable city than ever. Furthermore, renewable energy alternative selection problem involves many criteria such as operational, environmental, social, and economic, and each of them addresses the problem in a broader and different perspective.

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[*]Corresponding author.

In multi-criteria decision making (MCDM) problems, the most important problem is the way of handling uncertainty (Mardani *et al.*, 2015a, 2015b, 2017, 2018). In this type of problems, the criteria can be tangible or intangible. Having more intangible criteria than tangible criteria causes a harder evaluation process for experts. In this environment, MCDM methods need to determine the evaluation criteria, a set of possible alternatives, and collect the appropriate information about alternatives with respect to criteria, and to evaluate them for the decision makers' purposes (Tzeng and Huang, 2011). To handle these difficulties, many models have been proposed and among these models, Analytic Hierarchy Process (AHP) (Saaty, 1980), Analytic Network Process (ANP) (Saaty, 1996), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981; Zavadskas *et al.*, 2016), ELimination Et Choix Traduisant la REalité (ELECTRE) (Roy, 1991; Govindan and Jepsen, 2016), VIKOR (Opricovic, 1998; Mardani *et al.*, 2016), linguistic models (Cabrerizo *et al.*, 2017, 2018; Morente-Molinera *et al.*, 2019; Zhang *et al.*, 2018; Liu *et al.*, 2018) are the most used ones.

When considering real life conditions, things are not often precise, and they cannot be described by crisp or deterministic models. Thus, the capacity of making precise statements is quite challenging. In order to handle these vague and imprecise events, Zadeh (1965) introduced fuzzy sets together with degrees of membership of elements to these sets (Zadeh, 1965). Since that time, ordinary fuzzy sets have been extended to type-2, intuitionistic, hesitant, orthopair fuzzy sets, and neutrosophic sets. Zadeh introduced type-2 fuzzy sets to define the uncertainty of membership functions to reduce vagueness (Zadeh, 1975). Then, (Zadeh, 1975; Grattan-Guiness, 1975; Jahn, 1975; Sambuc, 1975) introduced interval-valued fuzzy sets (IVFSs), independently from each other. Atanassov introduced intuitionistic fuzzy sets (IFSs) to express decision maker's opinions more freely by using not only membership functions but also non-membership functions of the elements in a fuzzy set (Atanassov, 1986). Hesitant fuzzy sets (HFSs) were introduced by Torra (2010) in order to operate with a set of possible membership values for an element in a fuzzy set (Torra, 2010). Despite all these extensions, fuzzy sets could not handle all types of uncertainties such as indeterminate and inconsistent information.

In order to tackle this inadequacy, Smarandache (1995) introduced neutrosophic logic and neutrosophic sets (Smarandache, 1999). A neutrosophic set is composed of three subsets which are degree of truthiness (T), degree of indeterminacy (I), and degree of falsity (F). These subsets are between $]^-0, 1^+[$ non-standard unit interval (Rivieccio, 2008). Thus, a membership function of a neutrosophic number is represented by truth sub-set; non-membership function is represented by falsity sub-set; and hesitancy is represented by indeterminacy sub-set. These features constitute the superiority of neutrosophic sets over the other extensions of fuzzy sets. We utilize neutrosophic sets since their main advantage is the capability in distinguishing relativity and absoluteness of decision makers' preferences.

The first ELECTRE method, ELECTRE I, was introduced by Roy (1968). The roots of its development are based on the construction of a contradictory and very heterogeneous set of criteria, and quantitative and qualitative consequences which are not only associated with numerical ordinal scales but also are attached with imprecise, uncertain,

and ill-determined knowledge of data (Roy, 1968). The other types of ELECTRE methods are ELECTRE IS, ELECTRE II, ELECTRE III, ELECTRE IV, and ELECTRE TRI. These methods mainly hold ELECTRE I characteristics and link to its basic idea. Briefly, ELECTRE I and ELECTRE IS are introduced for the selection problems; ELECTRE TRI, for the assignment problems, and ELECTRE II, III and IV, for the ranking problems (Leyva López, 2005). Since our problem's characteristics hold heterogeneous and multi-criteria structure; qualitive and quantitative consequences build on interval-number scales; uncertain and indeterminate knowledge, it is proper to apply ELECTRE I method.

In this study, an IVN ELECTRE I method is developed and applied to a renewable energy sources alternative selection for a county municipality. The originality of this paper can be explained with 3 basics. Firstly, we develop a novel interval-valued neutrosophic ELECTRE I method and apply it to a renewable energy source selection. Secondly, a new and an efficient deneutrosophication and division operation is proposed. Finally, for validating the proposed method, we compare the results with the interval-valued neutrosophic (IVN) TOPSIS method. A sensitivity analysis with an explanatory pattern is also performed to demonstrate the stability of the ranking results of the IVN ELECTRE I method. We believe that our study can guide the researchers who are interested in decision making under imprecise and indeterminate environment.

The remainder of this paper is prepared as follows. Section 2 reviews the literature related to the neutrosophic MCDM. In Section 3, renewable energy source alternatives and criteria are determined. In Section 4, preliminaries for IVN neutrosophic sets are given. In Section 5, an application for a county municipality to determine the best renewable energy source is introduced by using the proposed IVN ELECTRE I method. The paper ends with the conclusions and suggestions for further research.

2. Literature Review: Neutrosophic MCDM Methods

Neutrosophic sets have been used in several single and multiple decision-making methods in recent years. The number of studies on neutrosophic sets and its applications has increased dramatically since 2010. The types of neutrosophic sets in the literature are singleton, interval-valued, triangular, or trapezoidal neutrosophic sets. These studies have been briefly summarized in the following.

Bausys *et al.* (2015) applied neutrosophic sets to COPRAS method for the decision making problems by using uncertain data. Sun *et al.* (2015) extended Choquet integral operator with interval neutrosophic numbers for multi-criteria decision making problems. Bausys and Zavadskas (2015) extended VIKOR method with interval valued neutrosophic sets for the multi-criteria decision making problems. Zavadskas *et al.* (2015) applied WASPAS method with single-valued neutrosophic set for the assessment of locations for the construction site of a waste incineration plant. Ye (2016b) introduced correlation coefficients of interval neutrosophic hesitant fuzzy sets for the MCDM problems. Li *et al.* (2016) introduced Some single valued neutrosophic number heronian mean operators for the MCDM problems. Ye studied the cross-entropy of single valued neutrosophic sets

(SVNSs) as an extension of the cross entropy of fuzzy sets. The practical example showed the effectiveness of the proposed cross entropy method for MCDM techniques (Ye, 2014). Ye developed a multiple attribute group decision-making method by using the neutrosophic linguistic numbers weighted arithmetic average (NLNWAA) and neutrosophic linguistic numbers weighted geometric average (NLNWGA) operators (Ye, 2016a). Ma *et al.* studied a problem of time-aware trustworthy service selection which is formulated as MCDM problem of creating ranked services list using cloud service interval neutrosophic set (CINS) (Ma *et al.*, 2016). It was solved by developing a CINS ranking method. The developed model which is based on a real-world dataset shows the practicality and effectiveness of the proposed approach. Huang defined a new distance measure between two SVNSs (Huang, 2016). The study figured out that neutrosophic sets are very effective to define incompleteness, indeterminacy and inconsistency information. Baušys and Juodagalvienė studied a location selection problem of the garage at the parcel of a single-family residential house by using an integrated method of AHP and Weighted Aggregated Sum-Product Assessment (WASPAS) with SVNSs (Baušys and Juodagalvienė, 2017). They reveal that the application of SVNSs allows to model uncertainty of the initial information clearly. Peng *et al.* presented an MCDM problem based on the Qualitative Flexible Multiple Criteria (QUALIFLEX) method where the criteria values are addressed by multi-valued neutrosophic information (Peng *et al.*, 2017a). Stanujkic *et al.* (2017) extended MULTIMOORA method to single valued neutrosophic sets. Zavadskas *et al.* (2017) applied single-valued neutrosophic MAMVA method for the sustainable market evaluation of buildings. The assessments showed that the given decisions by the proposed method are robust and can be applied to various application areas. Akram & Sitara studied an SVN graph structure which is a generalization of fuzzy graph structures (Akram and Sitara, 2017). Applications of SVN graph structures in decision-making problems showed that using neutrosophic sets allow to clarify uncertainty of the complex environments. The illustrative example of choosing the best manufacturing alternative in the flexible manufacturing system indicated the robustness of the proposed methodologies. Şahin presented prioritized aggregation operators for aggregating the normal neutrosophic information and then extended these operators to the generalized prioritized weighted aggregation operators (Şahin, 2017). The results of the study indicated that normal neutrosophic sets are a powerful tool for handling incompleteness, indeterminacy, and inconsistency of evaluation information. Ye (2017) introduced weighted aggregation operators of trapezoidal neutrosophic numbers for the MCDM problems. Liang *et al.* (2017) applied single-valued trapezoidal neutrosophic DEMATEL method for the evaluation of e-commerce websites. Zhang *et al.* proposed a restaurant decision support model using social information for tourists on TripAdvisor.com by using interval-valued neutrosophic numbers (Zhang *et al.*, 2017). The paper found out that the new model considers the active, neutral and passive information in online reviews all at once and takes the inter-dependency among criteria into consideration on tourists' decision-making. Peng *et al.* presented a new outranking approach for MCDM problems, which are developed in the context of a simplified neutrosophic environment by singleton subsets in [0, 1] (Peng *et al.*, 2017b). The comparison analysis showed that the use of neutrosophic sets is an influential way of handling indeterminacy. Ji *et al.* (2018) applied multi-valued neutrosophic TODIM method for the

selection of personnel under the consideration of risk preference decision-makers. Abdel-Basset *et al.* (2018) applied an integrated AHP–SWOT analysis by considering neutrosophic logic for the decision making of strategic planning. Feng *et al.* (2018) applied an integrated methodology consisting of DEMATEL and ELECTRE III methods by considering neutrosophic set environment for the shopping mall photovoltaic plan selection.

In this paper, unlike the above papers, an interval-valued neutrosophic ELECTRE I is presented for alternative energy source selection problem of a county municipality. Since evaluation criteria include not only uncertain but also incomplete, indeterminate and inconsistent characteristics in the evaluation process, interval-valued neutrosophic sets are used to handle this handicap. In the literature, multi-valued neutrosophic ELECTRE III and single valued neutrosophic ELECTRE methods have been developed by Peng *et al.* (2016, 2014), Feng *et al.* (2018). The models in Peng *et al.* (2016) and (2014) are based on single valued neutrosophic sets and do not present a flexible definition area for T, I, F values to decision makers. Feng *et al.* (2018) developed an interval valued neutrosophic ELECTRE III method for the shopping mall photovoltaic plan selection. However, our proposed method includes novel deneutrosophication and division operators together with comprehensive linguistic scales in order to weigh the criteria and to assess the alternatives. In this paper, we develop ELECTRE I method by using interval-valued neutrosophic sets to a new deneutrosophication method and a new division operator for interval-valued neutrosophic sets. We believe this paper can guide researchers to the application of interval-valued neutrosophic sets to other MCDM techniques.

3. Neutrosophic Sets: Preliminaries

Smarandache introduced neutrosophic sets as an extension of intuitionistic fuzzy sets. They have become very popular in recent years and have been used in many MCDM methods such as neutrosophic AHP (Radwan *et al.*, 2016); neutrosophic TOPSIS (Chi and Liu, 2013; Nădăban and Dzitac, 2016); neutrosophic EDAS (Peng and Liu, 2017).

DEFINITION 1. Let X be a universe of discourse. A single-valued neutrosophic set A in X is:

$$A = \left\{ x, \left(T_A(x), I_A(x), F_A(x) \right) \big| x \in X \right\}, \tag{1}$$

where $T_A(x)$, $I_A(x)$, and $F_A(x)$ represent the membership functions for truth, indeterminacy, and falsity, respectively. For each point x in X, $T_A(x), I_A(x), F_A(x) \in [0, 1]$, and $0 \leqslant T_A(x) + I_A(x) + F_A(x) \leqslant 3$ (Wang *et al.*, 2005a).

DEFINITION 2. Let X be a universe of discourse. An IVN set N in X is independently characterized by the intervals $T_N(x) = [T_{N(x)}^L, T_{N(x)}^U] \subseteq [0, 1]$, $I_N(x) = [I_{N(x)}^L, I_{N(x)}^U] \subseteq [0, 1]$, and $F_N(x) = [F_{N(x)}^L, F_{N(x)}^U] \subseteq [0, 1]$. They satisfy the condition $0 \leqslant T_N^L(x) + I_N^L(x) + F_N^L(x) \leqslant 3$. Thus, the IVNS N can be denoted as Wang *et al.* (2005b):

$$N = \left\langle \left[T_N^L(x), T_N^U(x) \right], \left[I_N^L(x), I_N^U(x) \right], \left[F_N^L(x), F_N^U(x) \right] \right\rangle. \tag{2}$$

We will denote Eq. (2) as $[T_N^L, T_N^U], [I_N^L, I_N^U], [F_N^L, F_N^U]$ for short.

Let $a = [T_a^L, T_a^U], [I_a^L, I_a^U], [F_a^L, F_a^U]$ and $b = [T_b^L, T_b^U], [I_b^L, I_b^U], [F_b^L, F_b^U]$ be two IVN numbers (IVNNs), the relations of them are shown as below (Wang *et al.*, 2005a; Zhang *et al.*, 2015):

1. $a^c = \langle [T_a^L, T_a^U], [1 - I_a^U, 1 - I_a^U], [F_a^L, F_a^L] \rangle$.
2. $a \subseteq b$ if and only if $T_a^L \leqslant T_b^L, T_a^U \leqslant T_b^U; I_a^L \geqslant I_b^L, I_a^U \geqslant I_b^U; F_a^L \geqslant F_b^L, F_a^U \geqslant F_b^U$.
3. $a = b$ if and only if $a \subseteq b$ and $b \subseteq a$.
4. $a \oplus b = \langle [T_a^L + T_b^L - T_a^L T_b^L, \ T_a^U + T_b^U - T_a^U T_b^U], [I_a^L I_b^L, \ I_a^U I_b^U], [F_a^L F_b^L, \ F_a^U F_b^U] \rangle$.
5. $a \otimes b = \langle [T_a^L T_b^L, T_a^U T_b^U] [I_a^L + I_b^L - I_a^L I_b^L, \ I_a^U + I_b^U - I_a^U I_b^U], [F_a^L \ + F_b^L - F_a^L F_b^L, \ F_a^U + F_b^U - F_a^U F_b^U] \rangle$.

DEFINITION 3. Let $\tilde{A} = \langle [T_1^L, T_1^U], [I_1^L, I_1^U], [F_1^L, F_1^U] \rangle$; $\tilde{B} = \langle [T_2^L, T_2^U], [I_2^L, I_2^U],$ $[F_2^L, F_2^U] \rangle$ be an interval-valued neutrosophic number where $T_2^L > 0$; $T_2^U > 0$; $I_2^L > 0$; $I_2^U > 0$; $F_2^L > 0$; $F_2^U > 0$. The division operation is given as below

$$
A \oslash B = \frac{\left(\begin{array}{c} \left[\min\left(\frac{T_1^L}{T_2^L}, \frac{T_1^L}{T_2^L}, \frac{T_1^U}{T_2^U}, \frac{T_1^U}{T_2^U}\right), \max\left(\frac{T_1^L}{T_2^L}, \frac{T_1^L}{T_2^L}, \frac{T_1^U}{T_2^U}, \frac{T_1^U}{T_2^U}\right)\right], \\ \left[\min\left(\frac{I_1^L}{I_2^L}, \frac{I_1^L}{I_2^L}, \frac{I_1^U}{I_2^U}, \frac{I_1^U}{I_2^U}\right), \max\left(\frac{I_1^L}{I_2^L}, \frac{I_1^L}{I_2^L}, \frac{I_1^U}{I_2^U}, \frac{I_1^U}{I_2^U}\right)\right], \\ \left[\min\left(\frac{F_1^L}{F_2^L}, \frac{F_1^L}{F_2^L}, \frac{F_1^U}{F_2^U}, \frac{F_1^U}{F_2^U}\right), \max\left(\frac{F_1^L}{F_2^L}, \frac{F_1^L}{F_2^L}, \frac{F_1^U}{F_2^U}, \frac{F_1^U}{F_2^U}\right)\right] \end{array} \right)}{\max \left(\begin{array}{c} \left[\min\left(\frac{T_1^L}{T_2^L}, \frac{T_1^L}{T_2^L}, \frac{T_1^U}{T_2^U}, \frac{T_1^U}{T_2^U}\right), \max\left(\frac{T_1^L}{T_2^L}, \frac{T_1^L}{T_2^L}, \frac{T_1^U}{T_2^U}, \frac{T_1^U}{T_2^U}\right)\right], \\ \left[\min\left(\frac{I_1^L}{I_2^L}, \frac{I_1^L}{I_2^L}, \frac{I_1^U}{I_2^U}, \frac{I_1^U}{I_2^U}\right), \max\left(\frac{I_1^L}{I_2^L}, \frac{I_1^L}{I_2^L}, \frac{I_1^U}{I_2^U}, \frac{I_1^U}{I_2^U}\right)\right], \\ \left[\min\left(\frac{F_1^L}{F_2^L}, \frac{F_1^L}{F_2^L}, \frac{F_1^U}{F_2^U}, \frac{F_1^U}{F_2^U}\right), \max\left(\frac{F_1^L}{F_2^L}, \frac{F_1^L}{F_2^L}, \frac{F_1^U}{F_2^U}, \frac{F_1^U}{F_2^U}\right)\right] \end{array} \right)}.
$$

DEFINITION 4. Let $a_j = \langle [T_{a_j}^L, T_{a_j}^U], [I_{a_j}^L, I_{a_j}^U], [F_{a_j}^L, F_{a_j}^U] \rangle$, $j = 1, 2, \ldots, n$ be a collection of IVNNs. Based on the weighted aggregation operators of IVNNs, the interval neutrosophic number weighted average operator is given as below (Biswas *et al.*, 2016):

$$
INNWA(a_1, a_2, \ldots, a_n) = \sum_{j=1}^{n} w_j a_i
$$

$$
= \left\langle \left[1 - \prod_{j=1}^{n} (1 - T_{aj}^L)^{w_j}, 1 - \prod_{j=1}^{n} (1 - T_{aj}^U)^{w_j} \right], \left[\prod_{j=1}^{n} (1 I_{aj}^L)^{w_j}, \prod_{j=1}^{n} (I_{aj}^U)^{w_j} \right], \right.
$$

$$
\left. \left[\prod_{j=1}^{n} (F_{aj}^L)^{w_j}, \prod_{j=1}^{n} (F_{aj}^U)^{w_j} \right] \right\rangle, \tag{3}
$$

where w_j $(j = 1, 2, \ldots, n)$ is the weight of a_j $(j = 1, 2, \ldots, n)$ with $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$.

Table 1
Scale of IVN decision matrix.

Linguistic term		$\langle [T^L, T^U], [I^L, I^U], [F^L, F^U] \rangle$
CB	Certainly bad	$\langle [0.1, 0.2], [0.6, 0.7], [0.8, 0.9] \rangle$
VB	Very bad	$\rangle [0.2, 0.3], [0.5, 0.6], [0.7, 0.8] \rangle$
B	Bad	$\langle [0.3, 0.4], [0.4, 0.5], [0.6, 0.7] \rangle$
BA	Below average	$\langle [0.4, 0.5], [0.3, 0.4], [0.5, 0.6] \rangle$
F	Fair	$\langle [0.5, 0.5], [0.1, 0.2], [0.5, 0.5] \rangle$
AA	Above average	$\langle [0.5, 0.6], [0.3, 0.4], [0.4, 0.5] \rangle$
G	Good	$\langle [0.6, 0.7], [0.4, 0.5], [0.3, 0.4] \rangle$
VG	Very good	$\langle [0.7, 0.8], [0.5, 0.6], [0.2, 0.3] \rangle$
CG	Certainly good	$\langle [0.8, 0.9], [0.6, 0.7], [0.1, 0.2] \rangle$

Table 2
DM based on expert j opinions.

Criterion	Type	AL_1	AL_2	...	AL_n
C_1	Linguistic cost	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	...	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$
C_2	Numerical cost	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	...	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
C_m	Linguistic Benefit	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	...	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$

There are few deneutrosophication methods for comparing neutrosophic numbers (Zhang *et al.*, 2015; Biswas *et al.*, 2016). We propose a new deneutrosophication method in order to compare the interval-valued neutrosophic numbers. It is given in Definition 5.

DEFINITION 5. Let $A = \langle (T^L, T^U), (I^L, I^U), (F^L, F^U) \rangle$ be an interval-valued neutrosophic number. The deneutrosophicated A value ($\mathfrak{H}(A)$) is given by Eq. (4):

$$\mathfrak{H}(A) = \frac{(T^L + T^U + (1 - F^L) + (1 - F^U) + T^L \times T^U - \sqrt{(1 - F^L) \times (1 - F^U)})}{4}$$
$$\times \left(\left(1 - \frac{[(I^L) + (I^U)]}{2} \right) - \left(\sqrt{(I^L) \times (I^U)} \right) \right). \tag{4}$$

4. Proposed Methodology

IVN ELECTRE I method's steps are given as follows:

Step 1: Construct the IVN decision matrices (D_j) based on experts' opinions (j) by using the scale which is given in Table 1 (Karaşan and Kahraman, 2017).

The illustrated decision matrix (DM) based on Expert j opinions is presented in Table 2.

Step 2: Aggregate the DMs to obtain aggregated IVN decision matrix (A) by using Eq. (3) as in Table 3.

Table 3
Aggregated DM.

Criterion	Type	AL_1	AL_2	...	AL_n
C_1	Linguistic cost	$\langle[T_A^L, T_A^U],[I_A^L, I_A^U],[F_A^L, F_A^U]\rangle$	$\langle[T_A^L, T_A^U],[I_A^L, I_A^U],[F_A^L, F_A^U]\rangle$	...	$\langle[T_A^L, T_A^U],[I_A^L, I_A^U],[F_A^L, F_A^U]\rangle$
C_{12}	Numerical cost	$\langle[T_A^L, T_A^U],[I_A^L, I_A^U],[F_A^L, F_A^U]\rangle$	$\langle[T_A^L, T_A^U],[I_A^L, I_A^U],[F_A^L, F_A^U]\rangle$	...	$\langle[T_A^L, T_A^U],[I_A^L, I_A^U],[F_A^L, F_A^U]\rangle$
⋮	⋮	⋮	⋮	⋱	⋮
C_m	Linguistic benefit	$\langle[T_A^L, T_A^U],[I_A^L, I_A^U],[F_A^L, F_A^U]\rangle$	$\langle[T_A^L, T_A^U],[I_A^L, I_A^U],[F_A^L, F_A^U]\rangle$	...	$\langle[T_A^L, T_A^U],[I_A^L, I_A^U],[F_A^L, F_A^U]\rangle$

Table 4
Normalized decision matrix.

Criterion	Type	AL_1	AL_2	...	AL_n
C_1	Linguistic cost	$\langle[T_r^L, T_r^U],[I_r^L, I_r^U],[F_r^L, F_r^U]\rangle$	$\langle[T_r^L, T_r^U],[I_r^L, I_r^U],[F_r^L, F_r^U]\rangle$	...	$\langle[T_r^L, T_r^U],[I_r^L, I_r^U],[F_r^L, F_r^U]\rangle$
C_2	Numerical cost	$\langle[T_r^L, T_r^U],[I_r^L, I_r^U],[F_r^L, F_r^U]\rangle$	$\langle[T_r^L, T_r^U],[I_r^L, I_r^U],[F_r^L, F_r^U]\rangle$	...	$\langle[T_r^L, T_r^U],[I_r^L, I_r^U],[F_r^L, F_r^U]\rangle$
⋮	⋮	⋮	⋮	⋱	⋮
C_m	Linguistic benefit	$\langle[T_r^L, T_r^U],[I_r^L, I_r^U],[F_r^L, F_r^U]\rangle$	$\langle[T_r^L, T_r^U],[I_r^L, I_r^U],[F_r^L, F_r^U]\rangle$	...	$\langle[T_r^L, T_r^U],[I_r^L, I_r^U],[F_r^L, F_r^U]\rangle$

Step 3: Calculate the weighted normalized DM (R).

Normalization of formulas for benefit (b_{ij}) and cost (c_{ij}) criteria is given in the following, respectively.

$$r_{ij} = \frac{b_{ij}}{\sqrt{\sum_{i=1}^{n} b_{ij}^2}}, \tag{5}$$

where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$.

$$r_{ij} = \frac{\frac{1}{c_{ij}}}{\sqrt{\sum_{i=1}^{n} (\frac{1}{c_{ij}})^2}}, \tag{6}$$

where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$.

Arithmetic operations are carried out with the neutrosophic formulas given in Definition 2, and Definition 3. After calculations, normalized IVN DM (R) is illustrated in Table 4.

Weighted normalized IVN DM (V) is obtained by multiplying the IVN weights vector (w_j) which is given in Table 5 with the normalized IVN DM (R) as in Eq. (7).

$$v_{ij} = w_j \otimes r_{ij}, \tag{7}$$

where, $w_j = \langle[T_w^L, T_w^U],[I_w^L, I_w^U],[F_w^L, F_w^U]\rangle$, $r_{ij} = \langle[T_r^L, T_r^U],[I_r^L, I_r^U],[F_r^L, F_r^U]\rangle$, and $v_{ij} = \langle[T_v^L, T_v^U],[I_v^L, I_v^U],[F_v^L, F_v^U]\rangle$.

Table 6 presents the weighted normalized IVN DM.

Table 5
Scale for criteria weighting (Karaşan and Kahraman, 2017).

Linguistic term		$\langle [T^L, T^U], [I^L, I^U], [F^L, F^U] \rangle$
TI	Trivial importance	$\langle [0.06, 0.22], [0.67, 0.78], [0.83, 1.00] \rangle$
UII	Unimportant importance	$\langle [0.22, 0.33], [0.56, 0.67], [0.72, 0.83] \rangle$
USI	Unsatisfied importance	$\langle [0.33, 0.44], [0.44, 0.56], [0.61, 0.72] \rangle$
LF	Lower than fair	$\langle [0.44, 0.56], [0.33, 0.44], [0.50, 0.61] \rangle$
FI	Fair importance	$\langle [0.50, 0.56], [0.11, 0.22], [0.44, 0.50] \rangle$
MF	More than fair	$\langle [0.50, 0.61], [0.33, 0.44], [0.44, 0.56] \rangle$
SI	Satisfied importance	$\langle [0.61, 0.72], [0.44, 0.56], [0.33, 0.44] \rangle$
II	Impactful importance	$\langle [0.72, 0.83], [0.56, 0.67], [0.22, 0.33] \rangle$
CII	Certainly impactful importance	$\langle [0.83, 1.00], [0.67, 0.78], [0.06, 0.22] \rangle$

Table 6
Weighted normalized IVN decision matrix.

Criterion	Type	AL_1	AL_2	$\cdots$	AL_n
C_1	Linguistic cost	$\langle [T_v^L, T_v^U], [I_v^L, I_v^U], [F_v^L, F_v^U] \rangle$	$\langle [T_v^L, T_v^U], [I_v^L, I_v^U], [F_v^L, F_v^U] \rangle$	$\cdots$	$\langle [T_v^L, T_v^U], [I_v^L, I_v^U], [F_v^L, F_v^U] \rangle$
C_2	Numerical cost	$\langle [T_v^L, T_v^U], [I_v^L, I_v^U], [F_v^L, F_v^U] \rangle$	$\langle [T_v^L, T_v^U], [I_v^L, I_v^U], [F_v^L, F_v^U] \rangle$	$\cdots$	$\langle [T_v^L, T_v^U], [I_v^L, I_v^U], [F_v^L, F_v^U] \rangle$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
C_m	Linguistic benefit	$\langle [T_v^L, T_v^U], [I_v^L, I_v^U], [F_v^L, F_v^U] \rangle$	$\langle [T_v^L, T_v^U], [I_v^L, I_v^U], [F_v^L, F_v^U] \rangle$	$\cdots$	$\langle [T_v^L, T_v^U], [I_v^L, I_v^U], [F_v^L, F_v^U] \rangle$

Step 4: Obtain the Concordance and Discordance Indices.

Let $A L_n = \{a, b, \ldots, n\}$ denote a finite set of alternatives.

Concordance index ($\mathbb{C}_{ab}$) measures are given by Eq. (8):

$$\mathbb{C}_{ab} = \{j \mid x_{aj} \geqslant x_{bj}\}. \tag{8}$$

Discordance index ($\mathbb{D}_{ab}$) measures the strength of the evidence against the Concordance index by Eq. (9):

$$\mathbb{D}_{ab} = \{j \mid x_{aj} < x_{bj}\}. \tag{9}$$

Step 5: Calculate the Concordance matrix.

The Concordance index $\mathbb{C}(a, b)$ between AL_a and AL_b is determined using Eq. (10):

$$\mathbb{C}(a, b) = \sum_{j \in \mathbb{C}(a,b)} \mathfrak{H}(w_j). \tag{10}$$

Through this calculation for all alternatives, concordance matrix is found as below:

$$\mathbb{C} = \begin{bmatrix} - & \mathbb{C}(1, 2) & \cdots & \mathbb{C}(1, m) \\ \mathbb{C}(2, 1) & - & \cdots & \mathbb{C}(2, m) \\ \vdots & \cdots & \ddots & \vdots \\ \mathbb{C}(m, 1) & \mathbb{C}(m, 2) & \cdots & - \end{bmatrix}. \tag{11}$$

Step 6: Calculate the Discordance matrix.

Similarly, the Discordance index $\mathbb{D}(a, b)$ between AL_a and AL_b is determined by Eq. (12):

$$\mathbb{D}(a, b) = \frac{\max_{j \in \mathbb{D}_{ab}} |v_{aj} - v_{bj}|}{\max_{j \in J; m,n \in I} |v_{mj} - v_{nj}|}, \tag{12}$$

where $v_{.j}$ is obtained by the deneutrosophicated weighted normalized IVN decision matrix based on Eq. (4).

If q and z are used to show the weighted normalized values, the discordance matrix can be given as in Eq. (13).

$$\mathbb{D} = \begin{bmatrix} - & \mathbb{D}(1, 2) & \cdots & \mathbb{D}(1, q) \\ \mathbb{D}(2, 1) & - & \cdots & \mathbb{D}(2, q) \\ \vdots & \cdots & \ddots & \vdots \\ \mathbb{D}(z, 1) & \mathbb{D}(z, 2) & \cdots & - \end{bmatrix}. \tag{13}$$

Step 7: Determine the threshold value for Concordance and Discordance matrices.

The threshold value for Concordance matrix (α_C) is computed by the average of the elements in matrix $\mathbb{C}$ via Eq. (14):

$$\alpha_{\mathbb{C}} = \sum_{a=1}^{m} \sum_{b=1}^{m} \frac{\mathbb{C}(a, b)}{m(m-1)}. \tag{14}$$

The threshold value for Discordance matrix (α_D) is computed by the average of the elements in matrix $\mathbb{D}$ via Eq. (15):

$$\alpha_{\mathbb{D}} = \sum_{a=1}^{m} \sum_{b=1}^{m} \frac{\mathbb{D}(a, b)}{m(m-1)}. \tag{15}$$

Step 8: Determine the acceptable relations based on ($\alpha_{\mathbb{C}}$) and ($\alpha_{\mathbb{D}}$). The values equal or larger than $\alpha_{\mathbb{C}}$ and the values smaller than $\alpha_{\mathbb{D}}$ are simultaneously used to determine the outranking relations in the kernel.

The proposed extension of ELECTRE I method offers ready-made scales to decision makers in order to express their opinions efficiently. It conducts new deneutrosophication and division operators for interval-valued neutrosophic sets. Besides, our model is relatively easy to use and produces robust decisions.

5. Application

Managers of a municipal which is close to sea coast want to invest in renewable energy technologies for self-meeting their energy need. Expert group indicated that they were not
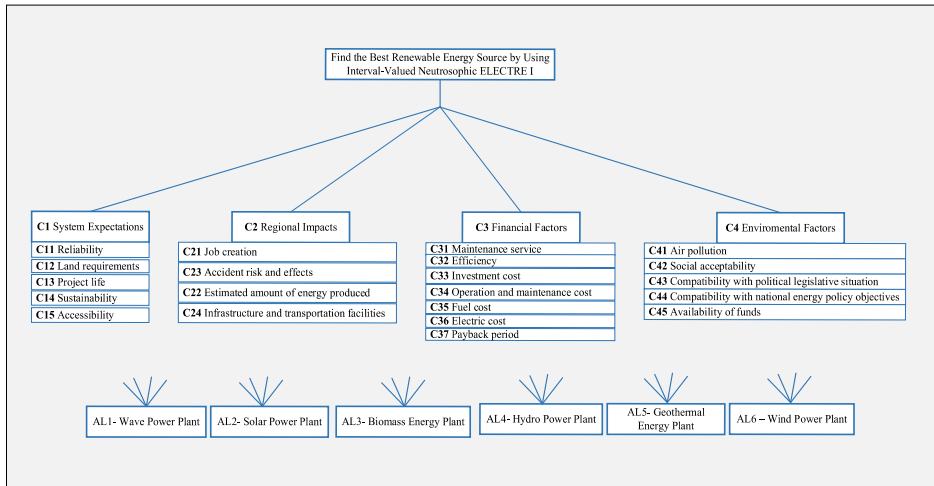
Fig. 1. Hierarchy of the application.

sure neither about the exact values of measurable criteria nor about the values of linguistic criteria since the related data depend on uncertain environmental, political, and economic conditions. Hence, we used neutrosophic sets in order to handle the uncertainty and indeterminacy caused by the mentioned conditions. Experts utilized Table 2 and Table 6 to score decision matrices. Figure 1 presents the hierarchy of the application.

5.1. *Renewable Energy Alternatives and Decision Criteria*

Renewable energy sources involve biomass energy, geothermal energy, ocean energy, solar energy, wind energy, and hydropower energy. They have an enormous potential to meet energy needs of the world. By doing that, the energy security of the world can be powered by modern conversion technologies by reducing the long-term price of fuels from conventional sources, and decreasing the use of fossil fuels. Using renewable energies does not only impact on reducing the air pollution, safety risks, and greenhouse gas emissions in the atmosphere but also they are recycled in nature. Furthermore, it reduces dependence on imported fuels and creates new jobs and provides regional employment. Taking into consideration the above, we firstly introduce the general characteristics of alternatives, then the selection criteria.

AL1 wave power plant: The immense energy potential of the oceans is being increasingly recognized all over the world (Hammar *et al.*, 2017). This immense energy which is called here 'ocean wave energy' is the conversion to the energy of wind waves by using generators which are placed on the surface of the ocean. The generated energy is usually used in desalination plants, power plants, and water pumps. The main factors that effect the rate of the energy output are determined by wave height, wave speed, wave length, water density, and temperature (Khan *et al.*, 2017).

AL2 solar power plant: Solar energy is simply an energy source provided by the sun in the form of solar radiation. It is also called photovoltaic energy which means conversion of light into electricity. Starting with the first use, it dates back to the year the 1870s, and this technology is pollution and often noise free. In order to establish a solar energy system, there are some basic criteria to evaluate, such as requirements and properties of installation area, accessibility to that area, the infrastructure of the transmission of the generated electricity, governmental funds for the investment (Onar *et al.*, 2015; Çelikbilek and Tüysüz, 2016).

AL3 biomass energy plant: Biomass energy is widely available, naturally distributed and, most importantly, converts waste into energy that helps to deal with pollution. Four main types of biomass, wood plants and herbaceous plants and grasses are the main types of interest for producing energy, with attention focused on the crops corn or maize, sugarcane, sorghum, and millets, as well as the switchgrass which has been utilized as a source of biofuel (McKendry, 2002; Cebi *et al.*, 2016)]. It has been used as an energy source from the 1800s. Since that time, several characteristics affect the performance of biomass fuel such as the heat value, moisture level, compositions, and size.

AL4 hydro power plant: Hydropower is power derived from the energy of falling water or fast running water. Hydropower plants are used to transform the kinematic energy of falling water to the electricity. A turbine converts the kinetic energy of falling water into mechanical energy. Then a generator uses the mechanical energy generated by the turbine for producing electrical energy. In order to establish a hydropower energy system, there are some basic criteria to evaluate such as efficiency, costs, environmental effects, governmental funds.

AL5 geothermal energy plant: Geothermal energy is produced from the heat generated by Earth's formation, and subsequent radioactive decay of the earth's minerals (Wang *et al.*, 2017). Geothermal energy relies on heat from Earth to generate steam and produce electricity. The utilization of geothermal energy depends on the demand for heat or electricity and the distance of the resource from the end consumer, resource temperature, and chemistry of the geothermal fluid (Amoo, 2014).

AL6 wind power plant: Wind energy is a carbon-free energy source depending on average wind speeds, wind turbine hubs, and turbulence intensity. There is a tendency of the use of wind energy that increased rapidly since the 1970s, starting with the oil embargo crisis. Since that time, it is possible to construct a wind energy system depending on country policies, supply chain issues of transmission and integration with the electricity system, compatibility of social and environmental conditions to the investment, economic concerns, regional deployment.

    Various criteria for the evaluation of renewable energy alternatives have been used by several researchers (Onar *et al.*, 2015; Çelikbilek and Tüysüz, 2016; Kahraman *et al.*, 2010a, 2010b, 2009; Kaya and Kahraman, 2010; Şengül *et al.*, 2015; Büyüközkan and Güleryüz, 2016; Diemuodeke *et al.*, 2016; Väisänen *et al.*, 2016; Quan and Leephakpreeda, 2015). After analysing these studies, the most common criteria have been listed and sorted for the proposed IVN ELECTRE I method. The evaluation criteria for renewable energy alternatives that will be used in this study are given in Table 7.

Table 7
Evaluation criteria for renewable energy alternatives.

Main criteria	Sub criteria
C1 system expectations	**C11** Reliability
	C12 Land requirements
	C13 Project life
	C14 Sustainability
	C15 Accessibility
C2 regional impacts	**C21** Job creation
	C22 Estimated amount of energy produced
	C23 Accident risk and effects
	C24 Infrastructure and transportation facilities
C3 financial factors	**C31** Maintenance service
	C32 Efficiency
	C33 Investment cost
	C34 Operation and maintenance cost
	C35 Fuel cost
	C36 Electric cost
	C37 Payback period
C4 environmental factors	**C41** Air pollution
	C42 Social acceptability
	C43 Compatibility with political legislative situation
	C44 Compatibility with national energy policy objectives
	C45 Availability of funds

5.2. *Problem Solution*

Table 8 presents the linguistic evaluations for the sub-criteria collected from the experts. These evaluations are aggregated to obtain the weights of the sub-criteria.

The aggregated weights of the sub-criteria results as interval-valued neutrosophic sets are given in Table 9.

After the calculation of criteria which is needed for weighted normalized IVN decision matrix and concordance interval matrix in the later parts, we construct the decision matrices with respect to experts. To indicate the types of criteria, *C-N*, *C-L*, *B-L*, and *B-N* are used as Cost-Numerical, Cost-Linguistic, Benefit-Linguistic, and Benefit-Numerical for short. Experts weights are 0.4 for academicians, and 0.3, for the managers from the energy sector. Table 10 illustrates the linguistic terms which are revealed by these experts.

The next step is the aggregation of decision matrices given in linguistic terms in Table 10. Aggregated IVN DM (*A*) is obtained by using Eq. (3) as in Table 11.

In the next step, we obtain the weighted normalized DM (*R*). In Eqs. (5), (6), and (7), all operations are calculated as is given in Definition 2. In Eq. (6), number 1 is represented in interval-neutrosophic set as $\langle [1, 1], [0, 0], [0, 0] \rangle$. The calculated criteria weights are taken from Table 9. Weighted normalized DM is given in Table 12.

In the next step, we calculate the concordance and discordance indices based on the proposed deneutrosophication method which is given in Definition 5. Due to the excessive number of pairwise comparisons, we will only present Concordance and Discordance

Table 8
Linguistic evaluations of sub-criteria with respect to experts.

Sub-criteria		DM1	DM2	DM3
C11	Reliability	II	SI	II
C12	Land requirements	LF	FI	FI
C13	Project life	LF	USI	UII
C14	Sustainability	II	TI	USI
C15	Accessibility	LF	USI	TI
C21	Job creation	LF	USI	USI
C22	Estimated amount of energy produced	SI	II	SI
C23	Accident risk and effects	TI	TI	USI
C24	Infrastructure and transportation facilities	USI	USI	TI
C31	Maintenance service	USI	USI	TI
C32	Efficiency	USI	TI	USI
C33	Investment cost	SI	SI	SI
C34	Operation and maintenance cost	SI	SI	MF
C35	Fuel cost	MF	SI	MF
C36	Electric cost	MF	SI	FI
C37	Payback period	MF	MF	FI
C41	Air pollution	MF	FI	FI
C42	Social acceptability	TI	UII	UII
C43	Compatibility with political legislative situation	LF	FI	LF
C44	Compatibility with national energy policy objectives	LF	USI	LF
C45	Availability of funds	CII	II	II

Table 9
Aggregated weighting results of the sub-criteria.

Criterion	Aggregated results	Criterion	Aggregated results
	$\langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$		$\langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$
C11	$\langle [0.693, 0.806], [0.52, 0.631], [0.251, 0.363] \rangle$	C33	$\langle [0.611, 0.722], [0.444, 0.556], [0.333, 0.444] \rangle$
C12	$\langle [0.478, 0.556], [0.172, 0.293], [0.466, 0.542] \rangle$	C34	$\langle [0.581, 0.693], [0.408, 0.52], [0.363, 0.475] \rangle$
C13	$\langle [0.351, 0.463], [0.424, 0.537], [0.536, 0.648] \rangle$	C35	$\langle [0.536, 0.648], [0.363, 0.475], [0.408, 0.52] \rangle$
C14	$\langle [0.479, 0.62], [0.549, 0.661], [0.448, 0.584] \rangle$	C36	$\langle [0.536, 0.634], [0.26, 0.386], [0.408, 0.503] \rangle$
C15	$\langle [0.312, 0.438], [0.447, 0.562], [0.619, 0.745] \rangle$	C37	$\langle [0.5, 0.595], [0.24, 0.361], [0.444, 0.538] \rangle$
C21	$\langle [0.38, 0.492], [0.396, 0.508], [0.564, 0.676] \rangle$	C41	$\langle [0.5, 0.579], [0.172, 0.293], [0.444, 0.522] \rangle$
C22	$\langle [0.648, 0.762], [0.475, 0.587], [0.295, 0.408] \rangle$	C42	$\langle [0.159, 0.291], [0.598, 0.709], [0.765, 0.896] \rangle$
C23	$\langle [0.149, 0.297], [0.59, 0.703], [0.759, 0.907] \rangle$	C43	$\langle [0.462, 0.556], [0.24, 0.361], [0.483, 0.575] \rangle$
C31	$\langle [0.26, 0.385], [0.502, 0.615], [0.671, 0.796] \rangle$	C44	$\langle [0.413, 0.525], [0.363, 0.475], [0.531, 0.643] \rangle$
C32	$\langle [0.26, 0.385], [0.502, 0.615], [0.671, 0.796] \rangle$	C45	$\langle [0.774, 1], [0.598, 0.709], [0.128, 0.283] \rangle$

indices of Alternative 1 in the following. Concordance indices for Alternative 1:

$$\mathbb{C}_{12} = \{C_{11}, C_{13}, C_{14}, C_{15}, C_{22}, C_{23}, C_{24}, C_{32}, C_{33}, C_{34}, C_{37}, C_{42}, C_{43}, C_{45}\},$$

$$\mathbb{C}_{13} = \{C_{11}, C_{14}, C_{15}, C_{22}, C_{32}, C_{33}, C_{34}, C_{36}, C_{37}, C_{42}\},$$

$$\mathbb{C}_{14} = \{C_{11}, C_{22}, C_{24}, C_{33}, C_{34}, C_{35}, C_{37}, C_{42}, C_{43}\},$$

$$\mathbb{C}_{15} = \{C_{13}, C_{24}, C_{32}, C_{33}, C_{37}, C_{42}\},$$

$$\mathbb{C}_{16} = \{C_{12}, C_{13}, C_{22}, C_{24}, C_{32}, C_{33}, C_{37}, C_{42}\}.$$

Table 10
DM based on expert opinions.

Criterion	Type	E1						E2						E3					
		AL1	AL2	AL3	AL4	AL5	AL6	AL1	AL2	AL3	AL4	AL5	AL6	AL1	AL2	AL3	AL4	AL5	AL6
C11	B-N	G	AA	BA	B	VB	G	G	BA	AA	AA	F	G	CB	B	BA	F	BA	CG
C12	C-N	BA	AA	CG	G	AA	F	BA	AA	G	VG	CG	AA	BA	B	VB	B	BA	F
C13	B-N	AA	G	BA	AA	G	BA	AA	G	VG	F	AA	BA	BA	AA	BA	VG	G	CG
C14	B-L	AA	F	AA	G	VG	B	AA	VB	B	B	BA	CG	AA	F	BA	B	B	VB
C15	B-N	AA	F	AA	VB	B	B	AA	F	BA	F	AA	BA	AA	F	BA	VG	G	CG
C21	B-N	AA	G	AA	F	BA	G	F	G	BA	VG	B	VB	AA	G	BA	F	VB	G
C22	B-N	G	BA	G	B	B	AA	AA	G	BA	VG	B	B	G	BA	F	AA	AA	AA
C23	C-L	BA	BA	VG	B	B	G	F	BA	F	CG	G	G	AA	BA	AA	AA	AA	G
C24	C-L	VG	F	CG	G	G	E	VB	CB	B	BA	F	CB	CG	A	CG	B	B	A
C31	C-L	B	B	BA	F	CB	G	B	BA	B	VB	AA	CG	B	BA	B	AA	AA	G
C32	B-L	AA	B	VB	AA	CG	AA	AA	BA	AA	BA	BA	AA	AA	VG	G	CG	BA	AA
C33	C-N	CG	AA	BA	BA	AA	BA	CG	BA	CG	B	B	BA	CG	B	B	VB	B	BA
C34	C-N	AA	BA	AA	AA	AA	G	AA	BA	F	VB	B	G	AA	CB	VB	B	AA	G
C35	C-N	BA	BA	F	VB	F	G	F	F	AA	AA	BA	G	BA	F	BA	F	F	G
C36	C-N	BA	F	AA	AA	F	G	BA	F	VB	B	F	BA	F	VB	B	G	F	G
C37	C-N	VG	F	VB	B	VB	BA	VG	G	CG	AA	F	BA	AA	BA	BA	G	BA	VG
C41	C-N	VB	F	VB	AA	AA	G	B	B	VB	AA	F	F	VB	B	F	BA	BA	VG
C42	B-L	BA	AA	G	AA	F	AA	VG	G	CG	VB	AA	G	CG	AA	F	BA	F	CG
C43	B-L	B	B	G	F	AA	BA	B	B	VB	F	B	BA	VB	CB	B	F	B	BA
C44	B-L	CB	VB	B	B	B	BA	CB	VB	B	G	AA	F	B	BA	B	G	B	VB
C45	B-N	CB	CB	AA	B	B	BA	CB	B	VB	G	F	AA	AA	BA	AA	B	B	BA

Table 11
Aggregated DM.

Criterion	Type	AL$_1$	AL$_2$	...	AL$_6$
C$_{11}$	Linguistic cost	⟨[0.437, 0.551], [0.452, 0.55], [0.39, 0.51]⟩	⟨[0.39, 0.49], [0.33, 0.428], [0.46, 0.557]⟩	...	⟨[0.623, 0.76], [0.45, 0.553], [0.175, 0.33]⟩
C$_{12}$	Numerical cost	⟨[0.4, 0.5], [0.3, 0.4], [0.45, 0.55]⟩	⟨[0.41, 0.51], [0.33, 0.428], [0.44, 0.541]⟩	...	⟨[0.45, 0.516], [0.14, 0.25], [0.4, 0.46]⟩
⋮	⋮	⋮	⋮	⋱	⋮
C$_{21}$	Numerical benefit	⟨[0.45, 0.536], [0.216, 0.32], [0.4, 0.48]⟩	⟨[0.55, 0.65], [0.4, 0.5], [0.3, 0.4]⟩	...	⟨[0.47, 0.57], [0.428, 0.53], [0.38, 0.483]⟩
⋮	⋮	⋮	⋮	⋱	⋮
C$_{45}$	Linguistic benefit	⟨[0.194, 0.33], [0.49, 0.59], [0.62, 0.755]⟩	⟨[0.245, 0.36], [0.431, 0.534], [0.59, 0.7]⟩	...	⟨[0.42, 0.52], [0.3, 0.4], [0.43, 0.535]⟩

Table 12
Weighted normalized DM.

Criterion	Type	AL$_1$	AL$_2$	...	AL$_6$
C$_{11}$	Linguistic cost	⟨[0.008, 0.013], [0.623, 1], [0.332, 0.67]⟩	⟨[0.009, 0.014], [0.616, 1], [0.372, 0.79]⟩	...	⟨[0.011, 0.017], [0.623, 1], [0.29, 0.557]⟩
C$_{12}$	Numerical cost	⟨[0, 033, 0.038], [1, 1], [0.84, 0.86]⟩	⟨[0.035, 0.04], [1, 1], [0.87, 0.89]⟩	...	⟨[0.02, 0.023], [1, 1], [0.74, 0.773]⟩
⋮	⋮	⋮	⋮	⋱	⋮
C$_{21}$	Numerical benefit	⟨[0.004, 0.007], [0.48, 1], [0.618, 0.805]⟩	⟨[0.004, 0.006], [0.5, 1], [0.59, 0.745]⟩	...	⟨[0.003, 0.005], [0.5, 1], [0.596, 0.76]⟩
⋮	⋮	⋮	⋮	⋱	⋮
C$_{45}$	Linguistic benefit	⟨[0.006, 0.017], [0.701, 1], [0.23, 0.49]⟩	⟨[0.009, 0.02], [0.7, 1], [0.23, 0.5]⟩	...	⟨[0.02, 0.04], [0.692, 1], [0.23, 0.502]⟩

Discordance indices for Alternative 1:

$$\mathbb{D}_{12} = \{D_{12}, D_{21}, D_{31}, D_{35}, D_{36}, D_{41}, D_{44}\},$$

Table 13

Concordance matrix of deneutrosoficated IVN values.

	0.72	0.51	0.47	0.23	0.35
0.28	–	0.38	0.22	0.19	0.12
0.54	0.62	–	0.49	0.3	0.41
0.47	0.78	0.51	–	0.27	0.35
0.77	0.81	0.7	0.73	–	0.62
0.68	0.88	0.59	0.65	0.38	–

Table 14

Discordance matrix of deneutrosoficated IVN values.

–	0.02	0.16	0.15	0.8	0.06
0.31	–	0.15	0.13	0.84	0.08
0.05	0.03	–	0.03	0.77	0.11
0.15	0.04	0.06	–	0.76	0.13
1	0.69	0.75	0.69	–	0.7
0.3	0.07	0.22	0.21	0.77	–

Table 15

Concordance index matrix.

–	**1**	**1**	0	0	0
0	–	0	0	0	0
1	**1**	–	0	0	0
0	**1**	**1**	–	0	0
1	1	1	1	–	1
1	**1**	**1**	**1**	0	–

$$\mathbb{D}_{13} = \{D_{12}, D_{13}, D_{21}, D_{23}, D_{24}, D_{31}, D_{35}, D_{41}, D_{43}, D_{44}, D_{45}\},$$

$$\mathbb{D}_{14} = \{D_{12}, D_{13}, D_{14}, D_{15}, D_{21}, D_{23}, D_{31}, D_{32}, D_{36}, D_{41}, D_{44}, D_{45}\},$$

$$\mathbb{D}_{15} = \{D_{11}, D_{12}, D_{14}, D_{15}, D_{21}, D_{22}, D_{23}, D_{31}, D_{34}, D_{35}, D_{36}, D_{41}, D_{43}, D_{44}, D_{45}\},$$

$$\mathbb{D}_{16} = \{D_{11}, D_{14}, D_{15}, D_{21}, D_{23}, D_{31}, D_{34}, D_{35}, D_{36}, D_{41}, D_{43}, D_{44}, D_{45}\}.$$

In the next step, we determine the Concordance matrix which is illustrated in Step 5 by using Eq. (10). After the calculations, the concordance and discordance matrices are obtained as in Tables 13–14.

Based on the threshold value that is calculated by using Eq. (14), the concordance index matrix is given in Table 15. The threshold value is calculated as 0.595.

Based on the threshold value that is calculated by using Eq. (15), the discordance index matrix is given in Table 16. The threshold value is calculated as 0.405.

The last step is the comparison of the Concordance and Discordance index matrices. In Table 15, the value 1 represents that the value of the index is equal to or larger than the threshold. In Table 16, the value 1 represents that the value of the index is smaller than the threshold. If we have the values 1 in the same cells of Tables 15 and 16, it is concluded that the row alternative is better than the column alternative. Through this matching, *AL6-*

Table 16
Discordance index matrix.

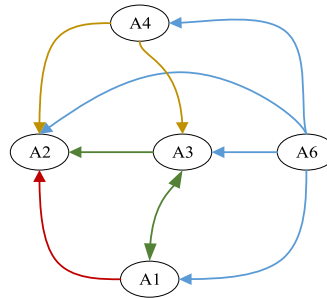| –	**1**	**1**	1	0	1
1	–	**1**	1	0	1
1	**1**	–	1	0	1
1	**1**	**1**	–	0	1
0	0	0	0	–	0
1	**1**	**1**	1	0	–

Fig. 2. Outranking relations of the alternatives.

Wind Power Plant is determined to be the best alternative that the municipality can invest in. The outranking relations of the alternatives are given in Fig. 2.

The arrows in Table 2 indicate that *AL6-Wind Power Plant* is the best among the alternatives, *A3-Hydropower Energy Plant* is the second best. *A1-Wave Power Plant – A3-Biomass Energy Plant* are non-comparable among themselves and *A5-Geothermal Energy Plant* is non-comparable among all alternatives.

5.3. *Comparative Analysis*

In this section, the proposed IVN ELECTRE I method is compared with IVN TOPSIS method developed by Chi and Liu (2013). Since we apply the same scales which are given in Table 1 and Table 5 for IVN TOPSIS method, the results in Table 12 are used for the next steps of the IVN TOPSIS. After the calculations, positive and negative ideal solutions of IVN TOPSIS are given in Table 17.

Distances to negative and positive ideal solutions are given in Table 18.

Closeness coefficient (cc_i) of each criterion is calculated as follows: AL1 $= 0.4961$, AL2 $= 0.5010$, AL3 $= 0.4972$, AL4 $= 0.5006$, AL5 $= 0.5016$, and AL6 $= -6.2766$. After the ranking of alternatives according to cc_i in ascending order *AL6-Wind Power Plant* is still the best alternative as in our proposed IVN ELECTRE I method. This comparison shows the reliability of our proposed method.

Table 17
Positive and negative solutions of the IVN TOPSIS.

	D^+	D^-
C11	$\langle[0.011, 0.017], [0.606, 1], [0.287, 0.557]\rangle$	$\langle[0.008, 0.013], [0.606, 1], [0.287, 0.557]\rangle$
C12	$\langle[0.02, 0.023], [1, 1], [1, 1]\rangle$	$\langle[0.035, 0.04], [1, 1], [1, 1]\rangle$
$\vdots$	$\vdots$	$\vdots$
C21	$\langle[0.006, 0.009], [0.472, 1], [0.59, 0.745]\rangle$	$\langle[0.002, 0.004], [0.472, 1], [0.59, 0.745]\rangle$
$\vdots$	$\vdots$	$\vdots$
C45	$\langle[0.02, 0.039], [0.685, 1], [0.214, 0.467]\rangle$	$\langle[0.006, 0.017], [0.685, 1], [0.214, 0.467]\rangle$

Table 18
Positive and negative ideal solutions of the IVN TOPSIS.

	Positive ideal solution	Negative ideal solution
AL1	$\langle[0.166, 0.168], [0.171, 0.109], [0.083, 0.106]\rangle$	$\langle[0.177, 0.174], [0.171, 0.109], [0.083, 0.106]\rangle$
AL2	$\langle[0.156, 0.156], [0.156, 0.206], [0.261, 0.234]\rangle$	$\langle[0.153, 0.155], [0.156, 0.206], [0.261, 0.234]\rangle$
AL3	$\langle[0.205, 0.206], [0.207, 0.167], [0.146, 0.152]\rangle$	$\langle[0.213, 0.21], [0.207, 0.167], [0.146, 0.152]\rangle$
AL4	$\langle[0.161, 0.159], [0.157, 0.152], [0.152, 0.153]\rangle$	$\langle[0.159, 0.159], [0.157, 0.152], [0.152, 0.153]\rangle$
AL5	$\langle[0.16, 0.161], [0.162, 0.175], [0.194, 0.188]\rangle$	$\langle[0.156, 0.158], [0.162, 0.175], [0.194, 0.188]\rangle$
AL6	$\langle[0.179, 0.191], [0.207, 0.663], [1.285, 1.804]\rangle$	$\langle[0.189, 0.183], [0.176, 0.152], [0.142, 0.066]\rangle$

5.4. *Sensitivity Analysis*

To demonstrate the stability of the ranking results, a sensitivity analysis (SA) is performed based on the weights of criteria. We develop a pattern to determine the one-at-a-time sensitivity for every sub-criterion. The values of these criteria are every linguistic term which is given in Table 5. After the changes on weights of sub-criteria through this pattern, IVN ELECTRE I operations according to changing weights are re-run and the selection of the best alternative is re-processed. The developed pattern is given in Table 19.

The final results of the SA with the determined best alternative are given in Table 20.

When the results are examined, it seems that the changes made on the 3 criteria which are *C12-Land requirements*, *C33-Investment cost*, and *C45-Availability of funds* have different solutions from the others for finding the best alternative. When the linguistic term is increased from *CLI-Certainly Low Importance* to *CHI-Certainly High Importance* for the criterion *C12-Land requirements, AL3-Biomass energy plant* becomes one of the best alternatives with *AL-6 Wind Power Plant* since biomass energy plant's energy production volume is exactly dependent on the area that it is established. When the linguistic term is increased to linguistic term *CHI-Certainly High Importance* on criterion *C33-Investment cost, AL3-Biomass energy plant* becomes again one of the best alternatives with *AL-6 Wind Power Plant*. But, while the linguistic term is *CLI-Certainly Low Importance*, AL5-Geothermal energy plant is the best alternative. Lastly, when the linguistic term is increased to linguistic term *CHI-Certainly High Importance* on criterion *C45-Availability of funds*, *AL1-Wave Power Plant* becomes the best alternative since it is an area that has not been invested by the private sector enough. In all cases, *AL6-Wind Power Plant* is the

Table 19
Pattern of the one-at-a-time SA.

Variables		Based on the sub-criteria			
		Solution sets	Solution sets	...	Solution sets
Variables	CLI	Best alternative	...	...	Best alternative
	VLI	:	...	⋱	:
	LI	:	...	⋱	:
	BAI	:	...	⋱	:
	AI	:	...	⋱	:
	AAI	:	...	⋱	:
	HI	:	...	⋱	:
	VHI	:	...	⋱	:
	CHI	Best alternative	...	...	Best alternative

Table 20
Results of the one-at-the-time sensitivity analysis.
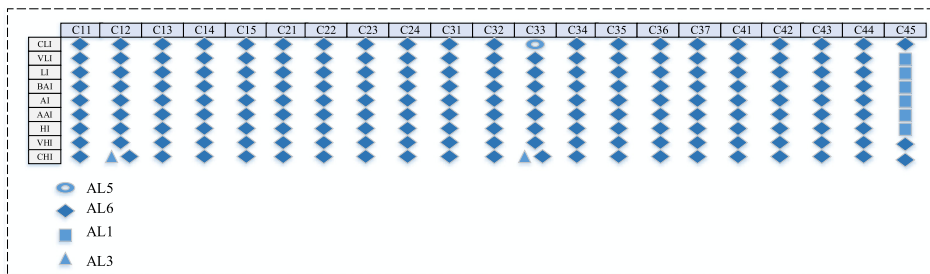
best alternative by a majority and only in special cases that match up with real life our proposed method chooses different alternatives.

6. Conclusion

In multi-criteria decision making (MCDM) problems, the most important problem is the way of handling not only the uncertainty that is the result of lack of knowledge, but also its incompleteness, indeterminacy, and inconsistency level due to the expert groups. The selection of the best renewable energy sources depends not only on alternatives and criteria but also on scoring alternatives with respect to criteria by experts. In this complex environment where the inconsistency arises, the scope of ordinary fuzzy sets is insufficient. To overcome these problems, neutrosophic logic is introduced by Smarandache. In this study, we applied neutrosophic sets to an MCDM model to overcome this impreciseness and indeterminacy in measuring the criteria numerically.

In this paper, an interval-valued neutrosophic multi-criteria group decision making with the ELECTRE method has been proposed for the selection of the most appropriate renewable energy source for a county municipality. Alternatives and criteria have been determined by experts' ideas and literature review. The importance degrees of the criteria have been determined by aggregation of expert opinions and the scores of alternatives are provided by experts for applying them to interval-valued neutrosophic ELECTRE. In the application, 21 sub-criteria were evaluated using interval-valued neutrosophic sets. According to the obtained results from the aggregation, *C45-Availability of Funds* is determined as the most efficient sub-criterion. The second and third important sub-criteria are *C11-Reliability* and *C22-Estimated Amount of Energy Produced*, respectively. In the interval-valued neutrosophic ELECTRE I method, there are 3 experts who evaluated 6 alternatives with respect to 21 sub-criteria. According to the results, *A6-Wave Power Plant* is determined as the best alternative for the most appropriate renewable energy source for a municipality. Sensitivity analysis demonstrates that our proposed model is robust. The usage of deneutrosophication operator can be mentioned as a drawback of the proposed method since a complete neutrosophic approach should be preferred.

For further studies, proposed division operation and deneutrosophication method can be extended to singleton neutrosophic sets, triangular neutrosophic sets, or trapezoidal neutrosophic sets. The proposed interval-valued neutrosophic ELECTRE method can be applied to the other areas such as location selection, strategy assessment, construction management, etc. The proposed method can be a basis for other possible neutrosophic outranking methods such as neutrosophic PROMETHEE method and neutrosophic ORESTE method.

Compliance with Ethical Standards

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A. Karasan is a research assistant at Yildiz Technical University in the Industrial Engineering Department. He received his BS degree in industrial engineering from the same university in 2013, and the MS degree in industrial engineering from the Istanbul Technical University in 2016. He is currently working toward the PhD degree in industrial engineering at the Istanbul Technical University. His research areas are decision making under uncertain environments, fuzzy sets and their extensions, multi-criteria decision-making methods, occupational health and safety analysis, and fuzzy inference system. He has several publications in the mentioned areas.

C. Kahraman is a full professor at Istanbul Technical University. His research areas are engineering economics, quality control and management, statistical decision-making, multi-criteria decision-making and fuzzy decision making. He published more than 500 journal papers and about 160 conference papers. He became the guest editor of many international journals and the editor of many international books from Springer and Atlantis Press. He is the member of editorial boards of 20 international journals. He organized various international conferences. He was the vice dean of ITU Management Faculty between 2004–2007 and the head of ITU Industrial Engineering Department between 2010–2013.