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AN EFFICIENT GENERALIZED FUZZY TOPSIS ALGORITHM FOR THE SELECTION OF THE HYBRID ENERGY RESOURCES: A COMPARATIVE STUDY BETWEEN SINGLE AND HYBRID ENERGY PLANT INSTALLATION IN TURKEY

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Abstract. This paper develops an efficient algorithm for selecting the most suitable and appropriate hybridized energy power plant using "fuzzy multi-criteria decision-making" (MCDM) in Turkey. This research compares the findings of existing studies with energy hybridization. The study investigated the method of suitable location selection to install renewable energy power plants. Installation of an energy power plant is quite a difficult task as there are many factors such as availability of resources and environmental or social factors that significantly impact determining the best energy resource plant to be implemented. The purpose of this research is to extend the single-resource plant installation policy to multi-resource (hybridized) energy usage. An efficient algorithm is developed with the help of combination theory and combined fuzzy TOPSIS method to choose the best suitable alternative out of all possible single and hybrid energy resources in Turkey. All criteria, alternatives, and numerical values are chosen identically with the previous literature to compare the efficiency of the developed method. The result obtains the decision for the best hybridization along with the most suitable combination of various energy resources and sMAPE analysis. The results also supports the real situation of energy resources in Turkey.

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1. Introduction and motivation

1.1. Renewable and non-renewable energy resources

Both the social and economic sectors rely heavily on energy. Consumption of energy is increasing sharply due to industrialization, population growth, and climate change. We need to compensate for this rise in energy demand by enhancing energy efficiency. Planning to increase energy efficiency is a very complicated task as it involves environmental, social, economic, and technical attributes into account. In order to select the most appropriate energy technology, conflicting quantitative and qualitative evaluation criteria must be considered. The demand for energy varies from one location to another location depending on the type of requirement. Industrialization may raise the economy of a country but to run the massive industry sector, plenty of electricity

Keywords. MCDM, intuitionistic fuzzy set, TOPSIS, hybridization.

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is required [36]. This huge requirement can be fulfilled by producing a lot of energy and high capacity energy plants need to be installed. Any country may have several energy resources like renewable and non-renewable sources. There are limited supplies of non-renewable resources available, owing to the fact that replenishing them takes a long time. The importance of non-renewable resources is that more power can be produced on demand by power plants which are using them. Renewable resources, on the other hand, are self-sustaining. Solar, wind, hydro, biomass, and geothermal are the major five renewable resources[1]. Renewable energy resources provide unlimited supply but the availability is limited at a certain limitation. For example, solar energy is not capable of generating high electricity on a cloudy day. Most of the researchers proposed different ways to resolve this problem by providing energy storage such as huge batteries to store energy from renewable resources when demand is low and can be used later on when demand is very high. Carbon dioxide gas is produced by most of the non-renewable energy sources such as oil, coal, and natural gas and fossil fuels are responsible for the emission of most of the greenhouse gases (GHGs). These gases are the basic cause of climate crises such as air pollution, loss of habitat and rising sea level, etc. So there should be a balanced use of both renewable and non-renewable resources of energy to achieve the goal of generating enough electricity without much affecting the environment and nature. Installation of energy plants should be done in such a way that it does not affect the environment and at the same time, it can utilize all the available energy resources effectively. The decision of installation of energy plant at a particular location is affected by many factors such as environmental factors, population growth, availability of transmission lines, and availability of open land area, etc.

1.2. Necessity of hybrid energy plant

Suitable Energy plant installation in a particular location can satisfy certain criteria but it may be possible that a single energy plant is not sufficient to fulfil the full demand of energy in that particular location. For example in a hilly area, the installation of a thermal plant can fulfil the energy demand of industry but on the other side, it may raise carbon emission which can affect the natural habitat of that location [28]. Therefore, this paper develops the concept of hybridization under which a combination of energy plants can be installed at a particular location depending on the availability of energy resources and existing infrastructure. As a result, they can lead to even more consistent and reliable energy production resulting in reduced combustible consumption and lower harmful emissions. Hybridization is the integration process that can be used to fulfil the energy demand by choosing the most suitable combination of energy plants. Hybridization is extremely important in the new era of sustainable energy production. In some particular locations, both Solar and wind plant can work effectively to overcome the problem of energy demand but in some other locations combination of wind, solar and thermal plants can be installed depending upon the availability of resources and various factors. Cavallaro *et al.* [12] proposed the idea of hybridization by providing an integrated system of concentrated solar power with natural gas. This type of system could improve the economic value of energy generated and can achieve the target of energy required.

1.3. Selection of suitable location

As there are lot of factors and criteria which can affect the decision of selecting an appropriate location for installing a power plant so decision-makers find it very hard to convey precise numerical values when their judgments are depending upon vague and uncertain data. The theory of fuzzy set is used for overcoming the challenges with uncertainty in situations where information is subjective, vague or incomplete [53]. Using linguistic terms makes it easy for an expert in energy planning to make a judgment. In early 1970s, a single criterion approach to energy problems was popular, with the goal of identifying the most cost-effective solution. The use of multi-criteria approaches increased in 1980 due to the awareness of environmental and social considerations into energy planning [33, 38]. Multi-criteria decision-making (MCDM) techniques are used to solve the issues which involve conflicting criteria and multiple objectives [3, 31, 37]. This study proposes a modified

[1]Renewable and Non-Renewable Energy Resources Explained, n.d. https://www.kqed.org/science/renewable-and-non-renewable-energy-resources-explained.

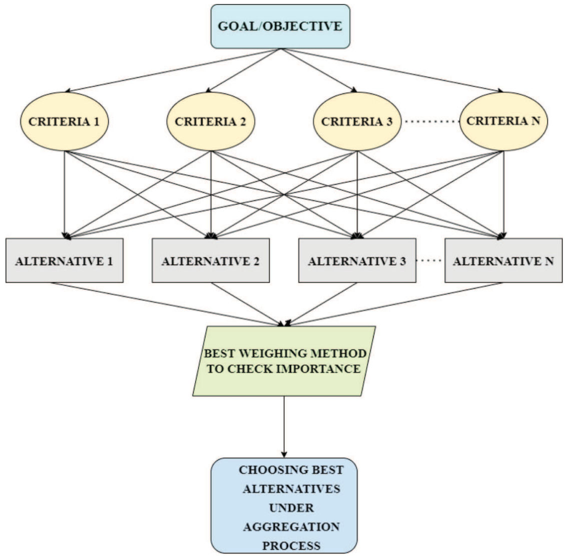

FIGURE 1. The structure of the multi-criteria decision-making (MCDM) process.

fuzzy TOPSIS technique for determining the best hybrid energy plant installation. TOPSIS is a multi-criteria decision-making (MCDM) method that calculates the distances between positive and negative ideal solutions based on expert evaluation.

Depending upon the above facts, this study proposes some research questions as follows.

(1) Is it possible to find the best hybrid energy when a number of single energy resource alternatives are provided?
(2) Which methodology should be applied in selection of hybrid energy plants?

1.4. Decision-making and MCDM

Decision-making is defined as a technique of natural thinking for all perceptual skilled beings [40]. Multi-criteria decision-making (MCDM) is a growing part or domain of operational research that deals with designing many mathematical tools for evaluating multiple conflicting criteria in decision-making issues. This assists decision-makers in selecting the best alternative from a set of alternatives by assessing them against several criteria or attributes [29]. The main issue of the MCDM method is the identification of some set of criteria, based on which different alternatives are to be compared. Bouyssou [11] defines a criterion according to which it is a tool that can be used to compare the set of alternatives from a specific point of view. Figure 1 illustrates the general structure of the MCDM process. The following are the various steps in the fundamental decision-making process.

– Identify the objective or goal of the decision-making process.
– Select the different criteria.
– Select different alternatives.
– Select the weighing methods.
– Aggregation process.

The MCDM can be categorized as the conventional and fuzzy MCDM. In linguistic terms, conventional methods are not sufficient to deal with ambiguity and vagueness, whereas Fuzzy MCDM methods are appropriate to overcome the issues related to vagueness and uncertainty [27]. Many researchers have been using the MCDM method in various fields of science and engineering, and their numbers have increased over the years. The location selection problem is one of the areas where the MCDM model has been used. Huang *et al.* [24] and Løken [31] used MCDM for the selection of construction locations in the energy field. The notion of hybridized energy resources is applied to the Fuzzy TOPSIS method to develop a novel and efficient fuzzy TOPSIS algorithm.

1.5. A case study of renewable energy resources in Turkey

In Turkey, a huge importance has been given to increasing renewable energy resources. The renewable energy law was imposed aiming to increase the use of renewable resources, reduction of GHGs, and improvement of the waste management system [10, 22]. An extensive amount of renewable resources is available in Turkey. The second-highest domestic energy creation in this country is resulting from renewable resources[2]. Coal is used as a primary and major energy resource and hydro is in the second position in Turkey. Thus, to reach sustainability goals, high preference has been given to implant a large-scale hydro-power project which can also satisfy the growing energy demand [52]. The government of Turkey expected production of 31 000 MW of electricity at the end of 2020 through hydro-power whereas the installed hydro-power capacity has reached up to 28 503 MW and energy generation through hydro came up with 87.09 TW by 2019[3]. The estimated potential of wind power is approximately 83 GW with 116 GW as an extended capacity. In 2019, Turkey installed wind turbines with a capacity of 687 MW which empowered the total capacity of 8056 MW wind power in that country[4]. 8.0 million meter square solar panels were manufactured in Turkey by 2004 and it was predicted that the total solar energy will be equivalent to 0.290 million tons of oil (Mtoe). Recently, in 2020, Turkey's solar power plant has increased by 50% since 2014, putting the country in third and ninth place in Europe and the world, respectively, in terms of additional solar power plants installed[5]. An adequate amount of geothermal energy is contained in Turkey. Since 1962, the cumulated data depicts that an amount of 4500 MW of geothermal energy persists by this country which can be used for energy generation [10]. In January 2021, the president and minister of Energy and Natural Resources of Turkey inaugurated three geothermal energy power plants (Sanko Energy Salihli 2, Salihli 3, and Maspo Ala-2). Salihli 2 and 3 plants have a capacity of 54.5 MW and are capable of producing an annual 500 GWh of electricity which saves around 280 000 tons of CO_2 emission[6].

1.6. The aim of the study and research gap

Till now remarkable research has been done related to the MCDM problem for the selection of a single location with single energy resources. Daneshvar Rouyendegh *et al.* [15] presented the multi-criteria decision-making method (MCDM) to resolve the problem of selecting the most suitable wind energy plant in Turkey. Wang *et al.* [48] suggested the MCDM model to determine the appropriate location for constructing a solar plant in Vietnam. Wang *et al.* [49] introduced the concept of fuzzy multi-criteria decision-making to choose the best site of a hydrogen power plant in Vietnam.

The hybridized energy plant was also discussed in existing literature but in limited and specific resources. Abdel-Basset *et al.* [1] have developed a new hybrid MCDM method for site selection of offshore wind energy plants. Dhiman and Deb [19] presented a fuzzy MCDM model for locating hybrid wind farms in the best possible location. In this study, we generalized the concept of hybridization with an arbitrary finite number of resources. A new and efficient algorithm is developed which determines the most suitable hybridized energy plant to be installed in a particular location. The developed method can obtain the optimal decision for any number and

[2]Energy Policies of IEA Countries – Turkey. https://iea.blob.core.windows.net/assets/07870364-750a-4231-a649-7c84c5d4b2f7/EnergyPoliciesofIEACountriesTurkey.pdf.

[3]International Hydro-power Association, n.d. https://www.hydropower.org/country-profiles/turkey.

[4]Reve, Evwind – Turkey Adds 687 MW of Wind Power in 2019. https://www.evwind.es/2020/03/29/turkey-adds-687-mw-of-wind-power-in-2019.

[5]Daily Sabah, n.d. https://www.dailysabah.com/business/energy/turkeys-electricity-generation-from-solar-plants-soars-50.

[6]Think Geoenergy, 2021. https://www.thinkgeoenergy.com/president-of-turkey-officially-inaugurated-three-geothermal-plants/.

type of energy resource. Moreover, this study extends the study of paper of Boran *et al.* [10] with the installation of a hybrid energy plant. A comparative study is shown to demonstrate the applicability and suitability of this hybrid plant over a single energy resource plant in Turkey.

2. Literature review

2.1. Fuzzy and Intuitionistic Fuzzy Set

The notion of fuzzy sets was first introduced by Zadeh [53]. The mapping from a set to the unit interval on the real line is known as a fuzzy set. Bellman [7] have developed a theory to explain the idea of multi-stage decision-making in a fuzzy environment. By introducing the concept of Intuitionistic Fuzzy Set (IFS), Atanassov [6] provided a generalization of fuzzy sets. Intuitionistic fuzzy sets (IFSs) introduced three functions that express the degree of membership, non-membership, and hesitancy. Atanassov [5] has defined the different operators over intuitionistic fuzzy sets. He also discussed the various properties of intuitionistic fuzzy sets. The Sanchez approach for medical diagnosis using intuitionistic fuzzy sets was introduced by De *et al.* [16]. Szmidt and Kacprzyk [45] have also used intuitionistic fuzzy sets for solving real-world problems which are based on imprecise data which may lead to inaccurate inferences. Lu and Ng [32] compared vague sets (VS) and intuitionistic fuzzy sets (IFS) in their study. Intuitionistic fuzzy sets (IFS) and vague sets are both generalizations of fuzzy sets. Vague sets are based on interval-valued based membership whereas intuitionistic fuzzy sets (IFS) use point-based membership. The generalized interval-valued-based membership used in vague sets is more descriptive. Later on, vague sets are proved as analogous to intuitionistic fuzzy sets. Intuitionistic fuzzy sets have been used by many researchers to solve multi-criteria decision-making problems in a variety of real-life scenarios [2, 15, 47].

2.2. Methods of multi-criteria decision-making

Yoon [51] introduced the concept of distance function for calculating distance between two alternatives and providing rating to the normalized attributes. TOPSIS method is proposed by Hwang *et al.* [25] for solving multiple objective decision – making problem. Two conflicting and commensurable distance functions were considered to find the compromise solution for k-objective problem. To solve the problem of evaluating airline service quality, Tsaur *et al.* [46] used "analytic hierarchy process" (AHP) and the "Technique of Order Preference Similarity to the Ideal Solution" (TOPSIS) method. There are lot of attributes such as safety, courtesy and comfort which are intangible so it's very difficult to measure the service quality. The AHP method is used to determine the weights of criteria, while the TOPSIS method is used to rank attributes. Li [30] used intuitionistic fuzzy sets to investigate the concept of multi-attribute decision making. To determine the optimal weights of attributes, he created linear programming models. Boran *et al.* [9] proposed the TOPSIS method, which has used an intuitionistic fuzzy set to choose the best supplier in a group decision-making scenario. Chen [14] has proposed the extended form of TOPSIS using triangular fuzzy numbers for group decision making problem. A vertex method was used to calculate the distance between two triangular fuzzy numbers. Beskese *et al.* [8] explores the research based on the wind turbine selection and developed an integrated decision-making system by integrating TOPSIS) with fuzzy Analytical Hierarchy Process (FAHP). Shahraki Shahdabadi *et al.* [42] used Multi Criteria Decision-Making Methods such as SAW, TOPSIS, and ELECTRE methods to investigate the viability of biomass energy generation. These methods have been tested and verified in appropriate locations in Iran's east and north east.Ghram and Moalla Frikhahela [21] proposes the Hierarchical Additive Ratio Assessment (ARAS-H) approach for ranking tourism destination website brands based on a four-level criteria hierarchy. To decompose the primary problem into sub-problems, this method is used to organise the criteria into a hierarchy tree. In a fuzzy data context, the TOPSIS approach can be used in conjunction with the ARAS-H method to achieve effective ranking. Sadabadi *et al.* [41] used the simple additive weighting method (SAW) to decompose the fuzzy multiple criteria decision making (FMCDM) problem into two linear programming models.

2.3. Hybrid energy plant

Aly *et al.* [4] identified hot spot locations of the concentrated solar power and photovoltaic energy plants in Tanzania. A hybrid energy plant had constructed using a Geographic information system multi-criteria decision-making analysis. Del Moral and Petrakopoulou [17] applied the concept of hybridization of a water generation system with biomass/concentrated solar power plant. This design has installed in Andalusia where the demand for water and energy was high. Sheu *et al.* [43] reviewed hybrid plant configurations involving concentrated solar plants (CSP) and fossil fuels in 2012. Srinivas and Reddy [44] introduced the idea of a hybrid solarbiomass power plant. Controlled use of biomass fuel along a variable amount of solar energy eliminates the requirement of solar energy storage and saves the cost of storage. Pramanik and Ravikrishna [39] presented a review report on different technologies used for concentrated solar power hybrid plants. In India, Nixon *et al.* [35] investigated the feasibility of a hybrid solar-biomass power plant. Hybrid plants are more cost-effective than commercial solar plants and thermal power plants. The cost of energy generated by a CSP-biomass hybrid-power plant is two times more than the energy generated by commercial CSP. Also, it is four times more than a thermal power plant. Abdel-Basset *et al.* [1] developed a new hybrid multi-criterion decision-making approach for the location of offshore wind energy plants. A hybrid methodology proposed for the choice of the most suitable locations of an offshore wind power station that involves the combination of Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE)-II and Analytical Hierarchy Process (AHP). Data Envelopment Analysis (DEA) and fuzzy models are now being utilized to create hybrid decision-making systems for the selection of suitable suppliers in situations where there are many decision-makers [26]. The details of author's contribution is illustrated in Table 1.

3. Mathematical formulation

3.1. Intuitionistic Fuzzy Set (IFS)

In this paper, a Mathematical model which is based on intuitionistic fuzzy TOPSIS method is introduced. Intuitionistic Fuzzy sets (IFS) are first introduced by Atanassov [6] to deal with the problem of vagueness and uncertainty. Numerous of decision making problems are resolved by using IFS. Suppose U is any finite set. The Intuitionistic Fuzzy set (IFS) I in U is defined as

$$I = \{\langle x, \mu(x), \nu(x)|\, x \in U\}. \tag{3.1}$$

Whereas, the membership functions

$$\mu : U \rightarrow [0,1] \quad \text{and} \quad \nu : U \rightarrow [0,1] \tag{3.2}$$

are signifying the degree of association and non-association with each element $x \in I$ under the condition

$$0 \leq \mu + \nu \leq 1. \tag{3.3}$$

Intuitionistic fuzzy set is better to use than Fuzzy set due to the availability of one more function associated with the element $x \in I$ given as

$$\pi(x) = 1 - \mu(x) - \nu(x) \tag{3.4}$$

where the function

$$\pi : U \rightarrow [0,1] \tag{3.5}$$

is known as the hesitation function of $x \in I$ under condition

$$0 \leq \pi(x) \leq 1. \tag{3.6}$$

TABLE 1. Author's contribution.

Author's name	Single energy plant installation	Hybrid energy plant installation	Intuitionistic fuzzy logic	Region of case study	Methodology
Ergul and Ozbek [20]	√	–	–	Turky	ANP, Fuzzy TOPSIS
Xuan *et al.* [50]	√	–	–	Uzbekistan	SWARA, COPRAS
Hoang *et al.* [23]	√	–	–	Vietnam	Group Best Worst Method, GIS-Based Fuzzy Logic
Shahraki Shahdabadi *et al.* [42]	√	–	–	Iran	SAW, TOPSIS, and ELECTRE
Abdel-Basset *et al.* [1]	√	–	–	Egypt	AHP, (PROMETHEE)-II
Turk *et al.* [47]	√	–	√	Turkey	GIS and Intuitionistic Fuzzy
Beskese *et al.* [8]	√	–	–	Turkey	Fuzzy AHP, TOPSIS
Wang *et al.* [48]	√	–	–	Viet Nam	FAHP, DEA, and TOPSIS
Noorollahi *et al.* [36]	√	–	–	Iran	GIS Method
Onar *et al.* [37]	√	–	√	Turkey	AHP
Boran *et al.* [10]	√	–	√	Turkey	Intuitionistic Fuzzy TOPSIS
Proposed study	√	√	√	Turkey	Intuitionistic Fuzzy TOPSIS

3.2. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) Method

TOPSIS method is most important and useful method for selecting the most appropriate alternative out of the of a various predetermined alternatives using distance measurement and by providing ranking to them. This method is based on the idea that the specified chosen alternative should be closest to the "positive ideal solution" and furthest from the "negative ideal solution." In fact, "the ideal solution" is that solution which maximizes the criteria for benefit and reduces the criteria for cost.

3.2.1. Assumptions of TOPSIS method

(1) Each decision matrix criterion or attribute has a monotonically increasing or monotonically decreasing utility.
(2) Each criterion or attribute must have a set of weights associated with it.
(3) Any outcome that isn't numerical form should be quantified using the appropriate scaling method.

3.2.2. Intuitionistic Fuzzy TOPSIS Methodology

Step 1. Determination of intuitionistic fuzzy decision matrix

The first step of IFTOPSIS method is to define "intuitionistic fuzzy decision matrix" in which the m rows represent the various alternatives and n columns represent the various criteria or attributes.

$$D = \begin{array}{c} \\ A_1 \\ \vdots \\ A_j \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & \cdots & C_j & \cdots & C_n \end{array} \\ \begin{bmatrix} f_{11} & \cdots & f_{ij} & \cdots & f_{1n} \\ \vdots & \ddots & \vdots & \cdots & \vdots \\ f_{j1} & \cdots & f_{jj} & \cdots & f_{jn} \\ \vdots & \ddots & \vdots & \cdots & \vdots \\ f_{m1} & \cdots & f_{mj} & \cdots & f_{mn} \end{bmatrix} \end{array}.$$

Step 2. Normalization of decision matrix

Normalization is the process in which the different attribute dimensions are transformed into non dimensional attributes so that comparison between attributes can be done effectively.

$$p_{ij} = \frac{f_{ij}}{\sqrt{\sum_{i=1}^{m} f_{ij}}}. \tag{3.7}$$

Step 3. Determination of weighted normalized decision matrix

Different criteria can have the different importance and the level of importance can vary for each criteria. So we can provide a grade of importance to each criterion. Let $W = \{w_1, w_2, w_3, \ldots, w_n\}$ be the set of grades of importance given to each criteria. An IFS F_W in U is written as

$$F_W = \{< f_{w_i}, \mu_{w_i}, \nu_{w_i} > | x_{w_i} \in U\}. \tag{3.8}$$

Whereas, the membership functions

$$\mu_{w_i} : U \to [0,1] \quad \text{and} \quad \nu_{w_i} : U \to [0,1] \tag{3.9}$$

are representing the membership and non-membership grade respectively of F_W

$$0 \leq \mu_{w_i} + \nu_{w_i} \leq 1. \tag{3.10}$$

The function

$$\pi_{w_i} = 1 - \mu_{w_i} - \nu_{w_i} \tag{3.11}$$

is called the hesitation function of F_W to U.

Let P_{ij} and F_W be two intuitionistic fuzzy sets of the set U then

$$P_{ij} \otimes F_W = \left\{ \left\langle f, \mu_{P_{ij}}(f) \cdot \mu_{F_W}(f), \nu_{P_{ij}}(f) + \nu_{F_W}(f) - \nu_{P_{ij}}(f) \cdot \nu_{F_W}(f) \right| f \in U \right\} \tag{3.12}$$

and

$$\pi_{P_{ij} \cdot F_W} = 1 - \nu_{P_{ij}}(f) - \nu_{F_W}(f) - \mu_{P_{ij}}(f) \cdot \mu_{F_W}(f) + \nu_{P_{ij}}(f) \cdot \nu_{F_W}(f). \tag{3.13}$$

The intuitionistic fuzzy weighted decision matrix is defined as:

$$D' = \begin{array}{c} \\ A_1 \\ \vdots \\ A_j \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & \cdots & C_j & \cdots & C_n \end{array} \\ \begin{bmatrix} f_{w11} & \cdots & f_{wij} & \cdots & f_{w1n} \\ \vdots & \ddots & \vdots & \cdots & \vdots \\ f_{wj1} & \cdots & f_{wjj} & \cdots & f_{wjn} \\ \vdots & \ddots & \vdots & \cdots & \vdots \\ f_{wm1} & \cdots & f_{wmj} & \cdots & f_{wmn} \end{bmatrix} \end{array}$$

where $f_{wij} = p_{ij} \otimes w_i,\ i = 1, 2, 3, \ldots m$.

Step 4. Determination of intuitionistic fuzzy positive ideal and intuitionistic fuzzy negative ideal solutions

Suppose and are representing the "benefit criteria" and "cost criteria" respectively. Let and be an "intuitionistic fuzzy positive ideal solution" and "intuitionistic fuzzy negative ideal solution". Then

$$R^{+} = (r_1^{+}, r_2^{+}, \ldots, r_n^{+}) \quad \text{where} \quad r_k^{+} = (\mu^{+}_{P_{ij}\cdot F_W}(f_k), \nu^{+}_{P_{ij}\cdot F_W}(f_k), \pi^{+}_{P_{ij}\cdot F_W}(f_k)), \quad k = 1, 2, \ldots, n \tag{3.14}$$

$$R^{-} = (r_1^{-}, r_2^{-}, \ldots, r_n^{-}) \quad \text{where} \quad r_k^{-} = (\mu^{-}_{P_{ij}\cdot F_W}(f_k), \nu^{-}_{P_{ij}\cdot F_W}(f_k), \pi^{-}_{P_{ij}\cdot F_W}(f_k)), \quad k = 1, 2, \ldots, n \tag{3.15}$$

where

$$\mu^{+}_{P_{ij}\cdot F_w}(f_k) = \{(\max_{ij}\{\mu_{P_{ij}\cdot F_w}(f_k)\} | k \in B)\},\ \{(\min_{ij}\{\mu_{P_{ij}\cdot F_w}(f_k)\} | k \in C)\} \quad 1 \le i \le m, 1 \le j \le n \tag{3.16}$$

$$\nu^{+}_{P_{ij}\cdot F_w}(f_k) = \{(\min_{ij}\{\nu_{P_{ij}\cdot F_w}(f_k)\} | k \in B)\},\ \{(\max_{ij}\{\nu_{P_{ij}\cdot F_w}(f_k)\} | k \in C)\} \quad 1 \le i \le m, 1 \le j \le n \tag{3.17}$$

$$\mu^{-}_{P_{ij}\cdot F_w}(f_k) = \{(\min_{ij}\{\mu_{P_{ij}\cdot F_w}(f_k)\} | k \in B)\},\ \{(\max_{ij}\{\mu_{P_{ij}\cdot F_w}(f_k)\} | k \in C)\} \quad 1 \le i \le m, 1 \le j \le n \tag{3.18}$$

$$\nu^{-}_{P_{ij}\cdot F_w}(f_k) = \{(\max_{ij}\{\nu_{P_{ij}\cdot F_w}(f_k)\} | k \in B)\},\ \{(\min_{ij}\{\nu_{P_{ij}\cdot F_w}(f_k)\} | k \in C)\} \quad 1 \le i \le m, 1 \le j \le n. \tag{3.19}$$

Step 5. Determination of the measures of separation using normalized Euclidean distance

Normalized distance such as Hamming distance or Euclidean distance etc. can be used to find distance of every alternative to positive and negative ideal solution. In this paper, we used normalized Euclidean distance. Let R_i^{+} and R_i^{-} be the measures of separation of each alternative from "intuitionistic fuzzy positive ideal" and "intuitionistic fuzzy negative ideal" solutions. Then

$$R_i^{+} = \sqrt{\frac{1}{2n}\left(\sum_{K=1}^{n}[(\mu_{P_{ij}\cdot F_w}(f_k) - \mu^{+}_{P_{ij}\cdot F_w}(f_k))^2 + (\nu_{P_{ij}\cdot F_w}(f_k) - \nu^{+}_{P_{ij}\cdot F_w}(f_k))^2 + (\pi_{P_{ij}\cdot F_w}(f_k) - \pi^{+}_{P_{ij}\cdot F_w}(f_k))^2]\right)} \tag{3.20}$$

$$R_i^{-} = \sqrt{\frac{1}{2n}\left(\sum_{K=1}^{n}[(\mu_{P_{ij}\cdot F_w}(f_k) - \mu^{-}_{P_{ij}\cdot F_w}(f_k))^2 + (\nu_{P_{ij}\cdot F_w}(f_k) - \nu^{-}_{P_{ij}\cdot F_w}(f_k))^2 + (\pi_{P_{ij}\cdot F_w}(f_k) - \pi^{-}_{P_{ij}\cdot F_w}(f_k))^2]\right)}. \tag{3.21}$$

Step 6. Calculating the relative closeness coefficient

The relative closeness coefficient of each alternative A_i is determined by using formula

$$RCC_i = \frac{R_i^{-}}{R_i^{+} + R_i^{-}} \quad \text{where} \quad 0 \le RCC_i \le 1 \quad (0 \le i \le 1). \tag{3.22}$$

The value of RCC_i lies between 0 and 1.

$$RCC_i = 1 \quad \text{if} \quad A_i = R_i^{+}$$
$$RCC_i = 0 \quad \text{if} \quad A_i = R_i^{-}.$$

Step 7. Ranking to each alternative

Ranking of each alternative can be done according to the calculate values of RCC_i in descending order.

4. Proposed methodology for hybridization

Hybridization is the process under which n type of hybrid energy plant options are there for installation and each option consists of different alternatives if there are n energy resources. For no hybridization, there are n alternatives. For hybridization of 2 energy resources, there are n_{c_2} alternatives. For hybridization of 3 energy resources, there are n_{c_3} alternatives. Proceeding to this way, for hybridization of $n-1$ energy resources, there are $n_{c_{n-1}}$ alternatives and for hybridization of n energy resources, there is only one alternative.

FIGURE 2. Selection of single resource energy resources.

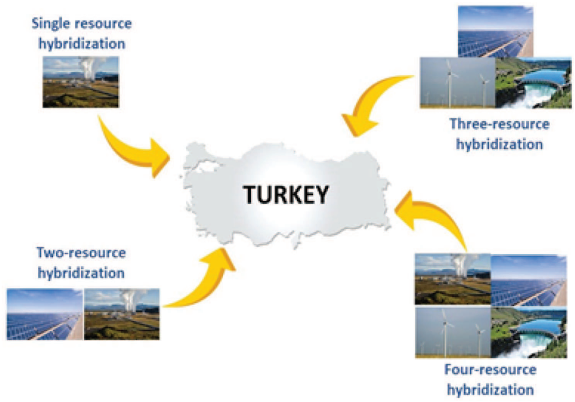

FIGURE 3. Selection of hybrid energy resources.

According to Boren *et al.* [10] study, four renewable energy resources (photovoltaic, hydro, wind, and geothermal) was considered and the best possible renewable resource was determined to install in Turkey (Fig. 2). In this study, all possible combinations of these four energy resources are assumed. Therefore, there are four options available for different combinations of plant installation such as single energy plant (no hybridization), two-resource hybridization, three-resource hybridization, and four-resource hybridization (Fig. 3). Each option consists of different alternatives: $A1$ to $A15$ as described in Figure 4. The generalized model for n resources depicted by Lemmas 4.1, 4.2, and Corollary 4.3.

Lemma 4.1. *If n denoted the number of single resources then the value of total number of alternatives is* $1 + n + \sum_{k=2}^{n=1} n_{c_k}$.

Proof.

The number of resources $= n$.
Under no hybridization.
Taking n number of resources, the number of possible alternatives $= n$.
Under hybridization.

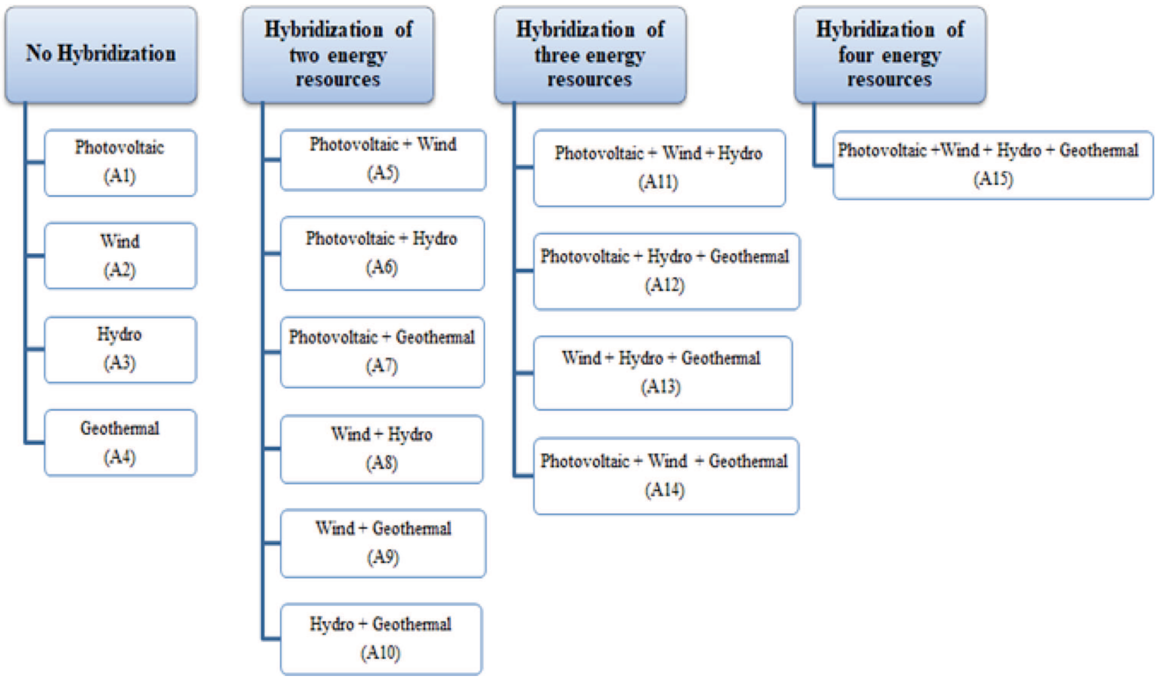

FIGURE 4. Different combinations of energy resources under hybridization.

Taking combination of 2 energy resources, the number of possible alternatives $= n_{c_2}$.
Taking combination of 3 energy resources, the number of possible alternatives $= n_{c_3}$.
$\vdots$
Taking combination of $n-1$ energy resources, the number of possible alternatives $= n_{c_{n-1}}$.
Taking combination of n energy resources, the number of possible alternatives $= n_{c_n} = 1$.
So we can say that if there are numbers of resources then the total possible number of alternatives can be calculated by using the formula

$$\begin{aligned} S_n &= n + n_{c_2} + n_{c_3} + \cdots + n_{c_{n-1}} + 1 \\ &= 1 + n + n_{c_2} + n_{c_3} + \cdots + n_{c_{n-1}} \\ &= 1 + n + \sum_{k=2}^{n-1} n_{c_k}. \end{aligned}$$

Lemma 4.2. *If n denoted the number of single resources and p denoted the total no. of criteria then total number of cells in intuitionistic fuzzy decision matrix* $= \left(1 + n + \sum_{k=2}^{n-1} n_{c_k}\right) p$.

Proof.

Under no hybridization.
Total number of input values $= np$.
Under hybridization.

Total number of cells in intuitionistic fuzzy decision matrix $= \left(1 + n + \sum_{k=2}^{n-1} n_{c_k}\right) p$.

Corollary 4.3. *If n denoted the number of single resources and p denoted the total number of criteria then total number of generated values under hybridization* $= \left(1 + \sum_{k=2}^{n-1} n_{c_k}\right) p$.

5. Proposed algorithm

Algorithm for applying the concept of hybridization is summarized as:

Step 1. Input the number of energy resources (n).

Step 2. Obtain all $N = 1 + n + \sum_{k=2}^{n-1} n_{c_k}$ number of single and hybridized resources (alternatives).

Step 3. Input the intuitionistic fuzzy membership values of n single resources.

Step 4. Input all intuitionistic fuzzy values for all weights corresponding to all criteria (p).

Step 5. Calculate all cell values of $p\left[1 + \sum_{k=2}^{n-1} n_{c_k}\right]$ cells by using sub-algorithm 5.1.

Step 6. Apply TOPSIS method of full decision matrix to obtain ranking.

5.1. Sub-algorithm (For average membership grades)

Step 1. Input the number of energy resources to be hybridized (k).

Step 2. Calculate the membership grades by using the formula $\frac{1}{k}\sum_{i=1}^{k}\mu_i, \frac{1}{k}\sum_{i=1}^{k}\nu_i, \frac{1}{k}\sum_{i=1}^{k}\pi_i$ for membership, non-membership, and hesitation for hybridized resources.

Figure 5 depicts the flowchart of proposed algorithm.

6. Numerical experimentation

The linguistic variables, weights, criteria, and alternatives are considered similar to Boren *et al.* [10] paper as well as the intuitionistic fuzzy membership values. The alternatives and criteria used are illustrated as follows. Alternatives: Hydro, Photovoltaic/Solar, Wind, Geothermal.

Criteria: Price, Emission of greenhouse gases (GHGs), Negative Social Impact, Availability of resources, Efficiency. Two cases namely, non-hybridization (Case 1) and hybridization (Case 2) are shown. The first case emphasizes the best suitable single energy resource to be installed in Turkey which is similar as paper of Boren *et al.* [10]. The second case elaborates the most appropriate hybrid energy resource and a comparative study of two cases is depicted. To perform the numerical experimentation some abbreviations are assumed which are depicted in Table 2. Table 3 presents the linguistic variables and their corresponding IF numbers. The criteria (with symbols) and their corresponding weights are shown in Table 4.

6.1. Case 1 (Non-hybridization)

In this case, only single resources are considered and the intuitionistic fuzzy decision matrix is constructed as

$$\begin{array}{c} \\ \text{Photovoltaic} \\ \text{Wind} \\ \text{Hydro} \\ \text{Geothermal} \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & C_2 & C_3 & C_4 & C_5 \end{array} \\ \begin{bmatrix} (0.84, 0.13, 0.03) & (0.64, 0.23, 0.13) & (0.79, 0.10, 0.11) & (0.23, 0.68, 0.09) & (0.31, 0.58, 0.11) \\ (0.57, 0.32, 0.11) & (0.21, 0.67, 0.12) & (0.63, 0.29, 0.08) & (0.58, 0.29, 0.13) & (0.18, 0.77, 0.05) \\ (0.21, 0.73, 0.06) & (0.38, 0.57, 0.05) & (0.71, 0.18, 0.11) & (0.81, 0.10, 0.09) & (0.46, 0.49, 0.05) \\ (0.42, 0.49, 0.09) & (0.38, 0.57, 0.05) & (0.61, 0.37, 0.03) & (0.43, 0.41, 0.16) & (0.25, 0.58, 0.17) \end{bmatrix} \end{array}.$$

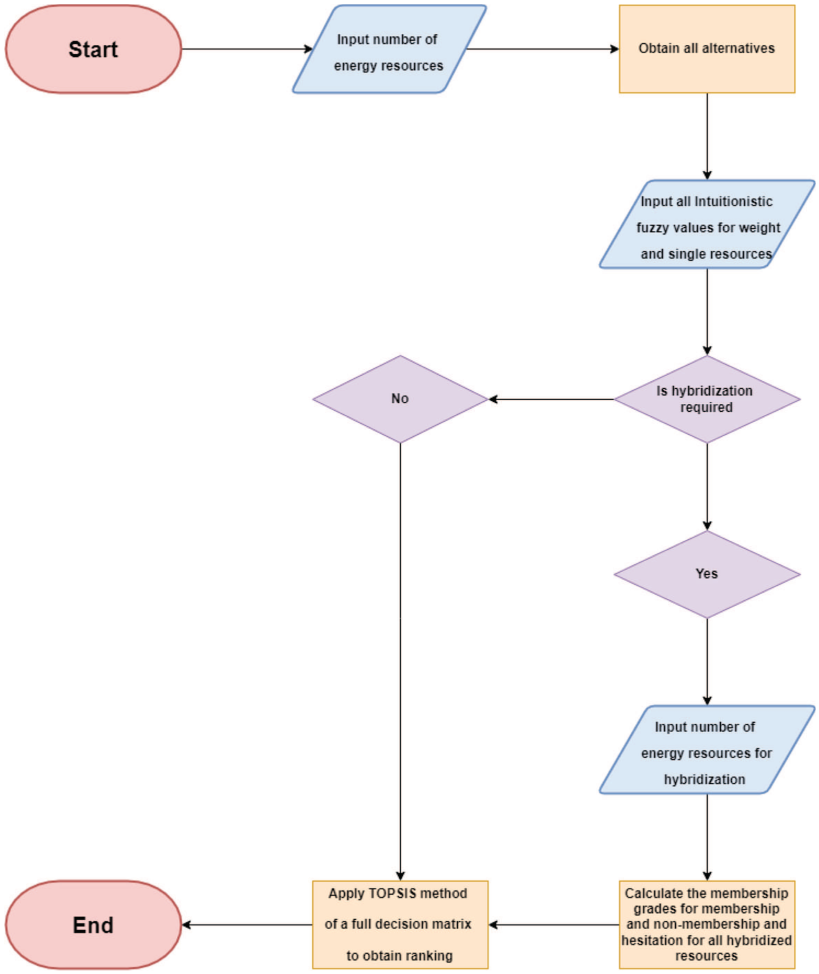

FIGURE 5. Flowchart of proposed algorithm.

Evaluating the price criterion C_1 for photovoltaic to demonstrate the method by which members of "intuitionistic fuzzy weighted decision matrix" are determined.

$$\mu(x_{11}) = 0.84 * 0.50 = 0.42 \tag{6.1}$$

$$\nu(x_{11}) = 0.13 + 0.45 - 0.13 * 0.45 = 0.52 \tag{6.2}$$

$$\pi(x_{11}) = 1 - 0.13 - 0.45 - (0.84 * 0.50) + (0.13 * 0.45) = 0.06. \tag{6.3}$$

Similar computation is applied to obtain the weighted intuitionistic fuzzy decision matrix with all alternatives and criteria for no hybridization which is given as follows.

$$\begin{array}{l} \\ \text{Photovoltaic} \\ \text{Wind} \\ \text{Hydro} \\ \text{Geothermal} \end{array} \begin{array}{c} \begin{array}{ccccc} \quad C_1 \quad & \quad C_2 \quad & \quad C_3 \quad & \quad C_4 \quad & \quad C_5 \quad \end{array} \\ \begin{bmatrix} (0.42, 0.52, 0.06) & (0.54, 0.31, 0.15) & (0.59, 0.19, 0.22) & (0.12, 0.82, 0.06) & (0.23, 0.62, 0.14) \\ (0.28, 0.63, 0.09) & (0.18, 0.71, 0.12) & (0.48, 0.36, 0.17) & (0.29, 0.60, 0.10) & (0.14, 0.79, 0.72) \\ (0.11, 0.85, 0.04) & (0.32, 0.61, 0.06) & (0.53, 0.26, 0.21) & (0.41, 0.51, 0.09) & (0.34, 0.54, 0.11) \\ (0.21, 0.72, 0.07) & (0.46, 0.43, 0.19) & (0.46, 0.42, 0.12) & (0.22, 0.68, 0.11) & (0.19, 0.62, 0.19) \end{bmatrix} \end{array}.$$

TABLE 2. Abbreviations used for different single and hybrid resources.

Types	Name	Abbreviation
No hybridization	Photovoltaic	$A1$
	Wind	$A2$
	Hydro	$A3$
	Geothermal	$A4$
2 Resources hybridization	Photovoltaic + Wind	$A5$
	Photovoltaic + Hydro	$A6$
	Photovoltaic + Geothermal	$A7$
	Wind + Hydro	$A8$
	Wind + Geothermal	$A9$
	Hydro + Geothermal	$A10$
3 Resources hybridization	Photovoltaic + Wind + Hydro	$A11$
	Photovoltaic + Hydro + Geothermal	$A12$
	Wind + Hydro + Geothermal	$A13$
	Photovoltaic + Wind + Geothermal	$A14$
4 Resources hybridization	Photovoltaic + Wind + Hydro + Geothermal	$A15$

TABLE 3. Linguistic variables for importance of criterion.

Linguistic variable	IFNs
Unimportant (UI)	$(0.35, 0.55)$
Medium (M)	$(0.50, 0.45)$
Important (I)	$(0.75, 0.10)$
Very important (VI)	$(0.85, 0.10)$

TABLE 4. The importance of criterion.

Symbols	Criteria	Weights
C_1	Price	Medium
C_2	Emission of GHGs	Very important
C_3	Availability of resources	Important
C_4	Efficiency	Medium
C_5	Negative social impact	Important

In this scenario, the benefit and cost criteria are considered as $B = \{C_3, C_4\}$ and $C = \{C_1, C_2, C_5\}$.

Now, determining "intuitionistic fuzzy positive ideal solution" and "intuitionistic fuzzy negative ideal solution" for photovoltaic case, the following values are obtained.

$$S^+ = \left\{ \begin{array}{r} (0.105, 0.852, 0.043), (0.179, 0.703, 0.118) \\ (0.593, 0.190, 0.217), (0.405, 0.505, 0.090) \\ (0.135, 0.793, 0.072) \end{array} \right\} \tag{6.4}$$

$$S^- = \left\{ \begin{array}{r} (0.420, 0.522, 0.058), (0.544, 0.307, 0.149) \\ (0.458, 0.424, 0.118), (0.115, 0.824, 0.061) \\ (0.345, 0.541, 0.114) \end{array} \right\}. \tag{6.5}$$

TABLE 5. Relative closeness coefficient of each alternative.

Energy resources	M^+	M^-	CC_i	Ranking
Wind	0.125	0.227	0.645	2
Photovoltaic	0.270	0.101	0.272	4
Geothermal	0.194	0.134	0.409	3
Hydro	0.123	0.242	0.664	1

Estimated distance between the alternative photovoltaic ($A1$) and "intuitionistic fuzzy positive ideal solution" which is determined by applying normalized Euclidean distance, given as follows.

$$\begin{aligned} M_{A1}^{+} &= \sqrt{\frac{1}{10}\begin{pmatrix} (0.105-0.420)^2+(0.852-0.522)^2+(0.043-0.058)^2 \\ \ldots(0.135-0.233)^2+(0.793-0.622)^2+(0.072-0.145)^2 \end{pmatrix}} \\ &= 0.270. \end{aligned} \tag{6.6}$$

Similarly, estimated distance between the alternative photovoltaic ($A1$) and "intuitionistic fuzzy negative ideal solution" is given as:

$$\begin{aligned} M_{A1}^{-} &= \sqrt{\frac{1}{10}\begin{pmatrix} (0.420-0.420)^2+(0.522-0.522)^2+(0.058-0.058)^2 \\ \ldots(0.345-0.233)^2+(0.541-0.622)^2+(0.114-0.146)^2 \end{pmatrix}} \\ &= 0.101 \end{aligned} \tag{6.7}$$

$$\begin{aligned} CC_i^{A1} &= \frac{M^-}{M^+ + M^-} \\ &= \frac{0.101}{0.270+0.101} \\ &= \frac{0.101}{0.371} \\ &= 0.2722. \end{aligned} \tag{6.8}$$

Estimated values of M^+ and M^- along with "relative closeness coefficient" for all given alternatives are shown in Table 5.

Based upon descending order of "relative closeness coefficient", for given location ranking of energy resources under no hybridization is

$$\text{Hydro} > \text{Wind} > \text{Geothermal} > \text{Photovoltaic}.$$

6.2. Case 2 (Hybridization)

In this case, we consider the situation to choose the best alternative under hybridization. Every possible combination the four basic alternatives ($A1$, $A2$, $A3$, $A4$) are shown in Figure 6. By using the proposed sub-algorithm 5.1, "intuitionistic fuzzy decision matrix" is obtained for all single and combination hybridized

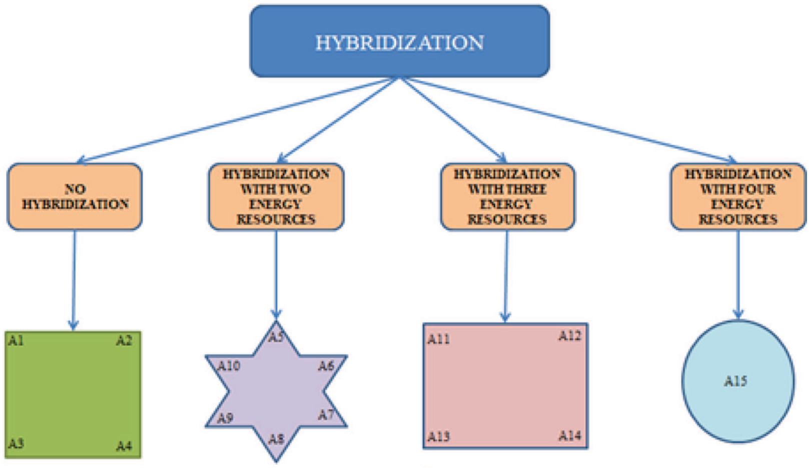

FIGURE 6. Possible alternatives under predefined criteria.

resources, given as follows.

	C_1	C_2	C_3	C_4	C_5
$A1$	$(0.84, 0.13, 0.03)$	$(0.64, 0.23, 0.13)$	$(0.79, 0.10, 0.11)$	$(0.23, 0.68, 0.09)$	$(0.31, 0.58, 0.11)$
$A2$	$(0.57, 0.32, 0.11)$	$(0.21, 0.67, 0.12)$	$(0.63, 0.29, 0.08)$	$(0.58, 0.29, 0.13)$	$(0.18, 0.77, 0.05)$
$A3$	$(0.21, 0.73, 0.06)$	$(0.38, 0.57, 0.05)$	$(0.71, 0.18, 0.11)$	$(0.81, 0.10, 0.09)$	$(0.46, 0.49, 0.05)$
$A4$	$(0.42, 0.49, 0.09)$	$(0.54, 0.37, 0.09)$	$(0.61, 0.36, 0.03)$	$(0.43, 0.41, 0.16)$	$(0.25, 0.58, 0.17)$
$A5$	$(0.71, 0.22, 0.07)$	$(0.43, 0.45, 0.13)$	$(0.71, 0.19, 0.95)$	$(0.41, 0.49, 0.11)$	$(0.25, 0.68, 0.08)$
$A6$	$(0.53, 0.43, 0.05)$	$(0.51, 0.40, 0.09)$	$(0.75, 0.01, 0.11)$	$(0.52, 0.39, 0.09)$	$(0.39, 0.54, 0.08)$
$A7$	$(0.63, 0.31, 0.06)$	$(0.59, 0.30, 0.11)$	$(0.70, 0.23, 0.07)$	$(0.33, 0.55, 0.13)$	$(0.28, 0.58, 0.05)$
$A8$	$(0.39, 0.53, 0.85)$	$(0.30, 0.62, 0.09)$	$(0.67, 0.23, 0.09)$	$(0.70, 0.0, 0.11)$	$(0.32, 0.63, 0.05)$
$A9$	$(0.50, 0.41, 0.10)$	$(0.37, 0.52, 0.11)$	$(0.62, 0.33, 0.53)$	$(0.51, 0.35, 0.10)$	$(0.22, 0.67, 0.11)$
$A10$	$(0.31, 0.61, 0.08)$	$(0.46, 0.47, 0.07)$	$(0.66, 0.27, 0.07)$	$(0.62, 0.25, 0.13)$	$(0.34, 0.54, 0.07)$
$A11$	$(0.54, 0.40, 0.07)$	$(0.41, 0.49, 0.10)$	$(0.71, 0.19, 0.10)$	$(0.54, 0.36, 0.10)$	$(0.32, 0.61, 0.07)$
$A12$	$(0.49, 0.45, 0.06)$	$(0.52, 0.39, 0.01)$	$(0.70, 0.21, 0.08)$	$(0.49, 0.40, 0.11)$	$(0.34, 0.55, 0.11)$
$A13$	$(0.40, 0.51, 0.08)$	$(0.38, 0.54, 0.08)$	$(0.65, 0.28, 0.73)$	$(0.61, 0.27, 0.13)$	$(0.30, 0.61, 0.09)$
$A14$	$(0.51, 0.42, 0.72)$	$(0.46, 0.42, 0.11)$	$(0.67, 0.25, 0.73)$	$(0.41, 0.46, 0.13)$	$(0.25, 0.64, 0.11)$
$A15$	$(0.11, 0.85, 0.04)$	$(0.44.0.46, 0.09)$	$(0.68, 0.23, 0.82)$	$(0.51, 0.37, 0.12)$	$(0.30, 0.61, 0.10)$

The intuitionistic fuzzy weighted decision matrix for combined single and hybridized energy resources is obtained by using the proposed algorithm. We provide an example of the process to obtain the computational value for the first criterion C_1 and for the alternative $A5$.

$$\mu(x_{51}) = 0.705 * 0.50 = 0.3525 \tag{6.9}$$

$$\nu(x_{51}) = 0.225 + 0.45 - 0.225 * 0.45 = 0.57375 \tag{6.10}$$

$$\pi(x_{51}) = 1 - 0.(0.3525 + 0.57375) = 0.07375. \tag{6.11}$$

$$\begin{array}{c} \\ A1 \\ A2 \\ A3 \\ A4 \\ A5 \\ A6 \\ A7 \\ A8 \\ A9 \\ A10 \\ A11 \\ A12 \\ A13 \\ A14 \\ A15 \end{array}\begin{array}{ccccc} C_1 & C_2 & C_3 & C_4 & C_5 \\ \end{array}\begin{bmatrix} (0.42,0.52,0.06) & (0.54,0.31,0.15) & (0.59,0.10,0.22) & (0.12,0.82,0.06) & (0.23,0.62,0.15) \\ (0.29,0.63,0.89) & (0.18,0.70,0.12) & (0.47,0.36,0.17) & (0.29,0.61,0.10) & (0.14,0.79,0.07) \\ (0.11,0.85,0.43) & (0.32,0.61,0.06) & (0.53,0.26,0.20) & (0.41,0.51,0.09) & (0.35,0.54,0.11) \\ (0.21,0.72,0.07) & (0.46,0.43,0.11) & (0.46,0.42,0.12) & (0.22,0.68,0.11) & (0.19,0.62,0.19) \\ (0.35,0.57,0.07) & (0.36,0.51,0.13) & (0.53,0.28,0.19) & (0.20,0.71,0.09) & (0.18,0.71,0.11) \\ (0.26,0.68,0.05) & (0.43,0.46,0.11) & (0.56,0.22,0.21) & (0.26,0.66,0.08) & (0.29,0.58,0.13) \\ (0.31,0.62,0.64) & (0.50,0.37,0.13) & (0.53,0.31,0.17) & (0.17,0.75,0.09) & (0.21,0.62,0.17) \\ (0.19,0.74,0.06) & (0.25,0.66,0.09) & (0.50,0.31,0.19) & (0.35,0.55,0.09) & (0.24,0.67,0.09) \\ (0.25,0.67,0.80) & (0.31,0.56,0.11) & (0.47,0.39,0.14) & (0.25,0.64,0.11) & (0.16,0.71,0.13) \\ (0.16,0.78,0.06) & (0.39,0.52,0.09) & (0.50,0.34,0.16) & (0.31,0.59,0.10) & (0.27,0.58,0.15) \\ (0.27,0.67,0.06) & (0.35,0.54,0.11) & (0.53,0.27,0.19) & (0.27,0.64,0.08) & (0.24,0.65,0.11) \\ (0.24,0.70,0.06) & (0.44,0.45,0.11) & (0.53,0.29,0.18) & (0.25,0.56,0.09) & (0.25,0.60,0.15) \\ (0.20,0.73,0.07) & (0.32,0.58,0.09) & (0.49,0.34,0.16) & (0.30,0.60,0.10) & (0.22,0.65,0.13) \\ (0.31,0.62,0.07) & (0.39,0.48,0.13) & (0.50,0.32,0.22) & (0.21,0.70,0.09) & (0.19,0.68,0.14) \\ (0.26,0.68,0.06) & (0.38,0.51,0.11) & (0.51,0.31,0.22) & (0.26,0.65,0.09) & (0.23,0.64,0.13) \end{bmatrix}.$$

Determining "intuitionistic fuzzy positive ideal solution" and "intuitionistic fuzzy negative ideal solution" as

$$S^{+} = \left\{ \begin{array}{r} (0.105, 0.8515, 0.0435), (0.1785, 0.703, 0.1185) \\ (0.5925, 0.190, 0.2175), (0.405, 0.505, 0.090) \\ (0.135, 0.793, 0.072) \end{array} \right\} \tag{6.12}$$

$$S^{-} = \left\{ \begin{array}{r} (0.420, 0.5215, 0.0585), (0.544, 0.307, 0.149) \\ (0.4575, 0.424, 0.1185)\ , (0.115, 0.505, 0.38) \\ (0.345, 0.541, 0.114) \end{array} \right\}. \tag{6.13}$$

"Estimated distance" between the alternative $A5$ and "intuitionistic fuzzy positive ideal solution" is calculated by applying "normalized Euclidean distance" given as follow:

$$M_{A1}^{+} = \sqrt{\frac{1}{10}\left(\begin{array}{c} (0.3525 - 0.105)^2 + (0.5736 - 0.8515)^2 + (0.738 - 0.1785)^2 \\ \ldots (0.1836 - 0.135)^2 + (0.7075 - 0.793)^2 + (0.1088 - 0.072)^2 \end{array} \right)}$$
$$= 0.17907. \tag{6.14}$$

Similarly, estimated distance between the alternative photovoltaic ($A5$) and "intuitionistic fuzzy negative ideal solution" is given as:

$$M_{A1}^{-} = \sqrt{\frac{1}{10}\left(\begin{array}{c} (0.3525 - 0.420)^2 + (0.5736 - 0.5215)^2 + (0.738 - 0.0585)^2 \\ \ldots (0.1836 - 0.345)^2 + (0.7075 - 0.541)^2 + (0.1088 - 0.114)^2 \end{array} \right)}$$
$$= 0.17585. \tag{6.15}$$

Relative closeness coefficient of $A5$ is calculated as

$$CC_i^{A5} = \frac{M^{-}}{M^{+} + M^{-}}$$

$$= \frac{0.17585}{0.17585 + 0.17907}$$

TABLE 6. Relative closeness coefficient of all alternatives.

Energy resources	M^+	M^-	CC_i	Ranking
$A1$	0.270285	0.175075	0.39311	15
$A2$	0.124827	0.235997	0.65405	3
$A3$	0.122575	0.237842	0.659908	2
$A4$	0.193711	0.160527	0.453162	13
$A5$	0.179075	0.175849	0.495456	10
$A6$	0.172313	0.171064	0.498181	9
$A7$	0.222603	0.149912	0.402431	14
$A8$	0.093047	0.222455	0.705082	1
$A9$	0.144319	0.187101	0.564543	6
$A10$	0.143767	0.188583	0.567423	5
$A11$	0.140637	0.181284	0.56313	7
$A12$	0.174499	0.162005	0.481435	11
$A13$	0.12133	0.194991	0.616435	4
$A14$	0.177524	0.163808	0.479908	12
$A15$	0.150727	0.172028	0.532998	8

TABLE 7. Ranking of combination of energy resources.

Ranking	Alternative number	Combinations
1	$A8$	Wind + Hydro
2	$A3$	Hydro
3	$A2$	Wind
4	$A13$	Wind + Hydro + Geothermal
5	$A10$	Hydro + Geothermal
6	$A9$	Wind + Geothermal
7	$A11$	Photovoltaic + Wind + Hydro
8	$A15$	Photovoltaic + Wind + Hydro + Geothermal
9	$A6$	Photovoltaic + Hydro
10	$A5$	Photovoltaic + Wind
11	$A12$	Photovoltaic + Hydro + Geothermal
12	$A14$	Photovoltaic + Wind + Geothermal
13	$A4$	Geothermal
14	$A7$	Photovoltaic + Geothermal
15	$A1$	Photovoltaic

$$= \frac{0.17585}{0.35492}$$

$$= 0.495463. \tag{6.16}$$

Estimated values of M^+ and M^- along with "relative closeness coefficient" of all 15 alternatives are illustrated in Table 6.

Based upon descending order of "relative closeness coefficient", for given location ranking of energy resources under hybridization is given in Table 7. The comparison study with Boran *et al.* [10] is provided in Table 9.

TABLE 8. Changes in criteria weights.

Cases	Description	sMAPE (with Case 1)
1	Initial weights which are used to obtain the ranking of single and hybridized resources (Tab. 7).	–
2	Price is considered as the highest priority (very important) and other criteria are assigned with medium important.	13.67
3	The emission of GHGs is considered as very important and other criteria are assigned with medium important.	4.42
4	Availability of resources is considered as very important and other criteria are assigned with medium important.	7.09
5	Efficiency is considered very important and other criteria are assigned with medium important.	13.07
6	Negative social impact is considered as very important and other criteria are assigned with medium important.	4.97
7	Price is considered as the highest priority (very important) and other criteria are assigned with very unimportant.	22.75
8	The emission of GHGs is considered as very important and other criteria are assigned with very unimportant.	13.41
9	Availability of resources is considered as very important and other criteria are assigned with very unimportant.	16.61
10	Efficiency is considered very important and other criteria are assigned with very unimportant.	16.85
11	Negative social impact is considered as very important and other criteria are assigned with very unimportant.	14.99

TABLE 9. Comparison table with Boran *et al.* [10].

Ranking	Boran *et al.* [10]	This study
1	Hydro	Wind + Hydro
2	Wind	Hydro
3	Geo-thermal	Wind
4	Photovoltaic	Wind + Hydro + Geothermal

7. Sensitivity analysis

In this section sensitivity analysis is performed to obtain the sensitivity of each criterion. To perform this analysis the weight of each criterion is changed. The variations of weights are shown by some cases. Table 8 depicts the changes in criteria weights and the sMAPE values in 11 different cases. The sMAPE analysis is performed to investigate the criterion with highest sensitivity (Figs. 7 and 8). From Cases 2 to 6 investigates the sMAPE between the original parameters weights and changing each criteria with very important. On the other hand, Cases 7 to 11 depicts the sMAPE between the original parameter weights and changing each parameters with very unimportant.

8. Managerial insights

The current study retains a huge impact on policy-making for energy plant installation as well as social development. With the growing energy demand, it became difficult to satisfy all demands without harming environmental and social-economic factors. This study may overcome many problems regarding energy plant

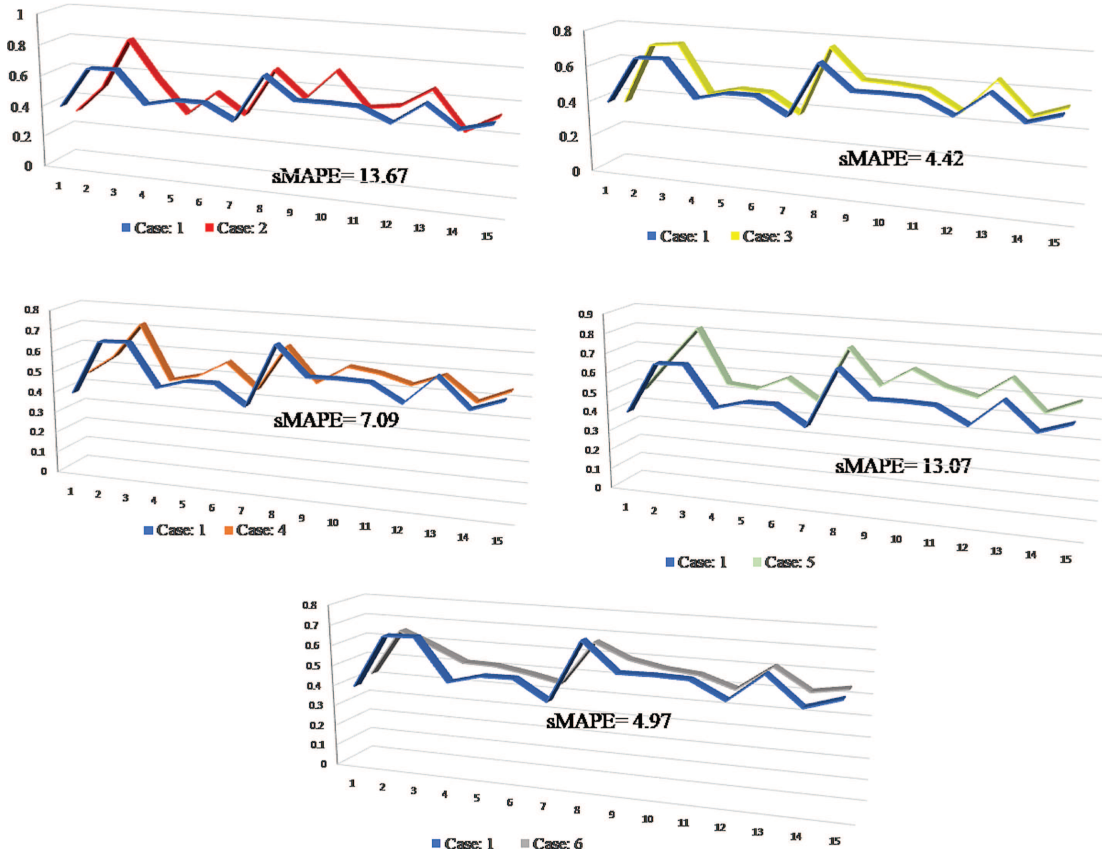

FIGURE 7. sMAPE analysis between Case 1 and medium cases.

installation difficulties. The intuitionistic fuzzy approach can efficiently deal with the uncertainties while measuring the important factors associated with energy plant installation. The factors influencing the plant installation in a region can deal with more accuracy. Hybridized resources can satisfy the energy demand with minimal effect on environmental and social factors. This research developed an efficient algorithm for choosing the most effective hybridized resources.

According to the ranking of alternatives, it is observed that the combination of wind and hydro receives the top position. In present scenario, hydro is the second most largest renewable energy resources in Turkey and wind is one of the most promising alternatives of renewable energy sectors. Thus, the recent picture of energy sector in Turkey also validates the obtained results from numerical simulation.

9. CONCLUSIONS

This study compares the decisions for the installation of hybridized power plants with the non-hybridized plant (single resource plant) based on several criteria. The idea developed in this paper is an extended version of Boran *et al.* [10] single resource energy plant installation in Turkey. An efficient hybrid TOPSIS algorithm is applied to identify the most suitable energy plant to be installed in a location to obtain the desired results. Under no hybridization, TOPSIS Method provides the ranking to the individual energy plant based on a few particular predefined Criteria. Using the same assumptions and same criteria as used in Boran *et al.* [10], we obtain the most suitable hybrid energy plant to be installed in Turkey. Instead of installing a single resource energy plant,

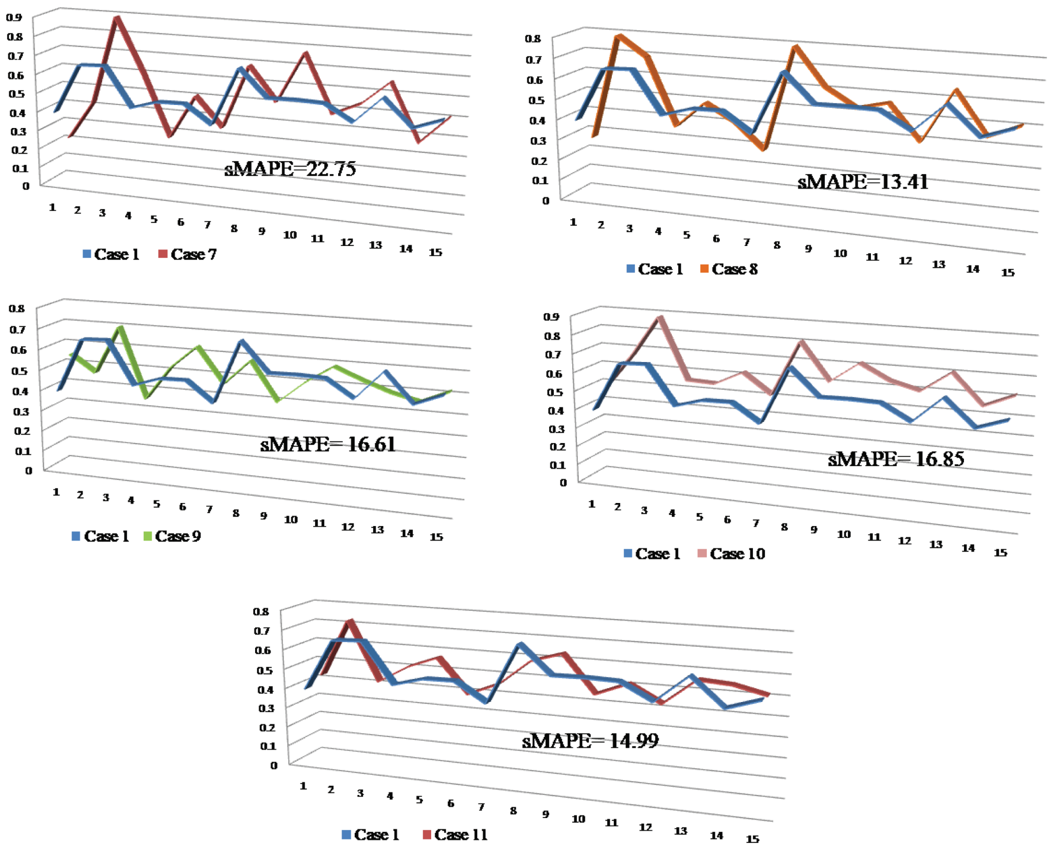

FIGURE 8. sMAPE analysis between Case 1 and very unimportant cases.

hybridization gives the best alternative to the decision-maker for installing a combination of different energy plants in a particular location which can provide improved decisions with satisfying all criteria. According to the obtained results, it is observed that the hybridized plant based on wind and hydroelectric would be ranked first whereas only hydroelectric was placed in the first position in Boran *et al.* [10] (Tab. 9). In the second position, hydroelectric was obtained which revealed as wind in Boran *et al.* [10]. Therefore, in terms of hybridization, this study achieves a better result compared to single energy resource. The obtained result also relates to the real case study of renewable energy condition in Turkey as hydro is the second most used energy resource in that country. Moreover, wind is also approaching towards a very promising resource. This study also provided the sensitivity analysis by using sMAPE which came out with the remarks that price might be the highest sensitive criterion.

This research might be improved with some extensions and improvisations. The weights were categorized with an intuitionistic fuzzy concept, whereas triangular, rectangular, and neutrosophic sets can also be used as it is the more advanced version of fuzzy sets. Therefore, the concept of neutrosophic sets should deal with uncertainty in an advanced manner. For betterment of final outcome, a new CRITIC-TOPIS combined technique can be used [18]. The criteria used in this study may be sub-categorized with more intermediate forms such as social impact can be sub-categorized with increased and decreased job opportunities. Moreover, optimization modelling [13, 34] can also be utilized for cost minimization due to transport facilities to run an energy plant.

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