Applied Decision Analytics

Journal homepage: www.ada-journal.org
ISSN: 3104-2945

# An MCDM-based Optimization Approach for Identifying Efficient Renewable Energy Sources under Fermatean Fuzzy Environment

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**ARTICLE INFO**

***Article history:***
Received 13 March 2026
Received in revised form26 April 2026
Accepted 17 May 2026
Available online 21 May 2026

***Keywords:***

Renewable energy source; Efficient renewable energy source; Fermatean fuzzy number (FFN); Optimization; DEMATEL.

**ABSTRACT**

In recent decades, the growing global demand for energy and the depletion of conventional fossil fuel resources have intensified the need for sustainable and renewable energy alternatives. Consequently, identifying efficient renewable energy sources has become a critical challenge for policymakers and energy planners worldwide. This study evaluates major renewable energy sources, including solar, wind, tidal, hydropower, geothermal, and biomass energy, with the aim of ranking them according to their technical efficiency. To achieve this objective, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method is applied within a Fermatean fuzzy framework to address uncertainty and ambiguity in expert judgments. Furthermore, a comparative analysis under different uncertainty scenarios is conducted to validate the robustness and reliability of the obtained results. The proposed approach provides a systematic decision-support framework for researchers, energy-sector authorities, and policymakers to facilitate sustainable and informed energy planning

## 1. Introduction

The current global scenario of energy requirements is going through a transition phase due to concerns about its sources. The amount of fossil fuel is limited, so it cannot fulfil the massive energy demands [1] of the increasing population. Conventional energy sources such as coal, petrol, diesel and natural gas are on the verge of scarcity. Thus, the requirement of alternative renewable energy sources has become the irreplaceable option in modern geo-political [2] scenario. In the face of an environmental crisis, renewable energy is going to play a vital role because of its almost negligible carbon emissions, providing relief from the hazards of global warming and increasing sea levels. So,

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https://doi.org/10.66972/ada21202627

investigating efficient renewable energy sources [3] has evolved as a necessity instead of only being an option. This task involves multiple renewable energy sources such as solar energy, wind energy, tidal energy, hydropower, geothermal energy and biomass, along with uncertainty of the real-life situations. Multi-Criteria Decision-Making (MCDM) models [4] address conflicts in the situation and provide a sustainable decision to obtain an optimal output. Among those MCDM techniques, we have chosen a method named Decision-Making Trial and Evaluation Laboratory (DEMATEL) [5] to fulfil our requirements. Real-world problems often have unclear, vague information and crisp numbers may provide inaccurate results. We have considered a fermatean fuzzy environment [6] to address the uncertainty and vagueness of complex real-life situations having complicated interlinked factors. We have selected three decision-makers who are experts in the energy and environmental sectors. They have provided their inputs in linguistic terms, drawing on their experience in renewable energy. It helped us to evaluate the results of our research work. The linguistic inputs are converted into fuzzy numbers for further computational procedure in our fermatean fuzzy DEMATEL model. Our proposed model aims to help researchers, authorities, private companies and government policymakers have the flexibility to make sustainable decisions toward the reform of energy dependency.

### *1.1 Evaluation of Renewable Energy Systems*

The domain of renewable energy systems consists of a variety of sustainable and widely accepted sources like solar [7], hydropower [8], wind [9], geothermal energy [10], biomass [11] and energy from ocean [12]. Each renewable energy source offers distinct advantages given its characteristics. It is important to evaluate the most effective renewable energy system in an era of rapid technological advancements. For instance, technologies of solar energy and wind energy systems are environmentally friendly and readily scalable. However, geothermal energy and hydropower systems are naturally linked with a stable output of energy. It is very challenging to find suitable renewable energy sources as they explicitly depend on the geographical, economic and environmental conditions. Available technological support, operational costs and investors' interest in long-term profitability make the selection process even more complex and data-driven.

### *1.2 MCDM modeling for Renewable Energy Sources*

MCDM problems are addressed within a systematic framework for evaluating criterion weights and using them to prioritize alternatives. Investigating the most efficient renewable energy source [3] essentially needs the examination of several conflicting criteria to identify the most efficient among all of the sources, which naturally converts it into an MCDM [4] based problem. In this research paper, a well-known MCDM-based approach, the Decision Making Trial and Evaluation Laboratory (DEMATEL) [5] is used to fulfil our purpose. Conventional MCDM methodologies are dependent upon only crisp-deterministic datasets. However, traditional MCDM frameworks often fail in real-world scenarios due to their inability to handle datasets characterised by ambiguity and vagueness. In such cases, the fuzzy number system [13] can be integrated with conventional MCDM approaches, allowing datasets to include linguistic terms in addition to crisp numerical values. These Fuzzy-based MCDM techniques are capable of addressing critical decision-making challenges.

### *1.3 Motivation of this study*

This research aims to develop a robust mathematical framework for identifying efficient renewable energy sources [3]. Selection of an appropriate renewable energy system is essential due to the scarcity of conventional fuel in the near future. An ideal energy source should be the least polluting, cost-effective and readily available for infrastructural integration. This study is motivated to fulfil the crucial research gaps noticed in traditional decision-making models for renewable energy sources. Apart from conventional MCDM models, DEMATEL [5] identifies the inter-dependency among all the renewable energy sources from the cause-effect relationships. The assessment of the energy sector often relies on uncertain, vague datasets and on experts' opinions. Linguistic inputs from experts may not always convey the exact value in a crisp manner using a numerical system. Traditional MCDM procedures fail to work under incomplete datasets. The amalgamation of fuzzy sets [14] enables us to determine realistic, reliable results even with the presence of incomplete or uncertain datasets with limited information. For accurate evaluation of the renewable energy system, we have employed the fermatean fuzzy sets (FFSs) [13] to deal with the vagueness of linguistic inputs. We aim to provide valuable outcomes via our MCDM [4] optimization approach under a DEMATEL method in a fermatean fuzzy environment for obtaining the efficient renewable energy sources. Our study will assist researchers in the field of green energy, government policy makers and private energy industries.

### 1.4 *Research outline*

Based on the discussion of renewable energy in the above section, we outline the research in this section. Obtaining the optimal renewable energy source is the primary objective of this research. There are six renewable energy sources, namely solar energy, wind energy, tidal energy, hydropower, geothermal energy and biomass, that are considered for the evaluation. An MCDM method named DEMATEL is chosen as the optimization tool and fermatean fuzzy numbers (FFNs) are taken as the tool for dealing with the uncertainty. Data inputs are obtained, in an unbiased manner, as linguistic terms from decision-making experts in their respective fields. After numerical computation of the data, a comparative analysis has been performed to ultimately validate the obtained results.

### 1.5 *Structure of this paper*

The structure of this research is represented in this section as follows: At first, an introduction to renewable energy is described in Section 1. Then, the literature review of renewable energy sources, the DEMATEL methodology and FFNs with renewable energy sources are discussed in Section 2. The mathematical preliminaries of the uncertainty tools are discussed in Section 3. Section 4 covers the mathematical procedure of the DEMATEL methodology in the FFN environments. Different kinds of renewable energy sources and the selection criteria are analyzed in Section 5. Further, Section 6 reveals the model formulation and the collection procedure of the data of this research in detail. The numerical illustration of the model and discussion of the obtained result are presented in Section 7. A comparative analysis is performed in Section 8 to validate the results. At the end, the result implication is described in Section 9 followed by the conclusions and future research scope covered in Section 10, respectively.

## 2. Literature survey of this study

A literature review stands for a short but conceptual examination throughout the already existing studies related to our chosen topic. In this section, we will discuss about the literature background of the different components of this research paper. Here, we are about to investigate and summarize critical outcomes, mathematical tools and methods co-existing in areas of the field. First, we focus on the background of the renewable energy sector, then on uncertainty measurement in a fuzzy environment and finally on a literature review of the MCDM method, namely the DEMATEL technique.

## 2.1 Background of Renewable Energy

We can obtain renewable energy from multiple natural resources, such as sunlight, wind flow, tides, biomass, river flow, etc., which are purely sustainable. These sources are resorted to nature in a continuous manner without creating any kind of scarcity. Researchers from various fields examined numerous applications of sustainable sources of renewable energy for multiple areas like electricity generation, agriculture, transportation and growth of rural regions. The study by Rahman, M.M. et al. [15] examined various applications of renewable energy, including solar dryers, lighting devices and hydropower-driven water pumps. In the model constructed by Dezhdar, A. et al. [16], they integrated solar energy with thermal energy from the ocean to generate electric current. They calculated the efficiency of the outcomes by considering the variations in temperature measurements. A study by Hu, Z. et al. [17] examined the future potential of using ocean thermal energy for refrigeration by generating power and developing aquaculture and agriculture on cold soils. The research by Pradhan, P. et al. [18] described an energy-efficient gasifier tool to fulfil the Indian conventional cooking requirements. An analysis on the utilization of wind turbines was conducted by Shahbazi, R. et al. [19] to assist farming in greenhouse environments and infrastructure for generating electricity. Research from Al-Atroush, M.E. et al. [20] suggested a new technology to generate power by geothermal energy via utiliZing pavement heat. The above-mentioned literature provides a foundation for our research on renewable energy. These studies explicitly demonstrate the need for a more integrated, data-driven approach to achieve scalability in the transition of the renewable energy sector. Some recent research on renewable energy using MCDM methods is summarized in Table 1.

**Table 1**
Some recent studies on Renewable Energy through MCDM Methodology

| Author | Year | Method used | Application area |
|---|---|---|---|
| [21] Yasin, Y. et al. | 2026 | MEREC and MAUT | Prioritization of renewable energy for sustainable development. |
| [22] Demir, G. et al. | 2026 | Bibliometric mapping | Trend analysis of research in renewable energy sector. |
| [23] Goswami, S. et al. | 2025 | CRITIC, EDAS, CODAS & CoCoSo | Sustainable renewable energy selection in India. |
| [24]Sadeghi et al. | 2025 | Hybrid MCDM | Comparative analysis of investments in renewable energy. |
| [25] Agliata, R. et al. | 2025 | WLC | Site selection for suitable renewable energy community projects. |
| [26]Ouria et al. | 2025 | TOPSIS | Optimization of plus-energy in the system of microgrid. |
| [27] Kumar, A. et al. | 2025 | Entropy and VIKOR | Identifying alternative energy sources in eastern India. |
| [28] Gazi, K.H. et al. | 2026 | CRITIC and VIKOR | Site Selection for solar photovoltaic power plant. |

## 2.2 Background of Mathematical tool

In real-world problems, crisp numbers are insufficient to capture the inherent vagueness of the situation. To address ambiguity in critical datasets, fuzzy numbers are essential. Lotfi A. Zadeh [14] first discovered fuzzy sets and fuzzy numbers, which were capable of dealing with the uncertainties of problems related to real-life situations. Various mathematicians have studied fuzzy sets and fuzzy numbers and have discovered several extensions of the concept. The well-known and useful extensions are such as pentagonal fuzzy numbers [28], trapezoidal fuzzy numbers (TrFNs) [29], triangular fuzzy numbers (TFNs) [30], neutrosophic fuzzy sets (NFSs) [31], intuitionistic fuzzy sets (IFSs) [32], Pythagorean fuzzy sets (PFSs) [33], soft fuzzy sets [34], spherical fuzzy sets [35], FFSs [13], q-rung orthopair fuzzy sets

[36], etc. In this work, we implement the concept of FFSs [37] to formulate the model and perform its computation. Some recent applications of FFNs in a discrete environment for MCDM are discussed as follows: the study of Görçün. et al. [38] used fermatean fuzzy concept to analyze blockchain technology for industries, Chakraborty, J. et al. [39] utilized FFNs for an alternative procedure for advanced decision analogy, Ejegwa, P.A. et al. [40] assessed security crises using fermatean fuzzy distance metric and Aydoğan. et al. [41] investigated site selection and ranking problems using the fermatean fuzzy MCDM method. Further, Göçer. et al. [42] implemented an extension of FFSs for prioritising renewable energy technologies and Xie, L. et al. [43] developed an advanced fermatean MCDM architecture for assessing physical fitness.

### 2.3 *Literature of MCDM method*

MCDM is a crucial and highly effective tool in the field of operations research. When evaluating complex decision-making problems in real life, we require MCDM techniques to handle situations involving interlinked criteria that conflict with one another. MCDM provide efficient solutions to problems containing multiple criteria and several alternative choices. We have various techniques for obtaining the weight of the criteria, such as the AHP [44], Entropy [45], MEREC [46], CRITIC [47], SWARA [48], etc. as well as multiple methodologies for ranking the most suitable alternatives namely TOPSIS [49], PROMETHEE [50], MARCOS [51], VIKOR [52], MOORA [53], etc. methods. Various decision makers, including policymakers, investors, management specialists, company owners and financial managers, gain profit with the help of MCDM techniques by evaluating optimal alternatives according to their preferences. Some recent instances of utilizing MCDM methods are as follows: site selection of a new airport in India [54], obtaining a suitable hostel location in an educational premises [55], site selection of an educational institution [56], site selection of a new canteen in an optimal way [57] and so on.

This study utilized the DEMATEL methodology [5] for obtaining the most efficient renewable energy source. Alinezhad, A. and Khalili, J. [58] introduced the DEMATEL technique in their 2019 study. Some recent applications of the DEMATEL methodology include: Pamučar, D. et al. [59] applied to analyzed the circular economy system and Lewandowska, K. et al. [60] investigated circular supply chain problems. Further, Basuri, T. et al. [61] described the ways of adaptation strategies for biomass energy in India and Gupta, S. et al. [62] investigated the barriers and drivers of sustainable growth in freight logistics with the help of DEMATEL techniques. Additionally, Samal, T. et al. [63] utilized a procedure for analysing a make-to-order production system and Biswas, A. et al. [64] analysed the challenges of adopting high-speed rail in the third-world countries by implementing the DEMATEL techniques. Then, Talebzadeh, H. et al. [65] investigated the optimization techniques for supply chain frameworks using the DEMATEL procedure. Also, Adhikari, D. et al. [66] investigated the educational importance for women empowerment utilising DEMATEL methodology.

## 3. Preliminaries of Mathematical Tools

In this section, we will shed light on fuzzy numbers and their extensions. Various problems, including segmentation and quality improvement, are addressed using fuzzy numbers. It can capture the uncertainty in models and datasets. The definitions and properties of the fuzzy sets and FFSs are discussed as follows:

### 3.1 Fuzzy Set and Fuzzy Number

In 1965, Zadeh [14] introduced the first fuzzy numbers as a useful method for handling uncertain quantities numerically. The generalisation of a real number, which refers to a connected set of possible values with weights in place of a single value, is called a fuzzy number. The specified weight here is the membership function.

**Definition 1.** ***Fuzzy Set*** *[14]*

*If $\mathfrak{Y}$ is a universal set and $y$ $(\in \mathfrak{Y})$ is an arbitrary element. The fuzzy set $\tilde{\mathscr{B}}$ on $\mathfrak{Y}$ is defined as*

$$\tilde{\mathscr{B}} = \left\{ (y, \mu_{\tilde{\mathscr{B}}}(y)) : y \in \mathfrak{Y} \right\}, \tag{1}$$

*where the membership function $\mu_{\tilde{\mathscr{B}}}(y) : \mathfrak{Y} \rightarrow [0, 1]$ is represents the belongness of the element $(y)$ in $\tilde{\mathscr{B}}$.*

**Remark 1.** ***Hesitancy in Fuzzy set:***

*Consider $\tilde{\mathscr{B}}$ be the fuzzy set define in Definition 1 with its membership function $\mu_{\tilde{\mathscr{B}}}(y)$. Then the hesitancy $(\pi_{\tilde{\mathscr{B}}}(y))$ of the fuzzy set $\tilde{\mathscr{B}}$ is*

$$\pi_{\tilde{\mathscr{B}}}(y) = 1 - \mu_{\tilde{\mathscr{B}}}(y), \tag{2}$$

*where $y \in \mathfrak{Y}$. The hesitancy value $(\pi_{\tilde{\mathscr{B}}}(y))$ of fuzzy set $(\tilde{\mathscr{B}})$ is always belongs to $[0, 1]$ for all $y \in \mathfrak{Y}$.*

**Example 1.** *Let us express, using the concept of fuzzy sets, whether a day will be rainy or not. The rainfall range is considered by setting $\mathscr{X} = \{1, 2, 3, 4, 5, 6, 7\}$. So, range $1$ reveals $0.4$ chances of rain, range $2$ reveals $0.9$ chances of rain, range $3$ reveals $1$ chances of rain, range $4$ reveals $0.9$ chances of rain, range $5$ reveals $0.4$ chances of rain, range 6 reveals $0.1$ chances of rain, range $7$ reveals $0$ chances of rain. So, the required fuzzy set is*

$$\tilde{\mathfrak{C}} = \left\{ (1, 0.4), (2, 0.9), (3, 1), (4, 0.9), (5, 0.4), (6, 0.1), (7, 0) \right\}.$$

**Definition 2.** ***Fuzzy Number*** *[27]*

*Fuzzy number $\tilde{\mathscr{B}}$ is a fuzzy Set defined on the set of real numbers $\mathbb{R}$ and satisfies the following conditions:*

1. *$\tilde{\mathscr{B}}$ is normal, i.e., there exists $z$ in $\mathbb{R}$ such that $\mu_{\tilde{\mathscr{B}}}(z) = 1$.*
2. *Membership function $\mu_{\tilde{\mathscr{B}}}(x)$ of $\tilde{\mathscr{B}}$ is convex, i.e.,*

$$\mu_{\tilde{\mathscr{B}}}\left(\lambda y + (1 - \lambda) z\right) \geq \min\left\{\mu_{\tilde{\mathscr{B}}}(y), \mu_{\tilde{\mathscr{B}}}(z)\right\}, \ \forall\, y, z \in \mathbb{R}, \ \lambda \in [0, 1]. \tag{3}$$

3. *Support of $\mu_{\tilde{\mathscr{B}}}$ is bounded, i.e., $\{y : \mu_{\tilde{\mathscr{B}}}(y) > 0\} \subset \mathbb{R}$.*
4. *Membership function $\mu_{\tilde{\mathscr{B}}}(y)$ of $\tilde{\mathscr{B}}$ is piece-wise continuous.*

**Example 2.** *Let us think, a student has scored good marks in the exam. It is never understood by just these words about his/her exact score."Good Score" is different for every person. Considering it as an object, we can apply the concept of fuzzy numbers. So, the membership function of the identifying object is from $0$ ("Not good score"/"Bad score" in fuzzy) to $1$ ("Good score" in fuzzy).*

**Remark 2.** *Fuzzy numbers are a special type of fuzzy set, which is defined on the set of real numbers $(\mathbb{R})$ and satisfies certain properties defined on Definition 2. Then all fuzzy numbers are fuzzy sets, but the converse is not true. In the numerical computation process, we consider fuzzy numbers rather than fuzzy sets because of their domain and certain properties defined in the later sections.*

### 3.2 Fermatean fuzzy sets and fermatean fuzzy numbers

Fermatean fuzzy sets (FFSs) are an extension of the traditional fuzzy set theory. Senapati, T. et al. [67] first introduced the FFS and fermatean fuzzy number (FFN) and further developed them beyond PFSs and IFSs. FFN is more flexible and effective for dealing with uncertainty problems than PFSs and IFSs. In addition to the traditional fuzzy set, the FFS comprises degrees of membership and non-membership, similar to IFS and PFS. The definitions and properties of FFSs are discussed as follows:

**Definition 3.** ***Intuitionistic Fuzzy Set (IFS)*** *[32]*
*An IFS $\tilde{\mathfrak{A}}$ is defined on a universal set $\mathcal{U}$ and form as*

$$\tilde{\mathfrak{A}} = \{(\xi, \mu_{\tilde{\mathfrak{A}}}(\xi), \nu_{\tilde{\mathfrak{A}}}(\xi))\,; \xi \in \mathcal{U}\}\,, \tag{4}$$

*where $\mu_{\tilde{\mathfrak{A}}}(\xi) : \mathcal{U} \to [0,1]$ represents the degree of membership and $\nu_{\tilde{\mathfrak{A}}}(\xi) : \mathcal{U} \to [0,1]$ represents the degree of non-membership in the set $\tilde{\mathfrak{A}}$. The degree of membership and non-membership also satisfy the relation $0 \leq \mu_{\tilde{\mathfrak{A}}}(\xi) + \nu_{\tilde{\mathfrak{A}}}(\xi) \leq 1$ for all $\xi \in \mathcal{U}$.*

**Remark 3.** *For an IFS define in Definition 3, degree of indeterminacy or hesitancy is denoted as $\pi_{\tilde{\mathfrak{A}}}(\xi)$ and evaluated as*

$$\pi_{\tilde{\mathfrak{A}}}(\xi) = 1 - (\mu_{\tilde{\mathfrak{A}}}(\xi) + \nu_{\tilde{\mathfrak{A}}}(\xi))\,, \tag{5}$$

*for all $\xi \in \mathcal{U}$.*

**Definition 4.** ***Pythagorean Fuzzy Set (PFS)*** *[68]*
*A PFS $\tilde{\mathfrak{B}}$ is defined on a universal set of discourse $\mathcal{U}$ and represents as*

$$\tilde{\mathfrak{B}} = \{(\psi, \mu_{\tilde{\mathfrak{B}}}(\psi), \nu_{\tilde{\mathfrak{B}}}(\psi))\,; \xi \in \mathcal{U}\}\,, \tag{6}$$

*where $\mu_{\tilde{\mathfrak{B}}}(\psi) : \mathcal{U} \to [0,1]$ represents the degree of membership and $\nu_{\tilde{\mathfrak{B}}}(\psi) : \mathcal{U} \to [0,1]$ represents the degree of non-membership of the set $\tilde{\mathfrak{A}}$. The degree of membership and non-membership also satisfy the relation $0 \leq (\mu_{\tilde{\mathfrak{B}}}(\psi))^2 + (\nu_{\tilde{\mathfrak{B}}}(\psi))^2 \leq 1$ for all $\psi \in \mathcal{U}$.*

**Remark 4.** *For a PFS defined in Definition 4, the degree of indeterminacy or hesitancy is denoted as $\pi_{\tilde{\mathfrak{B}}}(\psi)$ and determined as*

$$\pi_{\tilde{\mathfrak{B}}}(\psi) = \sqrt{1 - (\mu_{\tilde{\mathfrak{B}}}(\psi))^2 - (\nu_{\tilde{\mathfrak{B}}}(\psi))^2}, \tag{7}$$

*for all $\psi \in \mathcal{U}$.*

**Definition 5.** ***Fermatean Fuzzy Set*** *[67]*
*A Fermatean fuzzy set (FFS) $\tilde{\mathfrak{C}}$ is defined on a universal set of discourse $\mathcal{U}$ and represents as*

$$\tilde{\mathfrak{A}} = \{(\eta, \mu_{\tilde{\mathfrak{C}}}(\eta), \nu_{\tilde{\mathfrak{C}}}(\eta))\,; \eta \in \mathcal{U}\}\,, \tag{8}$$

*where $\mu_{\tilde{\mathfrak{C}}}(\eta) : \mathcal{U} \to [0,1]$ represents the degree of membership and $\nu_{\tilde{\mathfrak{C}}}(\eta) : \mathcal{U} \to [0,1]$ represents the degree of non-membership in the set $\tilde{\mathfrak{A}}$. The degree of membership and non-membership also satisfy the relation $0 \leq (\mu_{\tilde{\mathfrak{C}}}(\eta))^3 + (\nu_{\tilde{\mathfrak{C}}}(\eta))^3 \leq 1$, for all $\eta \in \mathcal{U}$.*

**Remark 5.** *For a FFS defined in Definition 5, the degree of indeterminacy or hesitancy is denoted as $\pi_{\tilde{\mathfrak{C}}}(\eta)$ and evaluated as*

$$\pi_{\tilde{\mathfrak{C}}}(\eta) = \sqrt[3]{1 - (\mu_{\tilde{\mathfrak{C}}}(\eta))^3 - (\nu_{\tilde{\mathfrak{C}}}(\eta))^3} \tag{9}$$

*for all $\eta \in \mathcal{U}$.*

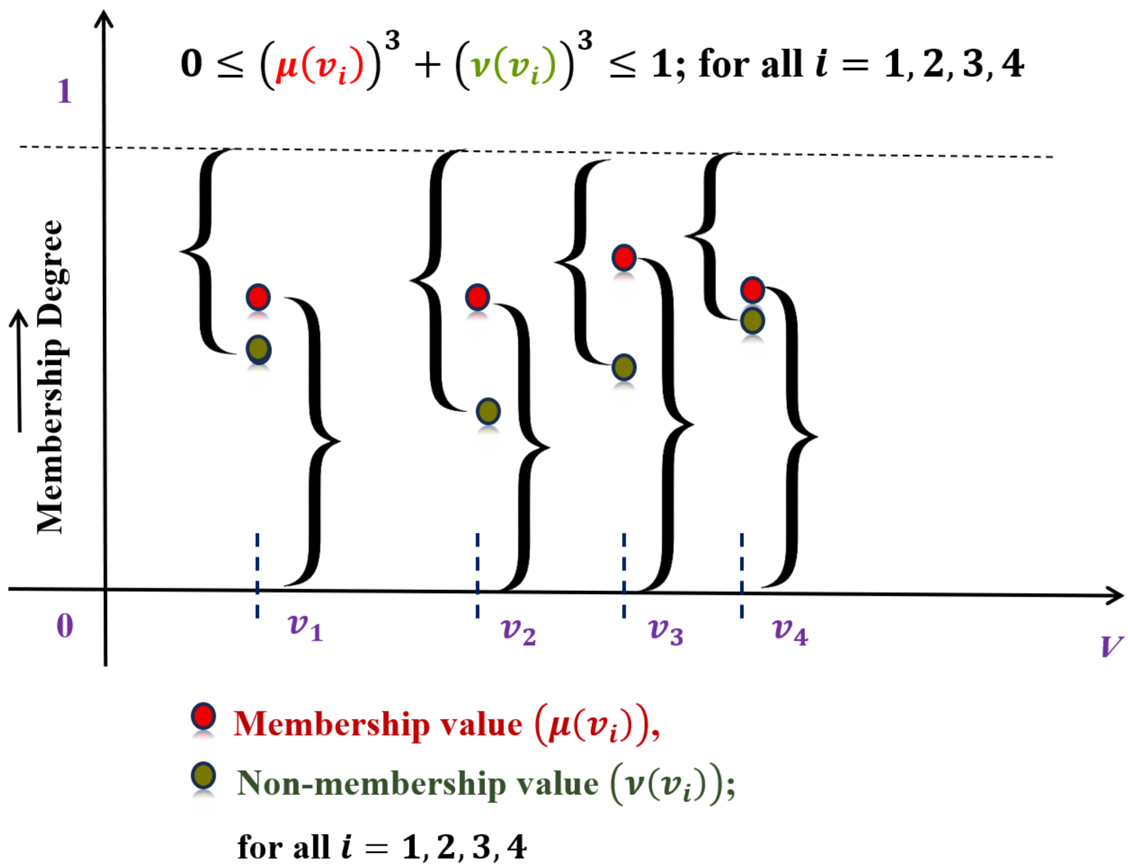


**Fig. 1.** Degree of membership and non-membership of an FFS

A graphical representation of membership and non-membership degrees of a FFS on a set of universe $(\mathcal{V})$ is given below in Figure 1. The membership value $(\mu(v_i))$ and non-membership value $(\nu(v_i))$ of FFS are shown in the graph for elements $v_i \in \mathcal{V}$ for $i = 1, 2, 3, 4$.

A graphical comparison among IFS, PFS and FFS is illustrated below through Figure 2. It shows the uncertainty capturing capacity of different fuzzy sets visually. The FFS captures more uncertainty than the IFS and the PFS, respectively.

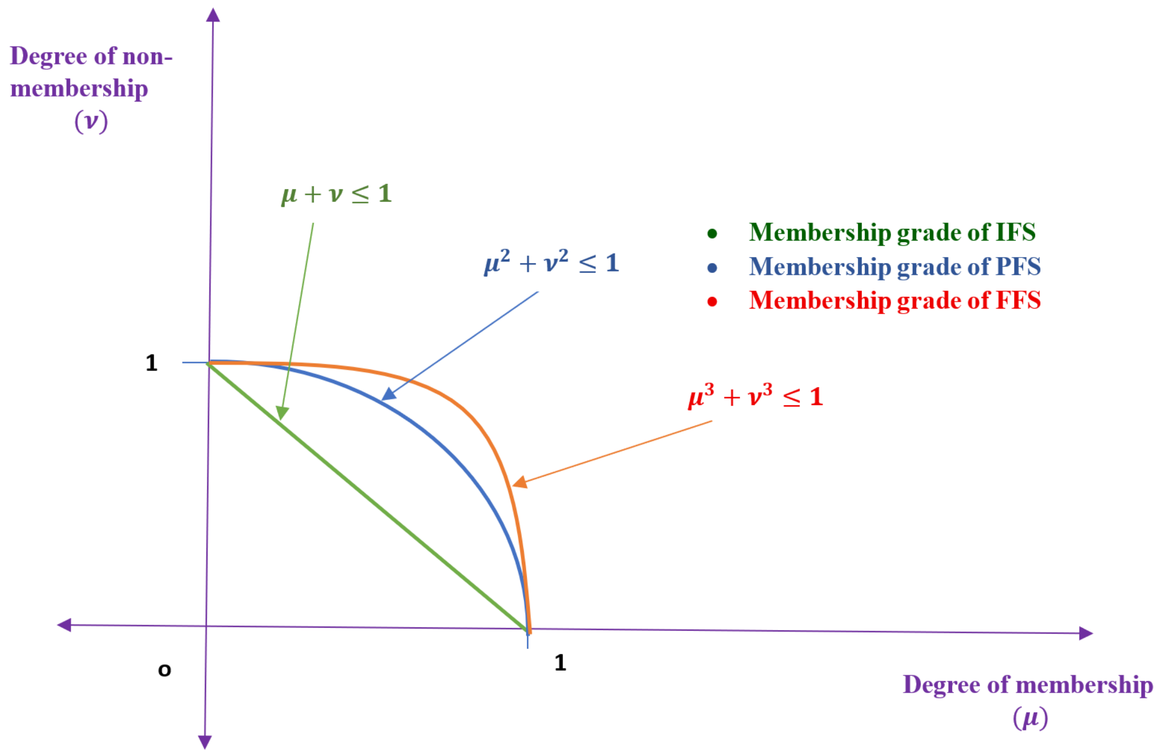


**Fig. 2.** Comparison of membership grades of IFS, PFS and FFS

**Properties 1.** *Let us assume* $\tilde{\mathscr{G}} = \{\chi, \mu_{\tilde{\mathscr{G}}}(\chi), \nu_{\tilde{\mathscr{G}}}(\chi)\}$ *and* $\tilde{\mathscr{H}} = \{\psi, \mu_{\tilde{\mathscr{H}}}(\psi), \nu_{\tilde{\mathscr{H}}}(\psi)\}$ *be the two FFSs define on universal set of discourse* $(\mathcal{U})$. *So, the union and the intersection of two FFSs followed by the complement of an FFS are defined as follows:*

***a) Union of two FFSs:***

$$\tilde{\mathscr{G}} \cup \tilde{\mathscr{H}} = \{\xi, \max\{\mu_{\tilde{\mathscr{G}}}(\xi), \mu_{\tilde{\mathscr{H}}}(\xi)\}, \min\{\nu_{\tilde{\mathscr{G}}}(\xi), \nu_{\tilde{\mathscr{H}}}(\xi)\}\}, \tag{10}$$

*where* $\xi = (\chi + \psi)/2$ *with* $\xi \in \mathcal{U}$.

***b) Intersection of two FFSs:***

$$\tilde{\mathscr{G}} \cap \tilde{\mathscr{H}} = \{\xi, \min\{\mu_{\tilde{\mathscr{G}}}(\xi), \mu_{\tilde{\mathscr{H}}}(\xi)\}, \max\{\nu_{\tilde{\mathscr{G}}}(\xi), \nu_{\tilde{\mathscr{H}}}(\xi)\}\}, \tag{11}$$

*where* $\xi = (\chi + \psi)/2$ *with* $\xi \in \mathcal{U}$.

***c) Complement of a FFS:***

$$\tilde{\mathscr{G}}^c = \{\xi, \nu_{\tilde{\mathscr{G}}}(\xi), \mu_{\tilde{\mathscr{G}}}(\xi)\}, \tag{12}$$

*where* $\xi = \chi$ *with* $\xi \in \mathcal{U}$.

**Proposition 1.** *Suppose* $\tilde{\mathscr{G}} = \{\xi, \mu_{\tilde{\mathscr{G}}}(\xi), \nu_{\tilde{\mathscr{G}}}(\xi)\}$, $\tilde{\mathscr{H}} = \{\chi, \mu_{\tilde{\mathscr{H}}}(\chi), \nu_{\tilde{\mathscr{H}}}(\chi)\}$ *and* $\tilde{\mathscr{I}} = \{\eta, \mu_{\tilde{\mathscr{I}}}(\eta), \nu_{\tilde{\mathscr{I}}}(\eta)\}$ *be three FFSs defined on universal set* $(\mathcal{U})$ *and* $\delta, \sigma > 0$ *are the scalar numbers. Then the following properties will be satisfied, as follows:*

*i)* $\tilde{\mathscr{G}} \cup \tilde{\mathscr{H}} = \tilde{\mathscr{H}} \cup \tilde{\mathscr{G}}$,

*ii)* $\tilde{\mathscr{G}} \cap \tilde{\mathscr{H}} = \tilde{\mathscr{H}} \cap \tilde{\mathscr{G}}$, *iii)* $\left(\tilde{\mathscr{G}}^c\right)^c = \tilde{\mathscr{G}}$,

*iv)* $\tilde{\mathscr{G}} \cup \left(\tilde{\mathscr{H}} \cup \tilde{\mathscr{I}}\right) = \left(\tilde{\mathscr{G}} \cup \tilde{\mathscr{H}}\right) \cup \tilde{\mathscr{I}}$,

*v)* $\tilde{\mathscr{G}} \cap \left(\tilde{\mathscr{H}} \cap \tilde{\mathscr{I}}\right) = \left(\tilde{\mathscr{G}} \cap \tilde{\mathscr{H}}\right) \cap \tilde{\mathscr{I}}$,

*vi)* $\delta\left(\tilde{\mathscr{G}} \cup \tilde{\mathscr{H}}\right) = \delta\tilde{\mathscr{G}} \cup \delta\tilde{\mathscr{H}}$, *where* $\delta \in \mathbb{R}^+$,

*vii)* $\left(\tilde{\mathscr{G}} \cup \tilde{\mathscr{H}}\right)^\sigma = \tilde{\mathscr{G}}^\sigma \cap \tilde{\mathscr{H}}^\sigma$, *where* $\sigma \in \mathbb{N}$,

*viii)* $\left(\tilde{\mathscr{G}} \cap \tilde{\mathscr{H}}\right)^c = \tilde{\mathscr{G}}^c \cup \tilde{\mathscr{H}}^c$, *where* $\sigma \in \mathbb{N}$.

**Definition 6.** ***Fermatean Fuzzy Number*** *[69]*

*A FFS $\tilde{\mathfrak{A}}$ over the set of real numbers ($\mathbb{R}$), which is normal (i.e., $\exists\, \eta$ in $\mathbb{R}$ such that $\tilde{\mathfrak{A}}(\eta) = 1$) and convex (i.e., all $\alpha-$cuts of $\tilde{\mathfrak{A}}_\alpha$, $\alpha \in [0,1]$), its membership function is piecewise continuous and support of of it is bounded. Those FFSs satisfying the above properties are called fermatean fuzzy numbers (FFNs).*

**Example 3.** *Consider $\mathfrak{G}$ be a FFN on the set of universe $\mathcal{U} = \{1,2,3,4,5\}$ and define as $\tilde{\mathfrak{G}} = \{(1,0.9,0.4),(2,0.85,0.45),(3,0.8,0.5),(4,0.75,0.55),(5,0.7,0.6)\}$. In FFN, the $\tilde{\mathfrak{G}}$, the element $1$ $(\in \mathfrak{G})$ has two membership values which are the true and false membership values, $\mu_{\tilde{\mathfrak{G}}}(1) = 0.9$ and $\nu_{\tilde{\mathfrak{G}}}(1) = 0.4$, respectively. In a similar way, this is true for the elements $2,3,4,5$ in $\mathcal{U}$.*

**Properties 2.** *Assume $\tilde{\mathscr{G}} = \{\xi, \mu_{\tilde{\mathscr{G}}}(\xi), \nu_{\tilde{\mathscr{G}}}(\xi)\}$ and $\tilde{\mathscr{H}} = \{\eta, \mu_{\tilde{\mathscr{H}}}(\eta), \nu_{\tilde{\mathscr{H}}}(\eta)\}$ are two FFNs over the universal set of discourse $\mathcal{V}$ along with $k, l > 0$ are two scalars. Then the arithmetic operations on FFNs are evaluated as*

1. ***Addition of two FFNs:***

$$\tilde{\mathscr{G}} \oplus \tilde{\mathscr{H}} = \left\{\xi + \eta, \sqrt[3]{(\mu_{\tilde{\mathscr{G}}}(\xi))^3 + (\mu_{\tilde{\mathscr{H}}}(\eta))^3 - (\mu_{\tilde{\mathscr{G}}}(\xi))^3(\mu_{\tilde{\mathscr{H}}}(\eta))^3}, \nu_{\tilde{\mathscr{G}}}(\xi)\nu_{\tilde{\mathscr{H}}}(\eta)\right\}, \tag{13}$$

2. ***Multiplication of two FFNs:***

$$\tilde{\mathscr{G}} \otimes \tilde{\mathscr{H}} = \left\{\xi\eta, \mu_{\tilde{\mathscr{G}}}(\xi)\mu_{\tilde{\mathscr{H}}}(\eta), \sqrt[3]{(\nu_{\tilde{\mathscr{G}}}(\xi))^3 + (\nu_{\tilde{\mathscr{H}}}(\eta))^3 - (\nu_{\tilde{\mathscr{G}}}(\xi))^3(\nu_{\tilde{\mathscr{H}}}(\eta))^3}\right\}, \tag{14}$$

3. ***Scalar multiplication of FFN:*** *For $k \in \mathbb{R}^+$,*

$$k \odot \tilde{\mathscr{G}} = \left\{k\xi, \sqrt[3]{1 - (1 - (\mu_{\tilde{\mathscr{G}}}(\xi))^3)^k}, (\nu_{\tilde{\mathscr{G}}}(\xi))^k\right\}, \tag{15}$$

4. ***Scalar power of FFN:*** *For $l \in \mathbb{N}$,*

$$\tilde{\mathscr{G}}^l = \left\{\xi^l, (\mu_{\tilde{\mathscr{G}}}(\xi))^l, \sqrt[3]{1 - (1 - (\nu_{\tilde{\mathscr{G}}}(\xi))^3)^l}\right\}. \tag{16}$$

**Proposition 2.** *Suppose* $\tilde{\mathscr{G}} = \{\xi, \mu_{\tilde{\mathscr{G}}}(\xi), \nu_{\tilde{\mathscr{G}}}(\xi)\}$ *and* $\tilde{\mathscr{H}} = \{\eta, \mu_{\tilde{\mathscr{H}}}(\eta), \nu_{\tilde{\mathscr{H}}}(\eta)\}$ *are the two FFNs and* $\delta, \sigma, \kappa > 0$ *are some real numbers. Then the arithmetic operations on FFNs satisfy the following properties*

*(i)*
$$\tilde{\mathscr{G}} \oplus \tilde{\mathscr{H}} = \tilde{\mathscr{H}} \oplus \tilde{\mathscr{G}}, \tag{17}$$

*(ii)*
$$\tilde{\mathscr{G}} \otimes \tilde{\mathscr{H}} = \tilde{\mathscr{H}} \otimes \tilde{\mathscr{G}}, \tag{18}$$

*(iii)*
$$\delta \odot (\tilde{\mathscr{G}} \oplus \tilde{\mathscr{H}}) = (\delta \odot \tilde{\mathscr{G}}) \oplus (\delta \odot \tilde{\mathscr{H}}), \tag{19}$$

*(iv)*
$$(\sigma + \kappa) \odot \tilde{\mathscr{G}} = (\sigma \odot \tilde{\mathscr{G}}) \oplus (\kappa . \tilde{\mathscr{G}}), \tag{20}$$

**Example 4.** *Let us consider two FFNs as* $\tilde{\mathscr{G}} = \{2, 0.63, 0.47\}$ *and* $\tilde{\mathscr{H}} = \{5, 0.37, 0.28\}$ *over the set of real numbers* $(\mathbb{R})$ *along with* $2.47 > 0$ *is a scalar. Then the arithmetic operations of FFNs* $\tilde{\mathscr{G}}$ *and* $\tilde{\mathscr{H}}$ *calculated as*

*(a)* ***Addition of two FFNs:***

$$\begin{aligned} \tilde{\mathscr{G}} \oplus \tilde{\mathscr{H}} &= \left\{2 + 5, \sqrt[3]{(0.63)^3 + (0.37)^3 - (0.63)^3 \times (0.37)^3}, 0.47 \times 0.28\right\} \\ &= \{7, 0.6604, 0.1316\} \end{aligned}$$

*(b)* ***Multiplication of two FFNs:***

$$\begin{aligned} \tilde{\mathscr{G}} \otimes \tilde{\mathscr{H}} &= \left\{2 \times 5, 0.63 \times 0.37, \sqrt[3]{(0.47)^3 + (0.28)^3 - (0.47)^3 \times (0.28)^3}\right\} \\ &= \{10, 0.2331, 0.4980\} \end{aligned}$$

*(c)* ***Scalar multiplication of FFN:***
*For* $2.47 \in \mathbb{R}^+$ *be a scalar, then*

$$\begin{aligned} 2.47 \odot \tilde{\mathscr{G}} &= \left\{2.47 \times 2, \sqrt[3]{1 - (1 - (0.63)^3)^{2.47}}, (0.47)^{2.47}\right\} \\ &= \{4.94, 0.7983, 0.1549\} \end{aligned}$$

*(d)* ***Scalar power of FFN:***
*For* $3 \in \mathbb{N}^+$ *be a scalar, then*

$$\begin{aligned} \tilde{\mathscr{G}}^3 &= \left\{2^3, (0.63)^3, \sqrt[3]{1 - (1 - (0.47)^3)^3}\right\} \\ &= \{8, 0.2500, 0.6544\} \end{aligned}$$

## 3.3 Reason behind selecting FFNs for uncertainty tool

Decision-making problems in situations such as renewable energy selection contain a high degree of uncertain data along with incomplete, vague information. Inconsistent judgments from decision makers arise due to the fluctuating stability of different renewable energy systems associated with multiple parameters. Traditional mathematical models backed by crisp numbers often fail to deal with imprecise datasets efficiently. So integration of fuzzy numbers has become essential in such cases. Among the various extensions of fuzzy numbers, we have chosen FFNs because it delivers a powerful and more flexible framework in comparison to classical fuzzy sets, IFSs and PFSs. The cubic constraints of the FFS allow a significantly vast domain for representing the opinions and hesitations of experts. Several researchers have employed FFN in various fields like industrial blockchain technology [38], advanced decision analogy [39], security crisis [40], ranking sustainable sites [41], renewable energy technologies [42] and assessment of physical fitness [43]. A comparison table in various fuzzy sets is provided in Table 2 for clarity.

**Table 2**
Comparison among three different fuzzy numbers

| Parameters | Intuitionistic fuzzy number [32] | Pythagorean fuzzy number [68] | Fermatean fuzzy number [13] |
|---|---|---|---|
| Membership & Non-membership | $\mu+\nu\leq 1$ | $\mu+\nu\leq 1$ or $\mu+\nu\geq 1$ | $\mu+\nu\leq 1$ or $\mu+\nu\geq 1$ |
| Boundedness | $0\leq\mu+\nu\leq 1$ | $0\leq\mu^2+\nu^2\leq 1$ | $0\leq\mu^3+\nu^3\leq 1$ |
| Indeterminacy degree | $\pi=1-\mu+\nu$ | $\pi=\sqrt{1-\mu^2-\nu^2}$ | $\pi=\sqrt[3]{1-\mu^3-\nu^3}$ |
| Constraint condition | $\mu+\nu+\pi=1$ | $\mu^2+\nu^2+\pi^2=1$ | $\mu^3+\nu^3+\pi^3=1$ |
| Characteristics | An IFS is not necessarily a Pythagorean or a FFS. | A PFS always satisfies the property of an IFS and holds more capacity to catch uncertainty. | A frematean fuzzy set always satisfies the properties of an IFS and PFS, but the converse may not be true. |
| Uncertainty | IFSs come into the game where the degree of non-membership function is influential. It is the simplest form among the three. | PFSs lie between IFS and FFSs in terms of handling the uncertainty through membership and non-membership degrees. | FFS becomes a necessity where accurate numerical values become significant for decision-making around complex situations. |

## 3.4 De-fuzzification of fermatean fuzzy number (FFN)

This section discusses the de-fuzzification techniques for FFN. The de-fuzzification method provides a crisp number for each fuzzy number, since there is no order relation on the fuzzy set and the fuzzy number. Numerous studies have used a variety of de-fuzzification techniques on FFNs. The following is a presentation of the de-fuzzification method used in this study:

**Definition 7.** ***De-fuzzification of FFN***
*Consider $\tilde{\mathfrak{A}}=\{(\eta,\mu_{\tilde{\mathfrak{A}}}(\eta),\nu_{\tilde{\mathfrak{A}}}(\eta)):\eta\in\mathbb{R}\}$ be a FFN define on $\mathbb{R}$. Then, the proposed de-fuzzification of FFN is defined as*

$$\mathscr{S}\left(\tilde{\mathfrak{A}}\right)=\eta\times\left(\mu^3_{\tilde{\mathfrak{A}}}(\eta)-\nu^3_{\tilde{\mathfrak{A}}}(\eta)+\frac{\pi^3_{\tilde{\mathfrak{A}}}(\eta)}{3}\right)^{\frac{1}{3}} \tag{21}$$

*where $\pi_{\tilde{\mathfrak{A}}}(\eta)$ be the indeterminacy value of the FFN $(\tilde{\mathfrak{A}})$ at $\eta\in\mathbb{R}$.*

**Example 5.** *Let* $\tilde{\mathfrak{G}} = (11, 0.95, 0.25)$ *be a FFN defined on the set of real numbers* $(\mathbb{R})$. *Then, the de-fuzzification values of* $\tilde{\mathfrak{G}}$ *is denoted as* $\mathscr{S}\left(\tilde{\mathfrak{G}}\right)$ *and evaluated as*

$$\begin{aligned}\mathscr{S}\left(\tilde{\mathfrak{G}}\right) =& 11 \times \left((0.95)^3 - (0.25)^3 + \frac{(0.502)^3}{3}\right)^{\frac{1}{3}} \\ =& 11 \times (0.857375 - 0.015625 + 0.042169)^{\frac{1}{3}} \\ =& 10.56\end{aligned}$$

## 4. Proposed MCDM methodology: DEMATEL

In this section, we are going to discuss the step-by-step analysis of the DEMATEL, specialized towards the environment of FFNs. By this procedure, we tackle with uncertainty using FFNs by applying a proposed de-fuzzification method for obtaining crispfication of fuzzy numbers. The procedure of the DEMATEL methodology is graphically represented in Figure 3. The computational procedure of this method is discussed as follows:

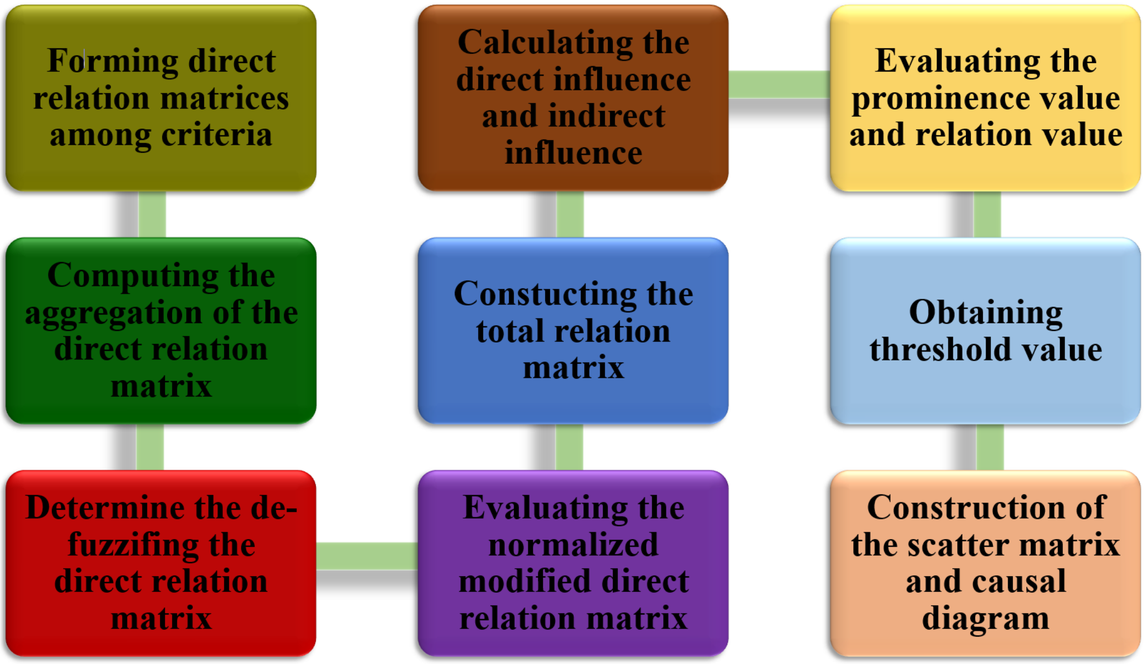


**Fig. 3.** Hierarchical structure of the DEMATEL methodology in FFN

Step 1: Formulating the initial direct relation matrix $(\tilde{\mathcal{M}}^l)$:
Let us assume $\beta$ number of renewable energy sources as criteria, with $\alpha$ number of experts considered for numerical computations. For every expert $(l)$, a pair-wise linguistic comparison scale is provided to build the initial direct relation matrix $(\tilde{\mathcal{M}}^l)$ where $l = 1, 2, \ldots, \alpha$. We will convert the linguistic inputs into the FFNs using a conversion table. The initial fermatean fuzzy

direct relation matrix $(\tilde{\mathcal{M}}^l)$ for $l$th expert personal can be expressed as

$$\begin{aligned}\tilde{\mathcal{M}}^l &= \begin{bmatrix} (\tilde{\mathscr{P}}_{11})^l & (\tilde{\mathscr{P}}_{12})^l & \dots & (\tilde{\mathscr{P}}_{1j})^l & \dots & (\tilde{\mathscr{P}}_{1\beta})^l \\ (\tilde{\mathscr{P}}_{21})^l & (\tilde{\mathscr{P}}_{22})^l & \dots & (\tilde{\mathscr{P}}_{2j})^l & \dots & (\tilde{\mathscr{P}}_{2\beta})^l \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ (\tilde{\mathscr{P}}_{i1})^l & (\tilde{\mathscr{P}}_{i2})^l & \dots & (\tilde{\mathscr{P}}_{ij})^l & \dots & (\tilde{\mathscr{P}}_{i\beta})^l \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ (\tilde{\mathscr{P}}_{\beta 1})^l & (\tilde{\mathscr{P}}_{\beta 2})^l & \dots & (\tilde{\mathscr{P}}_{\beta j})^l & \dots & (\tilde{\mathscr{P}}_{\beta\beta})^l \end{bmatrix}_{\beta\times\beta} \\ &= \left[(\tilde{\mathscr{P}}_{ij})^l\right]_{\beta\times\beta} = \left[\left\{\xi_{ij}, \mu_{\tilde{\mathscr{P}}_{ij}}(\xi_{ij}), \nu_{\tilde{\mathscr{P}}_{ij}}(\xi_{ij})\right\}^l\right]_{\beta\times\beta} \\ &= \left[\left\{(\xi_{ij})^l, \left(\mu_{\tilde{\mathscr{P}}_{ij}}(\xi_{ij})\right)^l, \left(\nu_{\tilde{\mathscr{P}}_{ij}}(\xi_{ij})\right)^l\right\}\right]_{\beta\times\beta}\end{aligned} \tag{22}$$

By utilizing the inputs from expert $l$ where $l = 1, 2, \dots, \alpha$, we understand the influence of criterion $i$ on criterion $j$ where $i, j = 1, 2, \dots, \beta$. Here $(\tilde{\mathscr{P}}_{ij})^l$ entry provides the ratings of $j$th criteria with respect to $i$th criteria given by $l$th DM. Moreover, $(\tilde{\mathscr{P}}_{ij})^l$ is a linguistic rating and further converted into a FFN.

Step 2: Evaluating the aggregated direct relation matrix $(\tilde{\mathcal{M}})$:
For synthesizing the conclusions of all $\alpha$ decision-making experts, we aggregate the individual matrices. We compute the aggregated relation matrix $(\tilde{\mathcal{M}})$ by utilizing $ij$th entry by aggregated from all $\alpha$ initial direct relation matrix $(\tilde{\mathcal{M}}^l)$ by Equation (23), as follows:

$$\begin{aligned}\tilde{\mathscr{P}}_{ij} &= \left\{\xi_{ij}, \mu_{\tilde{\mathscr{P}}_{ij}}(\xi_{ij}), \nu_{\tilde{\mathscr{P}}_{ij}}(\xi_{ij})\right\} \\ &= \left\{\frac{\sum_{l=1}^{\alpha}(\xi_{ij})^l}{\alpha}, \min_{l=1,2,\dots,\alpha}\left\{\left(\mu_{\tilde{\mathscr{P}}_{ij}}(\xi_{ij})\right)^l\right\}, \max_{l=1,2,\dots,\alpha}\left\{\left(\nu_{\tilde{\mathscr{P}}_{ij}}(\xi_{ij})\right)^l\right\}\right\}\end{aligned} \tag{23}$$

The aggregation operator describes in Equation (23) and aggregated direct relation matrix $(\tilde{\mathcal{M}})$ formed in Equation (24), as

$$\tilde{\mathcal{M}} = \left[\tilde{\mathscr{P}}_{ij}\right]_{\beta\times\beta} = \begin{bmatrix} \tilde{\mathscr{P}}_{11} & \tilde{\mathscr{P}}_{12} & \dots & \tilde{\mathscr{P}}_{1j} & \dots & \tilde{\mathscr{P}}_{1\beta} \\ \tilde{\mathscr{P}}_{21} & \tilde{\mathscr{P}}_{22} & \dots & \tilde{\mathscr{P}}_{2j} & \dots & \tilde{\mathscr{P}}_{2\beta} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \tilde{\mathscr{P}}_{i1} & \tilde{\mathscr{P}}_{i2} & \dots & \tilde{\mathscr{P}}_{ij} & \dots & \tilde{\mathscr{P}}_{i\beta} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \tilde{\mathscr{P}}_{\beta 1} & \tilde{\mathscr{P}}_{\beta 2} & \dots & \tilde{\mathscr{P}}_{\beta j} & \dots & \tilde{\mathscr{P}}_{\beta\beta} \end{bmatrix}_{\beta\times\beta} \tag{24}$$

where $\tilde{\mathscr{P}}_{ij}$ determined by using Equation (23), where $l = 1, 2, \dots, \alpha$ and $i, j = 1, 2, \dots, \beta$.

Step 3: Determine the de-fuzzified direct relation matrix $(\mathcal{M})$:
To perform standard matrix operations, we must convert the FFNs into crisp values using the de-fuzzification method proposed in Equation (21). From the the aggregated direct relation matrix $(\tilde{\mathcal{M}})$, we derive the de-fuzzified direct relation matrix $(\mathcal{M})$ formed in Equation (25) as follows:

$$\mathcal{M} = [\mathscr{P}_{ij}]_{\beta\times\beta} \tag{25}$$

where $\mathscr{P}_{ij}$ be the de-fuzzified value of the $ij$th entry $(\tilde{\mathscr{P}}_{ij})$ of the aggregated direct relation matrix $(\tilde{\mathcal{M}})$ with $i, j = 1, 2, \dots, \beta$.

Step 4: Calculate the normalizing direct relation matrix $(\mathcal{M}_n)$:
The normalized direct relation matrix $(\mathcal{M}_n)$ is evaluated by normalizing each and every entry of the de-fuzzified direct relation matrix $(\mathcal{M})$. The normalization process and normalizing direct relation matrix $(\mathcal{M}_n)$ shown in Equation (26), as

$$\mathcal{M}_n = \left[\mathscr{P}_{ij}^{n}\right]_{\beta\times\beta} = \left[\frac{\mathscr{P}_{ij}}{\max\limits_{1\le i\le\beta}\left\{\sum_{j=1}^{\beta}\mathscr{P}_{ij}\right\}}\right]_{\beta\times\beta} \tag{26}$$

where $\mathscr{P}_{ij}$ be the $ij$th entry of the de-fuzzified direct relation matrix $(\mathcal{M})$ with $i, j = 1, 2, \dots, \beta$.

Step 5: Constructing the total relation matrix $(\mathcal{T})$:
For both direct and indirect consequences out of criteria, $\mathcal{T}$ is the total relation matrix. It is obtained by the power series of the normalized matrix. It is computed as per the following equation:

$$\begin{aligned}\mathcal{T} = [\mathscr{T}_{ij}]_{\beta\times\beta} &= \lim_{h\to\infty}\left(\mathcal{M}_n + \mathcal{M}_n^2 + \cdots + \mathcal{M}_n^h\right)\\ &= \mathcal{M}_n(I_\beta - \mathcal{M}_n)^{-1}\end{aligned} \tag{27}$$

where $\mathcal{M}_n$ be the normalizing direct relation matrix and $I_\beta$ be an identity matrix of $\beta$ order.

Step 6: Computing the direct influence $(\mathfrak{P}_i)$ and indirect influence $(\mathfrak{Q}_i)$:
We compute the direct influence $(\mathfrak{P}_i)$ and the indirect influence $(\mathfrak{Q}_i)$ of the criteria $i$ form the total relation matrix $(\mathcal{T})$, as follows:

The direct influence $(\mathfrak{P}_i)$ of the criteria $i$ is determine from the total relation matrix $(\mathcal{T})$ using Equation (28), as

$$\mathfrak{P}_i = \sum_{j=1}^{\beta}\mathscr{T}_{ij} \tag{28}$$

for $i = 1, 2, \dots, \beta$ and the indirect influence $(\mathfrak{Q}_i)$ of the criteria $i$ is evaluated from the total relation matrix $(\mathcal{T})$ using Equation (29), as

$$\mathfrak{Q}_i = \mathfrak{Q}_j = \sum_{i=1}^{\beta}\mathscr{T}_{ij} \tag{29}$$

for $j = 1, 2, \dots, \beta$.

Step 7: Evaluating the prominence value $(\mathcal{G}_i)$ and relation value $(\mathcal{H}_i)$:
We obtain the prominence value $(\mathcal{G}_i)$ and relation value $(\mathcal{H}_i)$ from the direct influence $(\mathfrak{P}_i)$ and the indirect influence $(\mathfrak{Q}_i)$ values, using following equations:

The prominence value $(\mathcal{G}_i)$ represents the total significance of the criterion $i$ in the environment. It is evaluated by the equation as

$$\mathcal{G}_i = \mathfrak{P}_i + \mathfrak{Q}_i = \sum_{j=1}^{\beta}\mathscr{T}_{ij} + \sum_{i=1}^{\beta}\mathscr{T}_{ij} \tag{30}$$

and the relation value $(\mathcal{H}_i)$ expresses the net significance of the criterion. It is obtained by the equation given as

$$\mathcal{H}_i = \mathfrak{P}_i - \mathfrak{Q}_i = \sum_{j=1}^{\beta}\mathcal{T}_{ij} - \sum_{i=1}^{\beta}\mathcal{T}_{ij} \tag{31}$$

where $i, j = 1, 2, \ldots, \beta$. For $\mathcal{H}_i > 0$, the criterion is a cause, while $\mathcal{H}_i < 0$ reflects that the criterion is an effect in the system.

Step 7: Obtaining threshold value $(\mathfrak{W})$:
To minimise effects and visualise the key relationships, a threshold value $(\mathfrak{W})$ is determined. The usual procedure is to calculate the mean of all elements of the total relation matrix $(\mathcal{T})$ and the procedure is shown as

$$\mathfrak{W} = \frac{\sum_{i=1}^{\beta} \sum_{j=1}^{\beta} \mathcal{T}_{ij}}{\beta^2} \tag{32}$$

Step 8: Construction of the scatter matrix ($\sigma$) and causal diagram:
For visibly expressing the causal relationships, we formulate a scatter matrix $\Sigma = [q_{ij}]_{\beta \times \beta}$ depending upon the threshold value $(\mathfrak{W})$. Thus, we emit negligible effects and ensure the important dependencies:

$$q_{ij} = \begin{cases} 0 & (\text{i.e., Negligible Effect}) \quad ;\text{if } \mathcal{T}_{ij} < \mathfrak{W} \\ 1 & (\text{i.e., Significant Effect}) \quad ;\text{if } \mathcal{T}_{ij} \geq \mathfrak{W} \end{cases} \tag{33}$$

in which $\mathcal{T}_{ij}$ is the element of the total relation matrix $(\mathcal{T})$.

At the end, the causal diagram is mapped by utilizing $(\mathcal{G}_i - \mathcal{H}_i)$ on the vertical axis and $(\mathcal{G}_i + \mathcal{H}_i)$ on the horizontal axis, with arrows expressing the important relationships in which $\mathcal{T}_{ij} \geq \mathfrak{W}$.

## 5. Sources of Renewable Energy

The energies obtained from natural resources, which are replenished continuously and not depleted due to human consumption, are primarily known as renewable energies. In the modern era of energy scarcity, renewable energy has become a primary driver of global geopolitical tensions. Renewable energy sources are primary substitutes for fossil fuels and play a major role in reducing greenhouse gas emissions, moderating weather fluctuations and most importantly, ensuring the security of meeting energy demand for centuries. In this section, we have discussed all types of renewable energy sources, namely solar energy [7], wind Energy [9], tidal energy [12], hydropower [8], geothermal energy [70] and biomass energy [71], respectively. These renewable energy sources are environmentally friendly and generally emit minimal carbon. Different sources of renewable energies are graphically presented in Figure 4. Efficiency, advantages and disadvantages of all renewable energy sources are described below in detail:

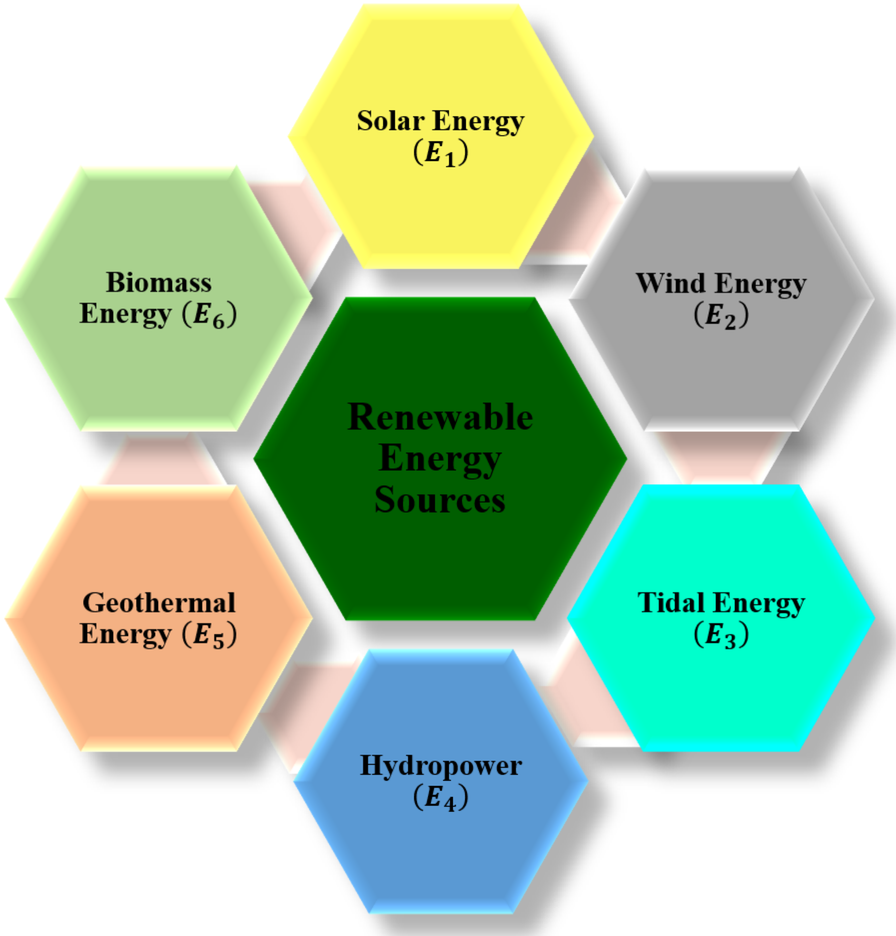


**Fig. 4.** Sources of renewable energies

### 5.1 *Solar Energy* $(\mathscr{E}_1)$

Directly or indirectly, the primary source of all energies on Earth is the Sun. Due to nuclear fusion in the Sun, hydrogen atoms combine and fuse into helium atoms, releasing an immense amount of energy in the form of electromagnetic radiation. Solar energy [7] is stored by using photovoltaic (PV) cells and solar thermal systems. Sunlight is directly converted into electricity by PV cells [72], whereas heat is produced from sunlight using solar thermal systems. In the tropical regions, solar energy is endlessly available and can be utilized for generations for producing electricity, heating water, illumination and making food. As of now, a typical mono-crystalline panel drifts by nearly $(22 - 24\%)$. Although the new technology of Perovskite-Silicon cells [73] achieves energy efficiency of $(30 - 33\%)$, it is establishing new market standards. Regarding their environmental impact, solar panels are generally eco-friendly. There is no emission of any pollutant gases from solar cells. Solar PV cells generally use the deserts and other unproductive lands. However, cleaning of this technology requires water, and production requires the use and release of harmful chemicals.

### 5.2 *Wind Energy* $(\mathscr{E}_2)$

Due to atmospheric heating, air flows from high-pressure to low-pressure regions. We get wind energy [9] via transforming the kinetic energy of the flowing air into electricity by the use of wind turbines and the generator inside the system. The wind turbines generally utilize the force of aerodynamic energy via rotor blades. On top of hills and in coastal regions, the situation for establishing a wind turbine is well-suited, owing to the regular high-speed wind flow. We get an efficiency of $(35\breve{}50\%)$ from the turbines of the wind farms with the assistance of strong and steady wind flow. Wind energy is among the most promising renewable energy sources due to its effectiveness [74] and low maintenance costs in the post-installation phase. Given its high sustainability, the operational cost is borne, in many cases, by agricultural land. There are no carbon emissions or emissions of any harmful fluids from the wind farms. But along with all of these advantages, the cost of installation [75] of wind turbines is very expensive and it also creates an unwanted death trap for the high-flying birds.

### 5.3 Tidal Energy $(\mathscr{E}_3)$

The production of tidal energy [12] has come to the attention of human society in recent times. We obtain tidal energy from ocean-tide turbulence arising from sea-level fluctuations. The tidal movement occurs due to the gravitational interactions among the Sun, Earth and Moon. The emerging sector of tidal energy installs underwater turbines and tidal barrages [76] in coastal regions to utilize resources from nature. By observing the positions and motions of the Earth, Moon and Sun, we can highly predict the locations of tides. Apart from solar energy and wind energy, tidal energy has a comparatively high density of energy efficiency, ranging $35\breve{}45\%$ by the use of well-planned, systematic turbines. Tidal turbines are highly sustainable with no requirement for fuel, but the initial construction cost is expensive. The production of tidal energy does not cause carbon emissions, but it adversely affects marine life and local biodiversity. Along with this, tidal turbines require repetitive maintenance [77] because of corrosion caused by the high presence of salt water.

### 5.4 Hydropower $(\mathscr{E}_4)$

We obtain hydropower by using turbines to convert flowing or falling water into electricity. Turbines are connected to generators and hydropower plants store water in dams to optimize their potential energy by rotating the turbines. In a global [8] scenario, it is the biggest one of the ancient origins of renewable energy today. The efficiency of hydropower plants is exceptionally high, reaching approximately $90\%$ and leaving negligible heat loss. The operational cost of these power plants is comparatively low and once made, can be sustained up to 50-100 years. In addition to producing electricity on a large scale, it can also assist in controlling water supply, irrigation [78] and flood management. However, the construction of hydropower plants requires substantial capital and a long construction period. Reservoirs may produce methane gas through decomposition of dead organic matter and fish migration [79], which can also affect the natural environment.

### 5.5 Geothermal Energy $(\mathscr{E}_5)$

The interior of the Earth is not totally cooled down yet. A lot of energy in the form of heat is still stored there. This is the source of geothermal energy [10], which again falls in the category of sustainable, renewable energy sources. We can obtain this energy in the form of heat from geothermal reservoirs and convert it into electricity. Active tectonic regions with large temperature gradients are prime sites for establishing geothermal power stations. Geothermal energy has a low efficiency of $10 - 20\%$ [70], yet it is highly reliable due to its inherently limitless capacity, making it available $24X7$. With low maintenance costs, geothermal energy is highly sustainable, producing almost zero carbon emissions. However, establishing a geothermal power station requires a good amount of capital investment. Geothermal power stations generally release gases such as hydrogen sulphide, but with comparatively low pollution compared to fossil fuels. The geothermal stations must be managed properly [80], otherwise there is a risk of minor earthquakes during drilling.

### 5.6 Biomass Energy $(\mathscr{E}_6)$

We obtain biomass energy from most organic waste materials, such as crop residues, food waste, wood, animal waste, and other biodegradable waste. Biomass [11] can be used as a direct alternative to fossil fuels by converting it into bio-ethanol, bio-gas and bio-diesel [71] to generate energy. We generally use biomass primarily for heating, for food production and for electricity generation. The efficiency of biomass energy can vary from $(20-25\%)$, but integrated power and heat can provide efficiency up to $80\%$. A suitable way to manage organic waste is to use it as a biomass energy source. We can also address the problem of landfills using the dispatchable organic waste. Theoretically, biomass is considered carbon-neutral, but combustion emits carbon dioxide and carbon monoxide, which affect the quality of the air and the health of citizens near the biomass power plant [81]. It is considered carbon-neutral when the harvest rate is lower than the growth rate. There is also a risk that deforestation will negatively impact biodiversity.

## 6. Model Structured and Data Collection

This section details the model formulation procedure and data sources. First, formulate the model, followed by the data sources and data collection procedure of this study.

### 6.1 Model structured

After an in-depth study of renewable power systems worldwide, a total of 6 renewable energy sources were identified for this research. Some direct relation matrices of order $6 \times 6$ are constructed by linguistic terms with the help of decision makers (DMs) and are shown in Table 4. We have implemented an MCDM methodology, namely DEMATEL, to evaluate the inputs numerically onward.

Three DMs have provided the necessary inputs based on their experience, knowledge and data sources in their respective fields. All data are taken in linguistic forms from all DMs. Three unbiased professional DMs are:

**DM1:** A professor researching in the field of renewable energy sources with more than 15 years of experience.

**DM2:** A senior government engineer from the Ministry of New & Renewable Energy (MNRE) department with more than a decade of working experience.

**DM3:** A CEO of a unicorn start-up based on a renewable energy system with more than 15 years of experience.

With the coordination of research institutes, government agencies and private businesses, the input data for the renewable energy system is comprised along with all available resources. A professor working in the field of renewable energy sources can assist by collecting the necessary data through experiments. Government engineers have access to historical industry survey data, which serves as the basis for evaluating renewable energy production and the local adoption challenges. The CEO of the unicorn start-up bring new insights towards the development of technologies for harnessing efficient energy sources and their cost to return portfolios. All the DMs provided insights from their own field of expertise and the integrated datasets accelerated the momentum of our research work.

## 6.2 Data collection

In this section, the data sources, collection procedure and datasets are illustrated. Initially, all the respective DMs provided the necessary inputs using linguistic terms. We have implemented the given data in the direct matrices according to the linguistic terms provided in Table 3. Further, the direct relation matrices shown in Table 4 are transferred into FFNs by using the conversion table of linguistic terms and FFNs given in Table 3. Afterwards, the direct relation matrices utilized in the DEMATEL methodology, as described in Section 4.

**Table 3**
Conversion table between linguistic terms with FFNs

| Linguistic terms | Acronym | Fermatean Fuzzy Number | De-fuzzification Value |
|---|---|---|---|
| Absolutely Impactful | AI | $(11, 0.95, 0.25)$ | 10.557 |
| Hugely Impactful | HI | $(9, 0.90, 0.30)$ | 8.296 |
| Strongly Impactful | SI | $(7, 0.85, 0.35)$ | 6.172 |
| Moderately Impactful | MI | $(5, 0.80, 0.40)$ | 4.192 |
| Weakly Impactful | WI | $(3, 0.75, 0.45)$ | 2.370 |
| Poorly Impactful | PI | $(1, 0.70, 0.50)$ | 0.734 |
| Not Impactful | NI | $(0, 0.65, 0.55)$ | 0.000 |

**Table 4**
Direct relation matrix $(\tilde{\mathcal{M}}^l)$ in linguistic terms given by the three DMs

| | Energy vs Energy | Solar Energy $(\mathscr{E}_1)$ | Wind Energy $(\mathscr{E}_2)$ | Tidal Energy $(\mathscr{E}_3)$ | Hydropower $(\mathscr{E}_4)$ | Geothermal Energy $(\mathscr{E}_5)$ | Biomass $(\mathscr{E}_6)$ |
|---|---|---|---|---|---|---|---|
| DM1 | Solar Energy $(\mathscr{E}_1)$ | NI | MI | HI | WI | WI | SI |
| | Wind Energy $(\mathscr{E}_2)$ | SI | NI | SI | WI | WI | MI |
| | Tidal Energy $(\mathscr{E}_3)$ | PI | PI | NI | WI | PI | WI |
| | Hydropower $(\mathscr{E}_4)$ | SI | SI | HI | NI | SI | HI |
| | Geothermal Energy $(\mathscr{E}_5)$ | SI | SI | HI | HI | NI | HI |
| | Biomass $(\mathscr{E}_6)$ | WI | PI | PI | PI | PI | NI |
| | **Energy vs Energy** | $\mathscr{E}_1$ | $\mathscr{E}_2$ | $\mathscr{E}_3$ | $\mathscr{E}_4$ | $\mathscr{E}_5$ | $\mathscr{E}_6$ |
| DM2 | Solar Energy $(\mathscr{E}_1)$ | NI | HI | HI | PI | WI | SI |
| | Wind Energy $(\mathscr{E}_2)$ | SI | NI | HI | PI | PI | SI |
| | Tidal Energy $(\mathscr{E}_3)$ | WI | WI | NI | PI | WI | PI |
| | Hydropower $(\mathscr{E}_4)$ | HI | SI | SI | NI | SI | HI |
| | Geothermal Energy $(\mathscr{E}_5)$ | HI | SI | AI | MI | NI | HI |
| | Biomass $(\mathscr{E}_6)$ | PI | PI | WI | PI | WI | NI |

**Table 4**
*Cont.*

| | Energy vs Energy | Solar Energy $(\mathscr{E}_1)$ | Wind Energy $(\mathscr{E}_2)$ | Tidal Energy $(\mathscr{E}_3)$ | Hydropower $(\mathscr{E}_4)$ | Geothermal Energy $(\mathscr{E}_5)$ | Biomass $(\mathscr{E}_6)$ |
|---|---|---|---|---|---|---|---|
| DM3 | Solar Energy $(\mathscr{E}_1)$ | NI | HI | SI | PI | WI | SI |
| | Wind Energy $(\mathscr{E}_2)$ | HI | NI | SI | PI | PI | SI |
| | Tidal Energy $(\mathscr{E}_3)$ | WI | PI | NI | WI | PI | PI |
| | Hydropower $(\mathscr{E}_4)$ | SI | HI | AI | NI | HI | HI |
| | Geothermal Energy $(\mathscr{E}_5)$ | SI | HI | AI | HI | NI | SI |
| | Biomass $(\mathscr{E}_6)$ | WI | PI | WI | WI | WI | NI |

## 7. Numerical Illustration and Discussion

In this section, the numerical evaluation of the most effective renewable energy sources is performed and the results are analysed in detail. We consider the fuzzy DEMATEL method discussed in Section 4 as an optimization technique in an uncertain environment, which is covered in Section 3. Furthermore, the Direct relation matrix $(\tilde{\mathcal{M}}^l)$ shown in Table 4 is considered as the data source for the numerical evaluation.

The fuzzy DEMATEL method assesses the required results as shown below. Table 4 build the direct relation matrix $(\tilde{\mathcal{M}}^l)$ by three DMs using Equation (22). Then, the aggregated direct relation matrices $(\tilde{\mathcal{M}})$ were evaluated with the help of Equation (23). The de-fuzzified aggregated direct-relation matrix $(\mathcal{M})$ is shown in Table 5 using Equation (21). Therefore, Equation (26) computed the normalized direct-relation matrix $(\mathcal{M}_n)$ in Table 6. To find the proper solution, evaluate the total-relation matrix $(\mathcal{T})$ in Table 7 utilizing Equation (27). Finally, the direct influence $(\mathfrak{P}_i)$, indirect influence $(\mathcal{Q}_j)$, prominence value $(\mathcal{G}_i)$ and relation value $(\mathcal{H}_i)$ values for every criteria are shown in Table 8 and calculated by Equations (28), (29), (30) and (31), respectively. The prominence value $(\mathcal{G}_i)$ and relation value $(\mathcal{H}_i)$ of the different renewable energy sources are provided the efficiency of the criteria through DEMATEL methodology, presented in Table 8.

**Table 5**
De-fuzzified aggregated direct-relation matrix $(\mathcal{M})$

| **Energy vs Energy** | $\mathscr{E}_1$ | $\mathscr{E}_2$ | $\mathscr{E}_3$ | $\mathscr{E}_4$ | $\mathscr{E}_5$ | $\mathscr{E}_6$ |
|---|---|---|---|---|---|---|
| Solar Energy $(\mathscr{E}_1)$ | 0.000 | 6.428 | 7.348 | 1.223 | 2.370 | 6.172 |
| Wind Energy $(\mathscr{E}_2)$ | 6.760 | 0.000 | 6.760 | 1.223 | 1.223 | 5.310 |
| Tidal Energy $(\mathscr{E}_3)$ | 1.713 | 1.223 | 0.000 | 1.713 | 1.223 | 1.223 |
| Hydropower $(\mathscr{E}_4)$ | 6.760 | 6.760 | 7.936 | 0.000 | 6.760 | 8.296 |
| Geothermal Energy $(\mathscr{E}_5)$ | 6.760 | 6.760 | 9.526 | 6.428 | 0.000 | 7.348 |
| Biomass $(\mathscr{E}_6)$ | 1.713 | 0.734 | 1.713 | 1.223 | 1.713 | 0.000 |

**Table 6**
Normalizing modified direct-relation matrix $(\mathcal{M}_n)$

| **Energy vs Energy** | $\mathscr{E}_1$ | $\mathscr{E}_2$ | $\mathscr{E}_3$ | $\mathscr{E}_4$ | $\mathscr{E}_5$ | $\mathscr{E}_6$ |
|---|---|---|---|---|---|---|
| Solar Energy $(\mathscr{E}_1)$ | 0.000 | 0.175 | 0.200 | 0.033 | 0.064 | 0.168 |
| Wind Energy $(\mathscr{E}_2)$ | 0.184 | 0.000 | 0.184 | 0.033 | 0.033 | 0.144 |
| Tidal Energy $(\mathscr{E}_3)$ | 0.047 | 0.033 | 0.000 | 0.047 | 0.033 | 0.033 |
| Hydropower $(\mathscr{E}_4)$ | 0.184 | 0.184 | 0.216 | 0.000 | 0.184 | 0.225 |
| Geothermal Energy $(\mathscr{E}_5)$ | 0.184 | 0.184 | 0.259 | 0.175 | 0.000 | 0.200 |
| Biomass $(\mathscr{E}_6)$ | 0.047 | 0.020 | 0.047 | 0.033 | 0.047 | 0.000 |

**Table 7**
Total relation matrix $(\mathcal{T})$ among the various renewable energies

| **Energy vs Energy** | $\mathscr{E}_1$ | $\mathscr{E}_2$ | $\mathscr{E}_3$ | $\mathscr{E}_4$ | $\mathscr{E}_5$ | $\mathscr{E}_6$ |
|---|---|---|---|---|---|---|
| Solar Energy $(\mathscr{E}_1)$ | 0.113 | 0.250 | 0.332 | 0.091 | 0.121 | 0.278 |
| Wind Energy $(\mathscr{E}_2)$ | 0.258 | 0.092 | 0.304 | 0.083 | 0.090 | 0.247 |
| Tidal Energy $(\mathscr{E}_3)$ | 0.092 | 0.077 | 0.067 | 0.069 | 0.061 | 0.090 |
| Hydropower $(\mathscr{E}_4)$ | 0.357 | 0.339 | 0.462 | 0.106 | 0.273 | 0.428 |
| Geothermal Energy $(\mathscr{E}_5)$ | 0.356 | 0.338 | 0.495 | 0.254 | 0.116 | 0.405 |
| Biomass $(\mathscr{E}_6)$ | 0.090 | 0.064 | 0.109 | 0.058 | 0.071 | 0.055 |

**Table 8**
Prominence $(\mathcal{G}_i)$ and relation $(\mathcal{H}_i)$ values with associated data among the energy sources

| **Energy** | $\mathfrak{P}_i = \sum_{j=1}^{b} \mathcal{T}_{ij}$ | $\mathcal{Q}_j = \sum_{i=1}^{b} \mathcal{T}_{ij}$ | $\mathcal{G}_i = \mathfrak{P}_i + \mathcal{Q}_i$ | $\mathcal{H}_i = \mathfrak{P}_i - \mathcal{Q}_i$ |
|---|---|---|---|---|
| Solar Energy $(\mathscr{E}_1)$ | 1.184 | 1.265 | -0.080 | 2.449 |
| Wind Energy $(\mathscr{E}_2)$ | 1.074 | 1.160 | -0.086 | 2.234 |
| Tidal Energy $(\mathscr{E}_3)$ | 0.455 | 1.771 | -1.316 | 2.225 |
| Hydropower $(\mathscr{E}_4)$ | 1.966 | 0.661 | 1.305 | 2.627 |
| Geothermal Energy $(\mathscr{E}_5)$ | 1.965 | 0.731 | 1.234 | 2.696 |
| Biomass $(\mathscr{E}_6)$ | 0.447 | 1.503 | -1.056 | 1.949 |

Based on the obtained results, we conclude that Table 8 accurately presents the numerical results of the fuzzy DEMATEL methodology among the criteria adopted for identifying efficient renewable energy sources. From this table, we can conclude about the degree of relationship of a particular criterion among other criteria from the prominence value $(\mathcal{G}_i)$. For example, Hydropower $(\mathscr{E}_4)$ and Tidal Energy $(\mathscr{E}_3)$ have the highest and lowest relationship with the other criteria, respectively. Furthermore, Geothermal Energy $(\mathscr{E}_5)$ and Solar Energy $(\mathscr{E}_1)$ have the second and third highest relationship with the remaining criteria, respectively. Lastly, the two criteria for Wind Energy $(\mathscr{E}_2)$ and Biomass $(\mathscr{E}_6)$ are the fourth and fifth highest, respectively.

To express the type of relationship between different criteria, the relation value $(\mathcal{H}_i)$ of the criteria is known from table 8. Positive $(+ve)$ and negative $(-ve)$ values of correlation value $(\mathcal{H}_i)$ indicate that the criteria belong to the cause group or sender and other criteria belong to the result group or receiver. Analyzing the whole model, it can be seen that, in our work, all the criteria belong to the cause group or sender, but none of the criteria belongs to the result group or receiver. Therefore, the causal diagram between the criteria for finding efficient renewable energy sources is clearly shown in Figure 5.

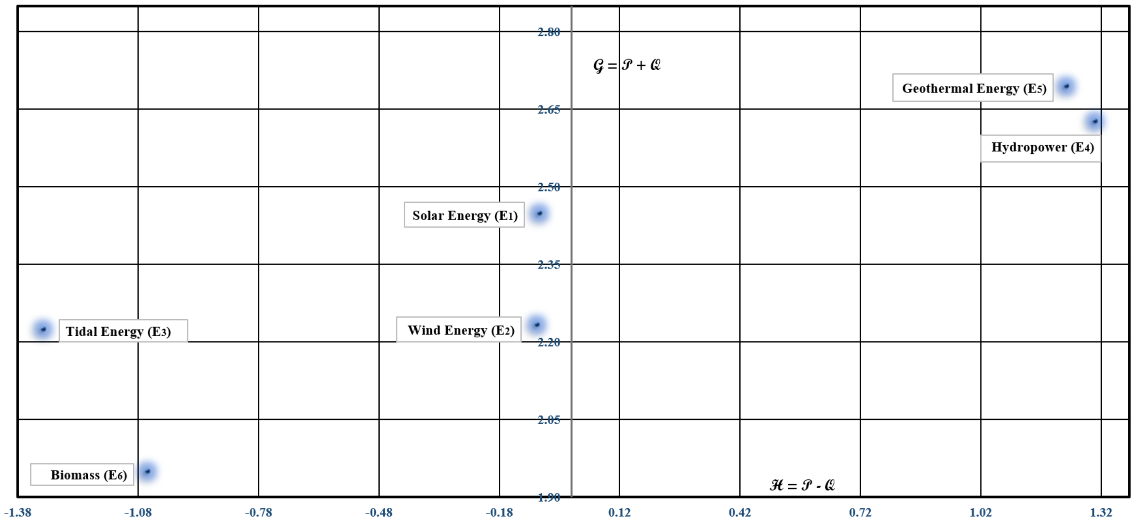


**Fig. 5.** Causal diagram for suitable renewable energy selection based on $\mathcal{G}_i$ and $\mathcal{H}_i$ values

For the proper visualization, we use the scatter matrix in Table 8 to draw the scatter diagram in Figure 6. From this diagram, we obtain a clear understanding of the interrelationships among the criteria of the proposed model with respect to the threshold value $0.197$, which facilitates the identification of renewable energy sources.

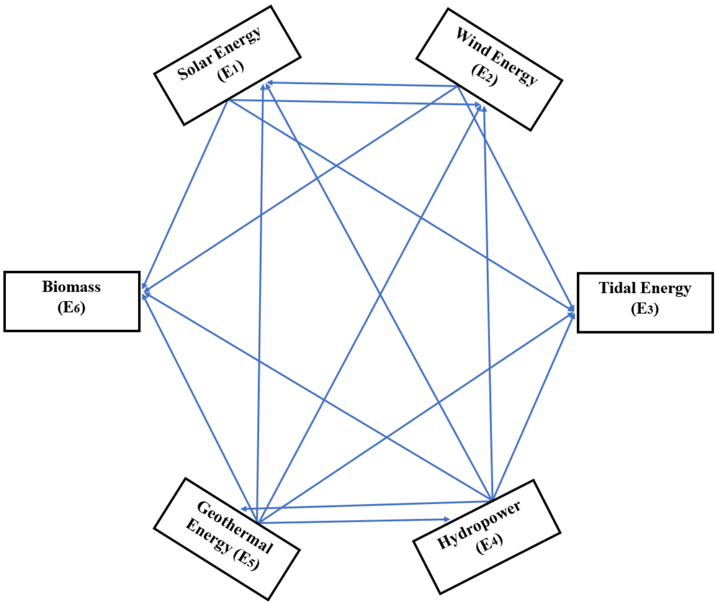


**Fig. 6.** Scatter diagram of the optimal renewable energy sources selection

## 8. Comparative Analysis

Comparative studies on the evaluation of efficient renewable energy sources are conducted in this section. These studies were conducted based on three different uncertainty tools, namely Pythagorean fuzzy numbers (PFNs), intuitionistic fuzzy numbers (IFNs) and fuzzy numbers (FN). Furthermore, compare with the FFN in terms of the prominence values $(\mathcal{G}_i)$ and relation values $(\mathcal{H}_i)$, both. Table 9 shows the prominence values $(\mathcal{G}_i)$ under different environments and Figure 7 graphically depicts this. Similarly, Table 10 displayed the relation values $(\mathcal{H}_i)$ under different environments and Figure 8 graphically represents this.

**Table 9**

Comparative studies on prominence values under different environments

| Energy | PFN | IFN | FN | FFN |
|---|---|---|---|---|
| Solar Energy $(\mathscr{E}_1)$ | 2.409 | 2.101 | 2.422 | 2.449 |
| Wind Energy $(\mathscr{E}_2)$ | 2.196 | 1.914 | 2.211 | 2.234 |
| Tidal Energy $(\mathscr{E}_3)$ | 2.190 | 1.939 | 2.211 | 2.225 |
| Hydropower $(\mathscr{E}_4)$ | 2.591 | 2.322 | 2.607 | 2.627 |
| Geothermal Energy $(\mathscr{E}_5)$ | 2.657 | 2.368 | 2.673 | 2.696 |
| Biomass $(\mathscr{E}_6)$ | 1.913 | 1.665 | 1.935 | 1.949 |

**Remark 6.** *From Table 9 and Figure 7, we can see that the prominence values $(\mathcal{G}_i)$ of the different renewable energy sources are similar on the basis of PFN, FN and FFN; however, they slightly fluctuate in the IFN environment. Therefore, from the prominence values $(\mathcal{G}_i)$, it is stated that the evaluated results are stable.*

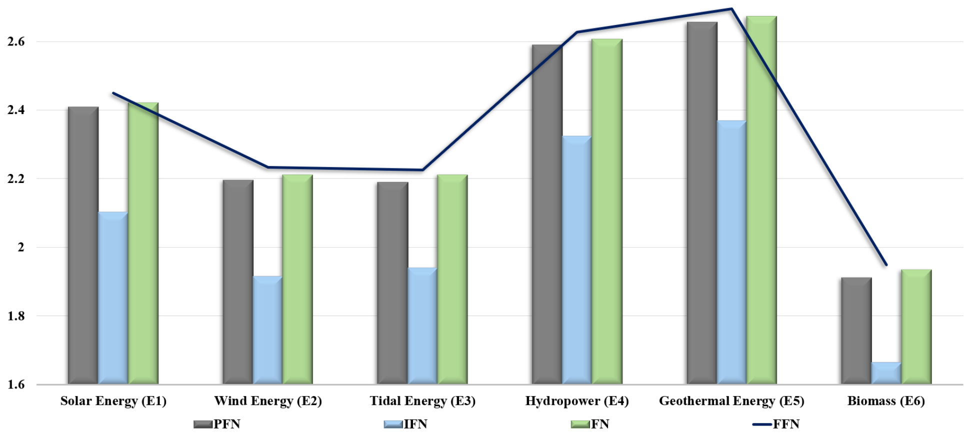


**Fig. 7.** Graphical analysis of prominence values under different environments

**Table 10**

Comparative studies on relation values under different environments

| Energy | PFN | IFN | FN | FFN |
|---|---|---|---|---|
| Solar Energy $(\mathscr{E}_1)$ | -0.084 | -0.097 | -0.083 | -0.080 |
| Wind Energy $(\mathscr{E}_2)$ | -0.086 | -0.079 | -0.085 | -0.086 |
| Tidal Energy $(\mathscr{E}_3)$ | -1.318 | -1.301 | -1.313 | -1.316 |
| Hydropower $(\mathscr{E}_4)$ | 1.311 | 1.313 | 1.303 | 1.305 |
| Geothermal Energy $(\mathscr{E}_5)$ | 1.234 | 1.203 | 1.231 | 1.234 |
| Biomass $(\mathscr{E}_6)$ | -1.057 | -1.039 | -1.053 | -1.056 |

**Remark 7.** *From Table 10 and Figure 8, we can state that the relation values* $(\mathcal{H}_i)$ *of the various renewable energy sources are almost similar under different uncertain environments. Then the relation values* $(\mathcal{H}_i)$ *are stable in the main results.*

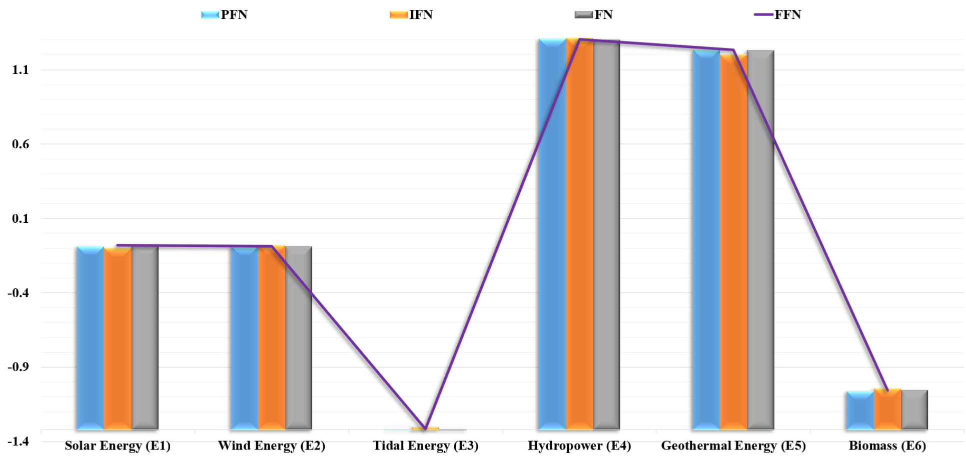


**Fig. 8.** Graphical analysis of relation values under different environments

# 9. Research implication

This research has multidimensional implications towards the development and implementation of renewable energy sectors in terms of sustainable energy planning and policymaking. We have integrated the DEMATEL methodology with the fermatean fuzzy environment to deal with the uncertainty and hesitation in experts' judgments in the decision-making domain. The collaboration of experts from heterogeneous fields enhances research quality through a robust mechanism in our integrated model that integrates multidisciplinary inputs. The prominence values suggest that hydropower and geothermal energy constitute the maximum overall influence in the system of various renewable energies. On the other hand, solar energy, wind energy, tidal energy and biomass are more dependent on systematic technological evaluations of infrastructural factors by different industries. Our integrated fermatean fuzzy DEMATEL model has demonstrated the ability to capture a high degree of uncertainty beyond intuitionistic and Pythagorean environments in such scenarios. This framework can be further extended to more complex situations, considering environmental planning, energy engineering and sustainable management systems. Overall, this research imparts a strategic, balanced collaboration among academia, government bodies and industrial management for sustainable policymaking in the renewable energy sector.

# 10. Conclusions and Future Research Scopes

Identifying viable renewable energy sources, such as solar, wind, hydroelectricity, and biomass, is essential for achieving sustainable energy development and reducing environmental pollution. They provide the cleanest and most reliable alternatives to fossil fuels. They ensure better decision-making by selecting the most cost-effective and environmentally friendly energy options. They can improve the accuracy of renewable energy assessments under uncertainty, yielding more reliable results. We have explored the direct and indirect effects of each criterion on related criteria for identifying efficient renewable energy sources in this paper. The criteria are taken as Solar Energy $(\mathscr{E}_1)$, Wind Energy $(\mathscr{E}_2)$, Tidal Energy $(\mathscr{E}_3)$, Hydropower $(\mathscr{E}_4)$, Geothermal Energy $(\mathscr{E}_5)$ and Biomass Energy $(\mathscr{E}_6)$. We use the concept of MCDM to determine the direct and indirect effects of the criteria. Data sets were collected based on linguistic variables from three decision experts. The linguistic terms direct relation matrix $(\tilde{\mathcal{M}}^l)$ is converted to a fuzzy number matrix for further steps. The fuzzy DEMATEL method was used to obtain the numerical results reported in Table 8. In conclusion, according to this table, the Hydropower $(\mathscr{E}_4)$ criterion has the highest correlation with the remaining criteria, and the Tidal Energy $(\mathscr{E}_3)$ criterion has the lowest correlation. Moreover, from the results obtained here, we see that in fact all criteria are in the cause group or dispatcher, but there are no criteria in the effect group or the receiver.

Future research could expand this work in different directions, such as from a theoretical perspective or through modelling. It can be used to identify relationships between criteria and work in various types of uncertainty environments for datasets, such as TFSs, TrFSs, IFSs, PFSs, NFSs, q-rung orthogonal fuzzy sets, etc. Again, for better results, other types of MCDM methods, such as AHP, Entropy, CRITIC, SWARA and ANP, can also be used. Moreover, different types of de-fuzzification techniques can be used in future. In the model part, anyone can use different perspectives to identify effective renewable energy sources, including power generation, environmental management, transportation sector, agriculture and sustainable development planning. As a result, you can use the results appropriately. In this way, effective renewable energy identification supports a green future while ensuring energy security and economic growth.

**Acknowledgement**
This research was not funded by any grant.

**Conflicts of Interest**
There are no conflicts of interest.

**References**

[1] Barrett, J., Pye, S., Betts-Davies, S., Broad, O., Price, J., Eyre, N., Anable, J., Brand, C., Bennett, G., Carr-Whitworth, R., et al. (2022). Energy demand reduction options for meeting national zero-emission targets in the united kingdom. *Nature energy*, *7*(8), 726–735. https://doi.org/10.1038/s41560-022-01057-y

[2] Khan, K., Su, C. W., Khurshid, A., & Qin, M. (2023). Does energy security improve renewable energy? a geopolitical perspective. *Energy*, *282*, 128824. https://doi.org/10.1016/j.energy.2023.128824

[3] Ang, T.-Z., Salem, M., Kamarol, M., Das, H. S., Nazari, M. A., & Prabaharan, N. (2022). A comprehensive study of renewable energy sources: Classifications, challenges and suggestions. *Energy strategy reviews*, *43*, 100939. https://doi.org/10.1016/j.esr.2022.100939

[4] Chakraborty, S., & Chakraborty, S. (2022). A scoping review on the applications of mcdm techniques for parametric optimization of machining processes. *Archives of Computational Methods in Engineering*, *29*(6), 4165–4186. https://doi.org/10.1007/s11831-022-09731-w

[5] Safaei, M., Sundararajan, E. A., Asadi, S., Nilashi, M., Aziz, M. J. A., Saravanan, M., Abdelhaq, M., & Alsaqour, R. (2022). A hybrid mcdm approach based on fuzzy-logic and dematel to evaluate adult obesity. *International Journal of Environmental Research and Public Health*, *19*(23), 15432. https://doi.org/10.3390/ijerph192315432

[6] Büyüközkan, G., Uztürk, D., & Ilıcak, Ö. (2024). Fermatean fuzzy sets and its extensions: A systematic literature review. *Artificial Intelligence Review*, *57*(6), 138. https://doi.org/10.1007/s10462-024-10761-y

[7] Maka, A. O., & Alabid, J. M. (2022). Solar energy technology and its roles in sustainable development. *Clean Energy*, *6*(3), 476–483. https://doi.org/10.1093/ce/zkac023

[8] Wasti, A., Ray, P., Wi, S., Folch, C., Ubierna, M., & Karki, P. (2022). Climate change and the hydropower sector: A global review. *Wiley Interdisciplinary Reviews: Climate Change*, *13*(2), e757. https://doi.org/10.1002/wcc.757
[9] Boadu, S., & Otoo, E. (2024). A comprehensive review on wind energy in africa: Challenges, benefits and recommendations. *Renewable and Sustainable Energy Reviews*, *191*, 114035. https://doi.org/10.1016/j.rser.2023.114035
[10] Rohit, R., Kiplangat, D. C., Veena, R., Jose, R., Pradeepkumar, A., Kumar, K. S., et al. (2023). Tracing the evolution and charting the future of geothermal energy research and development. *Renewable and Sustainable Energy Reviews*, *184*, 113531. https://doi.org/10.1016/j.rser.2023.113531
[11] Mutascu, M. (2023). Is biomass energy really sustainable in the united states? *Renewable and Sustainable Energy Reviews*, *181*, 113325. https://doi.org/10.1016/j.rser.2023.113325
[12] Khare, V., & Bhuiyan, M. A. (2022). Tidal energy-path towards sustainable energy: A technical review. *Cleaner Energy Systems*, *3*, 100041. https://doi.org/10.1016/j.cles.2022.100041
[13] Rani, P., Mishra, A. R., Saha, A., Hezam, I. M., & Pamucar, D. (2021). Fermatean fuzzy heronian mean operators and merec-based additive ratio assessment method: An application to food waste treatment technology selection. *International Journal of Intelligent Systems*, *37*(3), 2612–2647. https://doi.org/10.1002/int.22787
[14] Zadeh, L. (1965). Fuzzy sets. *Information and Control*, *8*(3), 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X
[15] Rahman, M. M., Khan, I., Field, D. L., Techato, K., & Alameh, K. (2022). Powering agriculture: Present status, future potential, and challenges of renewable energy applications. *Renewable Energy*, *188*, 731–749. https://doi.org/10.1016/j.renene.2022.02.065
[16] Dezhdar, A., Assareh, E., Keykhah, S., Bedakhanian, A., & Lee, M. (2023). A transient model for clean electricity generation using solar energy and ocean thermal energy conversion (otec)-case study: Karkheh dam-southwest iran. *Energy Nexus*, *9*, 100176. https://doi.org/10.1016/j.nexus.2023.100176
[17] Hu, Z., Deng, Z., Gao, W., & Chen, Y. (2023). Experimental study of the absorption refrigeration using ocean thermal energy and its under-lying prospects. *Renewable Energy*, *213*, 47–62. https://doi.org/10.1016/j.renene.2023.05.086
[18] Pradhan, P., Deore, S. P., Gadkari, P., Arora, A., & Mahajani, S. M. (2023). Field evaluation of biomass gasifier for bioenergy application: Case studies on institutional cooking in india. *Sustainable Energy Technologies and Assessments*, *59*, 103409. https://doi.org/10.1016/j.seta.2023.103409
[19] Shahbazi, R., Kouravand, S., & Hassan-Beygi, R. (2023). Analysis of wind turbine usage in greenhouses: Wind resource assessment, distributed generation of electricity and environmental protection. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *45*(3), 7846–7866. https://doi.org/10.1080/15567036.2019.1677810
[20] Al-Atroush, M., Marouf, A., Aloufi, M., & Marouf, M. (2023). A novel application of the geothermal asphalt pavement: A feasible e-fuel source. *Transportation Engineering*, *12*, 100183. https://doi.org/10.1016/j.treng.2023.100183
[21] Jameel, T., Yasin, Y., & Riaz, M. (2026). An integrated hybrid mcdm framework for renewable energy prioritization in sustainable development. *Spectrum of Decision Making and Applications*, *3*(1), 124–150. https://doi.org/10.31181/sdmap31202640
[22] Demir, G., Ecer, F., Yüksel, S., & Dinçer, H. (2026). A bibliometric mapping and trend analysis of mcdm in renewable energy research. *Energy Strategy Reviews*, *64*, 102079. https://doi.org/10.1016/j.esr.2026.102079

[23] Goswami, S. S., Tapankumar, T., Naik, N. C. K., Gowrishankar, J., Bhosle, N., Singh, A., Raju, G. S., Nagesh, D., & Santhosh, A. J. (2025). Multi-model mcdm framework for sustainable renewable energy selection in india: Integrating critic-edas-codas-cocoso. *Discover Sustainability*, *6*(1), 500. https://doi.org/10.1007/s43621-025-01069-0
[24] Sadeghi, A., Maleki, A., Ahmadi, M. H., & Kiani, A. H. (2025). Comparative evaluation of renewable energy investments: A multi-criteria decision-making approach. *Energy Conversion and Management: X*, *28*, 101190. https://doi.org/10.1016/j.ecmx.2025.101190
[25] Agliata, R., Busato, F., & Presciutti, A. (2025). Mcdm-based analysis of site suitability for renewable energy community projects in the gargano district. *Sustainability*, *17*(14), 6376. https://doi.org/10.3390/su17146376
[26] Ouria, M., Correia, A. F. M., Moura, P., Coimbra, P., & de Almeida, A. T. (2025). Mcdm optimization-based development of a plus-energy microgrid architecture for university buildings and smart parking. *Energies*, *18*(14), 3641. https://doi.org/10.3390/en18143641
[27] Mukherjee, A. K., Gazi, K. H., Mukherjee, S. B., Ciurdariu, L., Biswas, A., Ramalingam, S., Mondal, S. P., & PayalSingh. (2025). Identifying alternative energy sources: A multi-criteria intuitionistic fuzzy approach to sustainable alternatives. *Franklin Open*, *12*(100363), 1–29. https://doi.org/10.1016/j.fraope.2025.100363
[28] Gazi, K. H., Mukherjee, A. K., Mukherjee, S. B., Mondal, S. P., Salahshour, S., & Ghosh, A. (2026). Site selection for solar photovoltaic power plant using mcdm method with new de-i-fuzzification technique. *Analytics*, *5*(1), 1–10. https://doi.org/10.3390/analytics5010010
[29] Uluçay, V., Deli, I., & Şahin, M. (2018). Trapezoidal fuzzy multi-number and its application to multi-criteria decision-making problems. *Neural Computing and Applications*, *30*(5), 1469–1478. https://doi.org/10.1007/s00521-016-2760-3
[30] Dong, J., Wan, S., & Chen, S.-M. (2021). Fuzzy best-worst method based on triangular fuzzy numbers for multi-criteria decision-making. *Information Sciences*, *547*, 1080–1104. https://doi.org/10.1016/j.ins.2020.09.014
[31] Pramanik, S. (2022). Single-valued neutrosophic set: An overview. *Transdisciplinarity*, 563–608. https://doi.org/10.1007/978-3-030-94651-7_26
[32] Alkan, N., & Kahraman, C. (2023). Continuous intuitionistic fuzzy sets (cinfus) and their ahp&topsis extension: Research proposals evaluation for grant funding. *Applied Soft Computing*, *145*, 110579. https://doi.org/10.1016/j.asoc.2023.110579
[33] Gazi, K. H., Salahshour, S., Behera, P. K., Ghosh, A., & Mondal, S. P. (2026). Prioritization of iot challenges in multi-specialist hospital: Pythagorean fuzzy mcdm based approach. *Yugoslav Journal of Operations Research*, 1–50. https://doi.org/10.2298/YJOR251015008G
[34] Ashraf, S., Jana, C., Sohail, M., Choudhary, R., Ahmad, S., & Deveci, M. (2025). Multi-criteria decision-making model based on picture hesitant fuzzy soft set approach: An application of sustainable solar energy management. *Information Sciences*, *686*(121334). https://doi.org/10.1016/j.ins.2024.121334
[35] Seikh, M. R., & Chatterjee, P. (2025). Sustainable strategies for electric vehicle adoption: A confidence level-based interval-valued spherical fuzzy merec-vikor approach. *Information Sciences*, *699*, 121814. https://doi.org/10.1016/j.ins.2024.121814
[36] Ali, J. (2025). Copula extended power aggregation operators and merec method under linguistic q-rung orthopair fuzzy information: An application to plastic waste management solution selection. *Evolutionary Intelligence*, *18*(96). https://doi.org/10.1007/s12065-025-01080-4
[37] Gazi, K. H., Basuri, T., Biswas, A., Das, S. G., Salahshour, S., Ghosh, A., & Mondal, S. P. (2025). Performance evaluation of teachers by using fermatean fuzzy based mcdm approach. *Journal of Decisions and Operations Research*, *10*(2), 404–441. https://doi.org/10.22105/dmor.2025.514490.1931

[38] Görçün, Ö. F., Pamucar, D., & Biswas, S. (2023). The blockchain technology selection in the logistics industry using a novel mcdm framework based on fermatean fuzzy sets and dombi aggregation. *Information Sciences*, *635*, 345–374. https://doi.org/10.1016/j.ins.2023.03.113

[39] Chakraborty, J., Mukherjee, S., & Sahoo, L. (2024). An alternative approach for enhanced decision-making using fermatean fuzzy sets. *Spectrum of engineering and management sciences*, *2*(1), 135–150. https://doi.org/10.31181/sems21202411j

[40] Ejegwa, P. A., Anum, M. T., Kausar, N., Nwokoro, C. O., Aydin, N., & Yu, H. (2024). New fermatean fuzzy distance metric and its utilization in the assessment of security crises using the mcdm technique. *Mathematics*, *12*(20), 3214. https://doi.org/10.3390/math12203214

[41] Aydoğan, H., & Ozkir, V. (2024). A fermatean fuzzy mcdm method for selection and ranking problems: Case studies. *Expert Systems with Applications*, *237*, 121628. https://doi.org/10.1016/j.eswa.2023.121628

[42] Göçer, F. (2024). A novel extension of fermatean fuzzy sets into group decision making: A study for prioritization of renewable energy technologies. *Arabian Journal for Science and Engineering*, *49*(3), 4209–4228. https://doi.org/10.1007/s13369-023-08307-5

[43] Xie, L., Huo, Y., & Wang, X. (2026). An advanced fermatean fuzzy doc mcdm architecture for comprehensive quantitative assessment of physical fitness competency across academic institutions. *Scientific Reports*, *16*(14510). https://doi.org/10.1038/s41598-026-43046-1

[44] Darko, A., Chan, A. P. C., Ameyaw, E. E., Owusu, E. K., Pärn, E., & Edwards, D. J. (2019). Review of application of analytic hierarchy process (ahp) in construction. *International Journal of Construction Management*, *19*(5), 436–452. https://doi.org/10.1080/15623599.2018.1452098

[45] Stojčić, M., Zavadskas, E. K., Pamučar, D., Stević, Ž., & Mardani, A. (2019). Application of mcdm methods in sustainability engineering: A literature review 2008–2018. *Symmetry*, *11*(3), 350. https://doi.org/10.3390/sym11030350

[46] Keshavarz-Ghorabaee, M., Amiri, M., Zavadskas, E. K., Turskis, Z., & Antucheviciene, J. (2021). Determination of objective weights using a new method based on the removal effects of criteria (merec). *Symmetry*, *13*(4), 525. https://doi.org/10.3390/sym13040525

[47] Alinezhad, A., & Khalili, J. (2019a). Critic method. *New methods and applications in multiple attribute decision making (MADM)*, *277*, 199–203. https://doi.org/10.1007/978-3-030-15009-9_26

[48] Stanujkic, D., Karabasevic, D., & Zavadskas, E. K. (2015). A framework for the selection of a packaging design based on the swara method. *Engineering Economics*, *26*(2), 181–187. https://doi.org/10.5755/j01.ee.26.2.8820

[49] Behzadian, M., Otaghsara, S. K., Yazdani, M., & Ignatius, J. (2012). A state-of the-art survey of topsis applications. *Expert Systems with applications*, *39*(17), 13051–13069. https://doi.org/10.1016/j.eswa.2012.05.056

[50] Behzadian, M., Kazemzadeh, R. B., Albadvi, A., & Aghdasi, M. (2010). Promethee: A comprehensive literature review on methodologies and applications. *European journal of Operational research*, *200*(1), 198–215. https://doi.org/10.1016/j.ejor.2009.01.021

[51] Demir, G., Chatterjee, P., Kadry, S., Abdelhadi, A., & Pamučar, D. (2024). Measurement of alternatives and ranking according to compromise solution (marcos) method: A comprehensive bibliometric analysis. *Decision making: applications in management and engineering*, *7*(2), 313–336. https://doi.org/10.31181/dmame7220241137

[52] Mardani, A., Kazimieras, E. Z., Govindan, K., Senin, A. A., & Jusoh, A. (2016). Vikor technique: A systematic review of the state of the art literature on methodologies and applications. *Sustainability*, *8*(1), 37. https://doi.org/10.3390/su8010037

[53] Singha, R., Pathaka, V. K., Kumara, R., Dikshitb, M., Aherwarc, A., Singhd, V., & Singh, T. (2024). A historical review and analysis on moora and its fuzzy extensions for different applications. *Heliyon*, *10*(3), e25453. https://doi.org/10.1016/j.heliyon.2024.e25453
[54] Bhaduri, P., Gazi, K. H., Mondal, S. P., Biswas, A., Zhyber, T., & Ghosh, A. (2026). Selection of optimal sites for new airport in urban areas: An intuitionistic fuzzy based decision making study. *Applied Research Advances*, *2*(1), 1–34. https://doi.org/10.65069/ara2120262
[55] Azeem, M., Ali, J., & Ali, J. (2025). Complex fermatean fuzzy partitioned maclaurin symmetric mean operators and their application to hostel site selection. *OPSEARCH*, *62*, 608–642. https://doi.org/10.1007/s12597-024-00813-w
[56] Meng, Y., Chen, R., Huang, X., Liu, Y., Fu, C., Liu, Y., Li, Y., & Xu, Y. (2025). Enhancing educational equity and sustainability: A fuzzy-based framework for optimal school site selection. *International Journal of Digital Earth*, *18*(1), 2495735. https://doi.org/10.1080/17538947.2025.2495735
[57] Chakraborty, R., Ray, A., & Dan, P. K. (2013). Multi criteria decision making methods for location selection of distribution centers. *International Journal of Industrial Engineering Computations*, *4*(4), 491–504. https://doi.org/10.5267/j.ijiec.2013.06.006
[58] Alinezhad, A., & Khalili, J. (2019b). New methods and applications in multiple attribute decision making (madm). *New Methods and Applications in Multiple Attribute Decision Making (MADM)*, *277*, 1–233. https://doi.org/10.1007/978-3-030-15009-9
[59] Pamučar, D., Yazdani, M., Shaayesteh, M. T., Pavur, R., & Simic, V. (2025). Sustainable performance analysis of remanufacturing suppliers in supply chains: Circular economy perspective. *Supply Chain Forum: An International Journal*, 1–30. https://doi.org/10.1080/16258312.2025.2505402
[60] Werner-Lewandowska, K., Golinska-Dawson, P., & Mierzwiak, R. (2025). Enablers and barriers in building the circular supply chain through remanufacturing-grey dematel approach. *International Journal of Production Economics*, *284*, 109617. https://doi.org/10.1016/j.ijpe.2025.109617
[61] Basuri, T., Das, S. G., Ghosh, A., Biswas, A., Gazi, K. H., & Mondal, S. P. (2024). Challenges in the adaptation of biomass energy in india: A multi-criteria decision-making approach using dematel. *Acadlore Transactions on Applied Mathematics and Statistics*, *2*(4), 222–237. https://doi.org/10.56578/atams020403
[62] Gupta, S., & Gupta, N. (2026). Enhancing freight logistics: Overcoming barriers and driving sustainable growth with an integrated grey delphi dematel approach. *Benchmarking: An International Journal*, *33*(2), 368–391. https://doi.org/10.1108/BIJ-03-2024-0201
[63] Samal, T., Khanna, P., & Soni, U. (2025). Analysis of barriers in a make-to-order production system using grey-dematel approach. *IEEE Transactions on Engineering Management*, *72*, 2673–2679. https://doi.org/10.1109/TEM.2025.3579275
[64] Biswas, A., Gazi, K. H., Mondal, S. P., & Ghosh, A. (2026). Challenges for adapting high-speed rail network in developing countries: A picture fuzzy mcdm based approach. *Decision Making Advances*, 1–34. https://doi.org/10.31181/dma0002026123
[65] Talebzadeh, H., Fattahiamin, A., Talebzadeh, M., Sanaei, F., Moghaddam, P. K., & Espahbod, S. (2025). Optimizing supply chains: A grey-dematel approach to implementing larg framework. *Tehnički glasnik*, *19*(3), 382–389. https://doi.org/10.31803/tg-20240302201341
[66] Adhikari, D., Gazi, K. H., Basuri, T., Giri, B. C., Mandal, S., Ramalingam, S., & Mondal, S. P. (2026). Contribution of education in women empowerment: An innovative neutrosophic approach on mcdm method. *Journal of Uncertain Systems*, *19*(02), 2550026. https://doi.org/10.1142/S1752890925500266
[67] Senapati, T., & Yager, R. R. (2020). Fermatean fuzzy sets. *Journal of Ambient Intelligence and Humanised Computing*, *11*(2), 663–674. https://doi.org/10.1007/s12652-019-01377-0

[68] Peng, X., & Selvachandran, G. (2019). Pythagorean fuzzy set: State of the art and future directions. *Artificial Intelligence Review*, *52*(3), 1873–1927. https://doi.org/10.1007/s10462-017-9596-9
[69] Senapati, T., & Yager, R. R. (2019). Some new operations over fermatean fuzzy numbers and application of fermatean fuzzy wpm in multiple criteria decision making. *Informatica*, *30*(2), 391–412. https://doi.org/10.3233/INF-2019-1216
[70] Pambudi, N. A., & Ulfa, D. K. (2024). The geothermal energy landscape in indonesia: A comprehensive 2023 update on power generation, policies, risks, phase and the role of education. *Renewable and Sustainable Energy Reviews*, *189*, 114008. https://doi.org/10.1016/j.rser.2023.114008
[71] Mignogna, D., Szabó, M., Ceci, P., & Avino, P. (2024). Biomass energy and biofuels: Perspective, potentials, and challenges in the energy transition. *Sustainability*, *16*(16), 7036. https://doi.org/10.3390/su16167036
[72] Pastuszak, J., & Węgierek, P. (2022). Photovoltaic cell generations and current research directions for their development. *Materials*, *15*(16), 5542. https://doi.org/10.3390/ma15165542
[73] Duan, L., Walter, D., Chang, N., Bullock, J., Kang, D., Phang, S. P., Weber, K., White, T., Macdonald, D., Catchpole, K., & Shen, H. (2023). Stability challenges for the commercialization of perovskite-silicon tandem solar cells. *Nature Reviews Materials*, *8*(4), 261–281. https://doi.org/10.1038/s41578-022-00521-1
[74] Msigwa, G., Ighalo, J. O., & Yap, P.-S. (2022). Considerations on environmental, economic, and energy impacts of wind energy generation: Projections towards sustainability initiatives. *Science of The Total Environment*, *849*, 157755. https://doi.org/10.1016/j.scitotenv.2022.157755
[75] Kwok, K., & Hu, G. (2023). Wind energy system for buildings in an urban environment. *Journal of Wind Engineering and Industrial Aerodynamics*, *234*, 105349. https://doi.org/10.1016/j.jweia.2023.105349
[76] Shetty, C., & Priyam, A. (2022). A review on tidal energy technologies. *Materials Today: Proceedings*, *56*, 2774–2779. https://doi.org/10.1016/j.matpr.2021.10.020
[77] Ahmad, M. M., Kumar, A., & Ranjan, R. (2022). Recent developments of tidal energy as renewable energy: An overview. *River and Coastal Engineering: Hydraulics, Water Resources and Coastal Engineering*, 329–343. https://doi.org/10.1007/978-3-031-05057-2_29
[78] Schmitt, R. J. P., & Rosa, L. (2024). Dams for hydropower and irrigation: Trends, challenges, and alternatives. *Renewable and Sustainable Energy Reviews*, *199*, 114439. https://doi.org/10.1016/j.rser.2024.114439
[79] He, F., Zarfl, C., Tockner, K., Olden, J. D., Campos, Z., Muniz, F., Svenning, J.-C., & Jähnig, S. C. (2024). Hydropower impacts on riverine biodiversity. *Nature Reviews Earth & Environment*, *5*(11), 755–772. https://doi.org/10.1038/s43017-024-00596-0
[80] Sharmin, T., Khan, N. R., Akram, M. S., & Ehsan, M. M. (2023). A state-of-the-art review on geothermal energy extraction, utilization, and improvement strategies: Conventional, hybridized, and enhanced geothermal systems. *International Journal of Thermofluids*, *18*, 100323. https://doi.org/10.1016/j.ijft.2023.100323
[81] Rashidi, N. A., Chai, Y. H., & Yusup, S. (2022). Biomass energy in malaysia: Current scenario, policies, and implementation challenges. *Bioenergy research*, *15*(3), 1371–1386. https://doi.org/10.1007/s12155-022-10392-7