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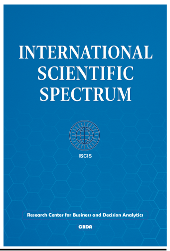

Evaluation of Different Solar Technologies Through Multiple Parameters: A MCDM-based Study in Uncertain Environment

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ABSTRACT

Renewable energy is one of the significant energy sources of recent times and a solution to various global problems, including environmental degradation, energy insecurity and the rising demand for sustainable development. Solar energy is one of the most important renewable sources and helps reduce dependence on fossil fuels. There are several Photovoltaic (PV) technologies and each has its pros and cons. In this study, we prioritized them based on multiple parameters statistically and mathematically. Two multi-criteria decision making (MCDM) methodologies are considered for the numerical evaluation in the triangular type-2 fuzzy numbers environment to consider the model uncertainty. Further, sensitivity analysis and comparative analysis are conducted to assess the system's stability, robustness and flexibility. This study provides guidance to select optimal solar technology for government and private companies, policy makers and individuals to develop sustainable and efficient energy sources.

1. Introduction

Nowadays, the rising demand for energy, along with the necessity of reducing the greenhouse effect and climate change, has led to a significant turn in the global energy scenario. We used to be dependent on fossil fuels as the primary source of energy, which became a major cause of climate imbalance. To address these challenges, it is necessary to shift towards the use of sustainable energy

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resources. This circumstance promotes renewable Energy Sources [1] (RES) as the most environmentally friendly and reliable solution. There are various types of Renewable Energy Sources (RES) such as solar energy[2], wind energy[3], hydro energy[4], etc. Among these renewable energy resources, Solar energy is highly used in new technologies and helps to form a clean environment with low carbon emissions. There are many advantages of using solar energy, such as scalability, abundance and environmental friendliness. These benefits of solar energy make it the best option to resolve the worldwide energy crisis. All countries are trying to achieve the target of installing the maximum number of solar roof panels [5]. However, the advancement of technology brings some advantages and disadvantages. Thus, identifying the best solar technology for a specific situation can be challenging.

1.1 *Evaluation of Solar Technology*

The field of solar energy incorporates various unique technologies. They are basically divided into two categories, namely Concentrated Solar Power (CSP) [6] and Photovoltaics (PV). Photovoltaics (PV) [7] is further distributed into different forms such as monocrystalline and polycrystalline silicon panels, thin-film technologies like CdTe and CGIS and some evolving technologies like perovskites and organic PV. Each of these technologies has its specific benefits. It is a very difficult task to select an appropriate solar technology, as every solar technology is rapidly advancing. In the process of selecting a solar technology, it is not enough to focus only on the initial investment or effectiveness in producing power. It is very important to focus on some other crucial facts, such as technical, economic, environmental and social aspects. These conflicting criteria make the process of decision-making more complex.

1.2 *MCDM model with Solar Technology*

Selecting an optimal solar technology requires the consideration of multiple conflicting criteria to identify the best alternative among all, which makes it basically a Multi-Criteria Decision Making (MCDM) problem. MCDM [8] is a systematic framework used to find the criteria weight and ranking of the alternatives. In this research, we have used the MEREC [9] method to calculate the weights of each criterion and then the COPRAS [10] method to rank all the alternatives.

Traditional MCDM methods only depend upon crisp and deterministic data. But in real-world modelling, traditional MCDM methodologies often fail because they cannot handle ambiguity and vagueness very well. In such a situation, the fuzzy set can be incorporated with the MCDM methods and the data can be represented in a better manner by using linguistic terms instead of exact numerical values. These fuzzy-based MCDM methods enable the control of complex decision-making problems.

1.3 *Motivation of this study*

We have already discussed the benefits of using MCDM [8] methods for assessing the different types of solar technologies and there exists a significant amount of research gaps. In some studies, a limited set of criteria, such as economic and technical factors, is considered and environmental and social impact are not taken into account. Most of the models either skip the importance of uncertainty or just include a basic fuzzy model, which are incapable of tackling complex decision-making problems. This study is there to fill this mentioned gap. Here, we will develop a hybrid fuzzy-MCDM model in an uncertain environment to identify the best alternative among different solar technologies. In this paper, we have taken a type-2 fuzzy number [11] to include uncertainty in data and two MCDM methods, namely MEREC [12] and COPRAS, are applied for calculating the weight of the criterion and for ranking the alternatives [13], respectively.

1.4 *Research outline of this research*

We design a research outline in this section on the basis of the above-mentioned details. Ranking different solar technologies based on various criteria in a proper way is the primary objective of this research. We have considered 5 alternatives and 8 criteria for the evaluation. Two MCDM methodologies, MEREC for calculating the weights of each criterion and COPRAS for ranking the alternatives and data sets, are used in the environment of triangular type-2 fuzzy numbers. Data inputs are gathered in linguistic terms in an unbiased way from different decision experts and numerically computed to obtain the result. Finally, a sensitivity and comparative analysis are done to verify the consistency of the obtained result.

1.5 *Structure of this paper*

The structure of this study is presented in this section. The introduction and motivation of this study are described in Section 1. Literature survey of this research on different aspects is performed in Section 2. Further, the basic concept of fuzzy sets and its extension, namely, triangular type-2 fuzzy numbers (TT2FN) are shown in Section 3. Additionally, a new de-fuzzification method on TT2FNs is presented in Section 3.5. Then, the proposed MCDM methodologies in a fuzzy environment are described in Section 4. The criteria selection and alternative identification for different solar technologies are covered in Section 5 and Section 6, respectively. Then the model formulation and data collection of this study are discussed in Section 7. Further, the numerical illustration and discussion on the proposed model are presented in Section 8. Then the comparative analysis and sensitivity analysis are covered in Section 9. Finally, the research implications, conclusions and future research scope are presented in Section 10 and Section 11, respectively.

2. Literature survey of this study

In this section, we will highlight the literature survey of this research paper. At first, the strategy for solar technologies will be discussed, followed by the studies of the background of Triangular Type-2 Fuzzy Numbers. Lastly, we will look into the literature survey of the MCDM methods, namely MEREC and COPRAS.

2.1 *Background on solar technologies*

Selecting an appropriate solar technology in the era of evolving renewable energy demands is a critical task. There are many factors that determine the ultimate selection. In this subsection, a short literature review on solar technologies is given. Mekhilef, S. et al. [14] in their paper discussed the application of different solar technologies in the agricultural sector. Wang, T. et al. [15] in their research article focused on the challenges and prospects of integrating solar technology with modern greenhouses in China. Bosetti. V. et al. [16] provided an expert elicitation survey on the future prospects of photovoltaic (PV) and Concentrated Solar Power (CSP) solar technologies in their paper. Fatemeh, H. F. et al. [17] in their work assessed the energy life cycle of applying solar technologies in greenhouse strawberry production. Some other research work on solar technologies is given in Table 1.

2.2 *Background of Mathematical tool*

Crisp numbers cannot capture the ambiguity inherent in real-world situations. To address uncertainty in conflicting critical data sets, we need to use fuzzy numbers [31]. There are several extensions

Table 1

Literature on Solar Technologies with MCDM-based study

Author	Year	Methodology	Application Area
[18] Zandi, I. et al.	2025	FFSWARA, RAM, CRADIS	Optimal sites for solar power plant installation
[19] Kaur, S. et al	2025	MARCOS	Sustainable component-level prioritization
[20] Sing, S. et a.	2024	AHP, COPRAS	Assessment of solar technologies
[21] Jbaihi, O. et al.	2024	GIS-MCDM	Optimal site screening
[22] Hosouli, S. et al.	2024	FAHP	Location selection for solar plant using MCDM model
[23] Wang, C.N. et al.	2023	AHP, MARCOS	Site selection of solar power plants
[24] Suman	2023	TOPSIS	Selection of photovoltaic cell technology
[25] Almasad, A. et al.	2023	AHP, PROMETHEE II	Implementation solar PV power plants
[26] Ramezanzade, M. et al.	2021	F-Entropy, F-MOORA	Ranking renewable energy projects
[27] Seker, S. et al.	2021	AHP, MULTIMOORA	A Socio-economic evaluation model for sustainable solar PV panels
[28] Hsueh, S. L. et al.	2021	Delphi–Fuzzy AHP	Application of AI-MCDM model on solar energy and rainwater collection
[29] Butkiene, I. S. et al.	2020	MCDM	Analysis the evaluation of renewable energy technologies in households
[30] Wang, T.C. et al.	2018	FAHP, DEA	Supplier selection of solar panel for the PV system

of fuzzy numbers, such as triangular fuzzy numbers [31], trapezoidal fuzzy numbers [32], interval valued fuzzy numbers [33], type-2 fuzzy numbers [34], neutrosophic fuzzy numbers [35], intuitionistic fuzzy numbers [36], etc. In this research paper, we used triangular Type-2 fuzzy numbers for evaluating the model. Roy, S. K. et al. [37] in their work applied Triangular Type-2 Intuitionistic Fuzzy number in water management problem. Janusz T. Starczewski [38] designs an efficient fuzzy logic system based on triangular type-2 fuzzy sets. Qin, J. et al. [39] used Triangular Interval Type-2 fuzzy numbers in Multiple Attribute Group Decision Making (MAGDM). Some other applications of triangular type-2 fuzzy numbers are given in Table 2.

Table 2

Literature on triangular type-2 fuzzy numbers (TT2FN) with MCDM based study

Author	Year	MCDM method used	Application Area
[32] Pereira, J. et al.	2025	ELECTRE TRI-C	Electrical power company problem
[40] Rani, S. et al.	2025	CODAS, COPRAS.	Extension of aggregation operator
[41] Rani, M.S. et al.	2025	TOPSIS, WASPAS.	Identifying risk factors of Zika virus
[42] N. Elyas.	2024	MULTIMAMOORA	Assessment of suppliers
[43] Aleksic, A. et al.	2023	MADM	Industrial and management applications
[44] Dutta, D. et al.	2021	f-MCDM	Multi-Criteria Multi-Attributes Decision Making
[45] Ozdemir, Y.S. et al.	2020	AHP, TOPSIS.	Strategy selection
[46] Singh, S. et al.	2018	MCDM	Agriculture-based industries set up in rural areas
[47] Senturk, S. et al.	2017	f-ANP	Modelling a third-party logistics company
[48] Zamri, N. et al.	2013	MADM	a novel Hybrid Fuzzy Weighted Average For MCDM

2.3 *Literature on MCDM methodologies*

Multi-Criteria Decision-Making (MCDM) is a very strong and useful optimization tool [49], which is used to solve several critical real-life problems. MCDM [8] is very efficient because there are multiple criteria and alternatives involved in a vital problem. There are various methodologies for calculating criteria weight, such as Analytic Hierarchy Process (AHP) [50], CRiteria Importance Through Intercriteria Correlation (CRITIC) [51], Entropy [36], Step-wise Weight Assessment Ratio Analysis (SWARA) [52], etc. and numerous methodologies for ranking the alternatives like Vlse Kriterijumska Optimizacija I

Kompromisno Rešenje (VIKOR) [53], Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA) [54], Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [55], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [56], etc. These MCDM techniques help the decision-makers to choose the optimal alternative while prioritizing the conflicting criteria in a dynamic and serious scenario. Some of the examples where MCDM techniques are used embrace site selection of a new airport [57], site selection of a new canteen in an educational institute [58], site selection for girls' hostel [59], etc., amongst others.

In this paper, we have used the MEthod based on the Removal Effects of Criteria (MEREC) for calculating criteria weights. The MEREC method was first introduced by Ghorabaee, M. K. et al. [60] in 2021. Saidin, M. S. et al. [61] used an advanced MEREC method in a fuzzy environment by modifying the normalization method. Some recent studies related to the application of the MEREC method are discussed in Table 3.

Table 3

Recent literature on the MEREC method with uncertainty

Author	Year	Uncertainty type	Application Area
[33] Seikh, M.R. et al.	2025	Interval-valued spherical fuzzy	Electric vehicle adoption
[62] Saranya, M. et al.	2025	Cubic Fermatean fuzzy	Healthcare waste management
[63] Debbarma, S. et al.	2025	q-rung orthopair fuzzy	Healthcare waste disposal
[64] Ali, J.	2025	Linguistic q-rung Orthopair Fuzzy Set	Selection of a solution for plastic waste management
[12] Liu, M. et al.	2024	Hesitant fuzzy sets	Improved distance measurement
[9] OLTEANU, A.L. et al.	2024	Fuzzy	European investment sectors
[65] Hasnan, Q.H. et al.	2024	Triangular fuzzy	Assessment of supliers
[66] Tripura, C. et al.	2024	Picture fuzzy	Video conferencing tool
[67] Fan, J. et al.	2024	Picture Fuzzy Sets (PFS)	Evaluating the performance of wearable health technology devices
[68] Zhang, H. et al.	2023	Spherical fuzzy	Stock Investment
[69] Narang, M. et al.	2023	Triangular Fuzzy Number (TFN)	An extension of MEREC method using Parabolic measure in fuzzy environment
[70] Mishra, A. R. et al.	2022	Single-Valued Neutrosophic Numbers (SVNNs)	Assessing Low Carbon Tourism Strategy
[71] Rani, P. et al.	2021	Fermatean Fuzzy Set (FFS)	Food waste treatment technology selection

In this paper, we have applied the Complex Proportional Assessment (COPRAS) method to rank the alternatives. Many research papers have applied the COPRAS method. Taherdoost, H. et al. [72] applied the COPRAS method for multi-criteria decision making. Amudha, M. et al. [73] in their paper used the COPRAS method in a fuzzy environment. Chinnasamy, S. et al. [74] used the COPRAS method to explore the present and future prospects of autonomous drones in various industries. In 2023, Madhusudhan Dasari Sreeramulu [75] included the COPRAS method in his paper to analyze wireless security and networks. Some recent applications of the COPRAS method are shown in Table 4.

3. Preliminaries of Mathematical Tools

Preliminaries of the mathematical tools are discussed in this section. In this research, we consider triangular type-2 fuzzy numbers (TT2FNs), an extension of fuzzy sets for modelling uncertainty. The fuzzy set was first introduced by Lotfi A. Zadeh [86] in 1965. The definition and properties of fuzzy sets and their extensions are described as follows:

Table 4
Recent studies on the COPRAS method with uncertainty

Author	Year	Uncertainty types	Application Area
[76] Otay, I. et al.	2025	Spherical Fuzzy Sets	Evaluating intelligent strategies for Smart cities
[77] Dhruva, S. et al.	2025	q-Rung Orthopair Fuzzy Set (qROFS)	Waste treatment methods selection for food sources
[78] Imamogolu, G. et al.	2024	Spherical fuzzy	Bloodmobile location selection
[79] Rahim, M. et al.	2024	p, q Quasirung Orthopair Fuzzy sets	Green Supplier Selection
[13] Yilmaz, I.	2023	DEA–fuzzy	Renewable energy
[80] Madhavi, S. et al.	2023	Fuzzy	Wireless sensor nodes
[81] Naz, S. et al.	2023	T-spherical fuzzy	Group decision-making
[82] Unvan, Y.A. et al.	2022	Fuzzy	Financial performance analysis
[83] Omerali, M. et al.	2022	Spherical fuzzy	Augmented reality application
[84] Bathrinath, S. et al.	2022	Fuzzy	Sustainability in ship ports
[10] Fan, J. et al.	2022	T-spherical fuzzy	Multi-criteria decision-making problem
[85] Nigam, M. K. et al.	2021	Fuzzy number	Assessment of risk in Enterprise resource planning (ERP) projects

3.1 *Fuzzy set and fuzzy number*

This section discusses fuzzy sets and fuzzy numbers in detail. In crisp theory, every element either belongs to the set or doesn't belong to the set, but there is no intermediate state. But in the fuzzy set theory [87], every element belongs, does not belong or partially belongs to the set based on the degree of membership value. The fuzzy set can be defined as follows:

Definition 1. ***Fuzzy set*** *[86]*

Consider $\mathfrak{X}$ to be a universal set. A set $(\tilde{\mathscr{F}})$ is define on $\mathfrak{X}$ is call fuzzy set, if it represent as follows

$$\tilde{\mathscr{F}} = \{(\eta, \mu_{\tilde{\mathscr{F}}}(\eta)) : \eta \in \mathfrak{X}\} \tag{1}$$

where $\mu_{\tilde{\mathscr{F}}}(\eta)$ be the membership function of fuzzy set $(\tilde{\mathscr{F}})$, define as $\mu_{\tilde{\mathscr{F}}}(\eta) : \mathfrak{X} \rightarrow [0,1]$.

Definition 2. ***$\alpha-$cut of fuzzy set*** *[88]*

Assume a fuzzy set $(\tilde{\mathscr{F}})$ define on a universal set $\mathfrak{X}$ and represent as $\tilde{\mathscr{F}} = \{(\tau, \mu_{\tilde{\mathscr{F}}}(\tau)) : \tau \in \mathfrak{X}\}$. Then the $\alpha-$cut of the fuzzy set $(\tilde{\mathscr{F}})$ is the collection of all elements (τ) of the set whose membership values $(\mu_{\tilde{\mathscr{F}}}(\tau))$ are greater than or equal to α, i.e.,

$$\tilde{\mathscr{F}}_{\alpha} = \{\tau : \mu_{\tilde{\mathscr{F}}}(\tau) \geq \alpha \,\&\, \tau \in \mathfrak{X}\} \tag{2}$$

Remark 1. ***Strong $\alpha-$cut of fuzzy set***

$\alpha-$cut of the fuzzy set $(\tilde{\mathscr{F}})$ is called a strong $\alpha-$cut of the fuzzy set $(\tilde{\mathscr{F}})$ if the membership value of all elements are greater than α, i.e.,

$$\tilde{\mathscr{F}}_{\tilde{\alpha}} = \{\tau : \mu_{\tilde{\mathscr{F}}}(\tau) > \alpha \,\&\, \tau \in \mathfrak{X}\} \tag{3}$$

Definition 3. ***Fuzzy number*** *[89]*

Let the set of real numbers $(\mathbb{R})$ be a universal set of discourse. A fuzzy set $(\tilde{\mathscr{E}})$ is called fuzzy number if it define on $\mathbb{R}$ and satisfied the following conditions

1. *Fuzzy set* $(\tilde{\mathscr{E}})$ *is normal, i.e.,* $\exists\, \zeta \in \mathbb{R}$ *such that* $\mu_{\tilde{\mathscr{E}}}(\zeta) = 1$,
2. *Support of fuzzy set* $(\tilde{\mathscr{E}})$ *is bounded, i.e., Support*$\left(\tilde{\mathscr{E}}\right) = \{\zeta : \mu_{\tilde{\mathscr{E}}}(\zeta) \geq 0, \zeta \in \mathbb{R}\} \subset \mathbb{R}$,
3. *Membership function* $(\mu_{\tilde{\mathscr{E}}}(\zeta))$ *is piecewise continuous,*
4. *Fuzzy set* $(\tilde{\mathscr{E}})$ *is a convex set, i.e., for every* $\xi_1, \xi_2 \in \mathbb{R}$, *we have* $\mu_{\tilde{\mathscr{E}}}(\lambda\xi_1 + (1-\lambda)\xi_2) \geq \min\{\mu_{\tilde{\mathscr{E}}}(\xi_1), \mu_{\tilde{\mathscr{E}}}(\xi_2)\}$ *for all* $\lambda \in [0,1]$.

3.2 Type-2 fuzzy set

This section discusses type-2 fuzzy sets, in which each element has two membership values. Type-2 fuzzy set was first introduced by Lotfi A. Zadeh [90] in 1975. The type-2 fuzzy set is an extension of the fuzzy set, where every element and its membership function is related to the 2nd membership function, which describes the belongingness of the element and its membership function in the set. The type-2 fuzzy set can be define as,

Definition 4. ***Type-2 fuzzy set*** *[34]*
Let $\tilde{\mathscr{G}} = \{(\eta, \mu_{\tilde{\mathscr{G}}}(\eta)) : \eta \in \mathfrak{X}\}$ *be a fuzzy set defined on a universal set* $\mathfrak{X}$. *Then the type-2 fuzzy set* $(\tilde{\tilde{\mathscr{H}}})$ *define by collection of element of fuzzy set* $\tilde{\mathscr{G}}$, *i.e.,*

$$\begin{aligned}\tilde{\tilde{\mathscr{H}}} &= \left\{(\xi, \mu_{\tilde{\tilde{\mathscr{H}}}}(\xi)) : \tilde{\tilde{\mathscr{H}}} \in \tilde{\mathscr{G}} \;\&\; \xi \in \mathfrak{X}\right\} \\ &= \{(\xi, \mu_{\tilde{\mathscr{G}}}(\xi), \mu_{\tilde{\tilde{\mathscr{H}}}}(\xi, \mu_{\tilde{\mathscr{G}}}(\xi))) : \xi \in \mathfrak{X}\}\end{aligned} \tag{4}$$

where $\mu_{\tilde{\mathscr{G}}}(\xi)$ *be the membership function of fuzzy set* $\tilde{\mathscr{G}}$ *and* $\mu_{\tilde{\tilde{\mathscr{H}}}}(\xi, \mu_{\tilde{\mathscr{G}}}(\xi))$ *be the membership function of type-2 fuzzy set* $(\tilde{\tilde{\mathscr{H}}})$ *with variables* ξ *and* $\mu_{\tilde{\mathscr{G}}}$, *define as* $\mu_{\tilde{\tilde{\mathscr{H}}}}(\xi, \mu_{\tilde{\mathscr{G}}}) : \mathfrak{X} \to [0,1]$.

Remark 2. *In a type-2 fuzzy set* $\tilde{\tilde{\mathscr{G}}}$ *[90], there are two membership functions for every arbitrary element in the set. The first one is the membership function* $(\mu_{\tilde{\mathscr{G}}}(\xi))$ *depend on the element* ξ *and the second one is the membership function* $(\mu_{\tilde{\tilde{\mathscr{H}}}}(\xi, \mu_{\tilde{\mathscr{G}}})(\xi))$ *depend on the element* ξ *and first membership function* $(\mu_{\tilde{\mathscr{G}}}(\xi))$, *respectively. Both membership functions are belongs to* $[0,1]$ *for any elements* $\xi \in \mathfrak{X}$.

Example 1. *Consider* $\tilde{\tilde{\mathscr{H}}}$ *to be a type-2 fuzzy set defined on the universal set* $\mathfrak{X}$. *Let two elements* ξ_1 *and* ξ_2 *in* $\mathfrak{X}$. *The type-2 fuzzy set is represented as*

$$\tilde{\tilde{\mathscr{H}}} = \{(\xi_1, \mu_{\tilde{\mathscr{G}}}(\xi_1), \mu_{\tilde{\tilde{\mathscr{H}}}}(\xi_1, \mu_{\tilde{\mathscr{G}}}(\xi_1))), (\xi_2, \mu_{\tilde{\mathscr{G}}}(\xi_2), \mu_{\tilde{\tilde{\mathscr{H}}}}(\xi_2, \mu_{\tilde{\mathscr{G}}}(\xi_2)))\}$$

where $\mu_{\tilde{\mathscr{G}}}(\xi_1)$ & $\mu_{\tilde{\mathscr{G}}}(\xi_2)$ *are first membership values and* $\mu_{\tilde{\tilde{\mathscr{H}}}}(\xi_1, \mu_{\tilde{\mathscr{G}}}(\xi_1))$ & $\mu_{\tilde{\tilde{\mathscr{H}}}}(\xi_2, \mu_{\tilde{\mathscr{G}}}(\xi_2))$ *are second membership values of the elements* ξ_1 & ξ_2 *of the fuzzy set* $\tilde{\tilde{\mathscr{H}}}$, *respectively. The geometric structure of the type-2 fuzzy set* $\tilde{\tilde{\mathscr{H}}}$ *is shown in Figure 1.*

Definition 5. ***Type-2 fuzzy number*** *[40]*
Consider $\tilde{\tilde{\mathscr{F}}}$ *to be a type-2 fuzzy set defined on the set of real numbers* $(\mathbb{R})$. *Then the* $\tilde{\tilde{\mathscr{F}}}$ *is called a type-2 fuzzy number if its membership functions satisfy the fuzzy numbers conditions (see Definition 3).*

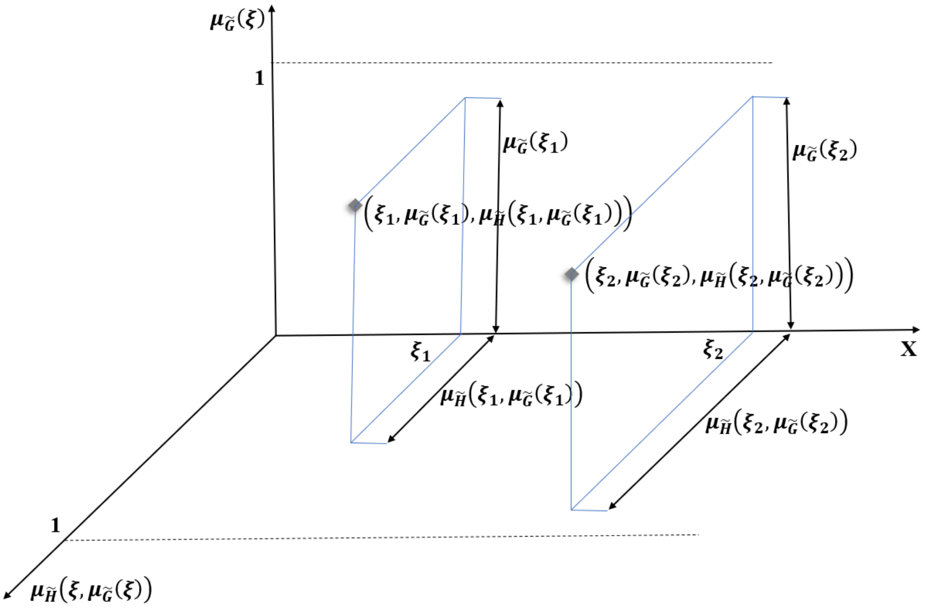


Fig. 1. Graphical representation of type-2 fuzzy set ($\tilde{\mathscr{H}}$)

3.3 *Triangular type-2 fuzzy number (TT2FN)*

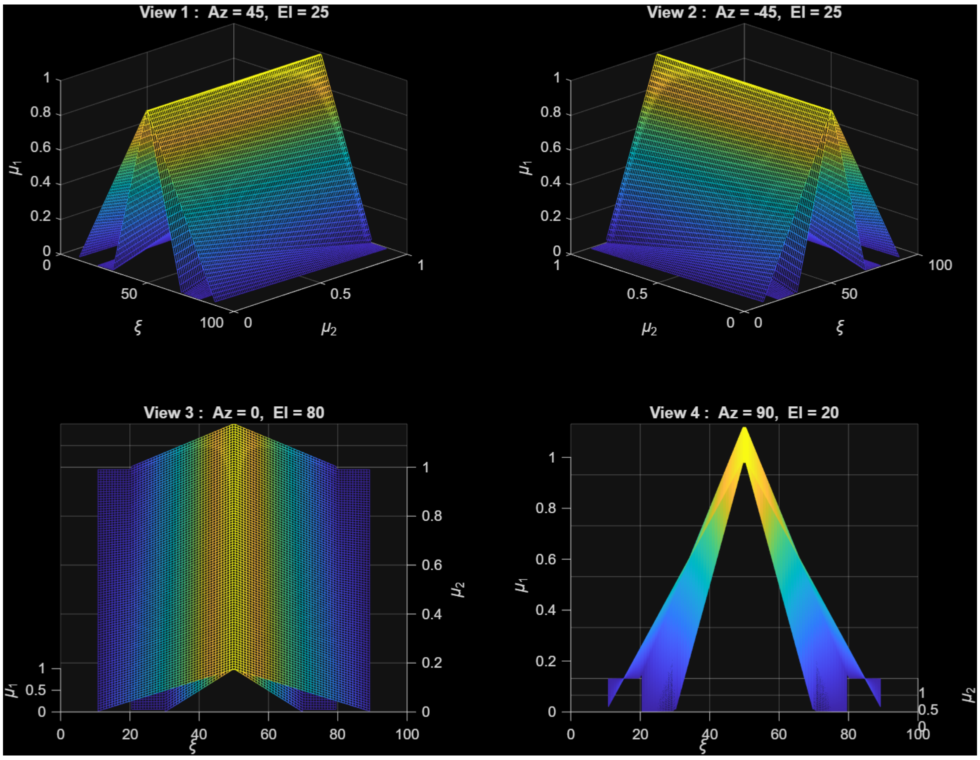
A triangular type-2 fuzzy number is a special type of type-2 fuzzy number, where every membership function is triangular in shape. Here we discussed on TT2FNs in details, as

Definition 6. ***Triangular type-2 fuzzy number (TT2FN)*** *[11]*

A triangular type-2 fuzzy number $\tilde{\mathscr{A}}$ define on the set of real numbers $(\mathbb{R})$ and denoted by $\tilde{\mathscr{A}} = \{(\xi, \mu_{\tilde{\mathscr{A}}}(\xi))\,;(\phi_1, \phi_2, \phi_3, \phi_4, \phi_5, \phi_6, \phi_7)\}$ where $\phi_1 \leq \phi_2 \leq \phi_3 \leq \phi_4 \leq \phi_5 \leq \phi_6 \leq \phi_7$ and $\phi_i \in \mathbb{R}$ with $i = 1, 2, \ldots, 7$. The membership function $(\mu_{\tilde{\mathscr{A}}}(\xi))$ has three components $\mu_{\tilde{\mathscr{A}}1}(\xi)$, $\mu_{\tilde{\mathscr{A}}2}(\xi)$ & $\mu_{\tilde{\mathscr{A}}3}(\xi)$ and define as

$$\begin{aligned}
\mu_{\tilde{\mathscr{A}}1}(\xi) &= \begin{cases} \frac{\xi-\phi_1}{\phi_4-\phi_1} & ;\phi_1 \leq \xi \leq \phi_4 \\ \frac{\phi_7-\xi}{\phi_7-\phi_4} & ;\phi_4 < \xi \leq \phi_7 \\ 0 & ;otherwise, \end{cases} \\
\mu_{\tilde{\mathscr{A}}2}(\xi) &= \begin{cases} \frac{\xi-\phi_2}{\phi_4-\phi_2} & ;\phi_2 \leq \xi \leq \phi_4 \\ \frac{\phi_6-\xi}{\phi_6-\phi_4} & ;\phi_4 < \xi \leq \phi_6 \\ 0 & ;otherwise, \end{cases} \\
\mu_{\tilde{\mathscr{A}}3}(\xi) &= \begin{cases} \frac{\xi-\phi_3}{\phi_4-\phi_3} & ;\phi_3 \leq \xi \leq \phi_4 \\ \frac{\phi_5-\xi}{\phi_5-\phi_4} & ;\phi_4 < \xi \leq \phi_5 \\ 0 & ;otherwise. \end{cases}
\end{aligned} \tag{5}$$

Remark 3. *The membership functions of the triangular type-2 fuzzy number (TT2FN) $(\tilde{\mathscr{A}})$ has three components $\mu_{\tilde{\mathscr{A}}1}(\xi)$, $\mu_{\tilde{\mathscr{A}}2}(\xi)$ and $\mu_{\tilde{\mathscr{A}}3}(\xi)$. All three membership functions are triangular in shape. The graphical structure of the Triangular type-2 fuzzy number (TT2FN) $(\tilde{\mathscr{A}})$ is shown in Figure 2.*



View 1 : Az = 45, El = 25

View 2 : Az = -45, El = 25

View 3 : Az = 0, El = 80

View 4 : Az = 90, El = 20

Fig. 2. Triangular type-2 fuzzy number (TT2FN) $(\tilde{\mathscr{A}})$ from different view

3.4 *Arithmetic operation of TT2FN*

Arithmetic operations on TT2FNs are defined in this section. Consider two triangular type-2 fuzzy numbers $\tilde{\mathscr{A}}$ and $\tilde{\mathscr{B}}$ are define on the set of real numbers $(\mathbb{R})$. The TT2FNs are define as $\tilde{\mathscr{A}} = \{(\xi, \mu_{\tilde{\mathscr{A}}}(\xi))\,;(\phi_1, \phi_2, \phi_3, \phi_4, \phi_5, \phi_6, \phi_7)\}$ and $\tilde{\mathscr{B}} = \{(\xi, \mu_{\tilde{\mathscr{B}}}(\xi))\,;(\psi_1, \psi_2, \psi_3, \psi_4, \psi_5, \psi_6, \psi_7)\}$ and λ be a scalar number. Then, the arithmetic operations on TT2FNs are evaluated as follows:

1. Addition of two TT2FNs:

$$\tilde{\mathscr{A}} \oplus \tilde{\mathscr{B}} = \big\{\big(\xi, \mu_{\tilde{\mathscr{A}}\oplus\tilde{\mathscr{B}}}(\xi)\big)\,;(\phi_1+\psi_1, \phi_2+\psi_2, \phi_3+\psi_3, \phi_4+\psi_4, \phi_5+\psi_5, \phi_6+\psi_6, \phi_7+\psi_7)\big\} \tag{6}$$

2. Scalar multiplication of TT2FN:

$$\lambda \times \tilde{\mathscr{A}} = \lambda\tilde{\mathscr{A}} = \begin{cases} \{(\xi, \mu_{\lambda\tilde{\mathscr{A}}}(\xi))\,;(\lambda\phi_1, \lambda\phi_2, \lambda\phi_3, \lambda\phi_4, \lambda\phi_5, \lambda\phi_6, \lambda\phi_7)\} & ;\lambda \geq 0 \\ \{(\xi, \mu_{\lambda\tilde{\mathscr{A}}}(\xi))\,;(\lambda\phi_7, \lambda\phi_6, \lambda\phi_5, \lambda\phi_4, \lambda\phi_3, \lambda\phi_2, \lambda\phi_1)\} & ;\lambda < 0 \end{cases} \tag{7}$$

   where λ is a scalar number.

3. Multiplication of two TT2FNs:

$$\tilde{\mathscr{A}} \otimes \tilde{\mathscr{B}} = \big\{\big(\xi, \mu_{\tilde{\mathscr{A}}\otimes\tilde{\mathscr{B}}}(\xi)\big)\,;(\phi_1\psi_1, \phi_2\psi_2, \phi_3\psi_3, \phi_4\psi_4, \phi_5\psi_5, \phi_6\psi_6, \phi_7\psi_7)\big\} \tag{8}$$

4. Scalar power of TT2FN:

$$\tilde{\mathscr{A}}^{\lambda} = \{(\xi, \mu_{\tilde{\mathscr{A}}^{\lambda}}(\xi))\,;(\phi_1^{\lambda}, \phi_2^{\lambda}, \phi_3^{\lambda}, \phi_4^{\lambda}, \phi_5^{\lambda}, \phi_6^{\lambda}, \phi_7^{\lambda})\} \tag{9}$$

   where λ is a non-negative scalar number.

3.5 De-fuzzification of TT2FN

De-fuzzification of triangular type-2 fuzzy numbers (TT2FNs) is defined in this section. Since there are no ordered pairs in the TT2FN system, TT2FN can be crisp at the points where the ordered pair relation holds. Several de-fuzzification methods exist in the TT2FN environment; however, in this study, we introduce a new de-fuzzification formula. The proposed de-fuzzification formula is

Definition 7. *Assume* $\tilde{\mathscr{A}} = \{(\xi, \mu_{\tilde{\mathscr{A}}}(\xi))\,; (\phi_1, \phi_2, \phi_3, \phi_4, \phi_5, \phi_6, \phi_7)\}$ *be a triangular type-2 fuzzy number (TT2FN) defined on the set of real numbers* $(\mathbb{R})$*. The de-fuzzified value of TT2FN* $\tilde{\mathscr{A}}$ *evaluated as*

$$\mathcal{D}\left(\tilde{\mathscr{A}}\right) = \frac{(\phi_1 + \phi_4 + \phi_7) + 2 \times (\phi_2 + \phi_4 + \phi_6) + (\phi_3 + \phi_4 + \phi_5)}{12} \tag{10}$$

Example 2. *Assume two triangular type-2 fuzzy numbers (TT2FNs)* $\tilde{\mathscr{A}}$ *and* $\tilde{\mathscr{B}}$ *define on the set of real numbers* $(\mathbb{R})$ *as* $\tilde{\mathscr{A}} = \{(\xi, \mu_{\tilde{\mathscr{A}}}(\xi))\,; (7, 8, 9, 11, 13, 14, 15)\}$ *and* $\tilde{\mathscr{B}} = \{(\xi, \mu_{\tilde{\mathscr{B}}}(\xi))\,; (4, 5, 6, 8, 10, 11, 12)\}$*, respectively. Then the de-fuzzification value of TT2FNs,* $\tilde{\mathscr{A}}$ *and* $\tilde{\mathscr{B}}$ *are*

$$\begin{aligned}
\mathcal{D}\left(\tilde{\mathscr{A}}\right) =& \frac{(7 + 11 + 15) + 2 \times (8 + 11 + 14) + (9 + 11 + 13)}{12} \\
=& \frac{132}{12} = 11 \\
\mathcal{D}\left(\tilde{\mathscr{B}}\right) =& \frac{(4 + 8 + 12) + 2 \times (5 + 8 + 11) + (6 + 8 + 10)}{12} \\
=& \frac{96}{12} = 8
\end{aligned}$$

4. Proposed methodology

Multi-Criteria Decision Making (MCDM) is a technique used to identify the optimal solution in a complex decision-making problem. There are various types of MCDM methods, some of which can be applied for finding the criteria weight and some of them can be used to rank the alternatives. In this paper, we will use the MEthod based on the Removal Effects of Criteria (MEREC) method for evaluating the criteria weight and the Complex Proportional Assessment (COPRAS) method for determining the rank of alternatives. These two methods are elaborately discussed in the following subsections.

4.1 MEthod based on the Removal Effects of Criteria (MEREC) Method

MEthod based on the Removal Effects of Criteria (MEREC) method is a newly developed, powerful technique used to find the criteria weight. Ghorabaee, M. K. et al. [60] introduced the MEREC method in their paper in 2021. This process is able to evaluate the criteria weight [61] without using the decision maker's opinion and the importance of each criterion is dependent on how the performance of alternatives is affected by removing that criterion.

In this study, we consider Φ number of criteria associated with Ψ number of alternatives to construct a decision matrix. There are Δ number of decision makers who give data in linguistic terms and further transfer into Triangular Type-2 Fuzzy Number (TT2FN) with the help of Table 5. Data are collected in unbiased and transparent ways. The decision matrices are formed in $\Psi \times \Phi$ order and the MEREC method is formulated to calculate the weight of the criteria as follows:

Step 1. Construct decision matrices $(\tilde{\mathfrak{D}}_\delta)$**:**
Identifies the criteria and alternatives in detail, conducts literature reviews and consults with

decision experts. There are Φ number of criteria, Ψ number of alternatives and Δ number of decision makers associated with this study. Therefore, Δ number of decision matrices built with $\Psi \times \Phi$ order in linguistic terms and transferred into TT2FNs using the conversion table.

The δth decision makers give the fuzzy decision matrices $(\tilde{\mathfrak{D}}_\delta)$, as follows

$$\tilde{\mathfrak{D}}_\delta = \begin{bmatrix} (\tilde{\mathfrak{A}}_{11})_\delta & (\tilde{\mathfrak{A}}_{12})_\delta & \ldots & (\tilde{\mathfrak{A}}_{1\phi})_\delta & \ldots & (\tilde{\mathfrak{A}}_{1\Phi})_\delta \\ (\tilde{\mathfrak{A}}_{21})_\delta & (\tilde{\mathfrak{A}}_{22})_\delta & \ldots & (\tilde{\mathfrak{A}}_{2\phi})_\delta & \ldots & (\tilde{\mathfrak{A}}_{2\Phi})_\delta \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ (\tilde{\mathfrak{A}}_{\psi 1})_\delta & (\tilde{\mathfrak{A}}_{\psi 2})_\delta & \ldots & (\tilde{\mathfrak{A}}_{\psi\phi})_\delta & \ldots & (\tilde{\mathfrak{A}}_{\psi\Phi})_\delta \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ (\tilde{\mathfrak{A}}_{\Psi 1})_\delta & (\tilde{\mathfrak{A}}_{\Psi 2})_\delta & \ldots & (\tilde{\mathfrak{A}}_{\Psi\phi})_\delta & \ldots & (\tilde{\mathfrak{A}}_{\Psi\Phi})_\delta \end{bmatrix}_{\Psi\times\Phi} \tag{11}$$

where $(\tilde{\mathfrak{A}}_{\psi\phi})_\delta$ be the rating in TT2FNs of ψth alternative based on ϕth criteria with $\phi = 1, 2, \ldots, \Phi$, $\psi = 1, 2, \ldots, \Psi$ and $\delta = 1, 2, \ldots, \Delta$, respectively.

The $\psi\phi$th entry of the decision matrices $(\tilde{\mathfrak{D}}_\delta)$ is $(\tilde{\mathfrak{A}}_{\psi\phi})_\delta$ be a TT2FN and formed as

$$\begin{aligned} (\tilde{\mathfrak{A}}_{\psi\phi})_\delta &= \Big(\{(\xi, \mu_{\tilde{\mathfrak{A}}}(\xi))\,; (\eta_1, \eta_2, \eta_3, \eta_4, \eta_5, \eta_6, \eta_7)\}_{\psi\phi}\Big)_\delta \\ &= \{(\xi_{\psi\phi}, \mu_{\tilde{\mathfrak{A}}}(\xi_{\psi\phi}))\,; (\eta_1, \eta_2, \eta_3, \eta_4, \eta_5, \eta_6, \eta_7)_{\psi\phi}\}_\delta \end{aligned} \tag{12}$$

where $\phi = 1, 2, \ldots, \Phi$, $\psi = 1, 2, \ldots, \Psi$ and $\delta = 1, 2, \ldots, \Delta$.

Step 2. Evaluate aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}})$:

Determine the aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}})$ from all Δ number of decision matrices given by Δ DMs by aggregating $\psi\phi$th entry of the decision matrices $(\tilde{\mathfrak{D}}_\delta)$. Aggregate the $\psi\phi$th entry of the decision matrices $(\tilde{\mathfrak{D}}_\delta)$ by aggregating η_ith coefficients, as follows:

$$\eta_i = \left(\prod_{\delta=1}^{\Delta} (\eta_i)_\delta\right)^{\frac{1}{\Delta}} \tag{13}$$

where $i = 1, 2, \ldots, 7$. Further, the aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}})$ formed as

$$\begin{aligned} \tilde{\mathfrak{D}} &= \left[\tilde{\mathfrak{A}}_{\psi\phi}\right]_{\Psi\times\Phi} \\ &= [\{(\xi_{\psi\phi}, \mu_{\tilde{\mathfrak{A}}}(\xi_{\psi\phi}))\,; (\eta_1, \eta_2, \eta_3, \eta_4, \eta_5, \eta_6, \eta_7)_{\psi\phi}\}]_{\Psi\times\Phi} \end{aligned} \tag{14}$$

where $\phi = 1, 2, \ldots, \Phi$ and $\psi = 1, 2, \ldots, \Psi$.

Step 3. Uniform aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}}^u)$:

Calculate the uniform aggregated fuzzy decision matrix $\left(\tilde{\mathfrak{D}}^u = \left[\tilde{\mathfrak{A}}^u_{\psi\phi}\right]_{\Psi\times\Phi}\right)$ by normalized every entry $\left(\tilde{\mathfrak{A}}_{\psi\phi}\right)$ of the aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}})$. Normalized the aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}})$ evaluated by normalized every coefficients (η_i), as follows:

$$\begin{aligned} \eta_i^u &= \frac{\eta_i}{\max\limits_{\psi=1,2,\ldots,\Psi}\left\{\max\limits_{i=1,2,\ldots,7}\{\eta_i\}\right\}} \\ \text{i.e., } (\eta_i^u)_{\psi\phi} &= \frac{(\eta_i)_{\psi\phi}}{\max\limits_{\psi=1,2,\ldots,\Psi}\left\{\max\limits_{i=1,2,\ldots,7}\{(\eta_i)_{\psi\phi}\}\right\}} \end{aligned} \tag{15}$$

where $i = 1, 2, \ldots, 7$, $\phi = 1, 2, \ldots, \Phi$ and $\psi = 1, 2, \ldots, \Psi$.

Step 4. Determine the de-fuzzified decision matrix $(\mathfrak{D})$:

The de-fuzzified decision matrix $(\mathfrak{D})$ is evaluated from the uniform aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}}^u)$ by de-fuzzifying every entry of it. De-fuzzify the TT2FN $(\tilde{\mathfrak{A}}_{\psi\phi})$ using Equation (10) and bulid the de-fuzzified decision matrix $(\mathfrak{D})$, as shows

$$\mathfrak{D} = [\mathfrak{A}_{\psi\phi}]_{\Psi\times\Phi} \tag{16}$$

where $\phi = 1, 2, \ldots, \Phi$ and $\psi = 1, 2, \ldots, \Psi$.

Step 5. Calculate the overall performance of alternative $(\mathfrak{P}_\psi)$:

Determine the overall performance of each alternative $(\mathfrak{P}_\psi)$ by Equation (17), as follows:

$$\mathfrak{P}_\psi = \frac{\sum\limits_{\phi=1}^{\Phi} \ln\left(1 - \mathfrak{A}_{\psi\phi}\right)}{\Phi} \tag{17}$$

where $\phi = 1, 2, \ldots, \Phi$ and $\psi = 1, 2, \ldots, \Psi$.

Step 6. Evaluate the alternatives' performance $(\mathfrak{Q}_{\psi\phi})$ by eliminating every criteria:

After that, the alternatives' performance value $(\mathfrak{Q}_{\psi\phi})$ calculate by eliminating every criteria (ϕ) using Equation (18). The alternatives' performance value $(\mathfrak{Q}_{\psi\phi})$ evaluate as

$$\mathfrak{Q}_{\psi\phi} = \frac{\sum\limits_{\phi=1,\ \phi\neq\psi}^{\Phi} \ln\left(1 - \mathfrak{A}_{\psi\phi}\right)}{\Phi} \tag{18}$$

where $\phi = 1, 2, \ldots, \Phi$ and $\psi = 1, 2, \ldots, \Psi$.

Step 7. Determine the aggregated absolute deviations value $(\mathfrak{R}_\phi)$:

Evaluate the aggregated absolute deviation $(\mathfrak{R}_\phi)$ of each criteria (ϕ) from the alternatives' performance value $(\mathfrak{Q}_{\psi\phi})$ and overall performance value $(\mathfrak{P}_\psi)$, as follows:

$$\mathfrak{R}_\phi = \sum_{\psi=1}^{\Psi} \left|\mathfrak{Q}_{\psi\phi} - \mathfrak{P}_\psi\right| \tag{19}$$

where $\phi = 1, 2, \ldots, \Phi$ and $\psi = 1, 2, \ldots, \Psi$.

Step 8. Calculate the weight of the criteria $(\mathfrak{W}_\phi)$:

Finally, the weight of the criteria $(\mathfrak{W}_\phi)$ is determined from the aggregated absolute deviation value $(\mathfrak{R}_\phi)$ using Equation (20), as

$$\mathfrak{W}_\phi = \frac{\mathfrak{Q}_\phi}{\sum_{\phi=1}^{\Phi} \mathfrak{Q}_\phi} \tag{20}$$

where $\phi = 1, 2, \ldots, \Phi$.

The weight of the criteria $(\mathfrak{W}_\phi)$ evaluated using Equation (20) by the fuzzy MEREC method is the optimal weight. These criteria weights are further utilized in other numerical processes. The algorithm of the MEthod based on the Removal Effects of Criteria (MEREC) method is described in Algorithm 1.

Algorithm 1 MEREC method algorithm in triangular type-2 fuzzy number (TT2FN) environment

```
Require: decision matrices $(\tilde{\mathfrak{D}}_\delta)$
Ensure: $\Phi$ number of criteria, $\Psi$ number of alternatives and $\Delta$ number of decision makers
  aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}})$
  uniform fuzzy decision matrix $(\tilde{\mathfrak{D}}^u)$
  de-fuzzified decision matrix $(\mathfrak{D})$
  performance of the alternative value $(\mathfrak{P}_\psi)$
  alternatives' performance $(\mathfrak{Q}_{\psi\phi})$
  aggregated of the absolute deviations $(\mathfrak{R}_\phi)$
  weight of the criteria $(\mathfrak{W}_\phi)$
  while $\delta \leq \Delta$ do
      determine $\tilde{\mathfrak{D}}$
      for $\phi \leq \Phi$ and $\psi \leq \Psi$ do
          evaluate $\tilde{\mathfrak{D}}^u$
          calculate $\mathfrak{D}$
          determine $\mathfrak{P}_\psi$
          evaluate $\mathfrak{Q}_{\psi\phi}$
          for $\phi \leq \Phi$ do
              evaluate $\mathfrak{R}_\phi$
              determine $\mathfrak{W}_\phi$
          end for
      end for
  end while
```

4.2 *Complex Proportional Assessment (COPRAS) Method*

In this subsection, we discuss the Complex Proportional Assessment (COPRAS) method in detail. The COPRAS method was introduced by E. K. Zavadskas and A. Kaklauskas [91] in 1996. This method [82] is well-known for ranking alternatives in complex decision-making problems involving both beneficial and non-beneficial criteria.

Here we consider Φ number of criteria and Ψ number of alternatives for this study. There are Δ number of decision makers who give data in linguistic terms and are further converted into Triangular Type-2 Fuzzy Number (TT2FN) with the help of a conversion table. All the decision makers (DMs) are unbiased, knowledgeable and professional in their respective fields. The decision matrices are built with $\Psi \times \Phi$ order and the COPRAS method is processed with the following steps:

Step A. Structured the decision matrices $(\tilde{\mathfrak{D}}_\delta)$:
The criteria and alternatives are selected based on detailed literature and consulting with the decision experts. The decision matrices $(\tilde{\mathfrak{D}}_\delta)$ are constructed in linguistic terms and further transferred into TT2FN by Table 5, which is shown in Equation (11) in Step 1 on the MEREC method.

Step B. Determine the aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}})$:
The aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}})$ evaluate from Δ number of decision matrices $(\tilde{\mathfrak{D}}_\delta)$ by using Equation (13) on the MEREC method.

Step C. Calculate the weighted fuzzy decision matrix $(\tilde{\mathfrak{D}}^w)$:
The weighted fuzzy decision matrix $(\tilde{\mathfrak{D}}^w)$ determine from the aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}})$ and criteria weight $(\mathfrak{W}_\phi)$ (in Equation (20)) by using scalar multiplication of TT2FNs define

in Equation (7). The weighted fuzzy decision matrix $(\tilde{\mathfrak{D}}^w)$ structured as

$$\tilde{\mathfrak{D}}^w = \left[\tilde{\mathfrak{B}}^w_{\psi\phi}\right]_{\Psi\times\Phi} = \left[\mathfrak{W}_\phi \times \tilde{\mathfrak{A}}_{\psi\phi}\right]_{\Psi\times\Phi} \tag{21}$$

where $\phi = 1, 2, \ldots, \Phi$ and $\psi = 1, 2, \ldots, \Psi$.

Step D. Evaluate the uniform weighted decision matrix $(\tilde{\mathfrak{E}}^u)$:
After that, the uniform weighted decision matrix $\left(\tilde{\mathfrak{E}}^u = \left[\tilde{\mathfrak{B}}^u_{\psi\phi}\right]_{\Psi\times\Phi}\right)$ evaluated from weighted fuzzy decision matrix $(\tilde{\mathfrak{D}}^w)$ by using Equation (15).

Step E. Calculate the maximum index $(\tilde{\mathfrak{M}}^+_\psi)$ and minimum index $(\tilde{\mathfrak{M}}^-_\psi)$ for each alternative:
Determine the maximum index $(\tilde{\mathfrak{M}}^+_\psi)$ and minimum index $(\tilde{\mathfrak{M}}^-_\psi)$ for each alternative by Equation (22), as follows:

$$\begin{cases} \tilde{\mathfrak{M}}^+_\psi = & \sum_{\phi=1}^{\Phi'} \tilde{\mathfrak{B}}^u_{\psi\phi} \\ \tilde{\mathfrak{M}}^-_\psi = & \sum_{\phi=\Phi'+1}^{\Phi} \tilde{\mathfrak{B}}^u_{\psi\phi} \end{cases} \tag{22}$$

where $\phi = 1, 2, \ldots, \Phi'$ are beneficial criteria and $\phi = \Phi' + 1, \Phi' + 2, \ldots, \Phi$ are non-beneficial criteria, respectively.

Step F. De-fuzzified the maximum index $(\tilde{\mathfrak{M}}^+_\psi)$ and minimum index $(\tilde{\mathfrak{M}}^-_\psi)$ values:
The maximum index $(\tilde{\mathfrak{M}}^+_\psi)$ and minimum index $(\tilde{\mathfrak{M}}^-_\psi)$ values are de-fuzzified by the de-fuzzification formula (shown in Equation (10)) and evaluated de-fuzzified maximum index $(\mathfrak{M}^+_\psi)$ and de-fuzzified minimum index $(\mathfrak{M}^-_\psi)$ values for all $\psi = 1, 2, \ldots, \Psi$.

Step G. Determine the relative weights $(\mathfrak{R}_\psi)$ of each alternative:
Calculate the relative weights values $(\mathfrak{R}_\psi)$ of each alternative (ψ) using Equation (23), as follows:

$$\mathfrak{R}_\psi = \mathfrak{M}^+_\psi + \frac{\left[\min\limits_{1\leq\psi\leq\Psi} \mathfrak{M}^-_\psi\right] \times \left[\sum_{\psi=1}^{\Psi} \mathfrak{M}^-_\psi\right]}{\mathfrak{M}^-_\psi \times \left[\sum\limits_{\psi=1}^{\Psi} \left(\frac{\min\limits_{1\leq\psi\leq\Psi} \mathfrak{M}^-_\psi}{\mathfrak{M}^-_\psi}\right)\right]} \tag{23}$$

where $\psi = 1, 2, \ldots, \Psi$.

Step H. Evaluate the performance index $(\mathfrak{P}_\psi)$:
Lastly, determine the performance index value $(\mathfrak{P}_\psi)$ of the each alternatives (ψ), as

$$\mathfrak{P}_\psi = \mathfrak{R}_\psi \times 100\% \tag{24}$$

where $\psi = 1, 2, \ldots, \Psi$.

Step I. Rank alternative:
Finally, rank the alternatives based on the performance index value $(\mathfrak{P}_\psi)$ evaluated in Equation (24) in descending order. The more performance index value $(\mathfrak{P}_\psi)$ describes that the alternative is prioritized and the less performance index value $(\mathfrak{P}_\psi)$ describes that the alternative is deprioritized, respectively. The algorithm of the Complex Proportional Assessment (COPRAS) method is described in Algorithm 2.

Algorithm 2 COPRAS method algorithm in triangular type-2 fuzzy number (TT2FN) environment

```
Require: decision matrices ($\tilde{\mathfrak{D}}_\delta$)
Ensure: $\Phi$ number of criteria, $\Psi$ number of alternatives and $\Delta$ number of decision makers
  aggregated fuzzy decision matrix ($\tilde{\mathfrak{D}}$)
  weighted aggregated decision matrix ($\tilde{\mathfrak{D}}^w$)
  unified weighted decision matrix ($\tilde{\mathfrak{E}}^u$)
  maximum index ($\tilde{\mathfrak{M}}^+_\psi$) & minimum index ($\tilde{\mathfrak{M}}^-_\psi$)
  de-fuzzify $\tilde{\mathfrak{M}}^+_\psi$ & $\tilde{\mathfrak{M}}^-_\psi$
  relative weights ($\mathfrak{R}_\psi$)
  performance index ($\mathfrak{P}_\psi$)
  while $\delta \leq \Delta$ do
      determine $\tilde{\mathfrak{D}}$
      for $\phi \leq \Phi$ and $\psi \leq \Psi$ do
          evaluate $\tilde{\mathfrak{D}}^w$
          calculate $\tilde{\mathfrak{E}}^u$
          determine $\tilde{\mathfrak{M}}^+_\psi$) & ($\tilde{\mathfrak{M}}^-_\psi$
          evaluate $\mathfrak{M}^+_\psi$ & $\mathfrak{M}^-_\psi$
          for $\psi \leq \Psi$ do
              evaluate $\mathfrak{R}_\psi$
              determine $\mathfrak{P}_\psi$
          end for
      end for
  end while
```

5. Criteria Selection

The demand for renewable energy sources is increasing day by day. Solar energy plays a vital role in fulfilling this requirement. There are many renewable solar technologies available but each has a set of advantages and disadvantages. Selecting an appropriate solar technology is a very challenging task as it involves multiple correlated factors. To evaluate the best solar technology, we have considered the conflicting criteria such as efficiency [92] of the solar technology, Greenhouse Gas (GHG) emissions [93] from the solar technology, the resources used [94] to construct a particular solar technology, Energy Payback Time (EPBT) [95] and Energy Return on Investment of each solar technology, the produced toxicity [96] from each of the solar technology, amount of required land [97] to sustain the solar technologies, government or private funding [98] to construct and sustain the solar technology and life expansion and maintenance of the solar devices, etc.

5.1 *Efficiency* (P_1)

Efficiency is an important criterion in the evaluation process of various solar technologies. Efficiency [92] of a technology directly contributes to the ability of the system, as this technology contributes to the conversion of incident solar radiation to usable electrical energy. Higher efficiency [99] of a solar technology increases the total energy production, and it reduces the requirement of land and infrastructure that is needed to establish a new power plant for obtaining the same amount of energy. Efficiency is also vital as, depending on it, the performance of a technology in different climates, sunlight and temperature is measured.

5.2 GHG Emission (P_2)

GHG emission [93] is also a crucial criterion in the selection process of solar technology. During the evaluation of a solar technology, it is important to check how much this technology is environmentally friendly and how much carbon will be produced over its life cycle. Despite the solar energy production systems producing no emissions during energy production, a negligible emission [100] is produced during transportation, installation, manufacturing and end-of-life process. The amount of greenhouse gases emitted varies for different solar technologies. If the GHG emissions increase, it will have an impact on the Earth's average temperature and unpredictable climate changes. Thus, through the inclusion of GHG emissions in the MCDM framework, the process of selecting the best solar technology becomes more reliable and helps to achieve the global decarbonization goals.

5.3 Resource Use (P_3)

The need for land area, raw materials, energy and water is different for different solar technologies during their life cycles. So, the resource [101] use can be taken as an important criterion for the selection of solar technologies. The sustainability and environmental impact of a technology can be measured through the number of resources needed for it and the availability of those resources. In some technologies, rare earth elements, silicon and special metals are used that may face supply shortages or environmental adversities. The availability of these resources, [94], the cost of extraction and geopolitical aspects can affect the production of the system in an uncertain environment.

5.4 EPBT/EROI (P_4)

Energy Payback Time (EPBT) and Energy Return on Investment (EROI) [102] are vital criteria in the selection process of solar technology. The ratio between the total energy a system generates and the amount of energy consumed over the system's lifetime is evaluated through EROI. The time required for a system to produce the same quantity of energy that was invested in its installation, manufacturing and maintenance is measured by EPBT. Thus, from EPBT and EROI, we can obtain a clear view about how a solar technology is suitable for long-term and overall sustainability [95] of that technology. The availability of resources, energy prices, and manufacturing processes may vary in uncertain conditions. These indicators help to assess the way a technology quickly becomes beneficial energetically and how the performance of the technology remains unaltered under varying circumstances.

5.5 Toxicity (P_5)

Toxicity [103] is a crucial criterion for selecting the best solar technology as an alternative. The materials used in various solar technologies can have different impacts on the human body and the environment. Some systems use chemical solvents, heavy metals or a few unusual elements that can be harmful if they are not properly managed at the time of production, use, or disposal. Inadequate waste-handling [96] infrastructure, issues related to supply chain, weak safety rules , or the risk of toxic exposure make this criterion even more important.

5.6 Land Use (P_6)

For the installation of a solar technology, land is required and the amount of land [104] is not the same for all solar technologies, so Land use is a vital criterion. The acceptance of a project among people and society is also affected by this criterion. Ground-mounted structures or large-scale PV farms may compete with biodiversity, housing, agriculture, and future development. The rooftop systems decrease land use [97] conflict; however, they may face infrastructural limitations. In an uncertain environment, land values fluctuate rapidly, land-use policies change over time, and in urban areas, growth patterns are unpredictable. In order to understand the spatial demands of each technology, it becomes even more crucial.

5.7 *Funding* (P_7)

Funding is an important criterion in the process of selecting the best solar technology. Financial feasibility [105] plays a major role in both long-term stability and deployment of solar technologies. Some of the systems require varying levels of operational expenditure, capital investment, and access to incentives or subsidies, and all of that influences the viability of the overall project. In unfavourable conditions, such as fluctuations in market prices, risk in financial aspects [98] and policy incentives, they change rapidly. The stability and availability of funds become significant in determining the adoption of technologies.

5.8 *Life Expansion and Maintenance* (P_8)

Life expectancy and maintenance [106] are chosen as criteria of evaluation because of the determination of the long-term reliability, stability in operations, and costs in the overall life-cycle of solar technologies. Systems that possess a longer lifespan and fewer maintenance requirements deliver better economic returns and reduce environmental impact. However, conditions including gradual damage, inverter replacement, weather conditions, and cleaning requirements have the ability to influence the frequency of maintenance and system longevity. In unfavourable situations, i.e., in situations with varying material quality, climatic conditions and feasibility of supply-chain changes, the reliability of maintenance and durability [107] is mostly considered.

6. Different Solar Technologies as Alternatives

In this research paper, we desire to form a model to select the optimum solar technology with maximum energy efficiency and minimal environmental damage. For this purpose, we have considered some essential criteria which are discussed in Section 5. Here, we have considered four solar tech devices that are capable to store and convert solar energy into usable forms, namely Monocrystalline PV (T_1) [108], Polycrystalline PV (T_2) [109], Thin-Film PV (T_3) [110] and Solar Thermal (T_4) [111] as alternatives. The solar technologies will be ranked considering the linguistic inputs provided by the decision-making experts, with the assistance of the mathematical model of this paper. The detailed discussions about the alternatives are done below:

6.1 *Monocrystalline PV* (T_1)

Monocrystalline PV [112] panels are mostly considered as one of the solar technologies with the highest efficiency. It delivers high energy output even under variable conditions, which makes the performance strong in an uncertain environment. However, the process of manufacturing is energy-intensive, which causes moderate GHG emissions. In this technology, high-purity silicon is used, so the use of resources is significantly high. Despite having a high EROI and suitable EPBT values in this technology, some chemical treatments are used in the process of production, which can create low amounts of toxicity concerns under poor waste management situations. Minimal land is required in monocrystalline [108] systems at the time of compact installations or deployment on rooftops; however, ground-mounted systems can still increase spatial considerations. These panels mostly require large-scale funding due to premium manufacturing structure, but their longevity most of the time increases up to 25 years with relatively limited demands in maintenance that make them functional and economically alluring over the long-term plans, while considering uncertain environmental conditions.

6.2 Polycrystalline PV (T_2)

Polycrystalline [113] offers lesser efficiency than Monocrystalline, which may reduce energy yield in regions with inconsistent sunlight. On the other hand, Polycrystalline PV has less complexity in manufacturing, which reduces both GHG emissions and overall consumption of resources. They also have adequately strong EROI and competitive EPBT values; thus, it becomes a practical choice for decision environments focused on costs. There is some use of industrial chemicals in silicon processing, so the concern regarding the toxicity is there, though these effects are usually manageable with adequate protocols regarding safety and security. Polycrystalline [109] panels need more land footprints than monocrystalline systems, but their lower cost makes them more accessible for installations where the funding is limited. They provide a balanced combination of performance, durability and affordability within unfavourable environmental and economic conditions, with a lifespan mostly ranging from 20–25 years with moderate maintenance requirements.

6.3 Thin-Film PV (T_3)

Thin-film [114] technologies—including Copper Indium Gallium Selenide (CIGS), amorphous silicon and Cadmium Telluride (CdTe) vary essentially from crystalline silicon systems. They have reduced efficiency but elevated performance stability under diffuse light, shading and high-temperature unfavourable scenarios. Their production [110] usually results in decreased GHG emissions and lower resource use, specifically for amorphous Silicon (a-Si), which avoids reliance on high-purity silicon. On the other hand, CIGS and CdTe technologies may bear high risks of toxicity due to the presence of copper-indium, tellurium and cadmium, which provide handling and recycling challenges. Thin-film systems generally require more area for equivalent output, though their flexible design supports and lightweight integration on large rooftops and uncertain regions. They require medium funding and usually have shorter lifespans ranging from 15–20 years, partially depending on the rate of degradation and maintenance requirements. In contrast to that, their rapid EPBT and considerable efficiency of material make them suitable for contexts in places where the priorities are low-cost deployment and adaptability.

6.4 Solar Thermal (T_4)

Solar thermal technologies [115] are different from PV systems, converting solar radiation into heat for the generation of electricity or direct thermal applications. They generally show [111] strong efficiency in regions that have a high irradiance but are more sensitive to climatic uncertainties, including temperature variations or cloud cover. In their life span, GHG emissions are relatively limited, and they consider abundant materials such as heat-transfer fluids, glass and steel, although certain types of fluid may cause toxicity concerns in case of leakage occurring. Solar thermal plants need more land areas, mostly exceeding those required for PV systems, which can create challenges in densely populated or agriculturally active regions. Financial requirements are generally higher than for other alternatives due to large-scale infrastructure requirements, though lengthening functional lifespans and predictable maintenance schedules reduce long-term economic costs. Solar thermal systems can provide durable performance if they are operated properly. However, they may face difficulties in uncertain environments with regions having a lack of appropriate water resources and stable sunlight.

7. Model Formulation and Data Collection

This section discusses the model formulation and data collection in detail. The hierarchical structure of the proposed model is presented in Figure 3. There are eight criteria and four alternatives selected based on a detailed literature review of recent studies and consulting with the decision experts. Therefore, decision matrices are constructed with 4×8 order given by three decision makers (DMs). All the DMs are experienced, knowledgeable, professional and unbiased in their fields. The DMs are as follows:

DM1: A professor from the renewable energy and engineering department with more than 10 years of experience,

DM2: A senior managing director of a private renewable solar energy production company with more than 15 years of experience,

DM3: A senior government engineer from the Ministry of New and Renewable Energy sector with more than 10 years of experience.

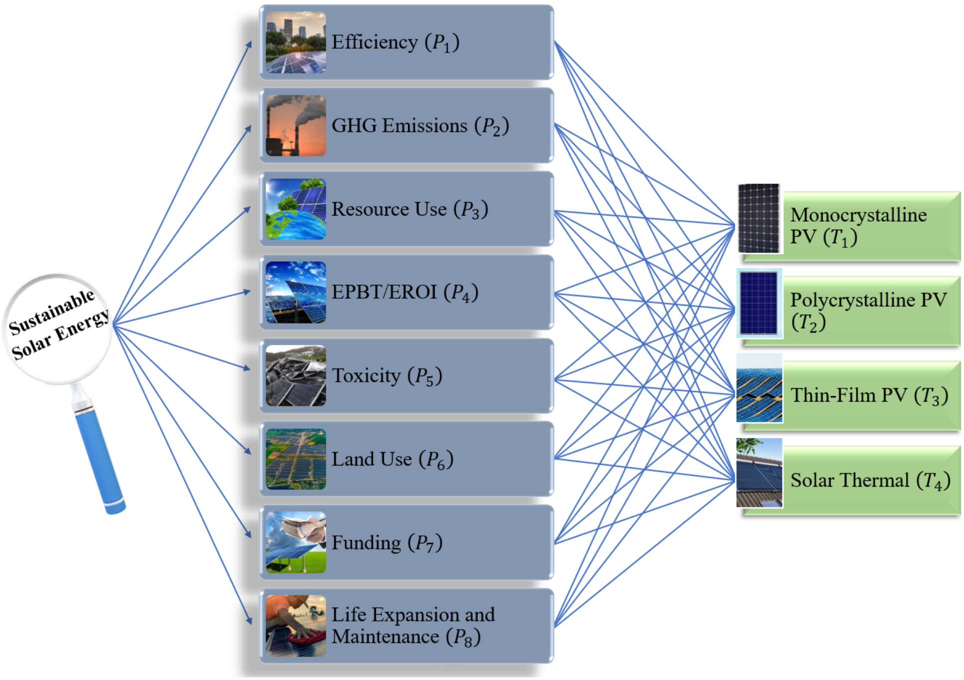


Fig. 3. Hierarchical structure

All DMs are provided with data in a decision matrix form in linguistic terms, which is then transformed into a triangular type-2 fuzzy number (TT2FN) using Table 5. The de-fuzzified values of the TT2FNs are shown in the table below and are calculated by using Equation (10). The decision matrices in linguistic terms are given by DMs, as shown in Table 6 and further utilized in the numerical section.

8. Numerical Illustration and Discussion

Numerical computation of the proposed evaluation of different solar technology models is performed in this section. Two MCDM methods under a triangular type-2 fuzzy number (TT2FN) environment are considered for this optimization model. First, determine the weights of the different

Table 5
Conversion table between linguistic terms and TT2FN

Linguistic terms	**Triangular Type-2 Fuzzy Number (TT2FN)**	**De-fuzzified value**
Extremely Significant (ES)	$\{(\xi, \mu_{\tilde{\mathscr{A}}}(\xi)) ; (7, 8, 9, 11, 13, 14, 15)\}$	11
Strongly Significant (SS)	$\{(\xi, \mu_{\tilde{\mathscr{A}}}(\xi)) ; (6, 7, 8, 10, 12, 13, 14)\}$	10
Fairly Significant (FS)	$\{(\xi, \mu_{\tilde{\mathscr{A}}}(\xi)) ; (5, 6, 7, 9, 11, 12, 13)\}$	9
Average Significant (AS)	$\{(\xi, \mu_{\tilde{\mathscr{A}}}(\xi)) ; (4, 5, 6, 8, 10, 11, 12)\}$	8
Below Significant (BS)	$\{(\xi, \mu_{\tilde{\mathscr{A}}}(\xi)) ; (3, 4, 5, 7, 9, 10, 11)\}$	7
Poorly Significant (PS)	$\{(\xi, \mu_{\tilde{\mathscr{A}}}(\xi)) ; (2, 3, 4, 6, 8, 9, 10)\}$	6
Weakly Significant (WS)	$\{(\xi, \mu_{\tilde{\mathscr{A}}}(\xi)) ; (1, 2, 3, 5, 7, 8, 9)\}$	5

Table 6
Decision matrices in linguistic terms between criteria and alternatives based on three DMs

	Criteria vs Alternatives	**Efficiency** (P_1)	**GHG Emissions** (P_2)	**Resource Use** (P_3)	**EPBT/EROI** (P_4)
DM_1	Monocrystalline PV (T_1)	ES	AS	SS	FS
	Polycrystalline PV (T_2)	FS	AS	AS	FS
	Thin-Film PV (T_3)	BS	PS	BS	SS
	Solar Thermal (T_4)	ES	FS	AS	AS

	Criteria vs Alternatives	**Efficiency** (P_1)	**GHG Emissions** (P_2)	**Resource Use** (P_3)	**EPBT/EROI** (P_4)
DM_2	Monocrystalline PV (T_1)	SS	AS	FS	FS
	Polycrystalline PV (T_2)	SS	FS	AS	AS
	Thin-Film PV (T_3)	AS	PS	BS	ES
	Solar Thermal (T_4)	SS	FS	FS	AS

	Criteria vs Alternatives	**Efficiency** (P_1)	**GHG Emissions** (P_2)	**Resource Use** (P_3)	**EPBT/EROI** (P_4)
DM_3	Monocrystalline PV (T_1)	ES	FS	SS	AS
	Polycrystalline PV (T_2)	SS	AS	FS	FS
	Thin-Film PV (T_3)	BS	BS	PS	SS
	Solar Thermal (T_4)	ES	SS	AS	FS

challenges as criteria using the MEREC method and then rank the various technologies as alternatives with the help of the COPRAS method. The numerical undergoes as follows:

The criterion weights are evaluated using the MEREC method, as discussed in Section 4.1 under the TT2FN environment in Section 3. The data are considered from the decision matrices shown in Table 6. The decision matrices are transformed from linguistic terms to TT2FN with the help of Table 5. Then aggregate the decision matrices and construct a single decision matrix $(\tilde{\mathfrak{D}})$ by Equation (13) and

Table 6
Cont.

	Criteria vs Alternatives	**Toxicity** (P_5)	**Land Use** (P_6)	**Funding** (P_7)	**Life Expansion and Maintenance** (P_8)
DM_1	Monocrystalline PV (T_1)	BS	PS	SS	ES
	Polycrystalline PV (T_2)	PS	SS	BS	SS
	Thin-Film PV (T_3)	FS	ES	AS	AS
	Solar Thermal (T_4)	FS	AS	ES	SS

	Criteria vs Alternatives	**Toxicity** (P_5)	**Land Use** (P_6)	**Funding** (P_7)	**Life Expansion and Maintenance** (P_8)
DM_2	Monocrystalline PV (T_1)	PS	BS	ES	SS
	Polycrystalline PV (T_2)	BS	FS	BS	FS
	Thin-Film PV (T_3)	AS	SS	AS	AS
	Solar Thermal (T_4)	SS	FS	SS	SS

	Criteria vs Alternatives	**Toxicity** (P_5)	**Land Use** (P_6)	**Funding** (P_7)	**Life Expansion and Maintenance** (P_8)
DM_3	Monocrystalline PV (T_1)	PS	PS	ES	ES
	Polycrystalline PV (T_2)	BS	SS	PS	FS
	Thin-Film PV (T_3)	FS	ES	FS	FS
	Solar Thermal (T_4)	AS	SS	ES	FS

evaluate the uniform aggregated fuzzy decision matrix $(\tilde{\mathfrak{D}}^u)$ using Equation (15), respectively. Then, determine the de-fuzzified decision matrix $(\mathfrak{D})$ as shown in Table 7. Then, we evaluated the overall performance of each alternative $(\mathfrak{P}_\psi)$ using Equation (17) and presented it in Table 8. After that, the alternatives' performance $(\mathfrak{Q}_{\psi\phi})$ by eliminating every criteria are calculated by Equation (18) and presented in Table 9. Further, the aggregated absolute deviations value $(\mathfrak{R}_\phi)$ are determined using Equation (19) and shown in Table 10. Finally, calculate the criteria weight $(\mathfrak{W}_\phi)$ of the evaluation of different solar technologies by Equation (20) and presented in Table 10.

Table 7
De-fuzzified decision matrix $(\mathfrak{D})$

Criteria vs Alternatives	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
Monocrystalline PV (T_1)	0.727	0.570	0.707	0.604	0.487	0.431	0.727	0.727
Polycrystalline PV (T_2)	0.659	0.570	0.609	0.604	0.512	0.659	0.453	0.636
Thin-Film PV (T_3)	0.499	0.432	0.487	0.721	0.667	0.727	0.568	0.568
Solar Thermal (T_4)	0.727	0.639	0.609	0.581	0.691	0.611	0.727	0.659

Table 8
Overall performance of the alternative $(\mathfrak{P}_\psi)$

Alternative	Monocrystalline PV (T_1)	Polycrystalline PV (T_2)	Thin-Film PV (T_3)	Solar Thermal (T_4)
$\mathfrak{P}_\psi$ value	-1.015	-0.899	-0.909	-1.077

Table 9
Alternatives' performance value $(\mathfrak{Q}_{\psi\phi})$ by eliminating every criteria

Criteria vs Alternatives	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
Monocrystalline PV (T_1)	-0.853	-0.910	-0.862	-0.899	-0.932	-0.945	-0.853	-0.853
Polycrystalline PV (T_2)	-0.764	-0.793	-0.781	-0.783	-0.809	-0.764	-0.823	-0.773
Thin-Film PV (T_3)	-0.823	-0.838	-0.826	-0.750	-0.772	-0.747	-0.804	-0.804
Solar Thermal (T_4)	-0.915	-0.950	-0.959	-0.968	-0.930	-0.959	-0.915	-0.943

Table 10
Criteria weight with associated data calculated by fuzzy MEREC methodology

Criteria	$\mathfrak{R}_\phi$	**Weight**
Efficiency (P_1)	0.545	0.140
GHG Emissions (P_2)	0.409	0.105
Resource Use (P_3)	0.472	0.121
EPBT/EROI (P_4)	0.500	0.128
Toxicity (P_5)	0.457	0.117
Land Use (P_6)	0.485	0.124
Funding (P_7)	0.505	0.129
Life Expansion and Maintenance (P_8)	0.528	0.135

From Table 10, we see that the criteria Efficiency (P_1) gets the maximum weight associated with Life Expansion and Maintenance (P_8) gets the second highest weight for this model. After that Funding (P_7) occupies third position followed by EPBT/EROI (P_4), Land Use (P_6), Resource Use (P_3) and Toxicity (P_5) gets fourth, fifth, sixth and seventh positions. Finally, the GHG Emissions (P_2) criteria receive the lowest weights in this proposed model. The graphical structure of the criteria weights is presented through the Pic diagram in Figure 4. These weights are further utilized in the COPRAS numerical process in a later section.

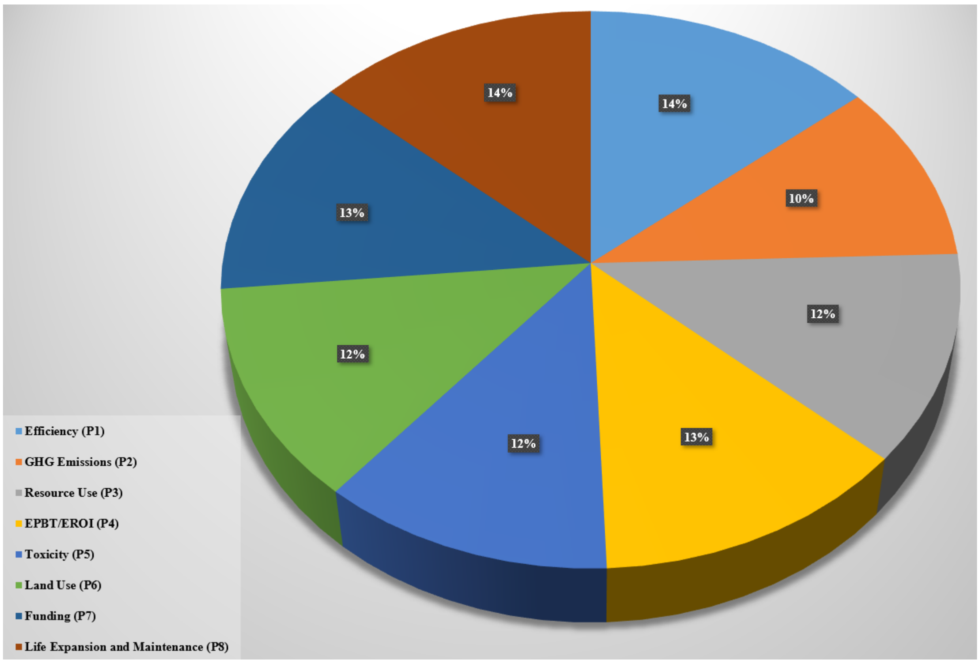


Fig. 4. Weight of the criteria in the Pie structure evaluated by the MEREC method

The ranking of the alternatives is calculated by the COPRAS method, as shown in Section 4.2 under the TT2FN environment in Section 3. All the data are shown in decision matrices format in Table 6 in linguistic terms and later transformed into TT2FN with the help of Table 5. The decision matrices are converted into an aggregated decision matrix $(\tilde{\mathfrak{D}})$ using Equation (13). After that, the weighted fuzzy decision matrix $(\tilde{\mathfrak{D}}^w)$ evaluated from $\tilde{\mathfrak{D}}$ and criteria weights $(\mathfrak{W}_\phi)$ by scalar multiplications of TT2FN, define in Equation (7). Then the uniform weighted decision matrix $(\tilde{\mathfrak{E}}^u)$ calculate by Equation (15) and the maximum index $(\tilde{\mathfrak{M}}_\psi^+)$ and minimum index $(\tilde{\mathfrak{M}}_\psi^-)$ for each alternative are determine using Equation (22), respectively. Then evaluated the De-fuzzified the maximum index $(\tilde{\mathfrak{M}}_\psi^+)$ and minimum index $(\tilde{\mathfrak{M}}_\psi^-)$ values using Equation (10) and shown in Table 11. Further, the relative weights $(\mathfrak{R}_\psi)$ of each alternative are calculated by Equation (23) and presented in Table 11. Finally, evaluate the performance index value $(\mathfrak{P}_\psi)$ of each alternative using Equation (24) and rank the alternatives based on this value. The ranking of alternatives with their performance index value $(\mathfrak{P}_\psi)$ is presented in Table 11.

Table 11

Ranking of the alternatives with $\mathfrak{P}_\psi$ value determined by fuzzy COPRAS methodology

Alternative	$\tilde{\mathfrak{M}}_\psi^+$	$\tilde{\mathfrak{M}}_\psi^-$	$\mathfrak{R}_\psi$	$\mathfrak{P}_\psi$	**Rank**
Monocrystalline PV (T_1)	2.887	2.145	5.670	100.00	1
Polycrystalline PV (T_2)	2.357	2.399	4.845	85.45	3
Thin-Film PV (T_3)	2.121	2.588	4.427	78.08	4
Solar Thermal (T_4)	2.721	2.676	4.952	87.34	2

From Table 11, we can conclude that the Monocrystalline PV (T_1) technology is the best photovoltaic technology for adoption. Further, the Solar Thermal (T_4) technology, Polycrystalline PV (T_2) technology and Thin-Film PV (T_3) are the second, third and fourth best photovoltaic technologies for adoption, based on our dataset. The graphical ranking of the alternatives with their performance index value $(\mathfrak{P}_\psi)$ is shown in Figure 5.

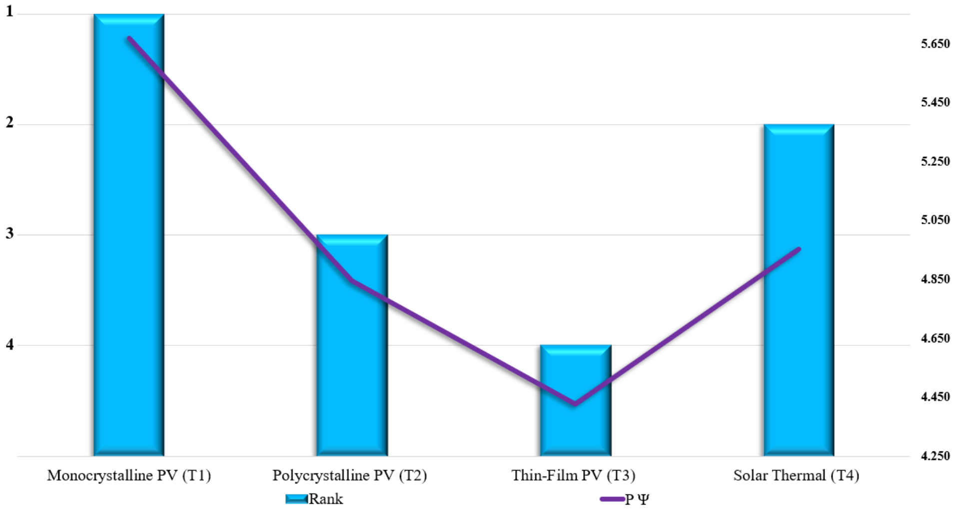


Fig. 5. Bar diagram of the alternatives based on $\mathfrak{P}_\psi$ value using fuzzy COPRAS method

9. Comparative Analysis and Sensitivity Analysis

This section presents a comparative analysis and sensitivity analysis of the proposed sustainable solar energy technology model. First, conducted the comparative analysis as follows:

9.1 Comparative analysis

The comparative analysis of the proposed MCDM model is conducted with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to assess the results' consistency and robustness. The result of the proposed sustainable solar energy technology model, obtained through a comparative analysis, is presented in Table 12. The results are similar to the proposed model (COPRAS method) and the TOPSIS method. Based on the evaluation results, the proposed model is consistent and robust. The bar diagram of the comparative analysis is shown in Figure 6.

Table 12

Comparative analysis of the sustainable solar energy technology model

Alternative	**COPRAS**	**TOPSIS**
Monocrystalline PV (T_1)	1	1
Polycrystalline PV (T_2)	3	3
Thin-Film PV (T_3)	4	4
Solar Thermal (T_4)	2	2

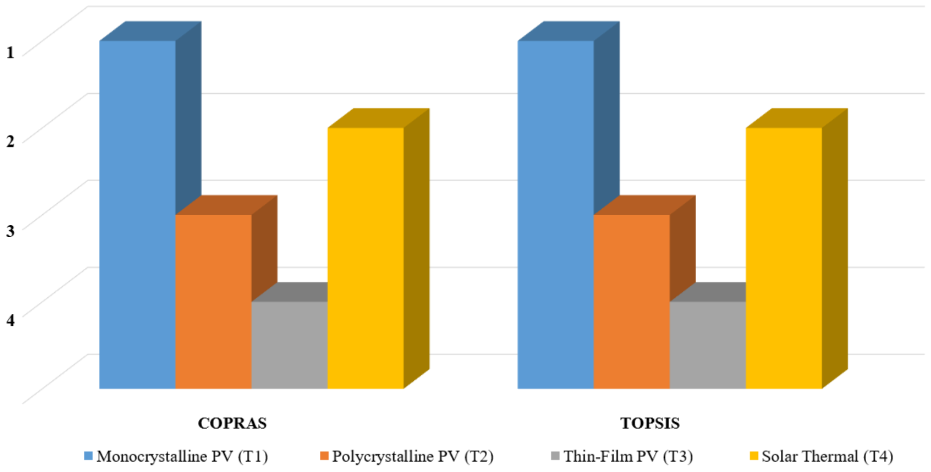


Fig. 6. Comparative analysis of the alternative ranking between COPRAS & TOPSIS methodologies

9.2 Sensitivity Analysis

This section presents a sensitivity analysis of the stability and flexibility of the proposed MCDM model. Three cases are considered for the sensitivity analysis and the cases are as follows:

Case 1. Removing criteria Resource Use (P_3):
Sensitivity analysis conducted by removing the criteria Resource Use (P_3), since it may be sufficient and there is no restriction on it. For those scenarios, this criteria have zero weight. The result of the modified model is presented in Table 13.

Case 2. Removing criteria Toxicity (P_5):
Sensitivity analysis is performed by removing the criteria Toxicity (P_5), since in the solar energy technology model, the possibility of toxic materials and gases is very low. Therefore, the criteria is eliminated from the model and the different solar technologies are ranked in the modified model. Results of the updated model are depicted in Table 13.

Case 3. Removing criteria Funding (P_7):
Sensitivity analysis is conducted by removing the criteria Funding (P_7), since for a developed country or large company, funding may not be a major issue. Then the criteria Funding (P_7) may be removed from the modified model. The ranking of the alternatives is presented in Table 13.

Table 13
Sensitivity analysis of the sustainable solar energy technology model

Alternative	Case 1	Case 2	Case 3	Proposed Model
Monocrystalline PV (T_1)	1	1	1	1
Polycrystalline PV (T_2)	3	3	2	3
Thin-Film PV (T_3)	4	4	4	4
Solar Thermal (T_4)	2	2	3	2

The ranking of the alternatives through sensitivity analysis by three different cases are shown in Table 13. The ranking of the alternatives are almost similar to the proposed model, except in case 3, alternatives Polycrystalline PV (T_2) and Solar Thermal (T_4) are interchanged with rank 2nd and 3rd, respectively. The graphical diagram of the alternatives' ranking for three cases compared with the proposed model is shown in Figure 7.

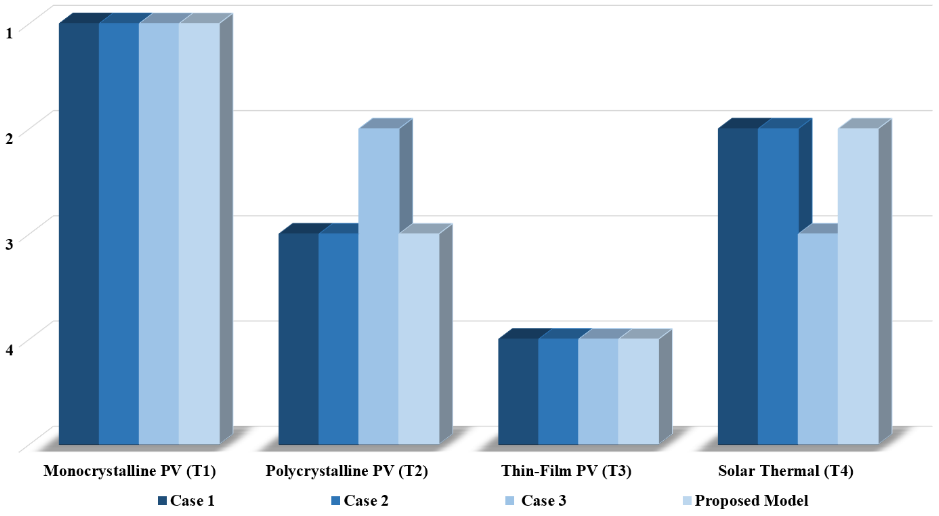


Fig. 7. Sensitivity analysis by three different scenarios with the proposed model

10. Research implication

This study provides a more realistic and reliable assessment of different types of solar technologies by incorporating MCDM methodologies. This study also shows the importance of including the criteria Efficiency, GHG Emission, Resource Use, EPBT/EROI, Toxicity, Land Use, Funding, and Life Expansion and Maintenance, rather than focusing solely on efficiency and expenditure. It also helps us identify which solar technologies will remain stable under uncertain conditions. Thus, this study will be helpful to policymakers and researchers in developing energy policies and making decisions in the field of solar technology. Investors will benefit from this research and can make the best investment decisions regarding solar energy plants. The sensitivity and comparative analyses demonstrate the stability and robustness of the results.

11. Conclusions and Future Research Scope

We can not imagine the modern age without a supply of sufficient energy and to meet the energy requirement, solar energy plays a significant role. There are various types of solar technologies that can be used to produce solar energy. In this paper, we have constructed a framework for evaluating different solar technologies and for this purpose, we have taken total 8 criteria into consideration. We obtained the opinions of 3 decision experts in linguistic terms and subsequently converted them into triangular type-2 fuzzy numbers (TT2FNs). Then, applying the MEREC method, we found that the criterion Efficiency (P_1) received the highest weight, the criterion Life Expansion and Maintenance (P_8) the second highest weight and so on. After that, we have applied the COPRAS method to find the ranking of 4 alternatives, which are Monocrystalline PV (T_1), Polycrystalline PV (T_2), Thin-Film PV (T_3), and Solar Thermal (T_4). After performing COPRAS method, Monocrystalline PV (T_1) have acquired the 1^{st} rank, Solar Thermal (T_4) have got the 2^{nd} rank and Polycrystalline PV (T_2) have got the 3^{rd} rank. Furthermore, we have performed a comparative analysis using the TOPSIS method to assess the flexibility and robustness of the results. Lastly, three cases were conducted on sensitivity analysis by removing some criteria to assess the consistency and reliability of the results.

There are also several directions for future research. In this paper, we have incorporated Triangular Type-2 Fuzzy Numbers (TT2FNs) to model uncertainty in the dataset, which can be extended to other newly developed fuzzy numbers. One may use another advanced MCDM method instead of using the MEREC-COPRAS based method. One may incorporate some other criteria to increase the complexity of the decision-making problem. Lastly, in the future, new technologies may emerge that are more efficient and sustainable, with real-world problems that can be compared with those of existing technologies.

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Conflicts of Interest

The authors declare no conflicts of interest.

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