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Prioritizing the Energy Mix Alternatives for Power Generation: An Integrated Multi-criteria Decision Making (MCDM) Model Approach

Gyanesh Kumar Sinha
NIIT University, Rajasthan -301705, India

Abstract
With the growing population and rising per capita income in India, electricity demand has grown significantly in the last couple of decades. The United Nations mandated all countries to achieve sustainable development goals while emphasizing net-zero emission targets to address global warming threats. The present study aims to rank various energy mix alternatives/sources (both fossil and renewable) using an integrated Fuzzy DEMATEL-BWM-Fuzzy TOPSIS model based on key criteria and sub-criteria for each energy alternative. Five key criteria or parameters and the associated sub-criteria for each criterion have been chosen based on the review of the literature. Five experts from the energy sector were asked for pairwise comparisons between energy mix alternatives and between the criteria selected. The study found that the environmental criterion is the most important criterion and GHG emissions as the most important sub-criterion for deciding the best source of energy for power generation. The energy mix comprising solar, hydroelectric, and wind was ranked highest as compared to any other mix of energy resources for power generation in India. The present study will be useful for policymakers in setting the priorities among all energy mix resources to address the energy needs of the country, with the main focus on meeting the Net-zero emission target in the long term in India

Key Words: Fuzzy DEMATEL, Fuzzy TOPSIS, Best-worst Method, Renewable Energy, Fossil Fuel, Climate Change, Net-zero Emissions

Introduction

Power Sector and Net Zero Emissions

India has seen rapid development in its economy in the past few decades. Fueled by population growth, rising per capita income, urbanization, and industrial development, this has led to the spurring in the growth of energy demand. As per the India Residential Energy Survey (IRES) report published in 2020, initiating aggressive implementation since September 2017 by the Government of India as part of Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya), nearly 97 percent of Indian households are electrified (Agrawal et. al., 2020). There are two sources for power generation -fossil fuel (thermal, gas-fired, geothermal, diesel) and non-fossil fuel (solar, wind, hydro, nuclear, biomass).

The 2015 Paris Agreement under the United Nations Framework Convention on Climate Change UNFCCC on climate change asked member countries to come up with a target for Net Zero Emissions in the pursuit of limiting the rise in the global temperature to 1.5 degrees Celsius (UNFCCC, 2016). Indian Government declared a five-fold strategy to combat climate change which is (i) increasing non-fossil energy capacity to 500 gigawatts (GW) by 2030, (ii) meeting 50 percent of its energy requirements from renewable energy by 2030, (iii) Reducing the total projected carbon emissions by one billion tonnes from now onwards till 2030, (iv) reduction in the carbon intensity of its economy by less than 45 percent by 20230, and (v) achieving the target of Net Zero by 2070 (Climate Action Tracker, 2021). However, in the year 2022, the Indian Government modified two of its declarations regarding non-fossil 500 GW capacity and meeting 50 percent of the energy requirement from renewable energy by 2023, and now it has set a goal of achieving 50 percent of installed capacity in renewable energy sources by 2030 (Nova, 2022). Table 1 summarizes the installed capacity of power generation in India. https://www.mospi.gov.in/publication/energy-statistics-india-2023

Table 1. Fuel-wise Installed Capacity of Power Generation in India

Fuel category	**Type**	**% Share in total**	**Installed capacity (MW)**
Fossil fuel	Coal	49.10%	2,05,235
	Gas	6.00%	24,824
	Lignite	1.6%	6620
	Diesel	0.10%	589
	Total Fossil Fuel	56.80%	2,37,269
Non-fossil fuel	RES (Including Hydro)	41.40%	1,73,619
	Wind, Solar & Other RE	30.20%	1,25,692
	Hydro	11.20%	46,850
	Solar	16.10%	67,078
	Wind	10.30%	42,868
	Biomass	2.50%	10,248
	Solar	16.10%	67,078
	Nuclear	1.60%	6,780
	Small Hydro Power	1.20%	4,944
	Waste to Energy	0.10%	554
	Total Non-Fossil Fuel	43.00%	1,79,322
Total Installed Capacity		**100.00%**	**417668**

Source: https://www.mospi.gov.in/publication/energy-statistics-india-2023

The renewable energy capacity of India has expanded significantly in the last few years, with the main focus on meeting its climate goals, with distinction of becoming the third-largest solar power producer globally. India's installed solar power capacity increased by over 25 times between 2014 and 2023 (Rawal, 2024). The country's wind power installed capacity has also grown by about 2.1 times over the past decade to nearly 45.89 GW (Rawal, 2024). India now ranks fourth globally in wind power installed capacity (Rawal, 2024). As of December 2025, the total installed renewable energy capacity in the country stands at 263 GW, accounting for 51.5 percent of the total installed generation capacity with 510 GW (PIB, 2025). This stands significantly higher as compared to March 2024 where the total installed renewable energy capacity was 191 GW, accounted for 43.12 percent of the total installed generation capacity (The Economic Times, August 2024). Table 2 presents the latest renewable energy installed capacity in India as of December 2025(https://thepublicworld.com/archives/114240)

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Table 2: Renewable Energy Installed Capacity in India

Sector	Installed Capacity (GW)	Under Implementation (GW)	Tendered (GW)	Total Installed/ Pipeline (GW)
Solar Power (a)	132.85	69.12	35.46	237.43
Wind Power (b)	53.99	30.11	1.8	85.9
Bio Energy (c)	11.61	---	---	11.61
Small Hydro (d)	5.16	0.44	---	5.6
Hybrid/ Round the Clock (RTC)/ FDRE (e)	---	59.24	11.48	70.72
Sub-Total (f = a+b+c+d+e)	**203.61**	**158.91**	**48.74**	**411.26**
Large Hydro (g)	50.35	25.33	---	75.68
Total RE (f+g)	**253.96**	**184.24**	**48.74**	**486.94**
Nuclear Power (h)	8.78	6.6	7	22.38
Total Non-Fossil Fuel (f+g+h)	**262.74**	**190.84**	**55.74**	**509.32**

Increased emphasis on reducing dependency on fossil fuels to meet the growing energy needs has changed the energy mix in India. Figure 1 shows a shift from more fossil fuel-based sources (conventional) of energy to non-fossil fuel sources of energy (renewable sources) to renewable sources from 2012-13 to 2021-22 (MOSPI, 2023)

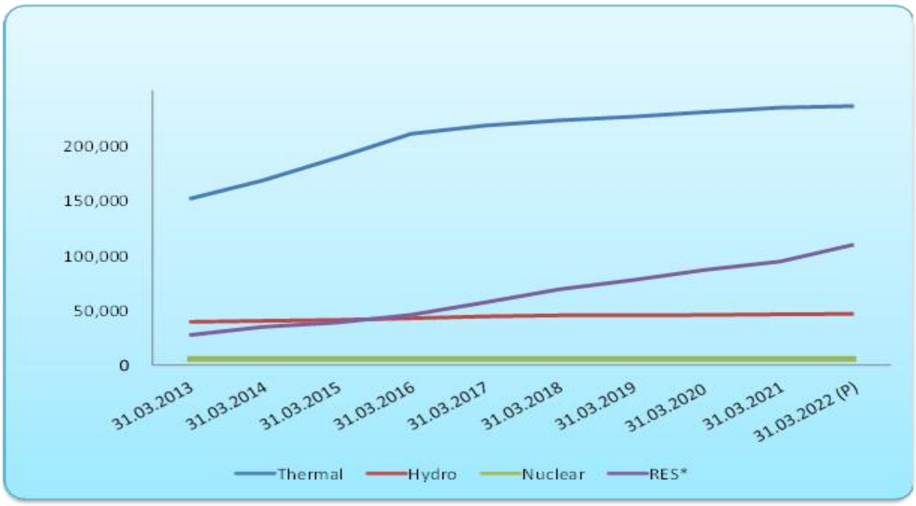

Fig. 1. Source-wise Trends in Installed Electricity Generation Capacity from Utilities (MW) in India

Source: https://www.mospi.gov.in/publication/energy-statistics-india-2023

Indian power sectors remained the largest contributor to GHG emissions, with 51.6 percent among all sectors of the economy, and coal contributes 71.4 percent of total GHG emissions in the power sector(IEA, 2021). Table 3 shows the CO_2 emissions by sector in India (year 2021)

Table 3. CO_2 emissions by sector, India, 2021

Sector of the Indian Economy	Value (Mt CO_2)	% of total
Electricity and heat producers	1165.721	51.15
Other energy industries	57.651	2.53
Industry	559.388	24.56
Transport	295.093	12.95
Residential	95.548	4.19
Commercial and public services	33.674	1.48
Agriculture	32.394	1.42
Final consumption not elsewhere specified	39.535	1.73

Source: IEA (2021). https://www.iea.org/countries/india/emissions

Problem statement

Climate change necessitated the Government of India to intensify its dependency on non-fossil fuels for power generation. In this line, India committed to meeting fifty percent of its power requirement through renewable energy, an accelerated pace for the expansion of renewable sources is required. The operating and maintenance costs for renewable sources have become cheaper when compared with fossil fuels for power generation. However, uninterrupted power generation from solar and wind is not possible due to their inherent limitations. Further, there is a significantly higher set-up cost for nuclear and hydroelectric power plants despite a clean source for power generation. CO_2 emissions from the natural gas-based power plant are very less compared to coal-based plants, but their reserves is comparatively limited. So, all the energy. There is a relatively higher cost for large hydroelectric and nuclear projects. The dramatic shift from fossil fuel to clean fuel (renewable energy sources) to meet energy requirements is not possible due to various constraints. As per the Economic Survey 2023-24, India's energy needs are projected to grow 2 to 2.5 times by 2047 (Mishra, 2024). Ragmoun & Ben-Salhab (2024) observed the increased renewable energy consumption could improve the environmental quality significantly. Given the huge energy demands and the challenges associated with renewable energy sources, such as intermittency, storage, and grid integration, India needs to diversify its energy mix to include other clean energy sources like nuclear energy, green hydrogen, and biofuels to meet the needs of its growing population as well as reduce its carbon footprint (Rawal, 2024).

Recognizing the importance of diversifying India's energy portfolio, the Union Budget 2024 announced measures to develop the country's nuclear energy capabilities (Rawal, 2024). As a clean power source, nuclear energy can significantly contribute to India's energy security, providing reliable, round-the-clock power, unlike intermittent renewables (Rawal, 2024). Therefore, factors like R&D, economic life, environmental constraints, social or political, and their inter-relationships must be examined for the feasibility and identification of the best suitable options from the given range of energy sources for power generation to achieve the net-zero emission target in the long run. One of the main studies aims to explore key decision criteria and sub-criteria for choosing the best energy mix alternatives or sources among all alternatives available.

Ojectives of the Study

The following are the objectives of the present research work
(i) To explore key attributes or criteria and sub-attributes or sub-criteria for selecting the energy mix alternative for power generation and their relative importance.
(ii) To examine the cause-effect relationship among each attribute for selecting the best energy mix alternative in India
(iii) To rank all energy mix alternatives based on all the attributes under study and select the best alternative feasible for power generation to meet the net-zero emission goal

Research Methodology

The present study used secondary sources like research articles from peer-reviewed journals, reports from the government, and other leading research agencies' websites for understanding the significance of power generation and associated carbon emissions, key conflicting factors or criteria, and sub-criteria impacting the decision-making in the selection of various energy mix alternatives. This study applied an integrated model combining the Best-worst method (BWM), Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL), and Fuzzy Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) (Solangi et. al., 2025). BWM was applied to determine the relative importance (weightage) of each criterion for a given goal of the most suitable energy mix alternative. The same technique was also applied to understand the relative importance of each sub-criterion within each criterion. Fuzzy DEMATEL was used to understand the causal relationship and interdependency relationship among the criteria. Finally, each decision alternative (energy mix resource) was ranked among itself by the fuzzy TOPSIS tool. The primary data was collected from experts in the energy sector by administering a structured questionnaire designed on the Saaty scale using triangular fuzzy numbers (TFN). Five experts were chosen as part of the research work. Expert 1 belonged to a leading public sector undertaking (PSU) in coal power generation with more than 25 years of experience. Expert 2 was from a solar power generation-based company with more than 15 years of experience. Expert 3 had rich experience of around 18 years in a wind power generation company. Expert 4 belonged to a power distribution company based in New Delhi, carrying more than 20 years of experience. Expert 5 had rich and diverse experience in both biomass and nuclear-based power generation companies. All experts chosen were working in senior managerial positions with rich technical knowledge, who had executed medium to large-scale projects in the power sector. Experts conducted pairwise comparisons among five key criteria (factors) and sub-criteria under each criterion to identify the weightage of each criterion and sub-criterion under each criterion of the factor (Kang et al., 2011). To determine the interdependency as well as the cause-and-effect relationship among criteria, pairwise comparison among those criteria was done by the same group of experts independently, followed by rating of each alternative under each criterion to rank them. The fuzzy Decision-Making Trial Evaluation Laboratory (DEMATEL) tool was used to examine the cause-and-effect relationship among all selected criteria (Gabus and Fontela, 1972). Fuzzy Techniques for Order Preference by Similarity to the Ideal Solution (TOPSIS) were applied to rank all the energy mix alternatives by maximizing the benefit criteria and minimizing the cost criteria (Wang and Lee, 2007).The flow chart for the proposed integrated model is presented in the

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diagram as shown in Figure 2

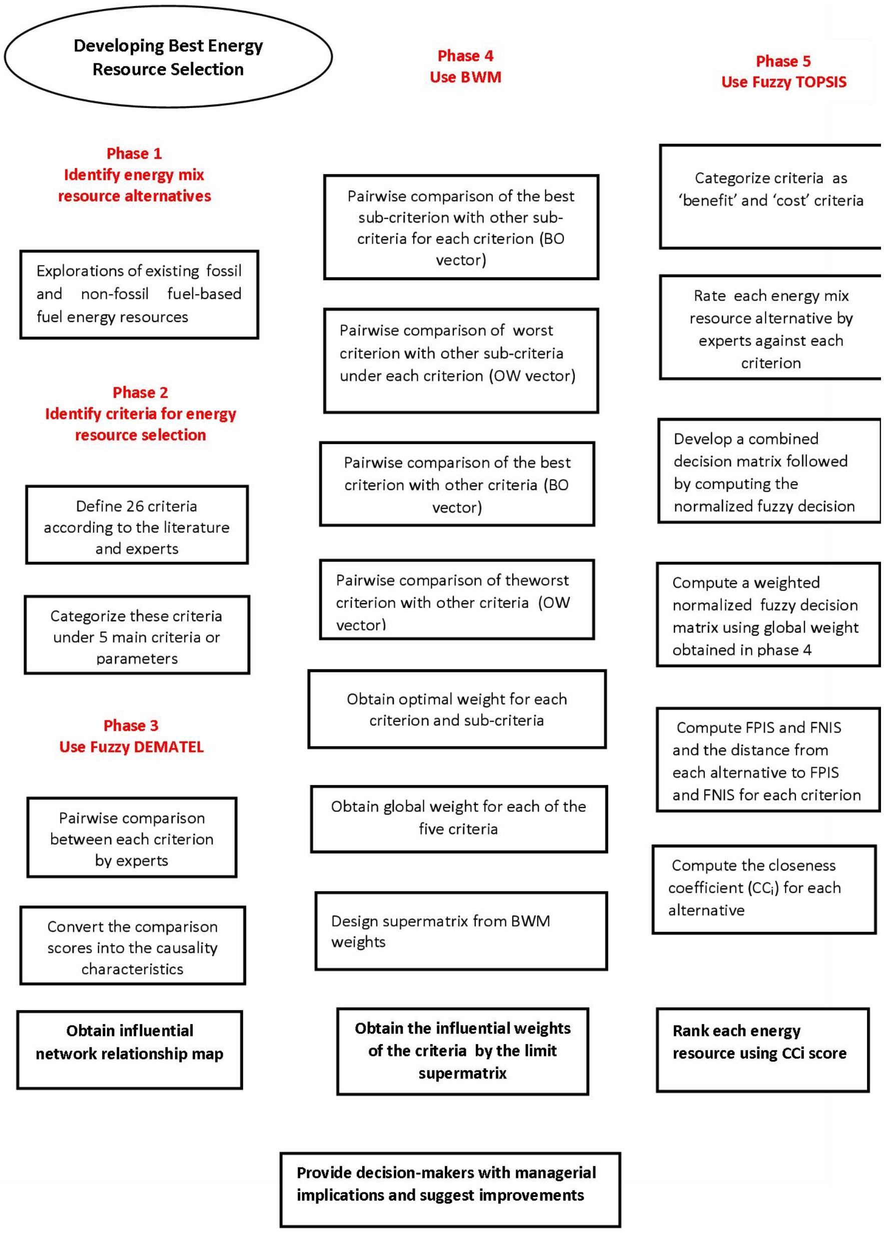

Fig. 2. Flow chart for the proposed research process

Source: Liu et al. (2020)

Review of Literature

A review of the literature was undertaken in two phases. The first phase involved the identification of key criteria and sub-criteria important for the selection of appropriate energy mix resources. In the second phase, the suitability of appropriate models and tools was explored and identified to collect the responses from the experts for the data analysis and ranking of energy mix alternatives.

Criteria and sub-criteria for the energy mix selection

Based on an extensive review of the literature, there are the following criteria and sub-criteria have been found for the selection of energy mix resources for electricity generation

Technical criterion

Efficiency is an important aspect under the technical criterion that measures the degree to which useful energy can be extracted from a given source of energy (Amer and Daim, 2011; Atmaca and Başar, 2012; Kaya and Kahraman, 2010; Talinli et al., 2010; Wang et al., 2009). Reliability measures the probability of performing an intended function under given circumstances or conditions for a specified period by technology (Amer and Daim, 2011; Kahraman et al., 2010; Wang et al., 2009). Resource availability sub-criterion indicates the continuous supply or availability of energy resources in a system (Amer and Daim, 2011; Aras et al., 2004; Chatzimouratidis and Pilavachi, 2009). Capacity of investment indicates the role of technology-related parameters such as geographical characteristics and production technology (Amer and Daim, 2011; Bürer and Wüstenhagen, 2009; Chatzimouratidis and Pilavachi, 2009; Iskin et al., 2012). Technology maturity signifies a specific technology's penetration in the energy mix at regional, national, and international levels(Amer and Daim, 2011; Chatzimouratidis and Pilavachi, 2009). Strategically leveraged technological innovation can have the potential to reduce ecological footprints (Toumi, 2025). The technological innovation sub-criterion indicates the attitude and persistent effort towards a radical technology.

Economical criterion

The investment cost sub-criterion measures how much expenditure is for setting up technology for power generation which includes the cost related to land, labor, equipment, infrastructure, installation etc. This aspect is the most used economic criterion to evaluate energy systems (Amer and Daim, 2011; Atmaca and Başar, 2012; Bürer and Wüstenhagen, 2009; Chatzimouratidis and Pilavachi, 2009; Cavallaroa and Cirolo, 2005; Daim et al., 2009). Operation and maintenance cost sub-criterion includes plant running cost, systems and equipment, personnel expenses, and funds spent for energy products and services (Atmaca and Başar, 2012; Chatzimouratidis and Pilavachi, 2009; Erdoğmuş et al., 2006; Iskin et al., 2012; Kaya and Kahraman, 2010; Kahraman et al, 2009; Leete et al., 2009; Önüt et al., 2008). R&D cost sub-criterion indicates those expenses that occur in the research and development of technological innovations (Amer and Daim, 2011; Leete et al., 2009). The return on investment sub-criterion evaluates how much the proposed energy alternative is economical and considers the project's worth of its investment, usually measured by NPV or payback period methods (Kahraman et al, 2009; Nigim et al., 2004; Wang et al. 2009). Production cost sub-criterion is calculated based on the cost of expected renewable energy resources (Amer and Daim, 2011; Dinica, 2012; Iskin et al., 2012).

Environmental criterion

The greenhouse gas (GHG) sub-criterion includes greenhouse gases such as CO_2, NOx etc. that mainly contribute to global warming, and some of them also lead to air pollution and acid rains (Amer and Daim, 2011; Cavallaroa and Cirolo, 2005; Iskin et al., 2012; Kahraman et al, 2009; Kaya and Kahraman, 2011; Önüt et al., 2008). Land use requirement sub-criterion corresponds to energy systems that need space to generate energy where energy investments cause strong demand for suitable land (Amer and Daim,2011; Iskin et al.,2012; Kaya and Kahraman, 2011; Wang et al., 2009). Impact on the ecosystem sub-criterion measures the potential risk to ecosystems.(Amer and Daim, 2011; Dinica, 2012; Iskin et al., 2012; Kahraman and Kaya, 2010; Talinli et al., 2010) can be given. The other sub-criteria were PM 2.5, noise pollution, and water pollution

Political criterion

The foreign dependency sub-criterion indicates the integration of national energy policies with renewable energy alternatives and considers the dependency of countries on international legislation (Erdoğmuş et al., 2006; Iskin et al.,2012; Önüt et al., 2008). Legislative Compatibility sub-criterion: how much the proposed policy is in line with government policies. It includes government incentives, the tendency of institutional actors, and the policy of public information (Kahraman et al, 2010). Energy policy sub-criterion indicates the compatibility of the national energy policy concerning renewable or non-renewable energy resources (Amer and Daim, 2011; Iskin et al.,2012; Talinli et al., 2010; Kahraman and Kaya, 2010). The financial support sub-criterion indicates public incentives and financial accessibility by utilizing energy resources (Bürer and Wüstenhagen 2009; Iskin et al., 2012).

Social criterion

The social benefits sub-criterion identifies all benefits of renewable energy sources, for instance, a social life and income generation that would prevent people from emigrating from rural lands for public welfare (Atmaca and Başar, 2012; Erdoğmuş et al., 2006;I skin et al.,2012; Önüt et al., 2008; Wang et al.2009). Social acceptability sub-criterion indicates people's approval and affirmative opinion on different energy sources (Amer and Daim, 2011; Cavallaroa and Cirolo, 200 5; Goletsis et al., 2003; Iskin et al., 2012; Kahraman and Kaya, 2010; Wang et al., 2009). Job creation sub-criterion indicates direct and indirect employment, as well as the creation of new professional areas indirectly (Amer and Daim, 2011; Erdoğmuş et al., 2006; Iskin et al., 2012; Wang et al., 2009).

Methodological Tools

There may be direct or indirect relations between many elements in decision-making problems with a high level of complexity. In these situations, it becomes a challenge for a DM to avoid all other factors and formulate an isolated evaluation between a single effect and a single factor (Chen and Chen, 2010). Moreover, strictly assuming a hierarchical structure that gives rise to linear activity with no dependence or feedback can cause problems that are different from the ones in non-hierarchical systems (Tzeng et al., 2007).). In the presence of a non-hierarchical system, DEMATEL can be appropriately applied. It can build the structure of a causal relationship with clear interrelations among criteria and sub-criteria for each criterion (Gabus and Fontela, 1972; Büyüközkan and Çifçi, 2011). DEMATEL is a very widely used technique across different disciplines and issues in decision making, including sustainable development (Rahman and Subramanian, 2012; Zhang et al., 2019; Lo et al., 2020). As the DEMATEL approach is not suitable for calculating the individual criteria's weight, the Best-Worst method can facilitate doing so. Rezaei (2015) introduced the Best-worst Method (BWM) as one of the MCDM tools that is used to evaluate the weights or importance of a set of decision criteria. There are two extreme criteria chosen in this method: one of them is chosen as 'best' and the other as the 'worst' criterion (Alshahrani et al., 2022). The best criteria are the ones with the most important role in decision-making, while the worst criteria have the opposite effect(Alshahrani et al., 2022). BWM is highly beneficial in the case of a complex or diverse set of evaluation criteria.

The Fuzzy TOPSIS technique is extended from the concept of TOPSIS which is applied to various MCDM problems in an uncertain environment (Chen, 2000; Singh and Benyoucef, 2011). It works well even with imprecise data (Rajak and Shaw, 2019). Fuzzy numbers were first applied by Chen and Hwang in 1992 to the TOPSIS method to establish the Fuzzy TOPSIS method (Baharin et al, 2021). In this method, decision makers' opinions for criteria and decision alternatives are represented using triangular fuzzy numbers (TFNs). Then, the alternatives will be ranked based on the distance that is nearest to the ideal solutions, and the selection will be based on the ranking result (Ertugrul and Oztas, 2014). Integration of all three models' methods can provide a better insight in the identification of important criteria and ranking decision alternatives and help in arriving at better decisions

Model Framework and Application

Fuzzy DEMATEL

The Fuzzy DEMATEL technique can be summarized in the following steps.

Step 1: Define the goal, decision alternatives, criteria, and sub-criteria

Step 2: Judgment by experts through a pairwise comparison among criteria in terms of influence and direction using a linguistic scale. The linguistic scales are changed to triangular fuzzy numbers (TFN) as represented in Table 4.

Table 4. The linguistic scale and corresponding TFNs

Linguistic scale	**TFN**
NO	0,0,.25
VL	0,.25,.5
L	.25,.50,.75
H	.50,.75,1
VH	.75,1,1

Source: Fakhrazad et. al.(2021). https://www.rairo-ro.org/articles/ro/abs/2021/05/ro200317/ro200317.html

Where, NO: No influence; VL: Very low influence; L: Low influence; H: High influence; VH: Very high influence (Kang et al., 2011)

Step 3: Develop a fuzzy initial direct relation matrix showing the judgment of expert k on the influence of one criterion i over another criterion j.

$$\widetilde{Z}_k = (\widetilde{Z}_{ijk}) n \times n \qquad (1)$$

$$\widetilde{Z}_k = \{(l_{ijk}, m_{ijk}, u_{ijk})\} n \times n \qquad (2)$$

$$\widetilde{Z}_k = \begin{bmatrix} 0 & \widetilde{Z}_{12k} & \cdots & \widetilde{Z}_{1nk} \\ \widetilde{Z}_{21k} & 0 & \cdots & \widetilde{Z}_{2nk} \\ \vdots & \vdots & \vdots & \vdots \\ \widetilde{Z}_{m1k} & \widetilde{Z}_{m2k} & \cdots & 0 \end{bmatrix} \quad (3)$$

Step 4: The judgments of K experts are aggregated,

$$\widetilde{Z} = (\widetilde{Z_{ij}}) n \, x \, n \quad (4)$$

$$= \left\{ \left(\frac{\widetilde{Z}_{ij1} \oplus \widetilde{Z}_{ij2} \oplus \ldots\ldots\ldots \oplus \widetilde{Z}_{ijk}}{K} \right) \right\} n \, x \, n$$

Step 5: A fuzzy normalized direct-relation matrix is generated.

$$\widetilde{X} = (\widetilde{X}_{ij}) n \, x \, n \quad (5)$$

$$\widetilde{X} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{n1} & \tilde{x}_{n2} & \cdots & \tilde{x}_{nn} \end{bmatrix} \quad (6)$$

Where $\widetilde{X}_{ij} = \frac{\widetilde{Z}_{ijk}}{r}$

$= \left(\frac{l_{ij}}{r}, \frac{m_{ij}}{r}, \frac{u_{ij}}{r} \right)$; r =$\max_{1<=n} \left(\sum_{j=1}^{n} u_{ij} \right)$

Step 6: Consider $\widetilde{X} = (l'_{ij,} \; m'_{ij,} \; u'_{ij,})$

Where $X_i = (l'_{ij}) nxn, (m'_{ij}) nxn, (u'_{ij}) nxn$

The elements of these matrices are extracted from $\widetilde{X}$ as follows:

$$X_l = \begin{bmatrix} 0 & l'_{12} & \cdots & l'_{1n} \\ l'_{21} & 0 & \cdots & l'_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ l'_{n1} & l'_{n2} & \cdots & 0 \end{bmatrix}, X_m = \begin{bmatrix} 0 & m'_{12} & \cdots & m'_{1n} \\ m'_{21} & 0 & \cdots & m'_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ m'_{n1} & m'_{n2} & \cdots & 0 \end{bmatrix}, X_u = \begin{bmatrix} 0 & u'_{12} & \cdots & u'_{1n} \\ u'_{21} & 0 & \cdots & u'_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ u'_{n1} & u'_{n2} & \cdots & 0 \end{bmatrix}$$

Step 7: The fuzzy total relation matrix

$$\widetilde{X} = \lim_{k \to \infty} \left(\widetilde{X^1} + \widetilde{X^2} + \ldots\ldots + \widetilde{X^k} \right) \quad (7)$$

$$\widetilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \cdots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \cdots & \tilde{t}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \cdots & \tilde{t}_{nn} \end{bmatrix} \quad (8)$$

$$\widetilde{t_{ij}} = (l''_{ij,} \; m''_{ij,} \; u''_{ij,}) \quad (9)$$

Where $[l''_{ij,}] = X_i * (I - X_i)^{-1}$

$[m''_{ij,}] = X_m * (I - X_m)^{-1}$

$[u''_{ij,}] = X_i * (I - X_u)^{-1}$

And I is the identity matrix

Step 8: The non-fuzzy total relation matrix t_{ij}

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$$t_{ij} = \left(\frac{l''_{ij} + m''_{ij} + u''_{ij,}}{4}\right) \quad (10)$$

Step 9: Identification of threshold value (α) by the expert to filter out insignificant causal relationships

Step 10: Computation for the matrices D and R

$$\mathrm{T} = [\mathrm{T}_{\mathrm{ij}}]_{\mathrm{nxn}} i, j \in \{1,2,3, \ldots n\} \quad (11)$$

$$\mathrm{D} = \sum_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{T}_{\mathrm{ij}} \quad (12)$$

$$\mathrm{R} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{T}_{\mathrm{ij}} \quad (13)$$

If D-R is positive (Dispatchers), the corresponding criteria greatly influence other criteria.
If D-R is negative (Receivers), the corresponding criteria are greatly influenced by other criteria.

Step 11: Using (D+R) and (D-R) values, make the impact relationship charts depicting the causal relationship of elements.

Best-Worst Method (BWM)
The BWM method is used for pairwise comparison of the internal criteria in the unweighted supermatrix of the Analytic Network Process (ANP) and applied for evaluation problems in various industries (Alshahrani et al., 2022). The following are the steps followed in the BWM (Kang et al., 2011)

Step 1: Identification of the decision criterion set by experts in consistent with the decision goals

Step 2: Selection of the best and worst criteria by experts

Step 3: Use the best criterion as a reference for pairwise comparisons with other criteria to create the Best-to-Others vector

Step 4: Use the worse criterion as a reference to do pairwise comparisons with other criteria to create Other -to-Worst vector in a similar way as mentioned in Step 3

Step 5: Find the optimal weight for each criterion: using the linear programming model

Fuzzy TOPSIS
The Fuzzy TOPSIS method is applied for the evaluation and ranking of alternatives under uncertain circumstances (Baharin et al, 2021). In this method, linguistic variables representing criteria weights and alternative ratings are transformed to the triangular fuzzy numbers (TFNs). In this technique, the fuzzy positive ideal solution (FPIS) the fuzzy negative ideal solution (FNIS) for alternatives are calculated. The steps listed below show the procedures of the Fuzzy TOPSIS method in evaluating the importance of criteria

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weights and the ranking of alternatives (Baharin et al., 2021)

Step 1: Construct the diagram representing the goal, criteria, sub-criteria, and decision alternatives

Step 2: Collect the responses from experts for the criteria and alternatives. They indicate the degree of importance for each criterion and rate the alternatives using linguistic variables presented in Table 4 andTable 5, respectively (Baharin et.al., 2021).

Table 4. Triangular fuzzy numbers for each linguistic variable under each criterion

Triangular Fuzzy Numbers	Linguistic Terms
{1.0, 1.0, 3.0}	V-L
{1.0, 3.0, 5.0}	L
{3.0, 5.0, 7.0}	A
{5.0, 7.0, 9.0}	H
{7.0, 9.0. 9.0}	V-H

Where V-L: Very ow; L: Low; A: Average; H: High; V-H: Very high

Table 5. TFNs corresponding to a linguistic variable for each alternative

Linguistic Terms	Triangular Fuzzy Numbers (TFNs)
Definitely good (D-G)	{9.0, 10.0, 10.0}
Extremely good (E-G)	{8.0, 9.0, 10.0}
Very good (V-G)	{7.0, 8.0, 9.0}
Very good (V-G)	{7.0, 8.0, 9.0}
Good (G)	{6.0, 7.0, 8.0}
Medium good (M-G)	{5.0, 6.0, 7.0}
Fair (F)	{4.0, 5.0, 6.0}
Medium poor (M-P)	{3.0, 4.0, 5.0}
Poor (P)	{2.0, 3.0, 4.0}
Very poor (V-P)	{1.0, 2.0, 3.0}
Extremely poor (E-P)	{0.0, 1.0, 2.0}
Definitely poor (D-P)	{0.0, 0.0, 1.0}

Source: Wang and Chan (2013);https://www.tandfonline.com/doi/full/10.1080/00207543.2012.754553

Step 3: Compute the aggregated fuzzy weight of each criterion, $\widetilde{W}_j$ of the kth decision maker described as

$$W_j \leq (w_{j1}, w_{j2}, w_{j3}) \qquad (14)$$

Where,

$$w_{j1} = \min_k \{w_{j1}^k\}$$

,

$$w_{j2} = \frac{1}{k}\sum_{k=1}^{k} (w_{j2}^k)$$

,

$$w_{j1} = \max_k \{w_{j3}^k\}$$

Step 4: Design the fuzzy decision matrix, $\widetilde{D}$ comprising alternatives, i, and criteria, j

$$\widetilde{D} = \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{bmatrix} \overset{[C_1 \quad C_2 \quad \cdots \quad C_n]}{\begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix}} (15)$$

Let $\tilde{x}_{ij}$ be the aggregated fuzzy ratings of alternative i with respect to each criterion, j in a group of K decision-makers

$$\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}) \qquad (16)$$

Where

$$a_{ij} = \min_k \{a_{ij}^k\}$$

,

$$b_{ij} = \frac{1}{k}\sum_{k=1}^{k} (b_{ij}^k)$$

,

$$c_{ij} = \max_k \{c_{ij}^k\}$$

$$\text{and} \quad x_{ij}^k = (a_{ij}^k,\ b_{ij}^k,\ c_{ij}^k)$$

Step 5: Normalize the fuzzy decision matrix using:

$$\tilde{r}_{ij} = \left[\frac{a_{ij}}{c_j^*}, \frac{a_{ij}}{c_j^*}, \frac{a_{ij}}{c_j^*}\right] \text{ and } c_j^* = max_i \{c_{ij}\} \text{ (benefit criteria)} \qquad (17)$$

$$\tilde{r}_{ij} = \left[\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right] \text{ and } a_j^- = max_i \{a_{ij}\} \text{ (cost criteria)} \qquad (18)$$

Step 6: Develop the weighted normalized fuzzy decision matrix, $\widetilde{V}$ by multiplying the normalized fuzzy decision matrix, $\tilde{r}_{ij}$ with the weights of evaluation criteria, $\widetilde{w_j}$ as follows:

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$\widetilde{V} = [\tilde{v}]_m$ i =1, 2,.......,m alternatives; j= 1,2,........, n criteria (19)

Where $\tilde{v}_j = \tilde{r}_{ij}\ x\ \widetilde{w}_{ij}$ (20)

Step 7: Find the FPIS, A^* and the FNIS, A^- (Baharin et al., 2021)

$A^* = (\tilde{v}_1{}^*, \tilde{v}_2{}^*, \ldots\ldots, \tilde{v}_n{}^*)$ where $\tilde{v}_j{}^* = \max_i\{v_{ij3}\}$ (21)

$A^- = (\tilde{v}_1{}^-, \tilde{v}_2{}^-, \ldots\ldots, \tilde{v}_n{}^-)$ where $\tilde{v}_j{}^- = \min_i\{v_{ij2}\}$ (22)

Step 8: Compute the distance of each alternative, (d_i^*, d_i^-) from FPIS and FNIS using the following equations:

$$d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j{}^*) \quad (23)$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j{}^-) \quad (24)$$

Where i = 1,2,...........,m

The distance between two fuzzy numbers $\tilde{a}$ and $\tilde{b}$ can be calculated as

$$d(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]} \quad (25)$$

Step 9: Closeness coefficient CC_i is calculated as

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*}\ ;\ i = 1,2,\ldots\ldots\ldots,m \quad (26)$$

Step 10: Ranking the alternatives based on the value obtained for the closeness coefficient of each alternative with respect to the ideal solution in descending The highest value of CC_i, which is nearest to the FPIS and the farthest from the FNIS, is chosen as the best alternative (Baharin et al., 2021).

Selection of criteria and sub-criteria

Based on the extensive literature, the following criteria and sub-criteria have been identified to select the best energy-mix alternatives as shown in Table 6

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Table 6. Criteria and sub-criteria for the energy mix alternatives

Criteria	Sub-criteria	Criteria	Sub-criteria
Economic/Financial	Investment cost	Social	Social benefits
	Operations and maintenance cost		Social acceptability
	R & D cost		Job creation
	Return in investment	Political	Foreign dependency
	Production cost		Synchronization with legislation
	Economic lifetime		Compatibility with energy policy
Technical	Efficiency		Financial support
	Resource availability		GHG emission level
	Reliability		PM2.5
	Investment capacity		Noise pollution
	Technological innovation		Water pollution

	Technology maturity	**Environmental**	**Land use requirement**
	Safety		**Impact on ecosystem**

Source: Author's compilation

Selection of decision alternatives

It is not feasible to rely on a single source of energy to provide electricity to the entire population of a country like India. A mix of energy resources is a viable option because of limitations as well as potential inherited with different sources of energy or fuel. Therefore, every energy alternative, for example, renewable energy, includes different sources of energy, like solar, wind, hydro, etc. are also included. For the present study, there are the following energy mix resource options have been identified as part of the decision alternatives, shown in Table 7

Table 7. List of energy resource alternatives

Alternative A1 Renewable (100%)
Alternative A2-Renewablw (75%)+ Non-Renewable-Non-Fossil (25%)
Alternative A3- Renewable (50%)+ Non-Renewable-Non-Fossil (25%) +Fossil (25%)
Alternative A4 -Renewable (75%) + Fossil (25%)

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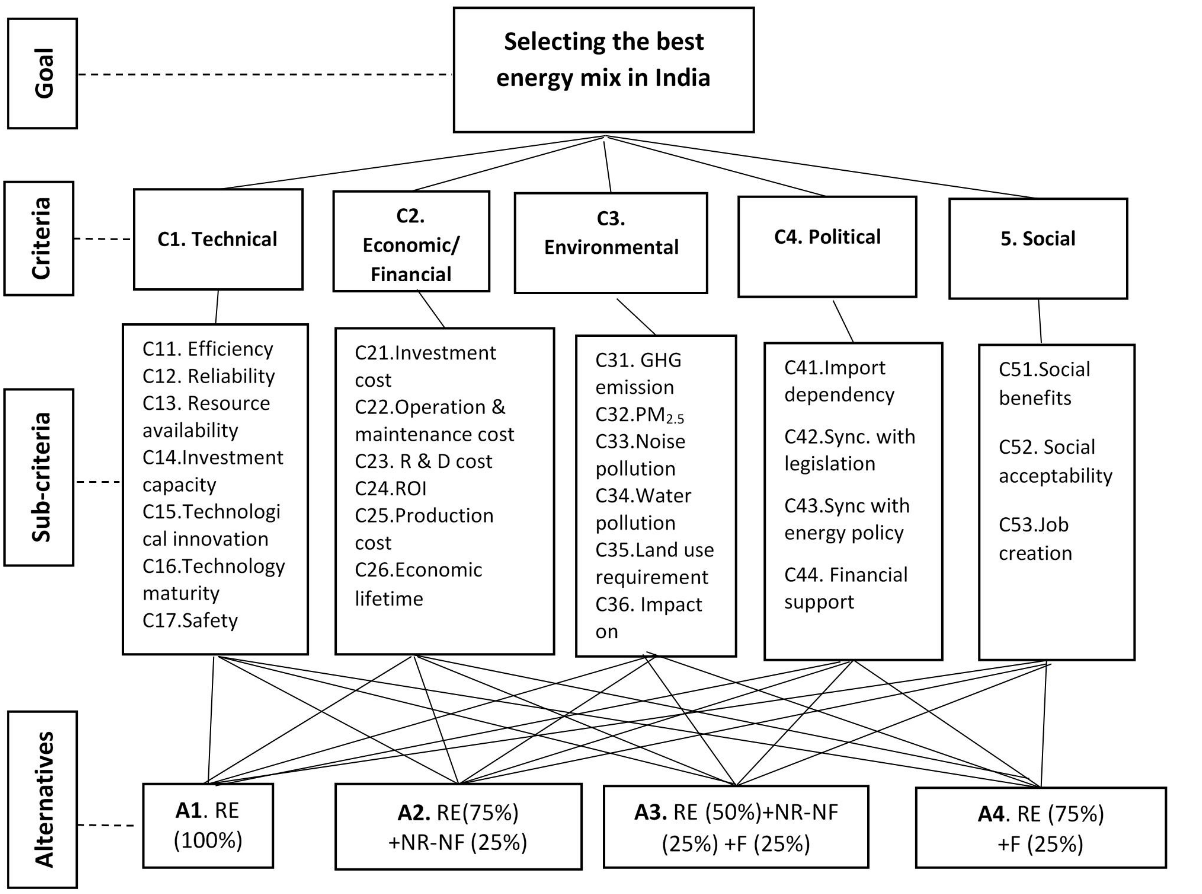

Fig. 3. Hierarchical structure for energy mix alternatives

Result and Discussion

The result of the study was divided into three parts (i) Fuzzy DEMATEL for understanding cause and effect variables among key criteria (or attributes), (ii) Best-Worst method for identification of relative importance or weights among key criteria and sub-criteria, and (iii) Fuzzy TOPSIS for ranking of the energy mix alternatives.

Fuzzy DEMATEL for Cause-and-Effect Variable

Step 1: Generate the fuzzy direct-relation matrix

The table 8 indicates the direct relation matrix, which is the same as the pairwise comparison matrix of the experts.

Table 8. The direct relation matrix

	Technical	Economic/ Financial	Environmental	Political	Social

Technical	(0.000,0.000,0.000)	(0.750,1.000,1.000)	(0.350,0.600,0.850)	(0.200,0.450,0.700)	(0.450,0.700,0.950)
Economic/ Financial	(0.600,0.850,1.000)	(0.000,0.000,0.000)	(0.300,0.550,0.800)	(0.200,0.450,0.700)	(0.350,0.600,0.850)
Environmental	(0.500,0.750,1.000)	(0.250,0.500,0.750)	(0.000,0.000,0.000)	(0.650,0.900,1.000)	(0.250,0.500,0.750)
Political	(0.550,0.800,1.000)	(0.600,0.850,1.000)	(0.500,0.750,1.000)	(0.000,0.000,0.000)	(0.450,0.700,0.950)
Social	(0.100,0.350,0.600)	(0.200,0.450,0.700)	(0.300,0.550,0.800)	(0.200,0.450,0.700)	(0.000,0.000,0.000)

Step 2: Normalization of the fuzzy direct-relation matrix

Table 9 shows the normalized fuzzy direct-relation matrix.

Table 9. The normalized fuzzy direct-relation matrix

	Technical	Economic/ Financial	Environmental	Political	Social
Technical	0.000,0.00) (0,0.000	0.190,0.253) (,0.253	0.089,0.15) (2,0.215	0.051,0.114,) (0.177	0.114,0.177,) (0.241
Economic/ Financial	0.152,0.215) (,0.253	0.000,0.00) (0,0.000	0.076,0.13) (9,0.203	0.051,0.114,) (0.177	0.089,0.15) (2,0.215
Environmental	0.127,0.190) (,0.253	0.063,0.127) (,0.190	0.000,0.00) (0,0.000	0.165,0.22) (8,0.253	0.063,0.12) (7,0.190
Political	0.139,0.20) (3,0.253	0.152,0.215,) (0.253	0.127,0.190) (,0.253	0.000,0.00) (0,0.000	0.114,0.177,) (0.241
Social	0.025,0.08) (9,0.152	0.051,0.114,) (0.177	0.076,0.13) (9,0.203	0.051,0.114,) (0.177	0.000,0.00) (0,0.000

Step 3: Calculate the fuzzy total-relation matrix

For calculating the fuzzy total-relation matrix, the normalized matrix, the inverse was first calculated, and then it was subtracted from the identity matrix, followed by multiplication of the normalized matrix was multiplied with the resulting matrix (Saeed et al, 2021). Table 10 shows the matrix.

Table 10. The fuzzy total-relation matrix

	Technical	Economic/ Financial	Environmental	Political	Social
Technical	(0.071,0.284,1.187)	(0.235,0.493,1.350)	(0.137,0.385,1.323)	(0.097,0.337,1.202)	(0.163,0.411,1.357)
Economic/ Financial	(0.193,0.437,1.352)	(0.065,0.266,1.112)	(0.120,0.354,1.279)	(0.090,0.317,1.169)	(0.134,0.371,1.303)
Environmental	(0.186,0.446,1.410)	(0.139,0.407,1.328)	(0.061,0.258,1.166)	(0.197,0.426,1.272)	(0.123,0.376,1.342)
Political	(0.209,0.489,1.524)	(0.221,0.503,1.480)	(0.183,0.446,1.478)	(0.061,0.265,1.170)	(0.176,0.444,1.488)
Social	(0.062,0.28	(0.082,0.30	(0.099,0.30	(0.076,0.26	(0.029,0.181

	1,1.128)	2,1.111)	0,1.128)	9,1.032)	,0.973)

Step 4: Defuzzification into crisp values

The matrix is shown in Table 11.

Table 11. The crisp total-relation matrix

	Technical	Economic/Financial	Environmental	Political	Social
Technical	0.433	0.616	0.53	0.467	0.554
Economic/Financial	0.577	0.407	0.501	0.448	0.517
Environmental	0.591	0.545	0.41	0.547	0.524
Political	0.637	0.639	0.598	0.41	0.596
Social	0.421	0.433	0.437	0.393	0.317

Step 5: Set the threshold value
For finding the internal relations matrix, the threshold value was calculated. After the threshold value is determined, which was found to be equal to 0.5020.502. All values in the matrix were compared with the threshold value. Value was set as zero in case values were found less than the threshold value. It means that the causal relation mentioned above was not considered (Saeed et al, 2021). Table 12 shows the significant relationship model.

Table 12. The crisp total- -relationships matrix by considering the threshold value

	Technical	Economic/Financial	Environmental	Political	Social
Technical	0	0.616	0.53	0	0.554
Economic/Financial	0.577	0	0	0	0.517
Environmental	0.591	0.545	0	0.547	0.524
Political	0.637	0.639	0.598	0	0.596
Social	0	0	0	0	0

Step 6: Causal relation diagram
In this step, the computation for D+R and D-R was done. D+R indicated the degree of importance of factor i in the entire system, while D-R indicated the magnitude of net effects contributed by factor *i* to the system.
The values for D+R and D-R are shown in Table 13.

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Table 13. Values for D-R and D+R

	R	D	D+R	D-R
Technical	2.659	2.601	5.26	-0.058
Economic/Financial	2.641	2.449	5.09	-0.192
Environmental	2.475	2.617	5.093	0.142
Political	2.266	2.882	5.148	0.616
Social	2.509	2.001	4.509	-0.508

Figure 4 shows a cause-effect diagram that indicates the model having significant relations. The x-axis shows the values of (D+R), and the y-axis shows the values of (D-R)

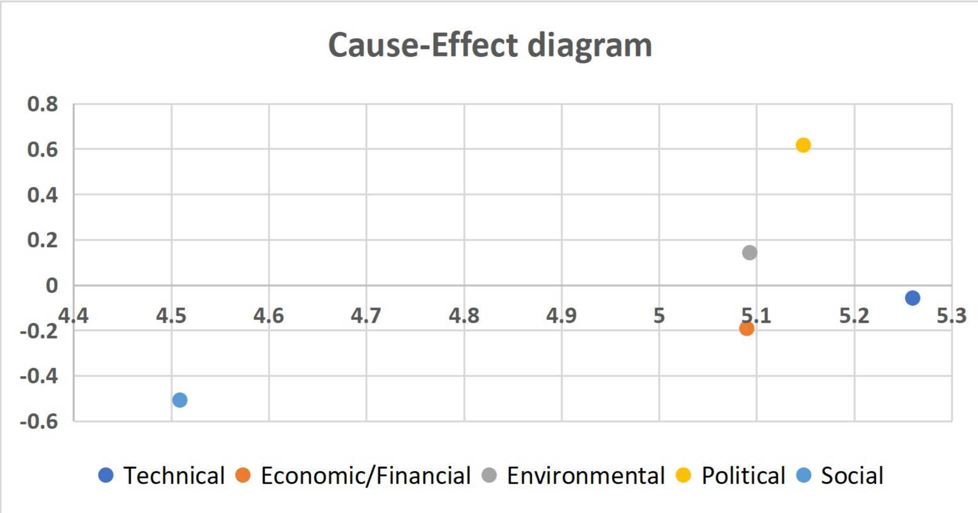

Fig. 4. Cause-effect diagram

Step 7: Interpretation of the results

The degree of importance by each factor in the system is indicated by D + R, which is a horizontal vector. The technical factor or criterion was ranked in first place, and Political, Environmental, Economic/Financial, and Social were followed in the next places. Environmental, Political are considered to be as causal variables or criteria, Technical, Economic/Financial, and Social were considered as effects.

The degree of a factor that influences the system is represented by D-R, which is a vertical vector. The vertical vector (D-R) represents the degree of a factor's influence on the system. Variables having D-R as positive values are causal variables, and variables having D-R as negative values are effect variables. In the first position, technical found the place, and Political, Environmental, Economic/Financial, and Social are ranked in next. Environmental and political are considered to be as causal variables, Technical, Economic/Financial, and Social are regarded as effects.

Weights of Criteria and sub-criteria using BWM

Step 1: The weight for each main criterion was computed based on pairwise comparison by experts using the Best-worst method. The consistency ratio was checked for the pairwise comparison against the associated threshold value. The pairwise consistency level was found to

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be acceptable

Step 2: The weight for each sub-criterion under each main criterion was computed based on pairwise comparison done by experts using the Best-worst method. The consistency ratio was checked for the pairwise comparison against the associated threshold value. The pairwise consistency level was found to be acceptable.

Step 3: The global weight for each sub-criterion was calculated by multiplying the weight of each sub-criterion by the weight of the respective main criterion. Table 14 shows the weight for the main criterion along with the global weight of respective sub-criteria

Table 14. Key criteria weight and sub-criteria's global weight

Key Criteria and Weight	**Sub-criteria**	**Sub-criteria weight**	**Global weight**	**Rank***
Technical: C1 (0.1657)	Efficiency	0.1399	0.0232	11
	Resource availability	0.2098	0.0348	16
	Reliability	0.1049	0.0174	9
	Investment capacity	0.3566	0.0591	19
	Tech innovation	0.0420	0.0070	2
	Tech maturity	0.1469	0.0243	12
	Consistency ratio =0.1248 Threshold value =0.3154	Acceptable consistency level		
Economic/Financial: C2 (0.0710)	Investment cost	0.1797	0.0128	6
	Operation & Maintenance cost	0.3672	0.0261	15
	R & D cost	0.1016	0.0072	3
	ROI	0.2031	0.0144	7
	Production cost	0.1016	0.0072	4
	Economic lifetime	0.0469	0.0033	1
	Consistency ratio =0.0714 Threshold value =0.3154	Acceptable consistency level		
Environmental: C3 (0.4438)	GHG emission	0.3418	0.1517	25
	PM2.5	0.0364	0.0161	8
	Noise pollution	0.0982	0.0436	17
	Water pollution	0.1309	0.0581	18
	Land use requirement	0.1964	0.0871	23
	Impact on	0.1964	0.0871	22

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	ecosystem			
	Consistency ratio =0.125 Threshold value =0.3154	Acceptable consistency level		
Political: C4 (0.1243)	Import dependency	0.0610	0.0076	5
	Legislation	0.2073	0.0258	13
	Energy policy	0.5244	0.0652	21
	Financial support	0.2073	0.0258	14
	Consistency ratio =0125 Threshold value =0.2521	Acceptable consistency level		
Social: C5 (0.1953)	Social benefits	0.3182	0.0621	20
	Social acceptability	0.5909	0.1154	24
	Job creation	0.0909	0.0178	10
	Consistency ratio =0.0666 Threshold value =0.1333	Acceptable consistency level		
Consistency ratio =0.0714 Threshold value =0.2819	Acceptable consistency level			

*High value for rank to be read as higher rank, and low value for rank to be read as lower rank

From Table 14, it can be observed that among the main criteria, the environmental criterion was considered of the highest importance by the experts, followed by social, technical, political, and economic or financial criteria when deciding on the best energy mix alternatives. Among the sub-criteria, GHG emission, land use requirement, and social acceptability were judged the top 3 important sub-criteria or attributes, and economic lifetime was considered the least important sub-criterion.

Fuzzy TOPSIS for Ranking of Energy Mix Resources

Step 1: Create a decision matrix

FUZZY TOPSIS was applied on 5 criteria to rank 4 alternatives. The expert's judgments were used to assign weight to each criterion. It was based on assigning the relative importance of each criterion over the other criterion to select the best energy mix alternative. The benefit criterion is represented by the plus sign, whereas the cost criterion is represented by a minus sign as shown in Table 15.

Table 15. Characteristics of Criteria

	name	type	weight
1	Technical	+	(0.500,0.700,0.900)
2	Economic	-	(0.300,0.500,0.700)
3	Environmental	+	(0.700,0.900,0.900)
4	Political	+	(0.300,0.500,0.700)
5	Social	+	(0.500,0.700,0.900)

Table 16 shows the fuzzy scale used in the model (Baharin et al., 2021).

Table 16. Triangular Fuzzy Numbers for pairwise comparison among criteria

Linguistic terms	**L**	**M**	**U**
Definitely poor_DP	0.0	0.0	1.0
Extremely poor_EP	0.0	1.0	2.0
Very poor_VP	1.0	2.0	3.0
Poor_P	2.0	3.0	4.0
Medium poor_MP	3.0	4.0	5.0
Fair_F	4.0	5.0	6.0
Medium good_MG	5.0	6.0	7.0
Good _G	6.0	7.0	8.0
Very good_VG	7.0	8.0	9.0
Extremely good_EG	8.0	9.0	10.0
Definitely good_DG	9.0	10.0	10.0

Source: Nedeljković et al. (2022);
https://www.tandfonline.com/doi/full/10.1080/00207543.2012.754553'

The energy mix alternatives in terms of various criteria were evaluated by experts and the results of the decision matrix are shown in table 17. As there were five experts participating in the in evaluation, therefore the matrix in table 17 represents the arithmetic mean of all experts' evaluation.

Table 17. Decision Matrix

	Technical	Economic	Environmental	Political	Social
RE	(4.600,5.600,6.600)	(3.800,4.800,5.800)	(8.400,9.400,10.000)	(4.800,5.800,6.800)	(8.000,9.000,9.800)
RE-NRNF	(6.600,7.600,8.600)	(4.800,5.800,6.800)	(7.800,8.800,9.800)	(4.800,5.800,6.800)	(4.200,5.200,6.200)
RE-NRNF-F	(7.400,8.400,9.400)	(5.800,6.800,7.800)	(5.600,6.600,7.600)	(4.800,5.800,6.800)	(3.800,4.800,5.800)
RE-F	(5.600,6.600,7.600)	(3.600,4.600,5.600)	(6.000,7.000,8.000)	(4.000,5.000,6.000)	(6.400,7.400,8.400)

Step 2: Create the normalized decision matrix (Alshahrani et al., 2022)

Based on the positive and negative ideal solutions, a normalized decision matrix was calculated as shown in Table 18 (Alshahrani et al., 2022).

Table 18. A Normalized decision matrix

A normalized decision matrix	Technical	Economic	Environmental	Political	Social
RE	(0.489,0.596,0.702)	(0.621,0.750,0.947)	(0.840,0.940,1.000)	(0.706,0.853,1.000)	(0.816,0.918,1.000)
RE-NRNF	(0.702,0.809,0.915)	(0.529,0.621,0.750)	(0.780,0.880,0.980)	(0.706,0.853,1.000)	(0.429,0.531,0.633)
RE-NRNF-F	(0.787,0.894,1.000)	(0.462,0.529,0.621)	(0.560,0.660,0.760)	(0.706,0.853,1.000)	(0.388,0.490,0.592)
RE-F	(0.596,0.702,0.809)	(0.643,0.783,1.000)	(0.600,0.700,0.800)	(0.588,0.735,0.882)	(0.653,0.755,0.857)

Step 3: Create the weighted normalized decision matrix

Considering the different weights of each criterion, the weighted normalized decision matrix was calculated (Kang et al., 2011). Table 19 shows the weighted normalized decision matrix

Table 19. The weighted normalized decision matrix

The weighted normalized decision matrix	Technical	Economic	Environmental	Political	Social
RE	(.245,.417,.632)	(.186,.375,.663)	(.588,.846,.900)	(.212,.426,.700)	(.408,.643,.900)
RE-NRNF	(.351,.566,.823)	(.159,.310,.525)	(.546,.792,.882)	(.212,.426,.700)	(.214,.371,.569)
RE-NRNF-F	(.394,.626,.900)	(.138,.265,.434)	(.392,.594,.684)	(.212,.426,.700)	(.194,.343,.533)
RE-F	(.298,.491,.728)	(.193,.391,.700)	(.420,.630,.720)	(.176,.368,.618)	(.327,.529,.771)

Step 4: Find FPIS (fuzzy positive ideal solution) and FNIS (fuzzy negative ideal solution)

Table 20 shows the positive and negative ideal solutions (Alshahrani et al., 2022).

Table 20. The positive ideal (PIS) and negative ideal (NIS) solutions

	PIS	NIS

Technical	(.394,.626,.900)	(.245,.417,.632)
Economic	(.138,.265,.434)	(.193,.391,.700)
Environmental	0.588,.846,.900)	(.392,.594,.684)
Political	(.212,.426,.700)	(.176,.368,.618)
Social	(.408,.643,.900)	(.194,.343,.533)

Step 5: Calculate the distance between each alternative and FPIS A* solution and the distance between each alternative and the fuzzy negative ideal solution A^{-}

The distance between each alternative and FPIS and the distance between each alternative and FNIS are respectively calculated and shown in Table 21 (al-Sulbi et al., 2021)

Table 21. Distance from positive and negative ideal solutions (Alshahrani et al., 2022)

Energy mix alternatives	Distance between alternative and FPIS	Distance between alternative and FPIS
RE	0.363	0.608
RE-NRNF	0.433	0.542
RE-NRNF-F	0.523	0.449
RE-F	0.671	0.301

Step 6: Calculate the closeness coefficient and rank the alternatives

The closeness coefficient of each alternative was calculated as per the following formula

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \qquad (27)$$

The best alternative is closest to the FPIS and farthest to the FNIS. The closeness coefficient of each alternative and its ranking order are shown in Table 22.

Table 22. Closeness coefficient

Decision Alternatives	Ci	rank
RE	0.626	1
RE-NRNF	0.556	2
RE-NRNF-F	0.462	3
RE-F	0.309	4

From table 22, it can be observed that renewable energy, which is comprised of solar, hydro-electric, and wind, is ranked as the best energy mix, followed by renewable (75%) plus biomass and nuclear (25%) as 2nd, renewable (50%) plus biomass & nuclear (25%) and fossil fuel as 3rd, and renewable (75%) plus fossil fuel (25%) as 4th ranked.

According to the results, decisions on the best energy mix alternative are impacted by five key criteria i.e., technical, economic or financial, environmental, political, and social. Environmental criteria (comprising majorly of GHG emission, water pollution, and land use requirements) as well as political criteria (comprising majorly of legislation, energy policy, Govt financial support) heavily influence the other criteria like technical (comprising majorly of efficiency, resource availability, reliability, investment capacity, technological innovation), economical (comprising majorly of costs related to investment, R &D, operations &

maintenance and production, return of investment, economic lifetime), social (comprising majorly of social benefits, social acceptability, potential for job creation). While evaluating the relative importance of each criterion over the other one, the output from the Fuzzy DEMATEL and BWM differs from each other to some extent. Fuzzy DEMATEL ranked technical, political, and environmental criteria as the top three, whereas BWM ranked environmental, social, and technical criteria as the top three among five criteria for meeting the goal of the best energy mix. Based on the global weights for the twenty-five sub-criteria, greenhouse gas emission (GHG), land use requirements, social acceptability, impact on the ecosystem, and energy policy were given the top five highly ranked weights, whereas economic lifetime, technological innovation, research & development cost, production cost, and import dependency were observed to be five least important sub-criteria for selecting the best energy mix. The fuzzy TOPSIS model provided the ranking for four different energy mix alternatives, in which a mix of renewable sources i.e. solar, hydroelectric, and wind was ranked as the best energy mix alternative, whereas renewable energy plus fossil-fuel-based sources ranked lowest as the energy mix alternative based on five criteria.

Conclusion and Implications

The present study attempted to identify various alternatives in terms of energy mix for power generation in India and rank them. For this purpose, key criteria and sub-criteria were explored through an extensive review of the literature. The research applied an integrated approach of using three extensively used models, i.e., Fuzzy DEMATEL, Best Worst method (BWM), and Fuzzy TOPSIS. The fuzzy DEMATEL was applied to examine the important cause-and-effect variables or criteria impacting decision alternatives. BWM was used to understand the relative weights among all key criteria, as well as global weights for all sub-criteria. Fuzzy TOPSIS was applied to rank all decision alternatives. For all three models, judgments from the five experts from the field of power generation and the energy sector, who were rich in experience and expertise, were solicited. Environmental and political variables were identified as causal variables, and technical, economic/financial, and social as effect variables. Sub-criterion GHG emission was computed as the highest weight or the most important sub-criterion. Solar, hydroelectric, and wind as energy resources were ranked the best energy mix alternatives.

A country like India cannot rely fully on a single source for power generation to meet the domestic, agricultural, and industrial requirements due to inherent constraints with each resource. Earlier studies failed to explore and evaluate the mix of energy resources that might suit to meet the energy requirements. The present study found environmental (such as GHG emission, land use requirement, etc.) and political (such as energy policy, financial support, etc.) factors as causal variables that would impact technical (like resource availability, technological innovation, etc.), social (like job creation, social benefits, etc.) and economic (Return of investment, operations, and maintenance cost, etc.) dimensions for keeping sustainability as the primary goal in the power generation sector. The results on the degree of importance among sub-criteria point out focus towards areas like resource availability, GHG emissions, energy policy, social acceptability, land use requirements, and impact on the ecosystem much needed to be in sync with the sustainable goal. Various studies suggest that dependency on fossil-based power generation has to be reduced and eliminated as early as possible not just because of GHG emissions, but also fast depletion of coal and gas reserves. In this connection, this research brings attention not only just to emphasize on use of green resources (like solar, hydro, wind, etc.) but equally to focus on resource conservation and social acceptability for power generation projects in the future. Therefore, the present study will be beneficial for policymakers and regulatory bodies in prioritizing the sources of energy, especially renewable sources with other non-fossil-based fuels for power generation in the medium term. Once achieving the scale of generation capacity and higher efficiency, the complete adoption of a renewable energy mix (dominated by solar and followed by hydro and wind) will be a way forward for India to achieve the net zero emission target by 2070 in the long run. Further study can be done to identify the composition of each fuel for energy mix optimization that might best suit the energy needs both in the medium as well as long-term.

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