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Article

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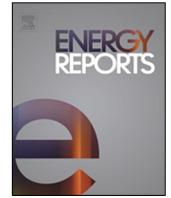
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Research paper

Measurement and analysis of wind energy potential using fuzzy based hybrid MADM approach



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ABSTRACT

Nowadays in India the renewable energy sources are continuum growing to accommodate the current demands of energy. Therefore, for an effective use of this energy, a careful and critical analysis is required. As per literature review, India was reported having a massive potential as superpower source in terms of wind energy. In the present research, an effort has been carried out to explore various decision making approaches such as TOPSIS, VIKOR, and Fuzzy analysis, to subsequently rank various Indian states with respect to their wind energy potential. In this perspective, potentiality indices have been found on the justification of five significant factors that influence the effective use of wind energy and then a classification has been proposed. It was found that the wind power density is the most significant parameter while the technical expertise has been found as the least significant among identified parameters. The results presented here indicates that among all alternative states of India, Tamilnadu and Maharashtra have the maximum potential to tap the wind energy potential. This study will act as a guide for various government agencies to re-evaluate and re-formulate their energy policies as well as will help various investors (under the 'Make in India' campaign) orientated to do business here, to take a well informed decision. The present study also provides a way to make strong policies, in the area of high wind energy potential, in order to maximize the use of renewable source of energy which allows to tackle the societal need and poverty.

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1. Introduction

Ever-increasing energy charges, extreme demand of energy, reviews over environmental supportability, and the global change in the climate; energy security and sustainable development are priority issues in the global agenda (Zhang, 2019). New and renewable energy technological tool sets are believed to be as one of the best possible solutions to meet up these challenges. Power calamity and green world vision are forcing authorities, researchers, and rule makers to review their viewpoint towards green solutions under technological constraints. This can be carried out mainly in two modes; (i) either choosing new ways or solutions which are very lengthy practice and time consuming or (ii) to make effort on effectual use of available sources. One of such available source is renewable energy sources; and among these sources, wind energy has been found potential

renewable energy source on the basis of advanced technology and low energy generation cost (Akdağ and Güler, 2018). However, these resources exist in plenty but in turn to fulfill current demands of energy, it is essential to have a vigilant perception for their efficient utilization. In Indian context, these are mainly categorized as hydro, solar and wind energy resources. Hydro and solar renewable energy resources are absolutely the greatest explored resources alongside, but these have various severe issues also (Fuselli et al., 2013). Solar power energy can be utilized only in day time and power generation also reduces during cloudy weather. Moreover, it has been reported that only 20% solar energy can be converted into electricity by most efficient solar cell (Green et al., 2019). Simultaneously, hydro-energy generation and development contain subject of time and a very huge capital tied-up in dams (Shahi, 2013). Furthermore, their upholding, cure and devastation are stated as the major issues and challenge (Sicchio, 1999). On the other hand, wind energy resources are environment friendly, clean, and provides favorable conditions for proficient exploitation of wind energy (Singh and Parida, 2013).

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Wind energy is the speedy rising renewable energy resource worldwide with an average growth rate of 30%. The report of ministry of new and renewable energy (MNRE) reveals that India is the 4th rank worldwide with installed capacity of more than 35.62 GW in energy generation from wind resource after USA, Germany and China (as on July 31, 2019) (Energy, M.o.N.R., 2019). The setup costs for wind energy are very less as compared to the hydro and solar plant. The advanced technological developments have been carried to get maximum power generation from available wind source. As per the technology and resource available within India, it has been estimated that on-shore wind energy utilization could be enhanced up to 102 GW for electricity generation (Association, I.W.E., 2019). India water territory is also quite impressive with 7517 KM of coastline and extends up to 12 nautical miles into the sea arena. This huge nature source of wind resource accessible in Indian scenario has the prospective to uphold the blooming in India in near future (EAI, 2017). Also, the Indian government has had a very positive outlook towards renewable energy sector in the past, and a number of government schemes and initiative are proposed and taken for this purpose. Make in India is one of the leading programs of Indian government to attract foreign investors in India for the manufacturing and establishment of plants in renewable energy sector also. Therefore, the contribution in this sector as gross domestic product (GDP) can be enhanced considerably. Economic growth, growing prosperity, increasing urbanization rates, and the energy consumption per capita are contributing to the country's increased demand for energy. Therefore, the investors will have massive opportunity to invest in India's area into sustainable energy sources (Chen and Zhang, 2019). Furthermore, in year 2016, the National Smart Grid Mission has been initiated by government of India to speed up smart grid establishment, as India is actively exploring renewable energy options such as wind, solar and others. With such volatile energy sources, a highly adaptive and intelligent grid is required rather than traditional grids. Smart grids are equipped with information and communication technologies (ICT), internet of things (IOT), sensor system, advanced monitoring, and decision system, which create an effective system to provide a consistent access of renewable power to grids (Thakur et al., 2015). This obviously indicates that wind energy development mission is the most potential source to meet the demand of energy in India. It has been observed that these development projects are fairly sizeable and involve enormous investments. However, there is very poor assessment of wind energy potential at global sites mostly in developing countries like India (Mahdy and Bahaj, 2018). To carry out wind energy projects in India, it is a prerequisite to know about the various technological factors, infrastructure, social issues, financial aspects, and government's perspectives. Furthermore, it is important to have a dependable investigation to resolve the frontline problems for making effective utilization of available wind energy resources.

In the present study, an effort has been made to investigate and assess the development and dispersal of wind energy potential in India. The present study investigates the major parameters which allows to identify the great potential of wind energy as a renewable source of energy. Besides, it provides a clear vision of the wind energy potential associated to the Indian State through which the government can focus on the pinpoint area to practice the maximum use of free and clean source of energy. This study will help India to expand its renewable energy sector, as well as reduce the dependence on conventional and other non-renewable resources of energy, which ultimately reduce the carbon footprints. It lay focus on the various geographical regions and encourage them to take the necessary steps to use and tap their wind energy potential (Cradden et al., 2016; Dai et al.,

2015). Such study is very critical activity, therefore, it prove to be essential because enable suitable solution by picking decisive parameters (Chen and Zhang, 2019; Vagiona and Kamilakis, 2018). Multiple attribute decision making (MADM) approaches were found as the best technique to deal with such type of problems in decision making (Kaya et al., 2019; Wang et al., 2018). The main aim of this approach is to find out the best optimal choice among the variety of alternatives for a specified assortment criteria. This methodology has been successfully executed to solve big variety of decision-making issues in technical research (Rathi et al., 2015a; Bagočius et al., 2014). Many popular decision taking methods are perceived under MADM category as reported in literature (Kaya et al., 2019). This includes graph theory and matrix approach (Rabbani et al., 2014), weighted product method, analytic hierarchy process (Saaty, 2014; Nikkhah et al., 2019), technique for order preference by similarity to ideal solution (TOPSIS) (Nanayakkara et al., 2019; Wu et al., 2018a), VlseKriterijumska Optimisacija I Kompromisno Resenje (VIKOR) (Liu et al., 2014; Rathi et al., 2017), simple additive weighting (Piasecki et al., 2019) multiplicative analytical hierarchy process (MAHP) (Cheng and Mon, 1994), Group decision making (Chen, 2000), and several more. These MADM techniques have been productively applied to various areas of engineering/sciences and among these decision approaches; TOPSIS and VIKOR are excellent decision making tools (Rathi et al., 2016a). These problem solving approaches have been implemented to various problems ranging from production planning (Chen and Liao, 2003), supplier selection (Jain et al., 2018), decision making (Mateusz et al., 2018), advanced manufacturing (Kulak and Kahraman, 2005), location selection (Senaroglu and Celebi, 2018), machine tool selection (Nguyen et al., 2014), and many more (Sasikumar and Vimal, 2019; Xu et al., 2017; Wang et al., 2019). The TOPSIS has been incorporated in the present work due to its rationality, comprehensibility, good computational efficiency, and ability to measure the relative performance for each alternative in simple mathematical form. These approaches work on crisp value of parameters. Consequently, in prominence of the purposes of the present study and perceptions gathered in past, present study utilized fuzzy-TOPSIS and fuzzy-VIKOR in integration with selection parameters weights compiled with MDL in order to determine potentiality index and consequent ranking of states of India as per wind energy potential. Thus, ultimate ranking score obtained using said approaches can be extremely valuable to the Indian government (central as well as states) for newer policy formulation, financial support allocation, and distributions for efficient use of existing wind energy resources.

The present work has been planned into six sections including introduction. Section 2 depicts evolution criteria of wind energy potential. Section 3 is devoted to preliminaries study of technique developed in the present work: TOPSIS, VIKOR, and fuzzy logic. Furthermore, Section 4 illustrates stepwise methodology adopted in the present research. The findings and discussion of the present research were presented in Section 5. The conclusions, limitations and future scope of the current research have been presented in Section 6.

2. Evaluation criteria

The first step for the assessment of the potential of wind energy in India is evaluation parameters identification. In this context, five prime parameters have been identified with their sub criteria that can have extensive impact on the potentiality of alternatives for tracing wind energy potential in India (refer Table 1).

These are derived from different studies conducted by researchers, archived in reputed databases and brainstorming

Table 1
Evaluation criteria.

S.no	Criteria	Code	Sub-criteria
1	Wind power density	P ₁	Mean energy density Annual mean wind speed Wind duration Elevated altitude
2	Availability of suitable land	P ₂	Land worth Environmental concerns Socio-economic impacts wind flow directions
3	Government initiatives	P ₃	National offshore wind energy policy FDI policy in renewable energy sector Renewable power obligation Green energy corridor project Financial Support
4	Grid connectivity	P ₄	Distance from the shore Power transmission grid nearness Closeness to energy demand zones
5	Technical prowess	P ₅	Proximity to construction facilities Technical feasibility

among various technical experts, societal spokespersons, government officials, financial experts and usual civilians (Fetanat et al., 2015; Wu et al., 2018b). It is essential to note that, due to social and geographical diversity as well as environmental aspect, the effect of these parameters may vary from place to place or region to region. A thorough facet of these parameters is detailed as follows:

2.1. Wind power density (P₁)

Wind is the fuel for wind power generation. One of the most essential wind attribute is mean energy density or power density of wind. Energy density of wind can directly influence the efficiency and readiness of wind energy potential. Wind power density can be classified as poor (<150 W/m²), average (150–250 W/m²), good (250–350 W/m²) and excellent (>350 W/m²) (Wind Power Density Categories, 2017). This is the most basic requirement for wind power generation and depends on a number of geographical and climatic factors. Also the wind turbine could be set up at elevated altitude to incarcerate more energy. When height of wind turbine changed from 10 to 50 m above the earth surface, the energy density of wind may boost almost double. Usually from the economic point of view, the wind power density is preferable to be as greater as 200 W/m² (Dai et al., 2015; Jamil et al., 1995).

2.2. Availability of suitable land (P₂)

Availability and land price are main aspects linked to execution of wind mills. These are thought to be fabricated on lesser worth land in order to diminish the total project cost. Additionally, other aspects such as local weather, direction of wind flow, physical aspects of land, environmental concerns, socio-economic impacts, and human and wildlife interruptions are the limitations towards a superior suitability site (Fetanat et al., 2015). The wind energy project should be set up away from buildings and residential areas, so as to avoid any obstruction to the wind flow. The areas near to bio-reserves and bird sanctuaries locations is usually not preferred for windmill sites (Vachaparambil et al., 2014). So, the areas having healthier connectivity are idyllically preferred otherwise it will cause difficulties in construction and maintenance of site.

2.3. Government initiatives (P₃)

Wind mills are costly projects and require enormous financial support. For this, Indian government is taking many attempts for publicizing wind energy usage via a variety of attractive policies. National offshore wind energy policy has been approved by the Indian government towards the end of the year 2015, which may reflect in considerable growth in wind energy capacity of India. In 2016–17, the additional capacity of wind power that reached 5.5 GW and foreign direct investment (FDI) under the automatic route pave the possibility to obtain up to 100% in the renewable energy sector. Some Amendments to the Ministry of Power's 2016 tariff plan was released to encourage the renewable energy which includes enhancement of renewable power obligations and generation obligation. The Ministry of New and Renewable Energy (MNRE) has announced a new bank loans up to a limit of \$2.3M to lenders for renewable power systems and public utilities based on renewable energy. The green energy corridor has been set up with an estimated investment of \$5.8B to ensure that renewable energy is evacuated from generation points to load centers by developing transmission infrastructure (Chen and Zhang, 2019). Apart from these; state governments have enforced numerous plans, for example, easy loans, long haul credit, arrive utilization pay, and funds for grid connectivity. Likewise, a few states particularly spend a lot of cash in exposure and mindfulness projects to advance use of renewable sources of energy (Mallet, 2001).

2.4. Grid connectivity (P₄)

An electrical framework is a sorted out system for conveying power from suppliers to shoppers. It comprises the creation of stations that deliver electrical power, high-voltage transmission lines which convey control from far off sources to request focuses, and dispersion lines connecting individual customers (Xu et al., 2017). Grid interconnection is regarded as a major challenge by the MNRE in case of off-shore wind energy, as the wind resources are dispersed geographically. Connecting renewable energy with the grids is a top priority for the government as it will benefit millions of households in Indian country and hence the government is setting up new projects in this regard (Mukhopadhyay et al., 2012).

2.5. Technical prowess (P₅)

Technology has always played a key role in the transformation of any nation. The Indian governments through its various new flagship programs like 'Make in India' are trying to shrink the technological gap by inviting manufacturing giants from all over the world to invest in India, and thus to gain the technical expertise from them. Global turbine manufacturers like Vestas and General Electric which were coming up in India provided a massive boost in this sector. Companies are based in particular states which have more proximity to the wind energy sites and facilitates for easy technical assistance, maintenance and repair, installations etc. A number of technical factors like poor installation, faulty design of turbine components, transmission losses, improper sighting and training leading to a low capacity utilization factor, pose a challenge for the effective utilization of wind energy in India (Rajsekhar et al., 1999).

3. Preliminaries

As indicated in the earlier sections, the current study focuses to identify the potentiality indices of wind resources in Indian states. This is evaluated by applying the fuzzy-TOPSIS integration in the company of MDL weights and validated against the VIKOR

results. The present strategy was applied to compute the ranking and potentiality index of the Indian states. The result of potentiality index is worth used by the governments to make policies and actions to support effectual use of existing wind energy resource.

3.1. TOPSIS

TOPSIS is fully recognized MADM technique, and was developed by renowned researchers Hwang and Yoon in early eighties (Lai et al., 1994). This method uses logical concepts to simplify the problems, which symbolizes preferences made by humans and allocate a value so that all can collectively provide outstanding and worst alternatives (Kim et al., 2013). Outstanding alternative comes out from application of TOPSIS methodology should encompass the narrowest distance from the positive ideal solution, and has the maximum gap from the negative ideal solution. The positive ideal solution increase the gain criteria and decrease the cost criteria, else the negative ideal solution increase the cost criteria and decrease gain criteria (Wang and Elhag, 2006).

3.2. VIKOR

VIKOR method was evolved for making solutions of complex decision making, mainly in such environment where we fails to set preferences (Opricovic and Tzeng, 2004). The main aim of VIKOR methodology is to rank given alternatives and find out compromise solution (feasible solution). A feasible solution means an agreement set up by common compromises and compromise solution of VIKOR is always nearest to the ideal one (Rathi et al., 2017). Elimination of units of criterion function in this method is done by using linear normalization. This method presents stout rankings because it actively reflects the views of many collections and reflects ambiguity in the input data.

3.3. Modified digital logic

MDL methodology is mainly employed to estimate the weightage for evaluation/selection parameters and it is a customized class of Digital logic. MDL possess salient benefits over Digital logic like; zero did not assign to less significant criterion and equal value may be assigned to two equally important criteria (Dehghan-Manshadi et al., 2007). Selection parameters discussed in above part have dissimilar effect on wind energy potential and therefore cannot be allotted equal weightage. Consequently, it turns out to be very essential to find the preferences of each criterion. With the consideration of decision experts, a decision table is created using a pair wise comparison relationship of selected parameters. One, two and three numeric values are assigned for less, equal or highly dominant parameters subsequently. It is very fundamental to compute number of probable positive decisions before framing of MDL matrix, using equation $N = n(n - 1)/2$, where n is number of available parameters. Final weightage is calculated by summation of all positive decisions (D) for any particular parameter on normalization (refer Eq. (1)).

$$W_j = \frac{D_j}{\sum_{j=1}^n D_j} \tag{1}$$

3.4. Fuzzy logic

It is a multivalued logic, and it permits mediatory values to be described in between usual assessments like good/bad, yes/no, true/false etc. The importance of this approach has been estimated from the reality that the nearly all human being-reasoning approaches are vague in nature (Zedeh, 1989; Wu et al., 2019). Fuzzy logic mainly used to solve problems in which there

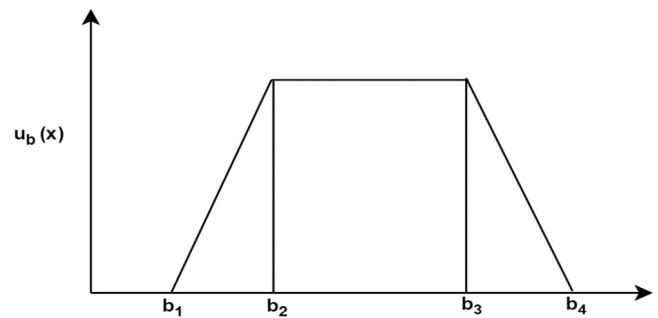


Fig. 1. Trapezoidal fuzzy number.

are no clear visions in between the two parameters. A fuzzy theory mainly works on fuzzy sets, identified by a membership function (Kumar et al., 2019). In these sets, membership function is assigned to every entity a membership grade in interval zero and one. This approach has proven a best way for solving judgmental problems where subjective and unclear information is available (Zadeh, 1965; Rathi et al., 2015b). Mainly fuzzy logic judgments of any function are difficult to compute without using linguistic variables. The value of linguistic variable is expressed in words/sentences in natural or unnatural language. These variables provide a means of approximate depiction of event which are generally difficult to explain in straight terms. In these variables general terms such a small, medium and large are used to detain corresponding numerical values (Rathi et al., 2016b). Various fuzzy numbers are employed to solve different problems based on situation. Trapezoidal fuzzy number (TFN) is deployed in present study (b_1, b_2, b_3, b_4) for $\{b_1, b_2, b_3, b_4 \in R; b_1 \leq b_2 \leq b_3 \leq b_4\}$ as depicted in Fig. 1.

This number has been adopted due to its ease of use, intuitive, coherent ordering, promoting representation and computationally simple. TFN also provides good outcomes because of its simple information flow (Roldán López de Hierro et al., 2019). Membership function $\mu_b(x)$ of this number is defined with the help of Eq. (2).

$$\mu_b(x) = \begin{cases} \frac{x - b_1}{b_2 - b_1}, & x \in [b_1, b_2] \\ 1, & x \in [b_2, b_3] \\ \frac{b_4 - x}{b_4 - b_3}, & x \in [b_3, b_4] \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

4. Proposed subjective fuzzy-TOPSIS/VIKOR approach

This section describes the steps involved in the adopted methodology for exploration of wind energy potential in India. Adopted methodology uses weights of evaluation criteria for pair wise comparison for all selected criteria tracked by fuzzy logic integration with TOPSIS and VIKOR methods to get most favorable alternatives. The computations of present study have been conducted by using MATLAB, 18 version software package. Flow chart of methodology for wind energy potential exploration has been shown in Fig. 2.

This finely shows that at initial level evaluation criteria was decided. Thereafter, on the basis of input gained decision compiler construct all decision matrixes for MDL, Fuzzy-TOPSIS, and VIKOR for finding Potentiality Index. It contains subsequent steps:

Step 1: MDL weights of evaluation criteria estimation

As per Section 3.3, MDL weights (W_j) are calculated for complete selection parameters. This provides the weightage of all considered criteria.

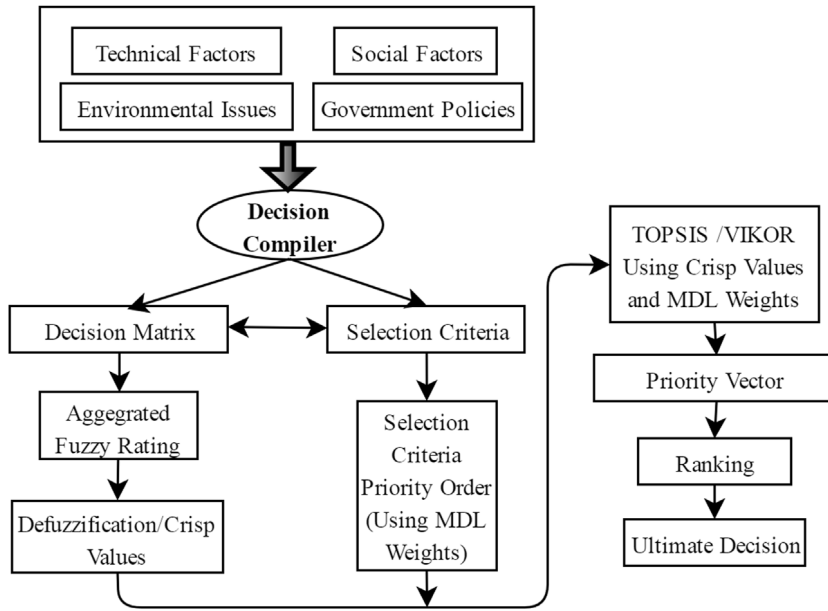


Fig. 2. Flow chart for proposed approach.

Step 2: Outline appropriate linguistic variables and equivalent fuzzy numbers. Fuzzy membership sets are required to compare all the available options for each given criterion. Decision makers allocate these fuzzy terms for each available alternative for comparisons of the alternatives based upon selected criteria.

Step 3: Construction of pair wise decision matrix.

Let q be the alternatives and p be the parameters. In projected model for k number of decision makers in the aggregated fuzzy score for C_j criterion is represented as $x_{ijk} = \{x_{ijk1}, x_{ijk2}, x_{ijk3}, x_{ijk4}\}$. For $i = 1, 2, \dots, p; j = 1, 2 \dots, q; k = 1, 2 \dots, k$, x_{ijk} is calculated as

$$\begin{cases} x_{ij1} = \min_k \{b_{ijk1}\} \\ x_{ij2} = \frac{1}{k} \sum b_{ijk2} \\ x_{ij3} = \frac{1}{k} \sum b_{ijk3} \\ x_{ij4} = \max_k \{b_{ijk4}\} \end{cases} \quad (3)$$

Thus the obtained decision matrix (M) is shown as:

$$M = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1p} \\ x_{21} & x_{22} & \dots & x_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ x_{q1} & x_{q2} & \dots & x_{qp} \end{bmatrix}$$

Step 4: Normalization

For any comparison the major requirement is that all contrasted quantities should be on the same scale. Therefore, aggregated fuzzy score was normalized in this step using the following Equations:

$$\mu_{ij} = \left(\frac{x_{ij1}}{x_{ij1}^+}, \frac{x_{ij2}}{x_{ij2}^+}, \frac{x_{ij3}}{x_{ij3}^+}, \frac{x_{ij4}}{x_{ij4}^+} \right), \quad j \in J \quad (4)$$

$$\mu_{ij} = \left(\frac{x_{ij1}^-}{x_{ij1}^-}, \frac{x_{ij2}^-}{x_{ij2}^-}, \frac{x_{ij3}^-}{x_{ij3}^-}, \frac{x_{ij4}^-}{x_{ij4}^-} \right), \quad j \in J' \quad (5)$$

where $x_{ij4}^+ = \max(x_{ij4}), j \in J; x_{ij1}^- = \min(x_{ij1}), j \in J'$ where J equivalent to higher preferred value and J' equivalent to lower preferred value.

Step 5: Defuzzification

It is a process of changing the output of fuzzy to quantified result (crisp value) in fuzzy logic system by real valued functions. Defuzzification is worked to get the crisp values for each criterion corresponds to every alternative. The input for this method is cumulative set and the output is a single number value. This method gives a quantitative result for the fuzzy numbers and linguistic variables assigned to given alternatives based upon decision maker's verbal reasoning. Eq. (6) provides the required crisp values given in Box 1. Obtained crisp values/ quantified result have integrated with weightage of selection criteria to compute ultimate ranking using TOPSIS and VIKOR approach as discussed with below steps.

TOPSIS Approach Steps

Step 6: Normalized the matrix as given below:

$$r_{ij} = \frac{f_{ij}}{\sqrt{\sum_{i=1}^m (f_{ij})^2}}; \forall j \quad (7)$$

Step 7: Calculate the weighted normalized decision matrix as given:

$$V_{ij} = [r_{ij}]_{m \times n} \times [W_j]_{n \times m}^{diagonal} \quad (8)$$

Step 8: Calculate the positive ideal and negative ideal solution:

The positive ideal solution V_j^+ and negative ideal solution V_j^- are as given below:

$$V_j^+ = \{(\max V_{ij}, j \in J_1), (\min V_{ij}, j \in J_2), i = 1, 2, 3 \dots m\}; \forall j \quad (9)$$

$$V_j^- = \{(\min V_{ij}, j \in J_1), (\max V_{ij}, j \in J_2), i = 1, 2, 3 \dots m\}; \forall j \quad (10)$$

where J_1 and J_2 represents higher best and lower best criteria respectively.

$$\begin{aligned}
 f_{ij} &= \text{Defuzz}(x_{ij}) = \frac{\int \mu(x) \cdot x dx}{\int \mu(x) \cdot dx} \\
 &= \frac{\int_{x_{ij1}}^{x_{ij2}} \left\{ \frac{(x - x_{ij1})}{(x_{ij2} - x_{ij1})} \right\} \cdot x dx + \int_{x_{ij2}}^{x_{ij3}} x dx + \int_{x_{ij3}}^{x_{ij4}} \left\{ \frac{(x_{ij4} - x)}{(x_{ij4} - x_{ij3})} \right\} \cdot x dx}{\int_{x_{ij1}}^{x_{ij2}} \left\{ \frac{(x - x_{ij1})}{(x_{ij2} - x_{ij1})} \right\} dx + \int_{x_{ij2}}^{x_{ij3}} dx + \int_{x_{ij3}}^{x_{ij4}} \left\{ \frac{(x_{ij4} - x)}{(x_{ij4} - x_{ij3})} \right\} \cdot x dx} \\
 &= \frac{-x_{ij1}x_{ij2} + x_{ij3}x_{ij4} + (1/3)(x_{ij4} - x_{ij3})^2 + (1/3)(x_{ij2} - x_{ij1})^2}{-x_{ij1} - x_{ij2} - x_{ij3} + x_{ij4}} \tag{6}
 \end{aligned}$$

Box I.

Step 9: Calculate the distance d_i^+ and d_i^- from the positive ideal solution and negative ideal solution respectively

$$d_i^+ = \left[\sum_{j=1}^n (V_{ij} - V_j^+)^2 \right]^{0.5}, \quad i = 1, 2, 3, \dots, m \tag{11}$$

$$d_i^- = \left[\sum_{j=1}^n (V_{ij} - V_j^-)^2 \right]^{0.5}, \quad i = 1, 2, 3, \dots, m \tag{12}$$

Step 10: Compute of TOPSIS rank index:

$$C_i^+ = \frac{d_i^-}{d_i^- + d_i^+} \tag{13}$$

States with highest rank index C_i^+ are preferred.

VIKOR Approach Steps

Step 6: Determination of ideal and negative ideal solutions;

The ideal solution f^* and negative ideal solution f^- are determined as

$$f^* = \{\max f_{ij}\} \tag{14}$$

$$f^- = \{\min f_{ij}\} \tag{15}$$

Step 7: Calculation of utility and regret measures

$$S_i = \sum_{j=1}^n W_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)}; \quad \forall i \tag{16}$$

$$R_i = \text{Max}_j \left[W_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \right]; \quad \forall i \tag{17}$$

where S_i and R_i represent the utility and regret measures, respectively and W_j is the relative weight assigned to the j th parameter using MDL.

Step 8: Calculation of VIKOR index

$$Q_i = v \left[\frac{S_i - S^*}{S^- - S^*} \right] + (1 - v) \left[\frac{R_i - R^*}{R^- - R^*} \right]; \quad \forall i \tag{18}$$

where Q_i represents i th alternatives VIKOR value, v is the group utility weight, it is generally considered as 0.5 (unsupervised) and;

$$S^* = \min_i S_i \tag{19}$$

$$S^- = \max_i S_i \tag{20}$$

$$R^* = \min_i R_i \tag{21}$$

$$R^- = \max_i R_i \tag{22}$$

Table 2
Subjective weights of the evaluation criteria calculated using MDL.

Parameters	P1	P2	P3	P4	P5	Positive decisions	Weights	Rank
Wind power density	2	3	3	3	3	12	0.3000	1
Availability of suitable land	1	2	3	3	3	10	0.2500	2
Government initiatives	1	1	2	3	3	8	0.2000	3
Grid connectivity	1	1	1	2	1	4	0.1000	5
Technical prowess	1	1	1	3	2	6	0.1500	4

Best alternative (states) with least value of VIKOR index Q_i is preferred.

5. Findings and discussion

The aim of current study is to determine the potentiality indices for healthier exploration of wind energy resources in Indian States. In this framework, the selected states of India are graded based on decisive factors that impact the potential investigation of wind energy. Fig. 3 demonstrates through a schematic hierarchy the current problem. First level shows the prime goal of this study that has to be accomplished through five shortlisted evaluation criteria Wind power density (P_1), Availability of suitable land (P_2), Government initiatives (P_3), Grid connectivity (P_4), and Technical prowess (P_5) as explained in Section 2 and in hierarchy second level.

These criteria have been picked out by several information and reports published by various government bureaus. Further, third level shows the eight Indian states (Andhra Pradesh S_1 , Gujarat S_2 , Karnataka S_3 , Kerala S_4 , Madhya Pradesh S_5 , Maharashtra S_6 , Rajasthan S_7 and Tamilnadu S_8) that are examined in current problem. These alternatives have shortlisted by wind power zones with wind power density greater than 200 W/m². This decision making is very complex because alternatives have complete Interdependency on selection parameters as shown in Fig. 3. Moreover, in present case apart from huge time, extensive knowledge of both technological and economic aspects is needed. After the parameters are recognized, the next prime thing is to weight these parameters, as which parameter has more effect on identified alternatives. The prioritization of said parameters was carried out by using MDL method. Decision matrix for MDL is shown in Table 2 and the selected parameters contributions are demonstrated in Fig. 4.

Wind power density is appeared as most influential parameter while the grid connectivity is appeared as least important parameter in Indian perspective. The next stage decides the probability index and the relating positioning of shortlisted states. In this specific situation, fuzzy methodology is utilized as it functions admirably for the issues where verbal prevailing should be changed

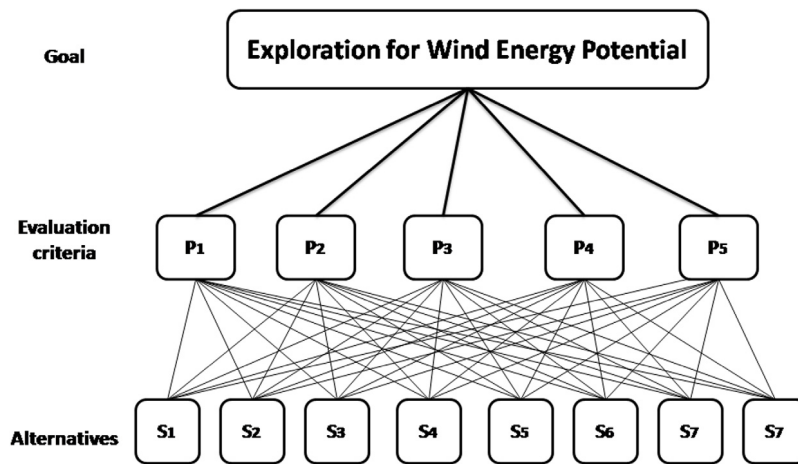


Fig. 3. Schematic hierarchy for exploration for wind energy potential.

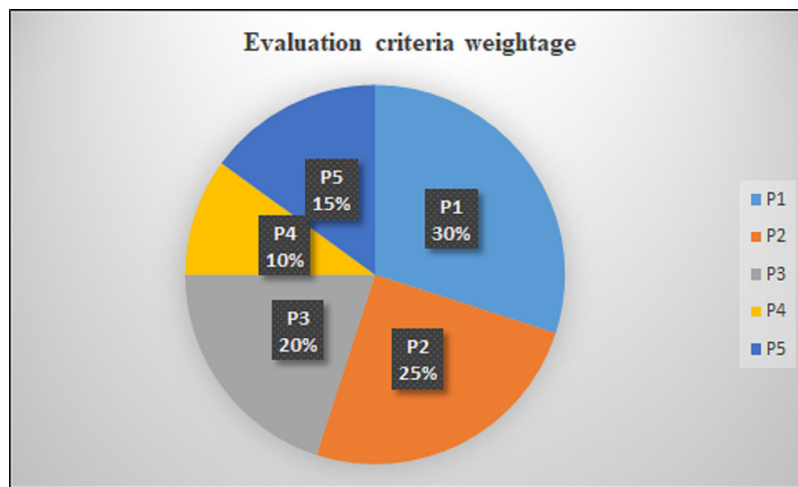


Fig. 4. Evaluation parameters contribution for wind energy potential exploration.

Table 3
Linguistic variables and corresponding fuzzy numbers.

Linguistic variable	Fuzzy number
Extremely high (EH)	(0.8, 0.9, 1.0, 1.0)
Very high (VH)	(0.7, 0.8, 0.8, 0.9)
High (H)	(0.5, 0.6, 0.7, 0.8)
Above average (AA)	(0.4, 0.5, 0.5, 0.6)
Average (A)	(0.2, 0.3, 0.4, 0.5)
Very low (VL)	(0.1, 0.2, 0.2, 0.3)
Extremely low (EL)	(0.0, 0.0, 0.1, 0.2)

Table 4
Linguistic decision matrix of wind energy exploration.

Indian states (Alternatives)	Evaluation criteria (Parameters)				
	P ₁	P ₂	P ₃	P ₄	P ₅
Andhra Pradesh (S ₁)	VH	VH	H	H	VH
Gujarat (S ₂)	VH	VH	EH	H	H
Karnataka (S ₃)	AA	H	AA	AA	AA
Kerala (S ₄)	A	A	AA	AA	AA
Madhya Pradesh (S ₅)	VL	A	VL	AA	EL
Maharashtra (S ₆)	VH	VH	VH	H	EH
Rajasthan (S ₇)	VL	A	A	AA	VL
Tamil Nadu (S ₈)	EH	EH	VH	H	VH

Table 5
Calculated crisp values for assigned fuzzy numbers.

Indian states (Alternatives)	Evaluation criteria (Parameters)				
	P ₁	P ₂	P ₃	P ₄	P ₅
Andhra Pradesh (S ₁)	0.8333	0.8333	0.6667	0.6667	0.8333
Gujarat (S ₂)	0.8333	0.8333	0.9444	0.6667	0.6667
Karnataka (S ₃)	0.5333	0.6667	0.5333	0.5333	0.5333
Kerala (S ₄)	0.3667	0.3667	0.5333	0.5333	0.5333
Madhya Pradesh (S ₅)	0.2333	0.3667	0.2333	0.5333	0.0778
Maharashtra (S ₆)	0.8333	0.8333	0.8333	0.6667	0.9444
Rajasthan (S ₇)	0.2333	0.3667	0.3667	0.5333	0.2333
Tamil Nadu (S ₈)	0.9444	0.9444	0.8333	0.6667	0.8333

over into subjective esteems. Table 3 contains the linguistic variables used for the exploration for wind energy potential and their equivalent fuzzy numbers.

The top range is expressed extremely high (EH) and the least is termed extremely low (EL). At first a Linguistic decision matrix (refer Table 4) for selected alternatives was framed for all evaluation criteria by the choice compilers with views of different decision makers.

A solitary decision matrix was framed as opposed to having a different decision matrix for every chief. A short time later, the linguistic factors and their comparing fuzzy rates are accumulated and defuzzification done using Eq. (6). Table 5 demonstrates the calculated crisp values/quantified results obtained using Eq. (6). Further next, obtained quantified results are employed to calculate the potentiality index using TOPSIS approach (Eqs. (7)–(13))

Table 6
Calculated TOPSIS and VIKOR ranks.

Indian states (Alternatives)	TOPSIS index	TOPSIS rank	VIKOR index	VIKOR rank
Andhra Pradesh (S_1)	0.927	4	0.1183	4
Gujarat (S_2)	0.954	3	0.0644	3
Karnataka (S_3)	0.417	5	0.4113	5
Kerala (S_4)	0.138	6	0.5879	6
Madhya Pradesh (S_5)	0	8	0.75	8
Maharashtra (S_6)	0.97	2	0.0555	2
Rajasthan (S_7)	0.014	7	0.7161	7
Tamil Nadu (S_8)	0.992	1	0	1

Table 7
Comparison of results with DEMATEL analysis.

Indian states (Alternatives)	TOPSIS rank	VIKOR rank	DEMATEL rank
Andhra Pradesh (S_1)	4	4	4
Gujarat (S_2)	3	3	3
Karnataka (S_3)	5	5	5
Kerala (S_4)	6	6	6
Madhya Pradesh (S_5)	8	8	7
Maharashtra (S_6)	2	2	2
Rajasthan (S_7)	7	7	8
Tamil Nadu (S_8)	1	1	1

of different states in integration with the selection parameters. Table 5 shows corresponding rank indices and ranks of the respective states. The results obtained by TOPSIS further validated with VIKOR ranks (using Eqs. (14)–(22)) to confirm consistency of ranks (refer Table 6). Additionally, the obtained results have been compared with Decision making trial and evaluation laboratory (DEMATEL) results in order to confirm the robustness of outcome. This technique was first developed to define the cause and effect relationship among the variables by the Geneva research center of the Battelle Memorial Institute (Si et al., 2018). DEMATEL not only exhibits the cause and effect relationship but also identify the critical factors of an intertwined system. It has successfully been applied as a precise decision making approach where the complex systems involve the indefinite and uncertain information like, supplier selection (Abdel-Basset et al., 2018); analyzing barriers of waste recycling (Chauhan et al., 2018); sustainable recycling partner selection (Lo et al., 2019); probabilistic safety analysis (Yazdi et al., 2020) etc.

A correlation of nearly 100% is revealed in the comparison with Decision making trial and evaluation laboratory (DEMATEL) results of both MADM approaches which show the robustness of our results (refer Table 7). It fairly shows that Tamilnadu is at the top as prime choice for investors while Madhya Pradesh stands at the bottom. Madhya Pradesh also comes in 200–250 W/sq-m wind power density zone but got lowest positioning due to poor land accessibility, absence of government activities and absence of mindfulness. This plainly demonstrates Madhya Pradesh government needs to attempt tremendous true endeavors. Another essential perception is that there is little difference in priority order of Rajasthan, Kerala and Madhya Pradesh; which implies that these states can be ordered in a similar class and a little change within assessment criteria may perhaps horribly influence positioning. Present study ultimately provides positive direction to government of India vision for achieving 175 GW installed capacity of renewable energy by 2022.

5.1. Sensitivity analysis

The sensitivity analysis is an important tool to find the variations in output with respect to the change in the outputs (Delgarm et al., 2018). The sensitivity analysis was performed using

Table 8
Sensitivity analysis.

S. No.	Rank	TOPSIS index	Max. variation through sensitivity analysis	Min. variation through sensitivity analysis
1	3	0.712799027	0.7377	0.7127
2	4	0.688015539	0.7092	0.688
3	5	0.131740959	0.1441	0.131
4	6	0.070408705	0.077	0.07
5	8	0	0	0
6	2	0.877839827	0.887	0.887
7	7	0.005928933	0.0053	0.0059
8	1	0.944061577	0.9508	0.944

what if analysis for the TOPSIS. The analysis was performed in the present case to check the effect for the variations in the input parameters of TOPSIS on the final evaluated results. The sensitivity analysis was performed for the variation of -20% and $+20\%$ in the input value of parameters. It has been identified that with the variation in the input parameters there is no major variations in the ranks of the TOPSIS. In the first case of Table 7, when was made a variation between -20% to $+20\%$, of the input values, of the present TOPSIS index was reached for the final variation a maximum of 0.0249, which do not significantly affect the present TOPSIS rank. Similarly, for the last case of Table 7 by making a variation of the input parameters, it was reported the maximum variation on the TOPSIS as 0.0068 that also do not significantly affect the rank. Therefore, with the variations -20% and $+20\%$ in the input parameters there is no much effect on the identified ranks (refer Table 8). So, the results gathered through TOPSIS approach are highly consistent and reliable.

6. Conclusions

The success rate of wind power plants is quite low in India cause of wrong project selection. The present study provides a novel applicability of hybrid MADM approaches by exploring the wind energy potential across Indian states. MDL method is utilized to compute weights of all affecting parameters for selection of the best alternative. Wind power density and Grid connectivity have been found to be most and least critical parameters, respectively. Further, the priority order of Indian states is determined using fuzzy TOPSIS approach integration with MDL weights and validated against VIKOR results. Tamilnadu was found to be the most appropriate states of India for tapping wind energy potential. Concurrently, Rajasthan, Kerala and Madhya Pradesh are named the bottom individuals from analogs group. Present study validates the feasibility of fuzzy logic developed using the TOPSIS and VIKOR approach for optimal exploration of wind energy potential in Indian context. The obtained results have been validated by DEMATEL approach and sensitivity analysis. This study will facilitate policy makers and government agencies to select the particular location to harness the maximum wind energy potential. Moreover, this will empower a healthy competition among the various state governments to take initiative for tapping the available sources of wind based renewable energy. The outcomes of present research will help practitioners, researcher's, government and industrialists to anticipate suitable site selection for wind power installation. Consequently, with present results, the attention on wind energy potential zones can be ranked at initial stage of projects, so, that the society will also benefit with sustainable development. The government and engineering managers should think more on wind energy potential zones prior execution of their projects.

The limitation of present study is that the proposed model has been developed on the basis of technical expert's opinions, reports, government officials and it is not tested pragmatically

to support the findings. This research is probing in nature and certain partiality may exist due to expert's judgment. In future, these limitations can be overcome by real-time execution of proposed model with any case company (wind energy installation organization) and secondly, the bias expert's judgment can be reduced by using statistical approach like principal component and/or confirmatory factor analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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