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MCDM and GIS based modelling technique for assessment of solar and wind farm locations in India

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A B S T R A C T

In the recent past, various factors have led to an increase in the use of renewable energy sources, among which, the depleting fossil fuel reserves, increasing fuel prices, and rising environmental concerns are the most prominent. With this increasing reliance on renewable energy sources, a proper assessment of the suitable sites becomes necessary for the optimum utilization of these resources. The present study investigates the spatial suitability of the solar and wind farms locations in India based on the technical, economic, and socio-environmental perspectives. The analysis is performed with the coupled use of the Geographical Information System (GIS) and Multi-Criteria Decision Making (MCDM) approaches. Analysis of present research work shows that 4.13% of the study area (133,874 km^2) is highly suitable for the deployment of solar plants while 0.91% of the total area (29,457 km^2) is highly suitable for the wind farms. The study further concludes that the Rajasthan state in India has the highest suitable land for the installation of solar plants (20,881 km^2) as well as wind farms (6323 km^2). The proposed model can be used for the development of policies related to renewable energy resources and the assessment of suitability of already sanctioned projects.

1. Introduction

Energy is a vital necessity for the sustainable development and well-being of any country. According to the International Energy Agency (IEA), fossil fuels are currently the primary sources of energy generation for the entire world [1]. Nearly 80% of the world's energy production is through fossil fuels such as crude oil, coal, and natural gas which respectively contribute 31%, 28%, and 22% to the total capacity [2]. Since the fossil fuel reserves are limited and unevenly distributed, this imbalance is expected to cause serious economic and political conflicts in the near future [2–4]. The depleting fuel reserves, increasing fuel prices, and rising environmental concerns have led to an increasing focus on the inexhaustible, renewable energy sources (RES) [5] which have already attained a significant capacity worldwide. The world's total installed RES capacity exceeded 2378 GW by the end of the year 2018 with increasing capacity enhancements thereafter. Among the various renewable energy sources, solar and wind energy are the most promising, rapidly growing, and mature technologies [2,5,6]. This is evident from the fact that during the year 2018, solar energy constituted 55%, the wind energy constituted 28% while the hydro energy comprised only 11% of the overall capacity enhancement [7]. The solar and wind energy are also helpful in the sustainable development by improving the quality of rural life, minimizing the economic burden, increasing energy security, reducing foreign dependency, creating jobs at the local level, and finally, reducing the emission of pollutants in the environment. The rapidly growing solar and wind energy resources have led to new challenges related to their dependency on climatic and weather conditions [8]. These have also created new issues like habitat loss, land degradation, noise generation and visual intrusion [9,10]. Nevertheless, to maximize the utilization of commercial resources and to minimize the impact of various issues, there is a clear need for a proper assessment of suitable locations for the installation of solar and wind farms [11]. Site selection for solar and wind energy resources is a complex and difficult task. In addition to issues like meteorological requirements, environmental concerns, and economic profitability, one also has to consider the societal challenges as well as the risks associated with plant construction and operation [12,13]. Sites with the highest availability of resources like solar radiation and wind velocity are not always the most feasible ones

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Nomenclature

GIS	Geographical Information System
MCDM	Multi-Criteria Decision Making
F-AHP	Fuzzy Analytical Hierarchy Process
IEA	International Energy Agency
RES	Renewable Energy Sources
IMD	Indian Meteorological Department
OWA	Order Weighted Averaging
ESRI	Environmental System Research Institute
GM	Geometric Mean
CR	Consistency Ratio
NREL	National Renewable Energy Laboratory

for the installation of solar and wind power plants. A number of other factors play a significant role in the assessment of suitable locations which can be categorized into climatic, ecological, economic factors [14,15]. Before investing capital in the infrastructure, a systematic analysis of the various factors affecting the performance and operational economy of renewable energy-based power plants is indispensable. In the current work, employing the Geographical Information System (GIS) and Multi-Criteria Decision Making (MCDM) based approaches for selecting the optimal locations of solar and wind power plants in India. These approaches have been widely used for the selection of suitable sites worldwide. GIS is a valuable tool in the multi-contexts decision making problems in which geo-referenced information's plays a significant role. GIS approach has the capabilities of data storage, data management, calculations, analysis, and visualization of georeferenced data [16]. Mainly, GIS visualizes raw, unrelated data into a meaningful manner when combined with expert's perception [17]. Similarly, the MCDM approach is a well-known decision support approach for solutions to complex problems where multiple factors affect a single goal [18,19]. The MCDM approach provides a suitable option through the evaluation and comparison of the characteristic properties of the alternatives [20]. Thus, by combining the two different approaches of GIS and MCDM, a unique and cohesive framework is possible that can handle complex spatial planning problems. There are many studies in the literature that employed GIS-based MCDM approaches for the evaluation of suitable locations. In the following, briefly discussed about the important previous works related to the use of the above-mentioned approaches for optimizing power plant locations across the world.

Aydin et al. [21] developed a decision support framework for selecting suitable sites for wind turbine installation in the western part of Turkey. Villacreses et al. [20] selected the most feasible locations for wind energy resources for Ecuador. Palmer et al. [22] determined optimal location for a large-scale power plant installation in the United Kingdom while fulfilling the economic, technical, and environmental requirements. Firozjaei et al. [23] integrated GIS tools with the Order Weighted Averaging (OWA) method for investigating the optimal locations for solar energy resources in Iran. Aly et al. [24] investigated the potential sites for implementing the Solar Photovoltaic (SPV) and Concentrated Solar Power (CSP) plants in the Republic of Tanzania. Charabi and Gastli [25] calculated the land suitability index for the installation of SPV and CSP power plants in Oman. Tsoutsos et al. [26] prioritized the available land area for sizing the sustainable wind farms in Crete. Christoforaki and Tsoutsos [27] carried out research work with the objective of assessment of wind power potential in the regional unit of Chania in western Crete by excluding the unsuitable sites and consideration of environmental impacts. Nematollahi and Chun Kim [28] investigated the feasibility of solar energy in the different regions of South Korea using minimum, average, and maximum values of yearly horizontal radiation measured by 24 weather stations during the span of five year. Dhunny et al. [29] developed a GIS and fuzzy logic integrated framework for the identification of economic feasible and sustainable sites for solar, wind and hybrid farms installation in Zimbabwe. Alkhalidiet et al. [30] analytically calculated the wind energy potential in the state of Kuwait using the wind velocity data at different hub heights of 50 m, 80 m, 100 m, and 120m respectively. There is no such literature available on the systematic evaluation of suitable sites for the wind and the solar farms in India according to the best of the authors' knowledge. This identifies the objectives of the current research work which are as follows:

- To investigate suitable sites for the installation of solar and wind farms in India using GIS and MCDM approaches.
- To explore the potential area in different states and union territories of India.
- To perform the sensitivity analysis based on the aspects of equal weight, economic, technical, and socio-environment.
- To estimate theoretical power potential from solar and wind in India.

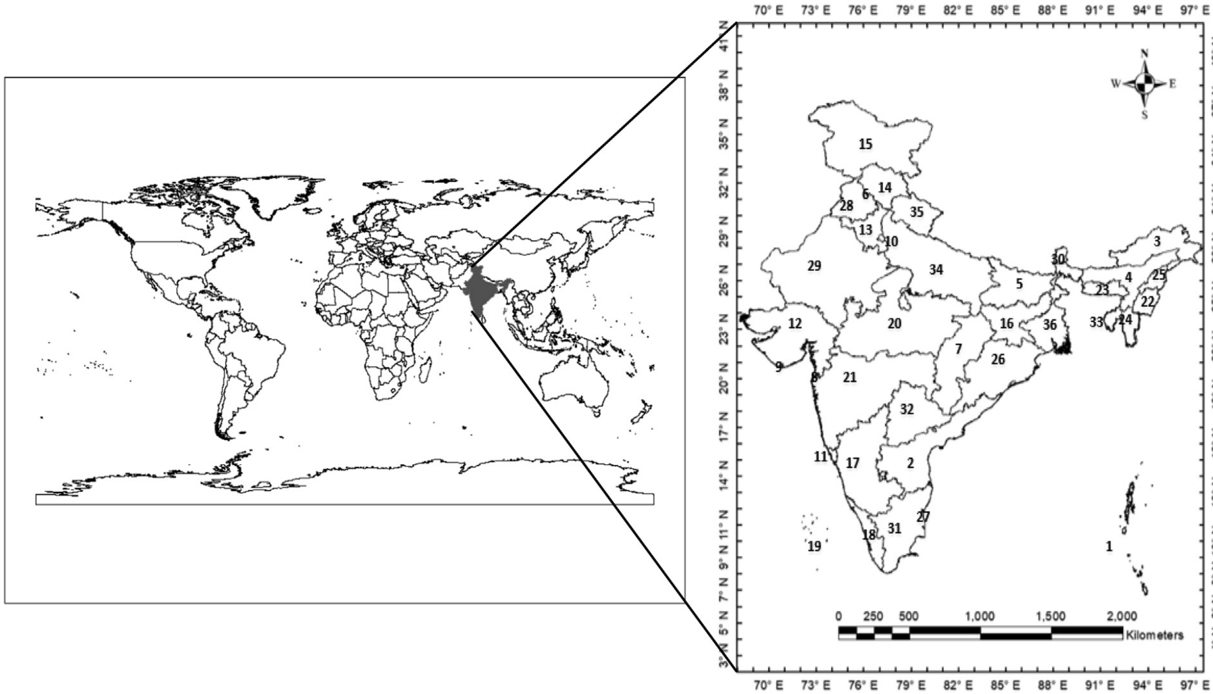
The current research work has the novelty that it investigates the spatial suitability for the two most technologically mature renewable energy sources, namely, the solar and the wind energy. This combination of the GIS and MCDM based approaches has not been used so far for the identification of suitable renewable energy locations in India. The current work also takes into account various suggestions made by regional experts, stakeholders, experts from different environmental associations, energy practitioners, and planning authorities which increases the acceptability and viability of the research work. The rest of the paper is organized as follows. Section 2 describes the research methodology adopted based on the decision criteria, AHP, and GIS-based approaches, Section 3 discuss the various results, Section 4 discuss the benefits, opportunities, and limitations of the research study and finally, Section 5 concludes this work and suggests the directions for the future work.

2. Methodology

This section briefly presents the details on the study area, the GIS and the MCDM approaches used, and the various evaluation criteria considered for the land suitability analysis for solar and wind farms.

2.1. Study area

The aim of the study is to perform an identification study of the suitable solar and wind farm locations in India which is the 7th largest country in the world with an area of 3.29 million square kilometers. India is geographically situated between 8°4′ to 37°6′ North latitude and 68°7′ to 97°25′ East longitude, the location in the world map is shown in Fig. 1. India has thirty states and six union territories and it shares borders with Pakistan, Nepal, Bhutan, China, and Myanmar [31,32]. India comprises of six different physiographic zones, namely, the northern mountains (Himalayas), the Indo-Gangetic plains, the Thar desert, the peninsular plateaus (plateaus, mountain ranges, Ghats, and Deccan plateau), the coastal plains, and finally, the islands (Lakshadweep, Andaman, and Nicobar) [33]. In terms of climate, the Indian Meteorological Department (IMD) designates India into four climatological seasons of winter, summer, monsoon or rainy season, and post-monsoon or



1. Andaman and Nicobar
2. Andhra Pradesh
3. Arunachal Pradesh
4. Assam
5. Bihar
6. Chandigarh
7. Chattisgarh
8. Dadra & Nagar Haveli
9. Daman & Diu
10. Delhi
11. Goa
12. Gujarat
13. Haryana
14. Himachal Pradesh
15. Jammu & Kashmir
16. Jharkhand
17. Karnataka
18. Kerala
19. Lakshdweep
20. Madhya Pradesh
21. Maharashtra
22. Manipur
23. Meghalaya
24. Mizoram
25. Nagaland
26. Orissa
27. Pondicherry
28. Punjab
29. Rajasthan
30. Sikkim
31. Tamil Nadu
32. Telangana
33. Tripura
34. Uttar Pradesh
35. Uttarakhand
36. West Bengal

Fig. 1. The geographical position of the study area.

autumn season. India has a comparatively higher annual average temperature ranging from 25 °C to 27.5 °C. Generally, the north-western part of the country records the lowest monthly mean temperature between 10 and 15 °C in the month of December while the northern region records the highest monthly mean temperature between 32 and 40 °C in the month of May. Normally, investigations related to the renewable energy generation are justified for countries with high average temperatures.

The Indian energy sector predominantly depends on fossil fuel resources which creates the challenges of energy security, climate change, fuel scarcity, and import dependence [34,35]. Among the fossil fuels, coal is widely used due to its cheap and easy availability. In 2013–14, the domestic coal demand stands at 516 million tons which is approx. 64 million tons higher than the previous year. The power utilities of India advised to import 50 million tons of coal from Australia, Indonesia, and South Africa. This created an economic burden of 6550 USD on nation. These fossil fuels also accounted for 58% (1047 million ton) of CO_2 emission in electricity generation application [32,36–38]. Recently, the Indian government has endorsed the renewable energy resources to overcome the above-mentioned challenges. India has a wide potential of renewable energy resources, for example, it has a potential of 6000 million GWh of solar energy per year with approximately 4–7 kWh/m^2 daily incidence of solar radiation [39]. Similarly, India has a total potential of 49.13 GW of wind energy which can be increased up to 100 GW with proper utilization of resources, greater land availability, and with larger capacity wind turbines [39]. Indian government also provides policy support to make renewable energy sources economically viable. The currently offered federal policies for solar and wind energy are as follows: (i) 80% accelerated depreciation on the solar projects, (ii) 0.5 Rs./kWh (USD 0.0068/kWh) generation-based incentives on the wind energy projects, and (iii) 30% viability gap funding on the solar project installation cost [40]. Considering the challenges, the huge solar, wind energy potential, and the various government incentives, a systematic analysis of the potential solar and wind power plant locations is the need of the hour for India to become self-reliant on renewable energy.

2.2. Methodology

In this study, the MCDM approach is combined with a GIS tool to identify suitable locations for solar PV and wind power installations in India. This study is structured into the five steps that are shown in Fig. 2. In step (I) the aim and objective of the research work are defined, step II includes an extensive literature review, selection of evaluation criteria, and data collection from open sources, government agencies. In step (III) and (IV), the MCDM (F-AHP) approach is used for weights and ranking of the energy alternatives. The commercial computer software ArcGIS 10.7 from the Environmental System Research Institute (ESRI) is then used for the digitization, conversion, analysis, and visualization of the spatial data. In Step (V), the available land area is categorized into five suitability scales of 'highly suitable', 'suitable', 'moderately suitable', 'less suitable', and 'not suitable'. Finally, in step (VI), explored the potential areas from different states and union territories of India.

2.3. Source of data

Spatial and attribute data used in the present research paper are obtained from secondary sources. Data sources for various criteria used for identification and evaluation of solar and wind power potential sites in India are different, hence discussed in detail in the proceeding lines. Solar radiation data are collected from the National Renewable Energy Laboratory, USA. These data are developed on a joint venture of the Ministry of New and Renewable Energy (MNRE), India and NREL, USA from 2000 to 2014. Wind speed at an altitude of 100 m above ground level for a spatial resolution of 1000 m × 1000 m is obtained from DTU wind energy global wind atlas. Wind speed data are in the form of wind speed frequency distribution for 12 direction sectors. Ground elevation and slope of land data (terrain data) on 900 m × 900 m spatial resolution are obtained from GTOPO30 global digital elevation model (DEM) produced by United States Geological Survey (USGS). Roads and inland water bodies' data are obtained from a digital chart of the world (DIVA-GIS). Airports location data are obtained from a dataset created by Addy & Lasma (2017). Wildlife designations are compiled from multi-sources like world database on protected areas, consortium, IUCN, and UNEP-WCMC (2005). Land-use and land-cover data are obtained from USGS land-use/land-cover dataset (1993). Urban agglomerations data are obtained from CIESIN, Columbia University, 2017, and NASA-SEDAC. Electric power transmission lines of India data are obtained from the Power

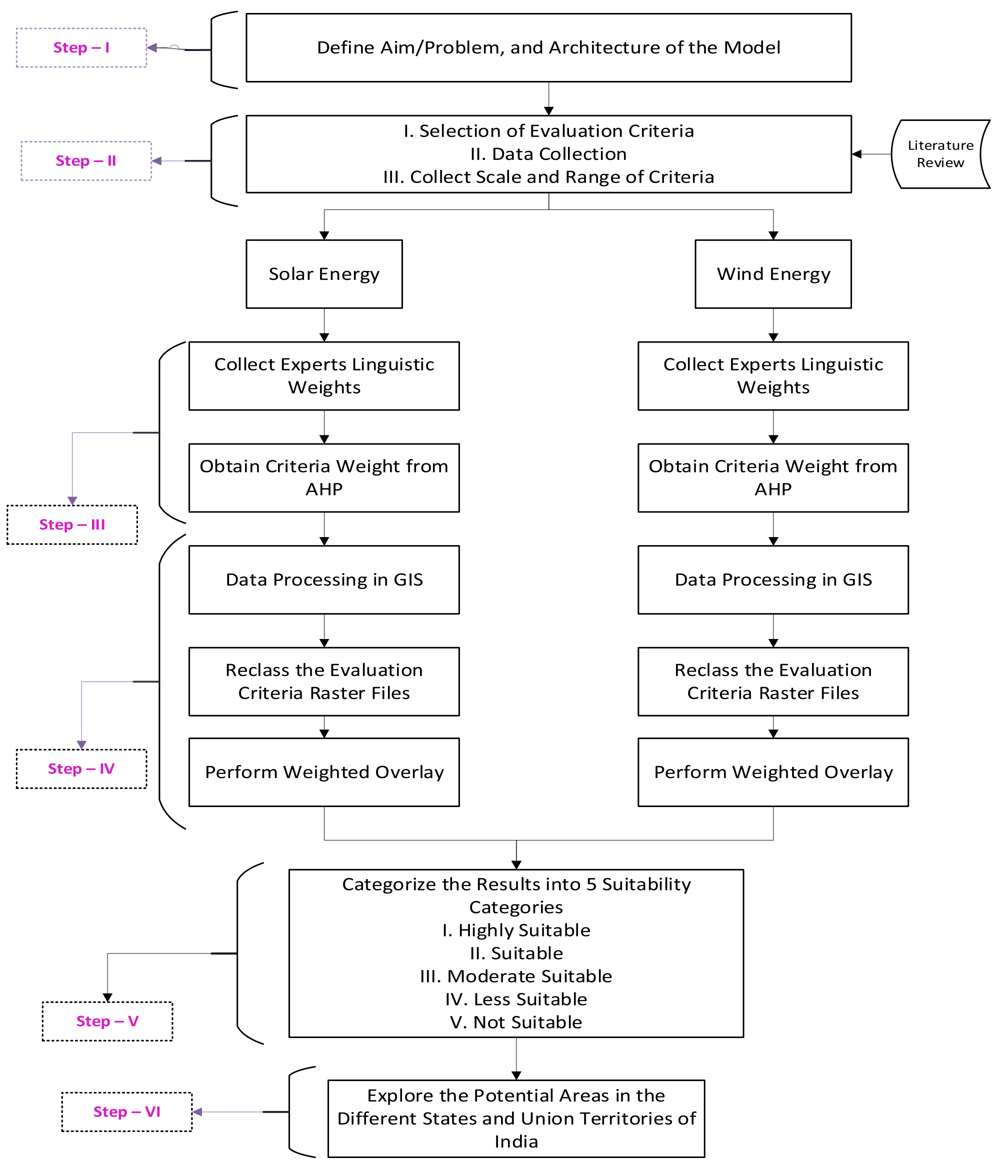


Fig. 2. Flow chart of research methodology.

and Gas Grid map of south Asia (2006) prepared by US AID. Existing power plant locations in India are obtained from CARMA power plant dataset as discussed in Table 1. During the analysis, the spatial resolution of each factor were converted into a common spatial resolution of 1000 m × 1000 m.

2.4. Evaluation criteria

The various evaluation criteria are considered based on the defined goal, study area, accessibility of data sets, spatial scale, and operational techniques. The criteria selected are based on the rigorous literature review as summarized in Table 2. The current research work is carried out based on the already established criteria.

The selected evaluation criteria comprise of three main categories, namely, technical, socio-environmental, and economic. The sub-factors falling into these main categories is shown in Fig. 3. The following section discusses and elaborates on the considered criteria with their importance.

2.4.1. Technical factors

In this section, briefly discussed about the various technical factors like solar radiation, wind speed, elevation, and aspect, etc. which affect the decision-making process.

2.4.1.1. Solar radiation. Solar radiation is the incoming energy from the sun at a particular point on the earth's surface. Its visible spectrum is responsible for the electrical energy output from solar farms. Therefore, it is a very important factor for the site selection of solar farms [59,60]. The National Renewable Energy Laboratory (NREL), USA classifies the solar radiation into four categories, namely, moderate (<4 kWh/m^2/day), good (4–5 kWh/m^2/day), very good (5–6 kWh/m^2/day), and finally, excellent (>6 kWh/m^2/day) radiation [61]. Also, various authors adopt different scales according to their country-specific norms. For example, Ali et al. [5] neglected areas with radiation of less than 3.5 kWh/m^2/day in their analysis for Thailand, Aly et al. [24] considered areas with at least 4.66 kWh/m^2/day of solar radiation as essential in Tanzania while Sanchez-Lozano et al. [62] considered areas with 5 kWh/m^2/day as essential in the south-east of Spain. India is among the best-suited countries for solar energy, the irradiance for which is shown in Fig. 4. Following the previous studies, this study considers the areas with global horizontal irradiance value less than 3.8 kWh/m^2/day as 'not suitable' for solar plants [33,63]. Further, 3.8 to 4.4 kWh/m^2/day as 'less suitable', 4.4–5.0 kWh/m^2/day as 'moderately suitable', 5.0–5.6 kWh/m^2/day as 'suitable', and higher than 5.6 kWh/m^2/day GHI categorized as the 'highly suitable' for installation of solar power plants. Following the discussed classification, final raster file of Indian solar radiation intensity was prepared in the ArcMap, which is shown in Fig. 4.

2.4.1.2. Wind speed. The average wind speed is also a key criterion for the determination of the economic feasibility and technical viability of wind farm installation sites. Hence, wind speed criterion is incorporated in almost every study [51,64]. As summarized in Table 3, investigators have considered different wind speeds in their analysis. For example, Gorsevski et al. [65] considered wind speed ranging from zero to 7.5 m/s, Ayodele et al. [66] excluded areas having wind velocity lower than 4.4 m/s, Ali et al. [5] considered a minimum wind velocity of 4 m/s for wind farms at different locations. Following the literature, the current research work considers a minimum wind speed of 3 m/s at a height of 100 m [64]. Accordingly, areas with a wind velocity of less than 3 m/s are classified as 'not suitable', 3–4 m/s as 'less suitable', 4–5 m/s as 'moderately suitable', 5–6 m/s as 'suitable', and finally, areas with more than 6 m/s of wind velocity are considered as 'highly suitable.' Following the discussed classification, final raster file of wind speed variation was prepared in the ArcMap, which is shown in Fig. 5.

2.4.1.3. Slope. The terrain slope is another influential factor for the selection of optimum locations for solar and wind power plants. The landscape slope influences the electrical output and construction cost of solar and wind farms [51,60]. Due to the lack of a clear consensus regarding the optimal value of terrain slope, various authors have adopted different values. For example, Merrouni et al. [58] accepted a maximum of 5% terrain slope, Uyan [2] excluded more than a 3% slope for solar power plants while Garni et al. [70] considered less than 5% terrain slope for the solar farms. For wind farms, Ayodele et al. [66] and Ali et al. [5] accepted a maximum slope of 15%. Based on the data from the literature, the current research work considers a maximum of 5-degree slope for solar energy and a 15-degree slope for wind energy.

Table 1
GIS data sets to identify suitable sites for solar and wind farms installation.

Subject	Description	File Type	Geometry	Spatial Resolution	References
Solar radiations	Global solar radiations (kWh/m^2/day)	Raster file		1000 m	[41]
Wind Speed	The subject contains the wind speed at a height of 100 m above surface level.	Raster file		1000 m	[42]
Terrain Data	Elevation	Raster file		900 m	[43]
Inland Water	It contains the rivers, canals, and lakes.	Vector	Polygon		[44]
Airports	It covers the national and international aerodromes or airports	Shape file	Point		[45]
Wildlife designations	Wildlife designations covers the national parks, biological corridors, Strict nature reserves, and sanctuary.	Vector	Polygon	Varied, compiled from multiple sources	[46]
Land use	Land use and land covered by forest, water bodies, wet lands, snow, and ice.	Raster		1000 m	[47]
Urban agglomerations	Covers the rural and urban locations of the India	Shape file	Point		[48]
Roads	Different state highways and national highways	Shape file	Poly line		[44]
Transmission Lines	Electric power transmission lines of India.	Shape file	Poly line		[49]
Power Plants	Locating the existing power plants in India	Shape file	Point		[50]

Table 2
Decision criteria considered in the previous studies.

Criteria	Hofer et al. [51]	Giamalaki and Tsoutsos [52]	Sanchez-Lozani et al. [53]	Ali et al. [5]	Noorollahi et al. [54]	Azizi et al. [55]	Aly et al. [24]	Sanchez-Lozani et al. [56]	Tahri et al. [57]	Merrouni et al. [58]
Solar resources	×	✓	✓	✓	✓	×	✓	✓	✓	✓
Wind resources	✓	×	×	✓	×	✓	×	×	×	×
Slope	✓	✓	✓	✓	✓	✓	×	✓	✓	✓
Aspect	×	✓	×	×	×	×	×	✓	✓	×
Elevation	×	✓	×	✓	✓	✓	×	×	×	×
Distance from Coastline	×	✓	×	×	×	×	×	×	×	×
Distance from Water bodies	×	✓	×	✓	×	✓	×	×	×	✓
Distance from Airports	×	×	×	✓	×	✓	×	×	×	×
Distance from Wildlife Designations	✓	×	×	✓	×	✓	×	×	×	×
Land use	✓	✓	✓	✓	✓	✓	×	×	✓	×
Distance from Urban areas	✓	×	✓	✓	✓	✓	✓	✓	✓	✓
Distance from Roads	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Distance from Transmission lines	✓	✓	✓	✓	✓	✓	✓	✓	×	✓
Distance from Power plants	×	×	×	×	×	×	×	✓	×	×

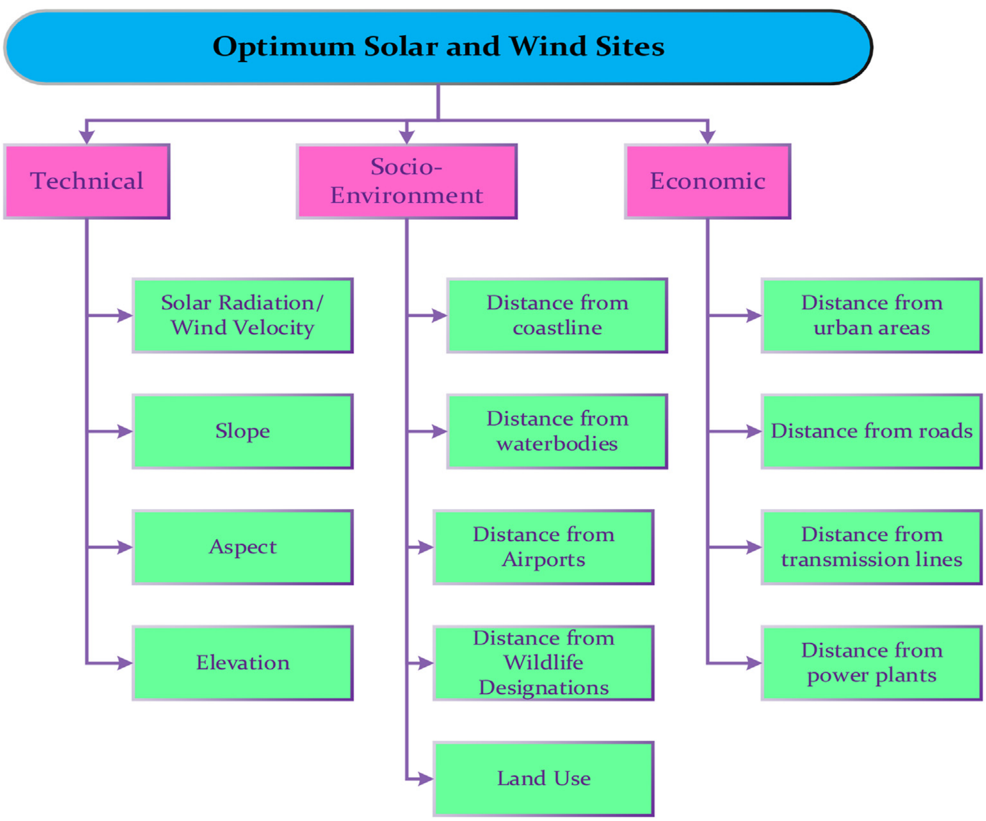


Fig. 3. Decision criteria considered for the evaluation of suitable sites.

2.4.1.4. Elevation. The elevation is yet another factor for the effective selection of optimum sites for solar and wind farms. Its importance is highlighted by various authors such as Giamalaki et al. [52] who argue that high altitude locations have less flora and fauna species while Zoghi et al. [59] mention that high altitude locations receive more solar energy due to thinner atmosphere. Following the literature summarized in Table 3, the current work adopts a maximum of 2000 m elevation for wind energy while a maximum of 1500 m elevation for solar energy.

2.4.1.5. Aspect. The aspect is an important factor for solar farms because it enhances the efficiency of solar farms by receiving the maximum amount of solar radiation. As India is located in the northern hemisphere, this means that the solar panels should be oriented towards the geographical south to receive the maximum amount of solar radiation from the sun.

2.4.2. Socio-environmental factors

In this section, briefly discussed about the various socio-environmental factors which affect the decision making related to solar and wind power site selection.

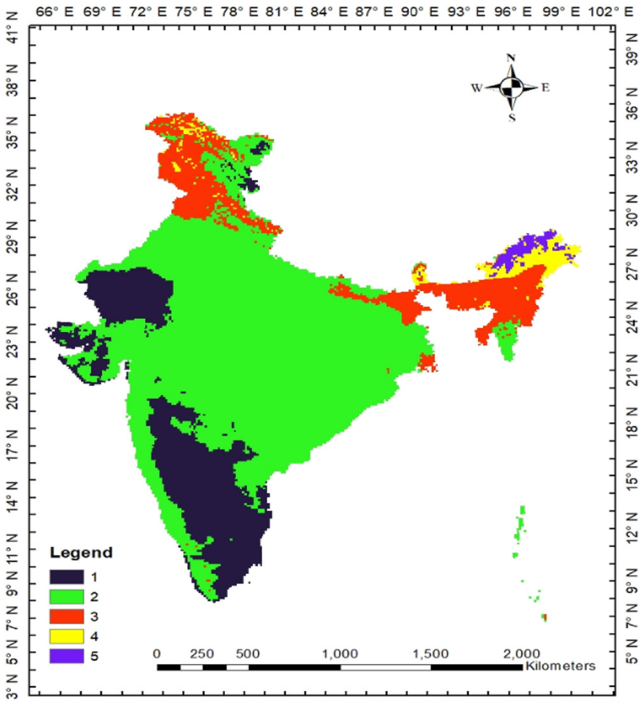


Fig. 4. Spatial distribution of global horizontal irradiance in India where legend 1 shows the highly suitable while legends 2, 3, 4, 5 respectively show the suitable, moderately suitable, less suitable, and not suitable areas.

2.4.2.1. Distance from the coastlines. It is an important factor from the technical, aesthetic, and environmental point of view. The distance from coastline creates issues like visual impacts on tourist activities, pressure on the marine ecosystem, the effect of salt on the life and efficiency of the equipment, and pollution-related incidents [52]. Following the previous literature and expert's advice, the current research work considers a 10 km area from the shoreline in the 'not suitable zone' including the buffer and exclusion zone. The complete details of classifications are provided in Tables 4 and 5.

2.4.2.2. Distance from waterbodies. Solar PV and wind farms may contaminate or pollute the aquifers like permanent water bodies, reservoirs, dams, lakes, and rivers, etc. To protect the natural water resources, the current research work considers the land within a 7 km distance from the water resources as 'not suitable' for the installation of solar and wind farms. Further details on the classification are given in Tables 4 and 5

2.4.2.3. Distance from airports. It is also an important factor due to the adverse effects of solar and wind farms on aviation activities including interference to the aviation radar's signals, distractions to the pilot's vision, etc. Therefore, solar and wind farms need to be located at a significant distance from the airports. Following the regulations of the Indian aviation department, the current study considers land within a 7 km distance from the airports to be in the 'not suitable' category.

2.4.2.4. Distance to wildlife designations. To preserve the natural wildlife and biodiversity, solar and wind farms should be installed at a significant distance from wildlife sanctuaries, national parks, etc. The current research work includes wetlands, national parks, wildlife sanctuaries, biological corridors, strict nature reserves, game reserves, and world heritage sites in the category of wildlife designations. In the previous studies, Gorsevski et al. [65] considered a minimum distance of 5 km while Aydin et al. [69] considered a distance of 1 km from the wildlife designations. However, based on the discussion with regional and local experts, a minimum distance of 10 km is considered in the current work to be in the 'not suitable' category. More details of the classification are provided in Tables 4 and 5.

2.4.2.5. Land use. The installation of an energy project requires a careful assessment of the available lands. Following the literature survey in Table 3, the barren or sparsely vegetated, cropland/grassland mosaic, dryland pasture, grassland, and shrubland are considered in the 'highly suitable' category. Similarly, deciduous broadleaf forest, evergreen broadleaf & needle leaf forest, mixed forest, snow or ice, wooded wetlands, urban and built-up lands are considered in the 'not suitable' category.

2.4.3. Economic factors

Here, discuss about the various factors related to the economics of solar and wind farms which mainly include the distance from urban areas, road network, electrical transmission network, and existing power plants.

2.4.3.1. Distance to urban areas. The distance to the urban areas is specifically relevant for solar and wind power studies. A significant distance is necessary to avoid inconvenience, visual intrusion in daylight, noise nuisance to human life, and for the future development of cities [5,55]. The current research work considers the land within a 10 km distance from urban areas as belonging to the 'not suitable' category based on the expert's viewpoint, public opinions, and relying on the gathered information from the previous studies.

2.4.3.2. Distance to road network. It is another important factor from an economic and environmental point of view. Suitable locations should be near to the road/transportation network that avoids unnecessary environmental damage and road construction costs. Literature suggests a range of suitable distance for power plants such as 500 m–10 km [5], 1.4–10 km [57], 1–10 km [65], and 20–200 km [59]. The current research work considers a distance of 10 km from the road network as belonging to the 'highly suitable' category. The complete classification and descriptions are provided in Tables 4 and 5

2.4.3.3. Distance to transmission lines. Similar to previous factors, it is also an important factor from economic and environmental aspects. An already existing transmission network minimizes the construction cost, ecological damage, and energy losses. Following the Indian Ministry of Power guidelines and expert suggestions, a 10 km area around the high voltage lines is considered as 'highly suitable'.

2.4.3.4. Distance from power plants. Minimum distance from already existing power plants will provide necessary things like road networks, transmission facilities, and water resources. Thus, it will provide higher economic viability and environmental stability. Based on the expert's advice, the land within a 10 km distance from the existing power plants is considered as 'highly suitable'. Fig. 6 graphically represents the availability of land area in each of the suitability classes. These suitability charts are further used in the analysis of weighted overlay operation. In the current research work, adopted a common legend nomenclature where legend 1 implies the 'highly suitable' land while legends 2, 3, 4, and 5 respectively imply the 'suitable', 'moderately suitable', 'less suitable' and 'not suitable' lands.

Table 3
Summary of decision criteria values considered in previous studies.

Criteria	Tahri et al. [57]	Giamalaki and Tsoutsos [52]	Gorsevski et al. [65]	Ayodele et al. [66]	Ali et al. [5]	Ali et al. [5]	M Uyan [2,67]	Noorollahi et al. [54]	Aly et al. [24]	Baseer et al. [68]	Aydin et al. [69]
Solar irradiation (GHI)	741 to 1967 kWh/m^2/year	1000 to 1800 and higher, kWh/m^2/year	–	–	–	3.5 to 5, kW/m^2/day	–	1300 to 2100 and higher, kWh/m^2/year	1700 to 2300, kWh/m^2/year	–	Higher than 4.5, kWh/m^2/day
Wind velocity	–	–	0–7.5 m/s	4.4–7.0 m/s	4 to 6 and higher, m/s	–	–	–	–	5 to 6 and higher, m/s	–
Slope	0–24%	0–28%	–	0–15%	0–15%	0–5%	0–3%	3–100%	–	–	0–7%
Orientation (Aspect)	South, and flat	South, southeast, southwest	–	–	–	–	–	South and flat	–	–	–
Elevation	–	0–1500 m	–	0–2000 m	0–200 m	0–200 m	–	0–4500 m	–	–	–
Distance from Coastline	–	50 to 200 and higher, m	–	–	–	–	–	–	–	–	–
Distance from Water bodies	–	100 to 400 and higher, m	–	–	0.4 to 1 and higher, km	0.4 to 1 and higher, km	–	–	0–9 km	–	Higher than 2500 m
Distance from Airports	–	–	–	–	–	–	–	–	–	Higher than 2500 m	Higher than 3000 m
Distance to Wildlife Designations	–	–	5000 to 30,000 m	–	3 to 4 and higher, km	1 to 2 and higher, km	–	–	–	–	Higher than 1000 m
Land use	Area without vegetation	A barren area with little or no vegetation	Shrub, barren, pasture, cropland	–	Barren grassland	Barren grassland	Barren and rocky	–	–	–	–
Distance to Urban areas	0 to 10 and higher, km	–	–	2000 to 20,000 and higher, m	1 to 3 and higher, km	0.5 to 1.5 and higher, km	500 –5000 m	15–350 km	8–45 km	2000 to 10,000 m	–
Distance to Road network	1.4–10 km	100–4000 m	1000 to 10,000 m	500 to 20,000 m	0.5 –10 km	0.5–10 km	100 –5000 m	20–200 km	0–20 km	0 to 10,000 m	0–10 km
Distance to Transmission lines	–	0 to 10,000 m	1000 to 20,000 m	250 to 20,000	0–10 km	0–10 km	0 to 10,000 m	500 m to 60 km	0–50 km	0 to 10,000 m	1–45 km

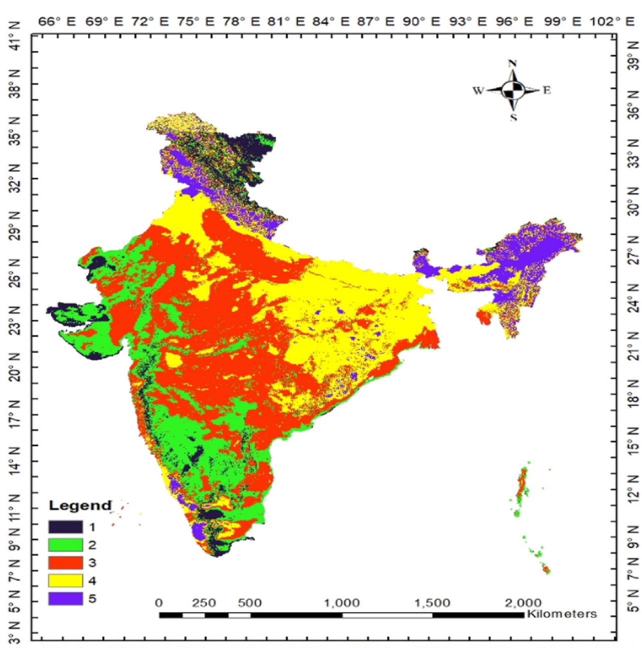


Fig. 5. Spatial distribution of average wind velocity in India at a hub height of 100m. Here legend 1 shows the highly suitable areas while legends 2, 3, 4, 5 respectively show the suitable, moderately suitable, less suitable, and not suitable areas.

2.5. Hierarchical model development

Assessment of suitable sites for solar and wind farms involves conflicting issues and certain complexities which necessarily require an advanced decision-making approach. Among the available alternatives, the Analytical Hierarchy Process (AHP) decision-making approach has a strong ability to deal with complex and conflicting problems with different criteria [71]. The AHP approach was developed by Prof. Satty in 1979 [58,72]. It is quite popular in the MCDM research domain because of the use of a hierarchical or network-based structure in which, the topmost level contains the goal of the research work, the middle level contains the criteria and sub-criteria used for the analysis, and finally, the bottom-most level contains the different alternatives for evaluation. It also decomposes the problem into many sub-problems that are analyzed or solved separately.

The pair-wise comparison among the criteria and sub-criteria is done using the 9-point Satty fundamental linguistic scale. To make the pair-wise comparison, five experts are selected and asked to share their opinions using the provided linguistic scale. These linguistic weights were converted into the fuzzy geometric mean (GM) value using Buckley's GM approach. These fuzzy geometric mean values were converted into the fuzzy weights, and further aggregated values of these fuzzy weights were given the weights or performance score of criteria.

The AHP approach provided a good factor to check the consistency of the expert's weight called the Consistency Ratio (CR) which is defined as

Table 4
Solar farms decision criteria values for different land suitability classes.

Factors	Suitability Ranking				
	Highly Suitable	Suitable	Moderately Suitable	Less Suitable	Not Suitable
	1	2	3	4	5
Solar radiation (kWh/m^2/day)	>5.6	5.0–5.6	4.4–5.0	3.8–4.4	<3.8
Slope (degree)	0–2	2–3	3–4	4–5	>5
Orientation (facing direction)	South, Flat	Southeast and Southwest	East and West	Northeast and Northwest	North
Elevation (m)	<300	300–700	700–1100	1100–1500	>1500
Distance from Coastlines (km)	>40	30–40	20–30	10–20	<10
Distance from Waterbodies (km)	>28	21–28	14–21	7–14	<7
Distance from Airports (km)	>28	21–28	14–21	7–14	<7
Distance to Wildlife Designations (km)	>40	30–40	20–30	10–20	<10
Land use	Barren or Sparsely Vegetated	Mixed Shrubland/grassland	Irrigated cropland and pasture	Herbaceous wetlands	Mixed forest
Distance to Urban Areas (km)	>40	30–40	20–30	10–20	<10
Distance to Road Network (km)	<10	10–20	20–30	30–40	>40
Distance to Transmission lines (km)	<10	10–20	20–30	30–40	>40
Distance from Power plants (km)	<10	10–20	20–30	30–40	>40

Table 5
Wind farms decision criteria values for different land suitability classes.

Factors	Suitability Ranking				
	Highly Suitable	Suitable	Moderately Suitable	Less Suitable	Not Suitable
	1	2	3	4	5
Wind Velocity (m/s)	>6	5–6	4–5	3–4	<3
Slope (degree)	0–6	6–9	9–12	12–15	>15
Elevation (m)	<500	500–1000	1000–1500	1500–2000	>2000
Distance from Coastlines (km)	>40	30–40	20–30	10–20	<10
Distance from Waterbodies (km)	>28	21–28	14–21	7–14	<7
Distance from Airports (km)	>28	21–28	14–21	7–14	<7
Distance to Wildlife Designations (km)	>40	30–40	20–30	10–20	<10
Land use	Barren or Sparsely Vegetated	Mixed Shrubland/grassland	Irrigated cropland and pasture	Herbaceous wetlands	Mixed forest
Distance to Urban Areas (km)	>40	30–40	20–30	10–20	<10
Distance to Road Network (km)	<10	10–20	20–30	30–40	>40
Distance to Transmission lines (km)	<10	10–20	20–30	30–40	>40
Distance from Power plants (km)	<10	10–20	20–30	30–40	>40

$$CR = \frac{CI}{RI}$$

where, RI is the random index while CI is the consistency index defined as

$$CI = \frac{(\lambda_{max} - n)}{n - 1}$$

In the above equation, λ_{max} is the maximum eigenvalue and n is the number of elements.

The CR values less than or equal to 10% imply that the obtained AHP results are significant, otherwise, the pairwise comparisons will have to be performed again to improve the consistency of the analysis.

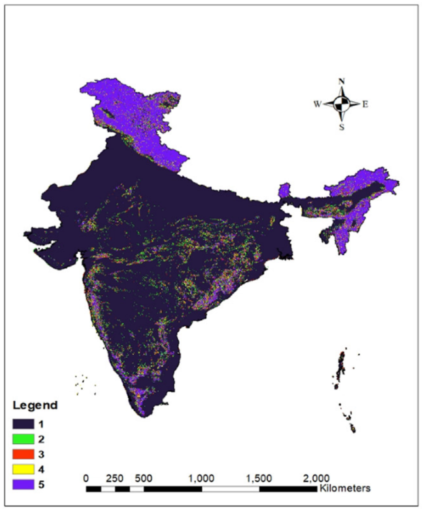
2.6. Geographic Information System (GIS)

Geographic Information System (GIS) is a tool used for digitization, conversion, analysis, and visualization of the spatial data [57] and is widely used for the planning of renewable energy-related projects which involve a variety of aspects such as economic, environmental, social and territorial. GIS easily manages these different aspects because of its in-built capabilities of investigating the territories, generation and sorting of data, capturing the geographic information, managing the commands, and visualization of the output [73]. GIS has multiple in-built tools, the current research mainly uses data management, conversion, and spatial analysis tools. Generally, the graphical output of the GIS approach belongs to the following five categories: 'highly suitable', 'suitable', 'moderately suitable', 'less suitable', and 'not suitable'. Table 6 provides the details of the classification scale along with the suitability score, various definitions, and explanations.

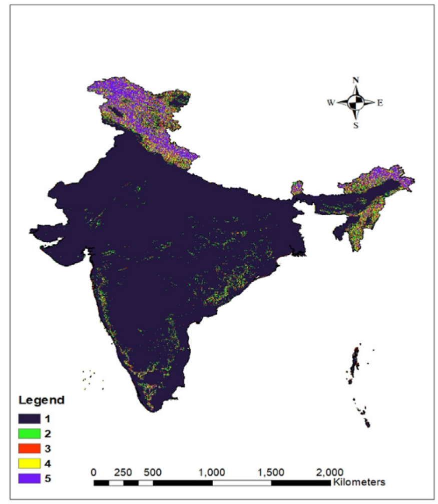
3. Results

Here, the results obtained from the analysis are summarized. This study aimed to evaluate the suitable sites for solar and wind farms in India using GIS and MCDM approach. Thirteen factors under the technical, socio-environment and economic aspects were selected based on the previous literature and according to the requirements of the study. The weights of the factors were obtained from the F-AHP approach and based on the experts' judgment collected from interviews. The technical, socio-environment and economic aspects are initially compared pair-wise to obtain the importance of each aspect. Table 7 shows that the technical aspect is the most important aspect with a preference score of 0.447 followed by the economic and socio-environment aspects. For solar farms, solar radiation is the most dominant factor with a weight of 0.170. With a weight of 0.116, the 'aspect' is the second most prominent factor while the distance to the transmission lines is the third important factor with a weight of 0.106. Distance to road network becomes the fourth choice followed by elevation and land-use factors. Distance from the coastlines is the least preferred criterion as shown in Fig. 7.

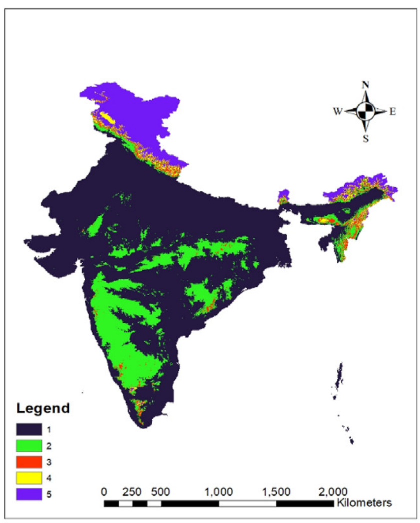
For wind farms, wind speed is the most dominant factor with a



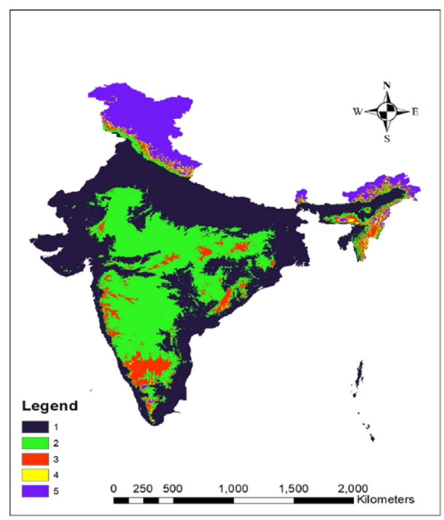
6.1. Slope for solar farms



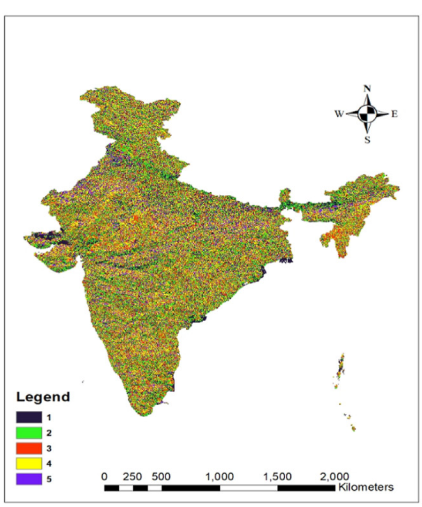
6.2. Slope for wind farms



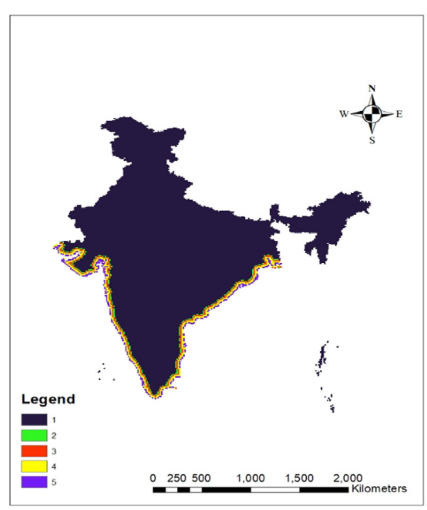
6.3. Elevation for solar farms



6.4. Elevation for wind farms

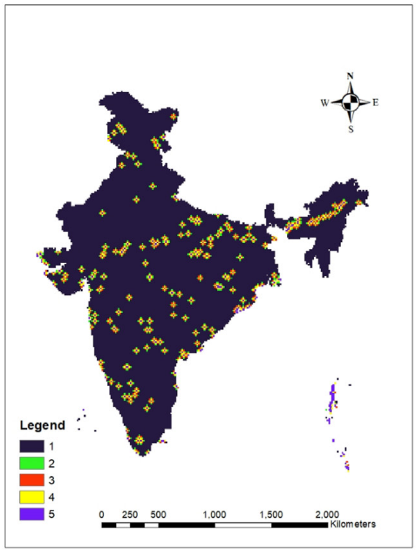


6.5. Aspect for solar farms

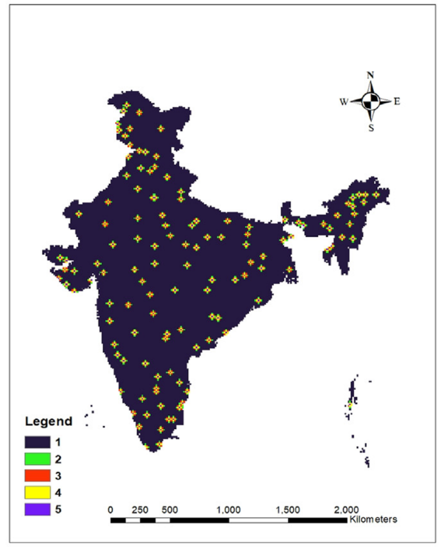


6.6. Coastline

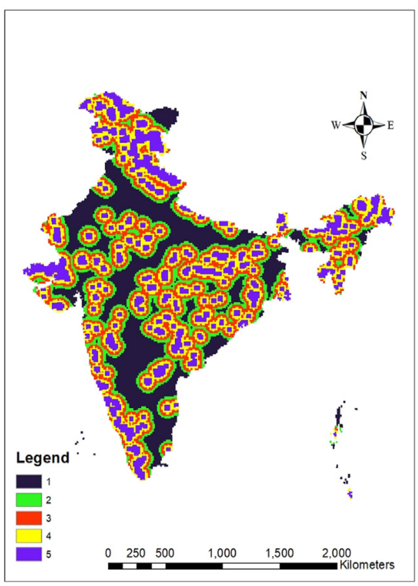
Fig. 6. Physical characteristics of the study area. Here, legend 1 shows the 'highly suitable' while the legends 2, 3, 4, and 5 respectively show the 'suitable', the 'moderately suitable', the 'less suitable', and the 'not suitable' land.



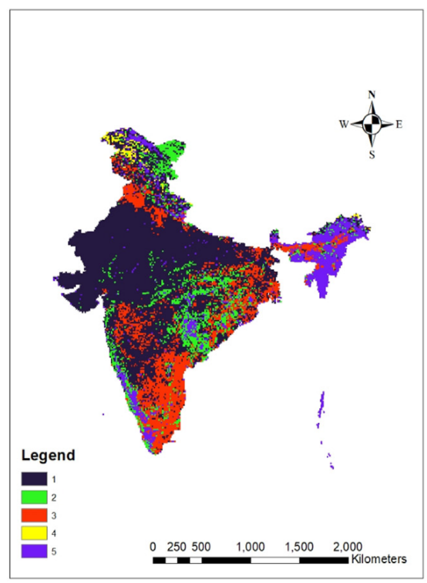
6.7. Waterbodies



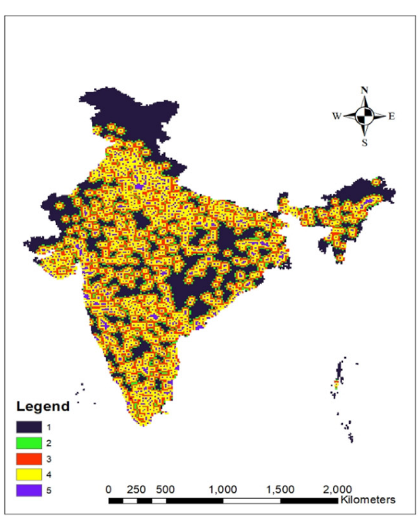
6.8. Airports



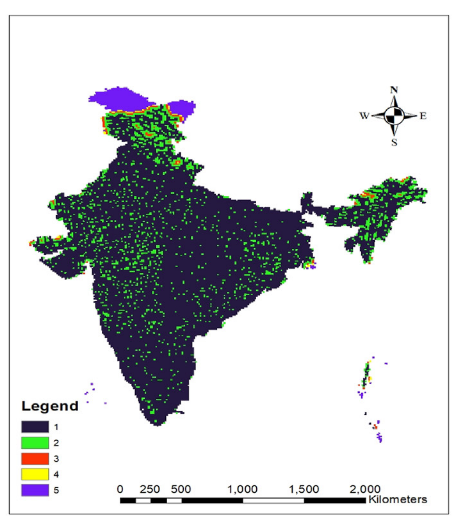
6.9. Wildlife



6.10. Land use



6.11. Urban areas



6.12. Roads

weight share of 0.217. The second preference is given to elevation with a weight of 0.135 while the distance to transmission lines is the third critical factor with a weight of 0.106. The slope becomes the fourth choice with a weight of 0.094 followed by the distance to the road network (weight 0.086) and land use (weight 0.084). Similar to solar farms, distance to the coastlines is the least preferred factor in the site selection for wind farms with a weight of 0.031. Fig. 8 shows the weights of criteria used for the evaluation of suitable sites for wind farms installation.

Suitable lands for solar and wind energy resources were assessed by combining all the GIS suitability maps (Fig. 6) and F-AHP weights using the weighted overlay technique in ArcGIS software. The final maps (Fig. 9) for both solar and wind energy resources were grouped into the five categories namely ‘highly suitable’, ‘suitable’, ‘moderately suitable’, ‘less suitable’ and ‘not suitable’. Results indicate that the highly suitable lands for solar and wind farms have respective areas equal to 133,874 km^2 and 29,457 km^2 representing a respective share of 4.13% and 0.91% of the total land area. Around 2,567,836 km^2 or 79.26% of the total land area is designated as the ‘suitable’ land for solar farms while around 2,602,763 km^2 or 80.43% of the total land area lies in the ‘suitable’ category for wind farms. The ‘not suitable’ category was not detected in the current analysis for both solar as well as wind power. Table 8 shows the statistical distribution of the remaining land suitability classes while Fig. 10 compares the assessment results of the solar plants and the wind farms.

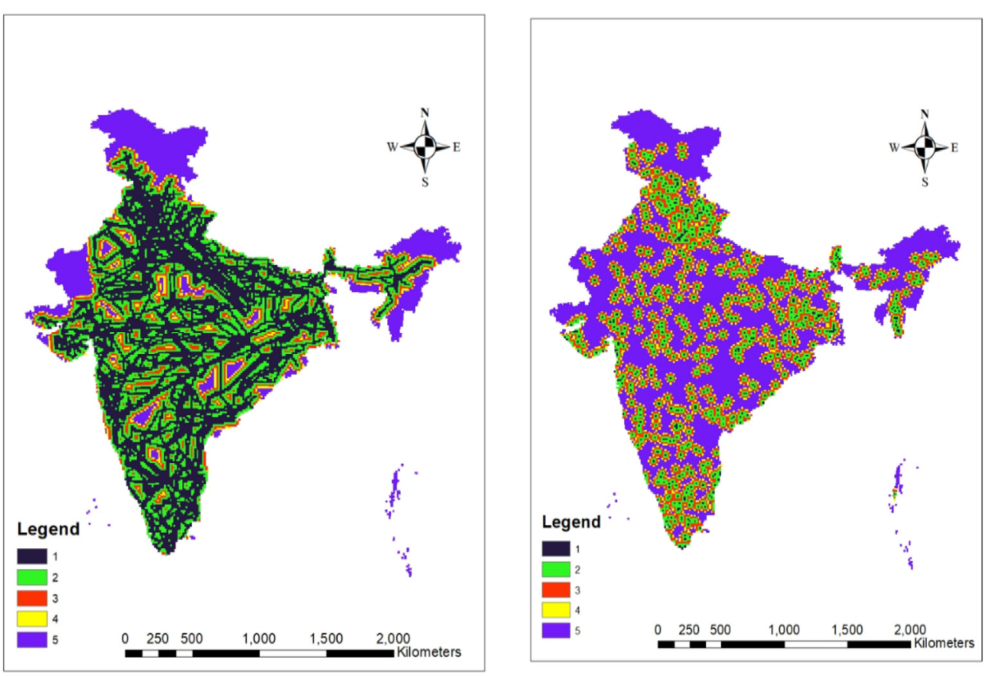
As explained in the introduction, India has thirty states and six union territories. Among all the states and union territories, the Rajasthan state has the highest ‘highly suitable’ land for both solar and wind energy. Rajasthan state has a 20,881 km^2 area as ‘highly suitable’ for solar energy while 6323 km^2 is ‘highly suitable’ for wind energy. Table 9 provides the complete statistical land suitability description for solar and wind energy in the union territories and different states of India. Uttar Pradesh has the second-highest ‘highly suitable’ land for solar farms while Andhra Pradesh has the second-highest ‘highly suitable’ land for wind farms. Fig. 11 shows the ‘highly suitable’ land in the top ten states of India for solar and wind farm installations.

3.1. Sensitivity analysis

Sensitivity analysis was carried out to understand the influence of each factor and to confirm the robustness of the analysis. In the previous sub-sections, suitable land for solar and wind farms were evaluated based on the weight assigned to the factors using the F-AHP approach. The sensitivity analysis here was performed by changing the criteria weights for four different cases, the details of which are provided in Table 10.

In equal weight criterion, an increment from 4.13% to 4.83% for the solar farms ‘highly suitable land’ area and from 0.91% to 1.87% for the wind farms ‘highly suitable land’ area show that the results are quite sensitive to the criterion weights. From a technical perspective (Case-II), factors like solar radiation, wind velocity, slope, elevation, aspect contribute significantly to the increase of the ‘highly suitable land’ area from 4.13 to 10.67% for solar farms and from 0.91 to 8.99% for the wind farms. In case-III, there is a significant increase in the ‘highly suitable land’ area from 4.13% to 27.45% for the solar farms while an increase from 0.91% to 26.28% for the wind energy. The reason behind this huge increase may be due to the fact that India has a large area outside the protected areas and constraints. Thus, minimizing the importance of resource factors (solar radiation, and wind velocity) leads to an increase in a suitable area. The economic aspect shows the least ‘highly suitable land’ area because of the poor availability of the infrastructure and transmission facilities. Table 11 provides the complete statistical classification of the suitability of lands. The sensitivity analysis results indicate that the output results are sensitive to the criteria weights and each considered criteria is influential in the evaluation of the study region.

Fig. 6. (*continued*).



6.13. Transmission lines	6.14. Power plants

Fig. 6. (*continued*).

Table 6
Land suitability scale [2,5].

Suitability Score	Definitions	Explanations	Color Code
1	**Highly suitable**	Perfectly suitable in all considered aspects	Purple
2	**Suitable**	Suitable to a great extent	Green
3	**Moderate suitable**	A compromising or moderately suitable	Red
4	**Less suitable**	Lowest suitability	Yellow
5	**Not suitable**	Completely constrained or unsuitable for installation	Blue

Table 7
Priority weights of decision criteria for solar and wind farms.

Categories/Criteria	Weights	Sub-Criteria	Solar sub-criteria	Solar Normalized Weights	Wind sub-criteria	Wind Normalized Weights
Technical	0.447	Solar irradiation/wind velocity	0.381	0.170	0.485	0.217
		Slope	0.171	0.076	0.211	0.094
		Orientation (Aspect)	0.260	0.116	–	–
		Elevation	0.188	0.084	0.303	0.135
Socio-Environment	0.255	Distance from coastlines	0.123	0.031	0.123	0.031
		Distance from waterbodies	0.175	0.045	0.175	0.045
		Distance from airports	0.142	0.036	0.142	0.036
		Distance to wildlife designations	0.229	0.058	0.229	0.058
		Land use	0.331	0.084	0.331	0.084
Economic	0.298	Distance to urban areas	0.197	0.059	0.197	0.059
		Distance to road network	0.288	0.086	0.288	0.086
		Distance to transmission lines	0.356	0.106	0.356	0.106
		Distance from power plants	0.159	0.047	0.159	0.047

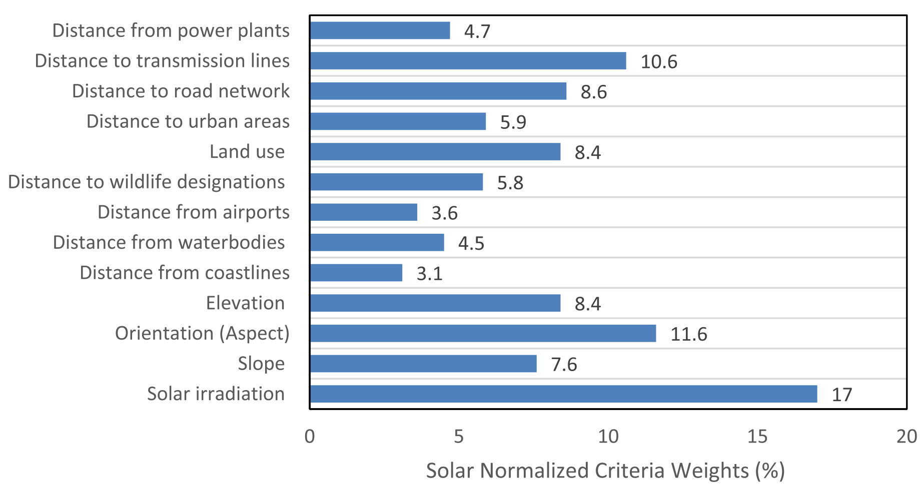


Fig. 7. Priority weights of the solar decision criteria.

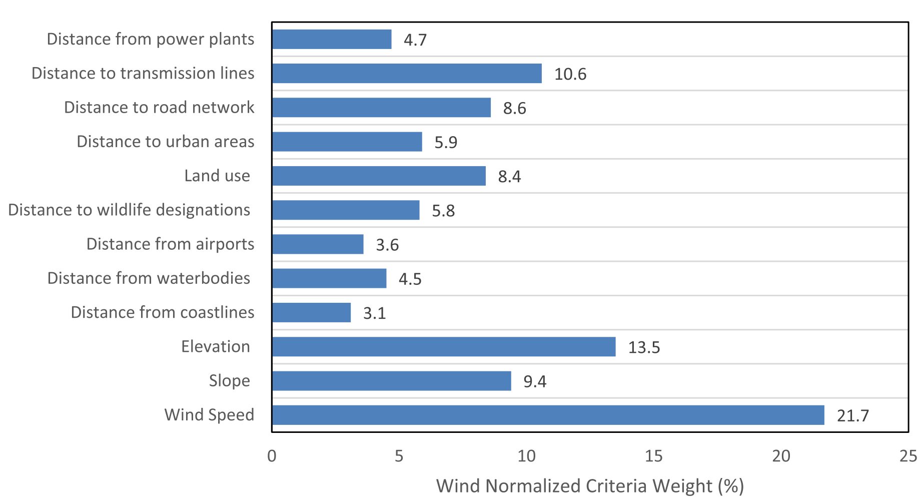
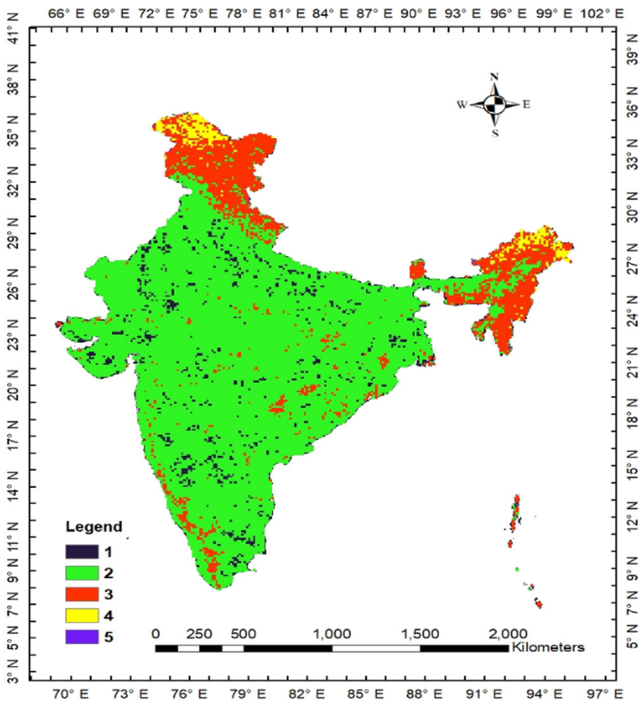
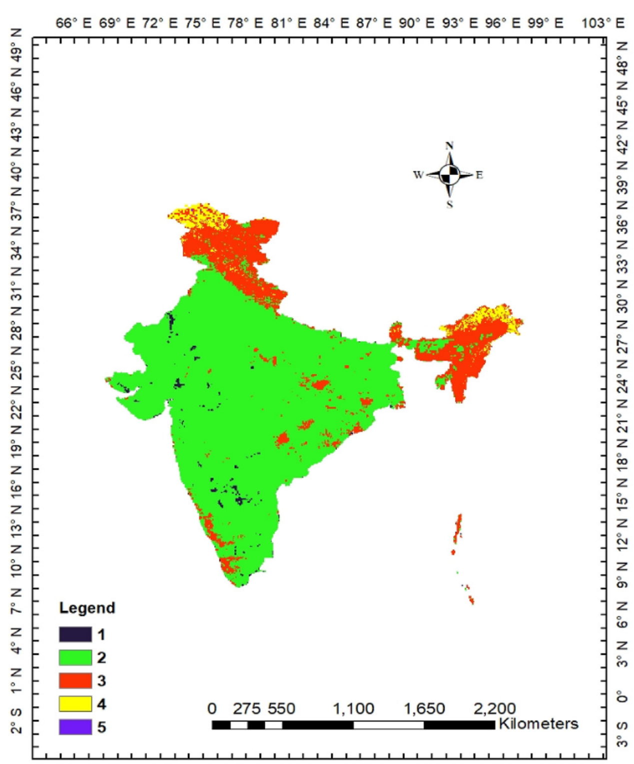


Fig. 8. Priority weights of the wind decision criteria.



(i). Solar farms suitability map of India.



(ii). Wind farms suitability map of India.

Fig. 9. The solar and the wind farms suitability map of India. Here, legend 1 shows the highly suitable land while legends 2, 3, 4, and 5 respectively show the suitable, moderately suitable, less suitable, and the not suitable lands.).

3.2. Theoretical power potential

The obtained results of suitable locations for solar and wind farms are mapped in Fig. 9. As a result, 133,874 km^2 area is highly suitable for solar power plants, whereas, 29,457 km^2 area highly suitable for wind farms. For these highly suitable land areas, theoretical electrical power potential is calculated. Theoretical power potential is mainly dependents on the available PV and wind turbine technologies, available land areas, and together plant facility requirements.

The theoretical solar power potential for the highly suitable land areas can be calculated based on the average solar radiation per unit surface area per day, the highly suitable land area, and the efficiency of the solar cells. Eq. (1) can be used to calculate theoretical electrical power potential [25,29,74–76].

$$TSPP = SR \times CA \times AF \times \eta \tag{1}$$

where TSPP is the theoretical power potential, SR is average solar radiation intensity (kWh/m^2/day), CA is the total selected highly suitable land area (km^2), AF is the area factor (%), and η is the efficiency of the solar energy conversion system (%). Here, the area factor indicates the maximum land area covered by the PV panels with the minimum shading effect. Area factor is taken as 70% from the previous studies [29,76]. The study considered the solar radiation intensity as 5.61 (kWh/m^2/day), which is the minimum value for the highly suitable land area category.

The study calculated the theoretical solar power potential using the mono and poly-crystalline typed four solar PV panels available in the Indian market. TATA solar power manufactured TP-300 PV module will generate a theoretical electric power potential of 3592 GW per year as shown in Table 12. Whereas, WAAREE, EMMVEE, and Canadian solar modules will generate 3612, 3594, and 3653 GW electrical power per year respectively.

According to the International Electrotechnical Commission (IEC) classification, India lies in the low wind speed with high mean turbulence intensity (IIIa/IIIb) regime. Following the IEC design norms, eight wind turbine models are selected that easily available in the Indian market. The detailed information about wind turbine models, IEC classes, and WT specifications are provided in Table 13.

Theoretical wind power potential for highly suitable land areas can be calculated based on the wind turbine generation capacity, rotor diameter, and the available total highly suitable land areas. Eq. (2) can be used to calculate theoretical wind power potential [77,78].

$$TWPP = TA \times AF \tag{2}$$

where, TWPP is the theoretical wind power potential (GW), TA is the total available highly suitable land area (km^2), and AF is the area factor (MW/km^2). In this study, wind turbines were arranged at a distance of 7D $\times$ 5D, where D is the rotor diameter [79]. Afterward, eight wind turbine models manufactured from Vestas India, Suzlon energy limited, GE wind energy limited, Inox wind limited, and Regen Powertech were considered for analysis. Among considered wind turbine models, ReGen Powertech VENSYS-77 has the highest area factor of 7.246, followed by GE (1.6–82.5 WT). In terms of TWPP, the ReGen Powertech VENSYS-77 will generate the highest 213.44 GW electrical power, while Suzlon S-120 generates a minimum of 122.75 GW electrical power.

Table 8
Statistical information on land suitability area for solar, and wind farms.

	1 (highly suitable)		2 (suitable)		3 (moderate suitable)		4 (less suitable)		5 (not suitable)	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Solar	133,874	4.13	2,567,836	79.26	473,309	14.61	64,904	2.00	–	–
Wind	29,457	0.91	2,602,763	80.43	546,636	16.89	57,044	1.77	–	–

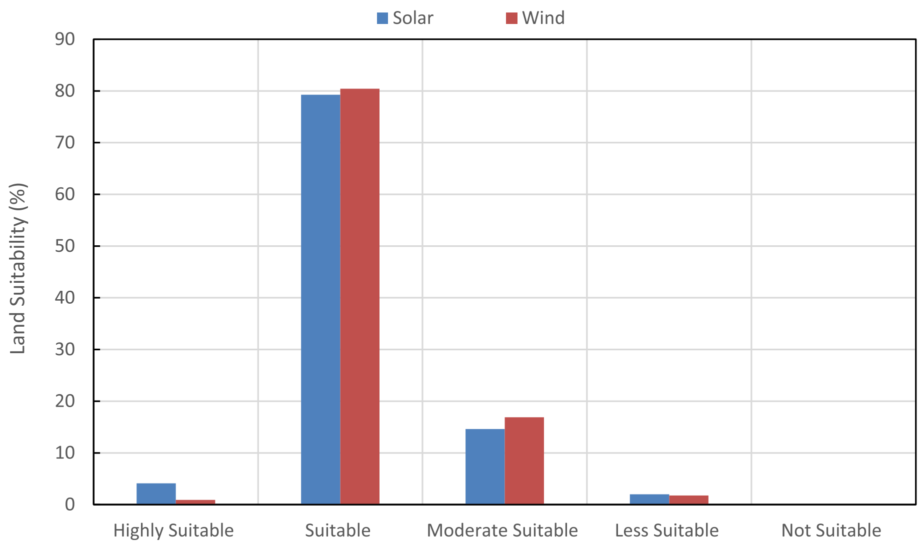


Fig. 10. Graphical interpretation of results of land suitability classes for solar, and wind farms.

Table 9
Statistical information of land suitability area for different states and union territories of India.

States	Highly Suitable (km^2)		Suitable (km^2)		Moderate Suitable (km^2)		Less Suitable (km^2)		Total Area (km^2)	
	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind
Andaman and Nicobar	–	–	976	350	3375	6063	–	–	4351	6413
Andhra Pradesh	6722	5821	147,591	151,361	3777	2691	–	–	158,090	159,873
Arunachal	–	–	1225	317	53,696	47,816	25,727	35,791	80,648	83,924
Assam	–	–	50,053	22,851	30,269	58,347	2	–	80,324	81,198
Bihar	3953	–	88,739	91,523	212	2395	–	–	92,904	93,918
Chandigarh	–	–	127	127	–		–	–	127	127
Chhattisgarh	4681	–	120,250	117,803	10,940	18,068	–	–	135,871	135,871
Dadra and Nagar Haveli	–	–	507	507	–	–	–	–	507	507
Daman and Diu	–	–	499	516	–	–	–	–	499	516
Delhi	150	–	1399	1549	–	–	–	–	1549	1549
Goa	–	–	2670	2411	672	918	–	–	3342	3329
Gujarat	13,748	5360	162,717	177,095	3320	837	–	–	179,785	183,292
Haryana	4871	–	39,443	44,324	19	09	–	–	44,333	44,333
Himachal	–	–	16,511	11,415	38,019	43,158	520	1228	55,050	55,801
Jammu and Kashmir	–	–	18,722	12,374	160,927	154,964	36,793	16,911	216,442	184,249
Jharkhand	1751		77,566	78,701	1268	1884	–	–	80,585	80,585
Karnataka	12,941	5407	167,512	177,004	12,173	10,305	–	–	192,626	192,716
Kerala	–	–	27,614	20,261	8846	17,126	–	–	36,460	37,387
Lakshadweep	–	–	–	32	–	–	–	–	0	32
Maharashtra	11,360	1093	285,953	301,124	9565	4310	–	–	306,878	306,527
Manipur	–	–	106	–	20,950	22,766	1027	193	22,083	22,959
Meghalaya	–	–	5708	2205	16,348	20,435	–	–	22,056	22,640
Mizoram	–	–	1533	342	18,677	20,546	169	63	20,379	20,951
Madhya Pradesh	5427	1971	298,437	301,599	5423	5717	–	–	309,287	309,287
Nagaland	–	–	1265	521	14,510	14,778	666	1653	16,441	16,952
Orissa	4687	–	138,680	137,307	11,325	18,240	–	–	154,692	155,547
Puducherry	–	–	441	537	–	15	–	–	441	552
Punjab	1443	–	48,229	48,119	215	2251	–	–	49,887	50,370
Rajasthan	**20,881**	**6323**	**322,151**	**338,926**	**1501**	**488**	–	–	**344,533**	**345,737**
Sikkim	–	–	1162	1122	5183	4985	–	710	6345	6817
Tamil Nadu	11,976	2172	108,315	122,588	7454	4922	–	–	127,745	129,682
Telangana	4005	567	110,123	113,902	854	513	–	–	114,982	114,982
Tripura	–	–	3871	4848	5374	4890	–	–	9245	9738
Uttar Pradesh	20,306	743	218,213	234,602	1547	5328	–	–	240,066	240,673
Uttarakhand	171	–	28,851	12,079	23,157	40,766	–	495	52,179	53,340
West Bengal	4801	–	70,677	72,421	3713	11,105	–	–	79,191	83,526
Total	**133,874**	**29,457**	**2,567,836**	**2,602,763**	**2,602,763**	**546,636**	**64,904**	**57,044**	**3,239,923**	**3,235,900**

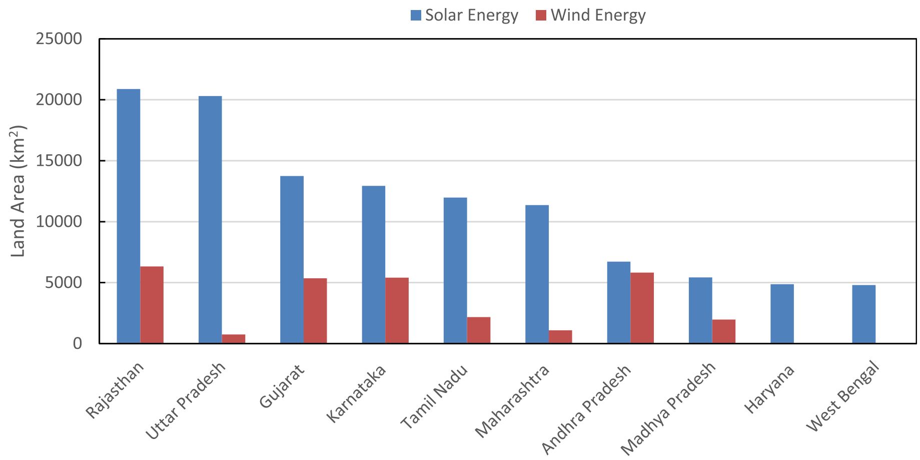


Fig. 11. Graphical representation of suitable land areas for solar, and wind farms in various states of India.

Table 10
Sensitivity analysis cases for technical, socio-environment, and economic aspects.

	Case – I (Equal-weight aspect)	Case – II (Technical aspect)	Case – III (Socio-environment aspect)	Case – IV (Economic aspect)
Technical	0.34	0.8	0.1	0.1
Socio-environment	0.33	0.1	0.8	0.1
Economic	0.33	0.1	0.1	0.8

Table 11
Statistical information of land suitability areas for four sensitivity cases.

		Highly suitable		Suitable		Moderate suitable		Less suitable		Not Suitable	
		Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Equal weight	Solar	156,985	4.83	2,636,149	81.06	447,970	13.78	10,660	0.33	–	–
	Wind	61,055	1.87	2,750,085	84.31	446,861	13.70	3983	0.12	–	–
Technical weights	Solar	350,216	10.67	2,300,255	70.10	391,793	11.94	237,287	7.23	1600	0.06
	Wind	290,406	8.99	2,512,075	77.77	261,740	8.10	155,304	4.82	10,443	0.32
Socio-environment weights	Solar	900,861	27.45	2,056,219	62.67	318,999	9.73	5072	0.15	–	–
	Wind	848,766	26.28	2,092,195	64.77	284,556	8.81	4451	0.14	–	–
Economic weights	Solar	45,437	1.38	2,032,560	61.95	1,099,510	33.51	103,644	3.16	–	–
	Wind	44,350	1.37	1,987,161	61.52	1,127,706	34.92	70,751	2.19	–	–

Table 12
Theoretical solar power potential on highly suitable land areas.

Manufacturer	PV Module	Technology	Solar Radiation (SR) (kWh/m^2/day)	Total area of selected site (km^2)	Area Factor (%)	Efficiency (%)	Theoretical Power Potential (GW)
TATA Solar Power	TP-300	Poly-crystalline	5.61	133,874	70	16.4	3592
WAAREE	WS-320	Mono-crystalline				16.49	3612
EMMVEE	E320P72	Poly-crystalline				16.41	3594
Canadian Solar	CS6X –320P	Mono-crystalline				16.68	3653

4. Discussion

Even though India has built an ambitious renewable energy installation target especially expanding solar and wind energy resources. But still, very slow progress has been observed in the installation of renewable energy sources compare to their targets. The possible reasons may be due to unavailability of evidence of energy resources, poor infrastructure, limited planning, and lack of political motivation. For all these reasons, the outcome of the study could facilitate the different government organizations, policy and decision-makers, researchers, and investors to bring more renewable energy into the national energy system. This study developed and applied a GIS-MCDM model to evaluate suitable sites for the development of two prominent onshore renewable energy sources i.e. solar and wind energy. This is the first kind of research study in India that would provide valuable information to the research community as well as potential investors pertaining to the most suitable locations for installing solar and wind farms. On the basis of publicly available data from different reliable sources, the present study evaluates the highly suitable locations for solar and wind farms. The outcome of the study will help to achieve future renewable energy targets.

Table 13
Theoretical wind power potential on highly suitable land areas.

Manufacturer	Wind Turbine Model	IEC Class	Rotor Diameter (m)	Capacity (MW)	7D × 5D Area (Km^2)	Area Factor (MW/Km^2)	Theoretical Wind Power Potential (GW)
Vestas	V120–2.2	IEC IIB/IEC S	120	2.2	0.504	4.365	128.58
Vestas	V110–2.0	IEC IIIA	110	2.0	0.4235	4.722	139.09
Suzlon	S-111	IEC IIIA	112	2.1	0.439	4.783	140.89
Suzlon	S-120	IEC S	120	2.1	0.504	4.167	122.75
Suzlon	S-128	IEC S	129	2.7	0.582	4.639	136.65
GE	1.6–82.5 WT	IEC IIIB	82.5	1.6	0.238	6.723	198.04
Inox Wind	93 RD + 80 HH	IEC IIIB	93	2.0	0.303	6.601	194.44
ReGen Powertech	VENSYS-77	IEC IIIA	77	1.5	0.207	7.246	213.44

4.1. Implication of research outcome

The Government of India (GOI) is highly intended to achieve their goals of (i) to achieve 175 GW of renewable power capacity by 2022, (ii) to produce about 40% of its electricity from "non-fossil fuel resources" by 2030, and (iii) to reduce emission intensity per unit of GDP by 30–35% by 2030 from the level of 2005 [80,81]. Therefore, the outcome of the study will help in achieving these goals by properly exploring the existing energy resources as well as assessing the new energy resources. It will be helpful in developing local and national infrastructure, to prepare a sufficient market base, develop grid and transmission systems, and to establish weather monitoring stations. Development of local and national infrastructure such as roads, and railways would also be beneficial for rural development and flexible transportation servicing. Whereas, identification of suitable sites will also provide an opportunity to develop a sufficient and strong market base near to facilities such as manufacturing industries, the construction sector, transportation facilities, and educational and training institutes. The output would also be beneficial in terms of the development of the grid and transmission system by minimizing the transmission and distribution losses and harnessing the untapped renewable energy potential. Following the research output, GOI may directly install the weather monitoring stations to validate the outcome, otherwise, assessment of suitable locations is a crucial and costly process. GOI may also plan to develop an attractive investment environment and open international trade and investment in highly suitable locations.

The results of the study will also enlighten and guide the policy and decision-makers. They may formulate adequate government policies to support and increase the installed power capacity of India. Other than this, they could disseminate awareness about the technology's benefits that will increase the chances of adoption of renewable technologies. Finally and importantly, they may also plan about the subsidies according to the availability and suitability of the renewable sites. The identification of highly suitable sites will also motivate and encourages investors and stakeholders to invest in green and renewable energy sources.

The implementation of the research outcomes will highly affect the rural and backward communities, especially due to the availability of renewable energy sources in rural remote areas. Due to the development of power plants in remote areas, more jobs will be created at the local and regional level. Moreover, to increase the social acceptance of projects, some social benefits will also be given to them such as health care, electricity, and education. Further, social welfare and living standards of the society will also increase with development in infrastructure and earning at the local level. Whereas from an industrialist's perspective, huge human resources will be available at a low cost, and the development of infrastructure will cheap as compared to urban areas.

4.2. Comparison and validation of findings

The primary aim of the study is to investigate suitable sites for solar and wind farm installation in India. During a deep and thorough literature review, the authors did not find the same streamlined studies which investigated the suitable sites for solar and wind farms. But, there were various studies that streamlined with the secondary objective of estimation of solar and wind power potential in India. The detailed analysis of these studies with the considered assumptions of land suitability and final theoretical power output is described below.

In the case of solar power, a study estimated 6000 GW and 2500 GW power generation from solar photovoltaic (SPV) and concentrated solar power (CSP) respectively. The installation of power plants was considered only on wastelands with a minimum threshold of 4 kWh/m^2/day of GHI and the terrain slope should be less than 2.1% [33]. Another study estimated utility-scale PV power potential in the range of 1300–5200 GW with a threshold GHI of 4.9 kWh/m^2/day [82]. Assuming the same assumptions of the previous studies, the outcome of the current research study is similar and equal.

In the case of wind power, a number of research studies are available. For example, one research study calculated 850–3400 GW range onshore wind power potential with a minimum of 5.5 m/s wind velocity, and area factor in the range of 2.25–9 MW/km^2 [82]. Another study estimated 4250.63 GW of onshore wind power potential in India excluding Himalayan areas and north-east states while assuming 15% of capacity utilization factor on the footprint area of 2,094,036 km^2 [83]. The third study estimated 486.6 GW wind power capacity potential with an area factor of 5 MW/km^2. The study excluded the areas beyond the 50 km from the high voltage transmission lines [84]. Afterward, a technical report calculated the footprint area of 0.84% and 0.91% of the total available area for wind and solar farms. The study assessed the area factor for the two area pattern of 5D × 7D, and 3D × 5D [79]. Finally, official GOI estimated a wind power potential of 153 GW on the Rank 1 potential locations at a hub height of 100 m [85]. Comparative studies indicate a similar behavior in area factor, foot-print area, and range of final power output. A review of comparative studies also indicated that the renewable energy potential is varied with the resource input data sets, exclusion criteria, buffer areas, land use and land cover input data sets, area factor, foot-print area, technological assumptions, and limitations [82].

4.3. Research limitations

The analysis has been carried out with the publicly available data from different reliable sources, but these data are not as much updated as compared to the commercially available data. The results can be further improved with the available ground measured data. Moreover, the uncertainties in the estimation of renewable power can be minimized in further research and dialogue by involving academia, industrialists, policy-makers, investors, stakeholders, and other experts, who are actively involved in the renewable power deployments. However, the study is facilitating the reproduction of improved results using the developed methodology, MCDM concepts, open-source GIS data, assumptions, and potential estimation. It is hoped that the incorporation of such extensive information related to its spatial and temporal variability in renewable energy capacity and system planning studies may provide policymakers, and appropriate rules for increasing the renewable energy contribution to the overall energy supply can go a long way.

5. Conclusions

The objective of the research work is to evaluate suitable sites in India for the installation of solar and wind farms. Assessing suitable sites for solar and wind farms is the primary and necessary step for the proper utilization of solar and wind energy potential. A combination of GIS and MCDM approach has been employed for the identification of solar and wind suitable sites taking into account the technical, socio-environment, and economic aspects.

The research work includes thirteen important factors selected from the literature and based on the expert's advice. The F-AHP approach was used to assign relative importance to the evaluation factors. The GIS approach prepared a spatial dimension of the decision criteria and elaborated them to produce the final five suitability classes of 'highly suitable', 'suitable', 'moderately suitable', 'less suitable', and 'not suitable'. Solar radiation, aspect, and distance from transmission lines are important factors for the solar farms while the wind speed, elevation, and distance from the transmission lines are important factors for the wind farms.

The study reveals that 4.13% (133,874 km^2) of the total surface area is 'highly suitable', 79.26% (2,567,836 km^2) of the area belongs to the 'suitable' category, 14.61% (473,309 km^2) of the area falls under the 'moderately suitable', and finally, 2% (64,904 km^2) of the total area comes under the 'less suitable' category for solar farms installation. Similarly, for wind energy, only 0.91% (29,457 km^2) of the total area is categorized into 'highly suitable', 80.43% (2,602,763 km^2) of the area is under the 'suitable' category, 16.89% (546,636 km^2) of the area is under 'moderately suitable', and finally, 1.77% (57,044 km^2) of the total area is 'less suitable' for the installation of wind farms. The 'not suitable' category is not detected for both the solar as well as the wind farms. Whereas, India has 3653 GW and 213.44 GW of theoretical Solar PV and wind power potential at the highly suitable land area (Rank 1).

This study also concludes that the Rajasthan state has the highest land suitability for both the solar and the wind farms among the different states and union territories. Apart from Rajasthan, states like Uttar Pradesh, Gujarat, Karnataka, Tamil Nadu, Andhra Pradesh, Maharashtra, Madhya Pradesh, Haryana, and West Bengal also have the overall highest land suitability for solar and wind farms. The sensitivity analysis performed for the four aspects of equal weight, economic, technical, and socio-environment concluded that suitable land output is sensitive to changes in criteria weights.

The current research work helps in properly exploiting the existing energy resources and infrastructure to fulfill the energy requirement of the country in harmony with the environment. In future work, other decision criteria such as visual impact, noise impact, population growth, and vegetation distribution, etc. will be included to enrich the model.

CRediT authorship contribution statement

S.K. Saraswat: Data curation, Conceptualization, Writing - original draft, Methodology, Visualization, Software, Investigation, Formal analysis, Writing - review & editing. **Abhijeet K. Digalwar:** Conceptualization, Methodology, Writing - review & editing, Supervision. **S.S. Yadav:** Writing - review & editing, Supervision. **Gaurav Kumar:** Visualization, Software, Writing - review & editing.

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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