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Analysis of wind power generation potential and wind turbine installation economics: A correlation-based approach

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ABSTRACT

Wind energy production is rapidly expanding worldwide, yet studies on wind energy potential in India remain limited. This study evaluates the wind power potential and conducts an economic cost analysis of wind turbine generator installations at varying hub heights (10m to 150 m) across 21 locations in India, representing a novel contribution to the field. The selected locations include 11 sites in Gujarat (Location-1), 10 sites in Tamil Nadu (Location-2), and one site in Ravangla, Sikkim (Location-3). Cubic factors methods are implemented to estimate Weibull parameters. Results reveal that at 150 m hub height, wind power density ranges from 123.17 to 308.86 W/m^2 in Gujarat, 80.64 to 427.12 W/m^2 in Tamil Nadu, and 183.24 W/m^2 in Sikkim. Kaluneerkulam in Tamil Nadu demonstrates excellent wind category potential, with energy costs ranging from \$0.0165 to \$0.0076 per kWh, decreasing as hub height increases. Sites across all three locations exhibit moderate to steady wind speeds, making them suitable for wind energy exploitation. An economic analysis of nine wind turbine types shows that Tamil Nadu achieves the lowest energy cost variation, followed by Gujarat and Sikkim. This study provides valuable insights for optimizing wind energy utilization in India.

1. Introduction

With a diverse and culturally rich population of over 1.45 billion [1], India ranks as the second-largest emerging economy globally [2]. This growth is driven by increasing industrialization and improved living standards [3]. India's economy is undergoing remarkable growth but simultaneously confronts significant challenges. These include fulfilling the increasing energy demands of its expanding population, ensuring a fully electrified energy supply, and working towards the reduction of pollutant and carbon emissions [4,5]. In recent decades, the uncontrolled release of greenhouse gases has become a primary contributor to pollution, resulting in significant ecological consequences such as environmental degradation, global warming, and climate change [6,7]. In line with the Paris Agreement, India is committed to reducing emissions intensity and aims to achieve a net zero target by 2070 [8,9]. The installed capacity of wind potential for countries such as China is 420 GW, the US 150 GW, Germany 65 GW, India 45 GW, Spain 30 GW, the UK 40GW and Brazil 30GW. Furthermore, the country has pledged to meet more than 50 % of its electricity needs through renewable energy sources by 2030, an essential step towards India's response to climate change and achieving sustainable development goals [9].

India ranks as the third most substantial consumer of energy globally. According to statistics, India's peak demand increased by 13 % to 243 GW in 2024 [10]. It is predicted to reach 277.2 GW in 2026–2027 and 366.4 GW in 2031–2032, suggesting that the energy demand will continue to rise [11]. Moreover, the escalating need for energy has led to a greater dependence on fossil fuels, particularly in the case of developing nations such as India. Furthermore, heightened reliance on a solitary energy source presents a substantial peril to any country's energy security and long-term viability [12]. People worldwide are noticing renewable energy sources, including wind, solar, and hydro

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Nomenclature

CDF	cumulative density functions
CF	cubic factor
COE	cost of energy
GIS	geographic information system
RMSE	root mean square error
WDF	Weibull density function
WPD	wind power density
WPP	wind power potential
WS	wind speed
WRA	wind resource assessment
NASA	National aeronautics and space administration
C_{TAC}	total annual cost ($)
E_{AEO}	annual electricity generation of WTG (kWh)
C	scale parameter
k	shape parameter
Γ	gamma function
ρ	air density
n	duration of the project
D	rotor radius (m)
N_p	nominal power (kW)
WTG	wind turbine generator

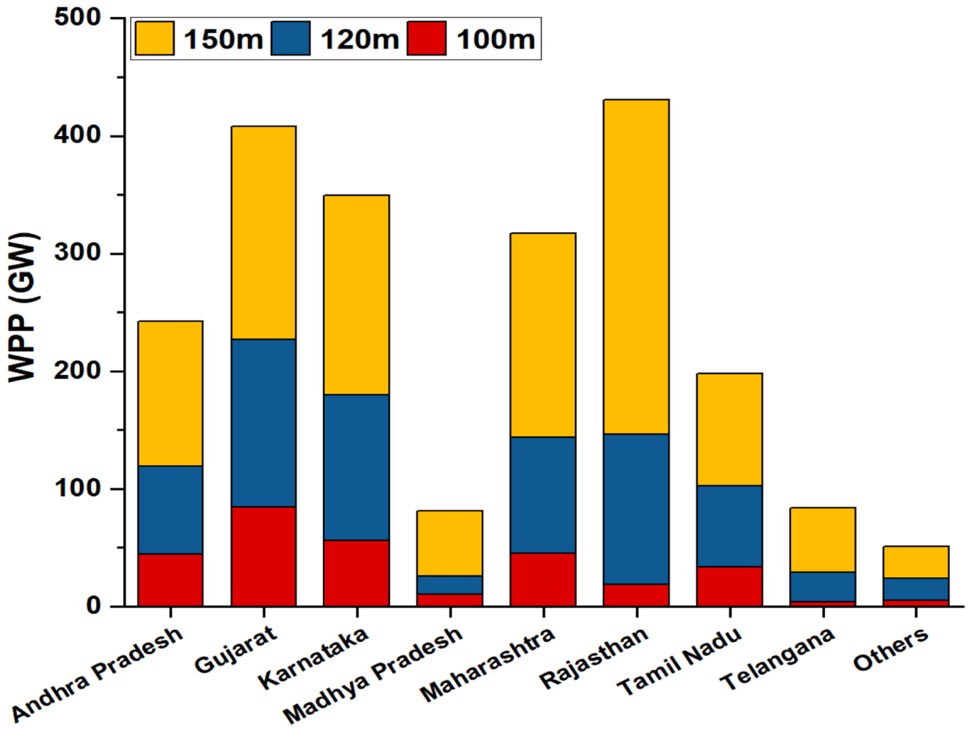

Fig. 1. Wind power potential at 100 m, 120 m and 150 m above ground level for Indian states.

[13–15]. Due to their intermittent nature, renewable energy sources enable large-scale storage of a low-carbon energy mix [16,17]. Over the last two decades, there has been a significant surge in wind energy demand, production, and supply in many locations worldwide [18–20]. The considerable expansion of wind energy development in recent decades may be primarily attributed to a comprehensive understanding of scientific and technological aspects [21–23]. Restricting the use of fossil fuels is undeniably a vital goal of the Paris Agreement, and almost every country has already pledged to promptly decrease carbon emissions by pursuing net-zero goals [24,25]. India aspires to establish a low-carbon development framework and mitigate its energy disparity via wind power [26]. With 44.736 GW of installed capacity as of December 31, 2023, it is among the top four wind markets and produced 64.64 billion units in 2019–20 [27]. The National Institute of Wind Energy, established by the Indian government, focuses on wind power potential (WPP) at various elevations. India is equipped with around 900 wind-monitoring stations that contribute to generating WPP maps at different heights above ground level. According to the most current predictions, the gross WPP recorded values of 302.25 GW at 100 m, 695.50 GW at 120 m, and 1163.9 GW at 150 m above ground level. Fig. 1 illustrates that the majority of WPP is found in eight windy states of India [28].

Even though the capacity of wind power is rapidly increasing, just a tiny portion of the nation's wind potential has been realized thus far. It is essential to use the untapped WPP to meet the energy demand. Several writers offered different approaches for WPP assessment at various heights. Weibull for WPP at multiple elevations (i.e., 30 m to 100 m) was provided by Chandel et al. [29] for the Indian state of Himachal Pradesh in the Western Himalayas. According to the acquired results, summertime is when wind speeds are highest, and wintertime is when they are lowest. In another research, Chandel et al. [30] assessed the suitability of the Hamirpur site for microturbines by evaluating the performance of WPP using WAsP at distances of 30 m to 100 m. The wind generating capacity of 21,268.3 MW was calculated by Sangroya and Nayak [31] till May 2014. The authors used the Weibull method to determine the WPP for 10 Indian states at a height of 90 m. Using geospatial tools like GIS and remote sensing, Ramachandra et al. [32] calculated the preliminary WPP for the Uttara Kannada area of Karnataka, India, at 70 m. The average yearly wind speed ranges from 2.5 m/s to 3.0 m/s. Hossain et al. [33] presented GIS to identify WPP at 80 m for Indian sites. The

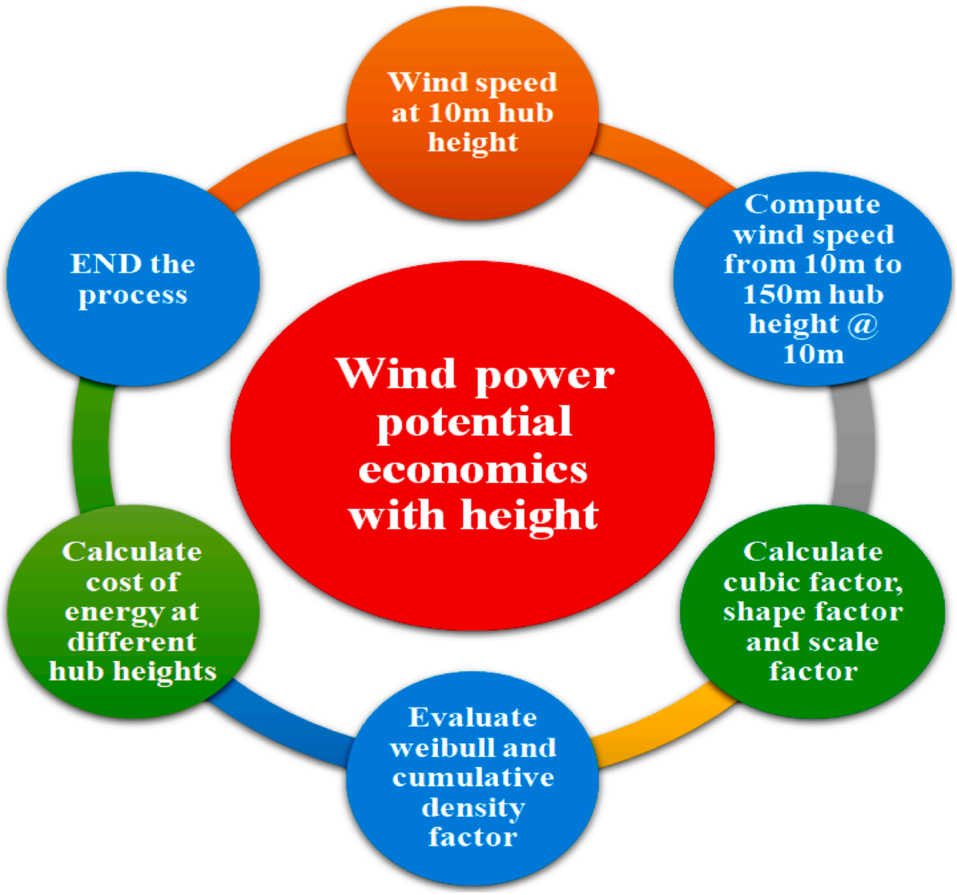

Fig. 2. Economic cost study of wind turbine installation at varying tower height using proposed wind power generating potential assessment.

Table 1
Wind energy resource classification and categorization [50].

Wind class	Wind resource category	Wind power density (W/m^2)	Wind speed (m/s)
1	Poor	50–200	3.5–5.6
2	Marginal	200–300	5.6–6.4
3	Moderate	300–400	6.4–7.0
4	Good	400–500	7.0–7.5
5	Excellent	500–600	7.5–8.0
6	Excellent	600–800	8.0–8.8
7	Excellent	Above 800	Above 8.8

estimated wind farm potential is found to be 4,250,639.912 MW. Singh and Prakash [34] used the Weibull probability distribution at 10 m to ascertain the presence of WPP in the regions of Lohardaga, Devghar, Jamshedpur, Chaibasa, and Ranchi, located in the state of Jharkhand, India. It is suggested that a wind turbine cannot produce power at a height of 10 m.

Reddy et al. [35] performed a statistical analysis at 50 m Gadanki, India, to identify WPP. With an average wind speed of 2.9 m/s, 332.8 kWh/m^2 of energy may be extracted annually. After conducting a wind resource assessment for Arctic communities, Her et al. [36] concluded that a 100 kW wind turbine with a capacity factor of 16.7 % and a levelized energy cost of $1.15/kWh would be appropriate. In their study, Dayal et al. [37] evaluated wind resources in Fiji's Udu, Nabouwalu, and Rakiraki regions. The values for wind speed (WS) were determined as Udu=7.0 m/s, Nabouwalu=7.1 m/s, and Rakiraki=7.6 m/s, whereas WPP measured as Udu=294 W/m^2, Nabouwalu=512 W/m^2, and Rakiraki=401 W/m^2. The wind efficiencies for these sites (i.e. Udu, Nabouwalu, and Rakiraki) are 97 % to 98 %. Neupane and colleagues [38] extensively analysed Nepal's wind potential, determining a total of 1686 MW of harnessable wind energy. The research shows that the provinces of Karnali and Gandaki have relatively high Wind Power Potential (WPP). According to Franke et al. [39], China's WPP ranged between 1783 TWh to 39,000 TWh. Wind turbine designs, land usage, and meteorological data sets influence WPP.

Vinhoza and Schaeffer [40] analyzed offshore WPP for Brazil. A total of 1688 GW of gross potential, 330 GW of potential for the environment and society, and 1064 GW of technology are offered. Ayik et al. [41] performed WPP for South Sudan. At 10 m, WS varies from 5.08 m/s and 2.36 m/s, and WPP varies from 128.36 W/m^2 to 14.39 W/m^2. Kumar et al. [42] estimate Weibull parameters using multiverse optimization for the Tirumala region in India. The highest mean WS is 6.621 m/s at 65 m and 5.12 m/s at 10 m in December. At a height of 150 m, Murthy and Rahi [43] examined WPP for Bheemunipatnam in northern Andhra Pradesh, India. It was determined that the location experienced moderate and consistent WS in addition to a gusty WS of 13.3 m/s. Deep et al. [44] utilized the Weibull model to estimate the wind energy potential of 17 Indian coastal regions. Upon analysis, it was determined that the WS data gathered exhibited bias. After accounting for sample errors, the authors concluded that the Weibull model is suitable for studying India's wind climate. The key contribution of this research study is as following:

- Addressing research gap in WRA: The analysis bridges the knowledge gap by analyzing wind energy potential across 21 locations in India, where limited research has been conducted despite the country's significant untapped wind power potential.
- Advanced modeling techniques for wind energy evaluation: The research employs the power law, cubic factor (CF) method, and Weibull model to effectively evaluate wind energy potential,

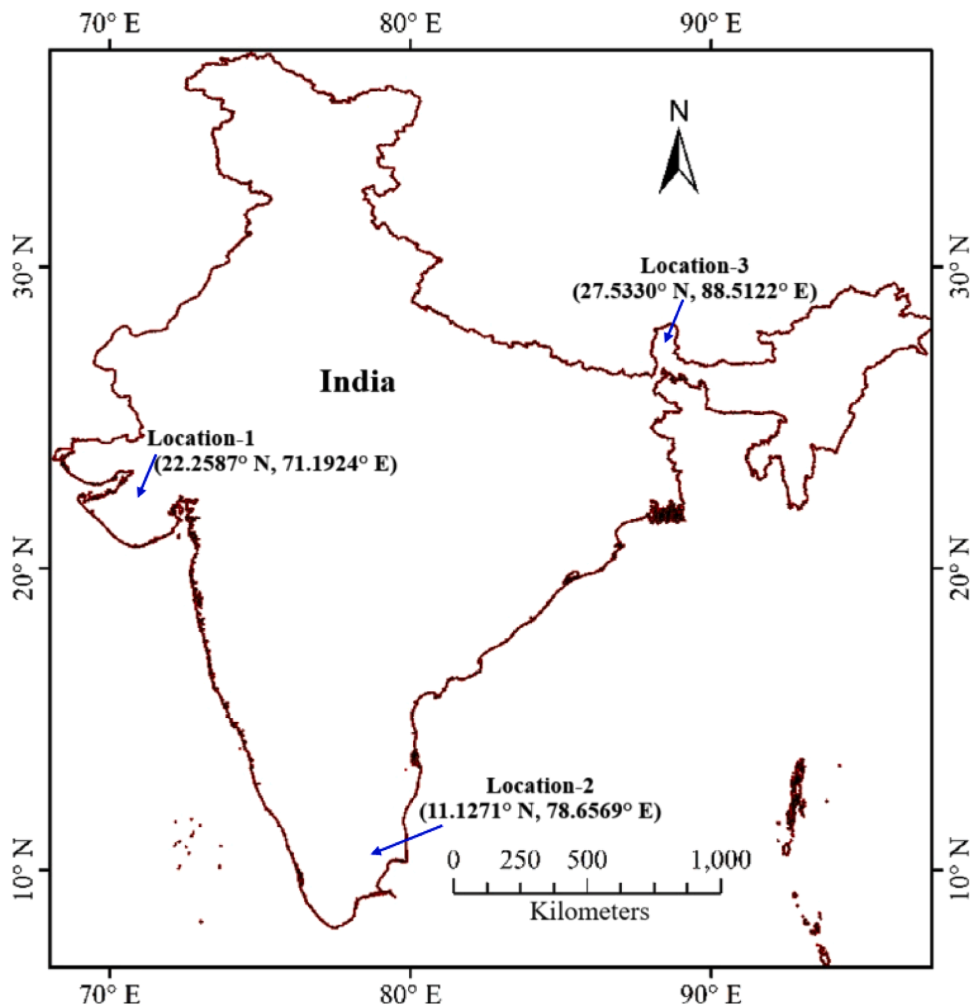

Fig. 3. Map showing Gujarat, Tamil Nadu, and Sikkim in India [51].

Table 2
Latitude and longitude of 21 selected locations.

Site no.	State	Site name	Latitude (°N)	Longitude (°E)
1	Gujarat	Khambhada	22.14	71.94
2		Mahidad	22.27	71.2
3		Rojmal	22.03	71.5
4		Sangasar	22.32	72.10
5		Suvarda	22.38	70.1
6		Vandhiya	23.29	70.34
7		Vadgam	24.08	72.5
8		Lodrani	23.89	70.6
9		Sinugra	23.09	69.9
10		Lamba	21.90	69.3
11		Dhrobana	23.93	69.75
12	Tamil Nadu	Kaluneerkulam	8.90	77.45
13		Kamagiri	12.36	77.88
14		Kanyakumari	8.08	77.54
15		Muttom	8.12	77.31
16		MS Puram	9.90	78.09
17		Servallar Hills	8.70	77.35
18		Agasthiampalli	10.35	79.85
19		Kalai Nagar	9.96	78.12
20		Kainankarai	10.68	78.3
21	Sikkim	Ravangla	27.30	88.3

including estimating Weibull parameters (scale factor 'c' and shape factor 'k').

- Novel analysis at elevated hub heights: Unlike prior studies that focus on wind power potential up to 90 m, this study extends the evaluation to hub heights of up to 150 m, demonstrating the impact of increased altitude on power generation and highlighting its importance for Indian locations.
- Comprehensive economic analysis of wind turbine installations: The economic viability of nine different wind turbine types is systematically assessed for hub heights ranging from 10 m to 150 m in 10 m increments, providing valuable insights into cost-effective wind energy solutions.
- Practical implications for wind energy deployment: The findings offer critical information for optimizing wind resource assessment and guiding the efficient installation of wind turbine generators, thereby supporting India's renewable energy goals and load demand requirements.

The structure of this document is as follows: Section 2 provides a representation of research methods. Section 3 displays the results and discussions. Section 4 present conclusions.

2. Research methodology

Fig. 2 illustrates the suggested methodology, which includes the systematic process for assessing the potential of wind power production and conducting cost analysis for installing wind turbines at varying tower heights. Firstly, the historical dataset is collected from the meteorological department at 10 m height. From January 1984 to December 2014, the data is derived from the National Aeronautics and Space Administration's (NASA) database and represents the monthly average

Table 3
Wind turbine details.

Manufacturer	Model	Diameter (m)	Power (kW)	Rated speed (m/s)	Cut-out speed (m/s)	Cut-in speed (m/s)	Maximum Cp
Enercon	E53/800	52.9	800	12.5	28.0	2.0	0.49
Enercon	E82/2000	82.0	2000	12.4	28.0	2.0	0.50
Enercon	E70/2300	71.0	2300	14.5	28.0	2.0	0.50
Enercon	E82/2300	82.0	2300	13.5	28.0	2.0	0.50
Enercon	E82/3000	82.0	3000	16.1	28.0	2.0	0.50
Enercon	E101/3000	101.0	3000	11.7	28.0	2.0	0.48
Shandong Swiss Electric	YZ87/2.0	87.0	2000	11.0	20.0	2.3	0.52
Shandong Swiss Electric	YZ82/1.5	82.0	1500	10.2	20.0	2.3	0.43
Shandong Swiss Electric	YZ78/1.5	78.0	1500	10.5	25.0	2.3	0.48

Table 4
Variation of average WS, CF, K, C (m/s), WPD for height 10 to 150 m.

Site no.	State	Locations	WS	CF	K	C	WPD
1	Gujarat	Khambhada	4.28–6.30	1.38	2.91	4.80–7.07	56.11–179.32
2		Mahidad	3.80–5.59	1.28	3.24	5.83–8.60	96.56–308.86
3		Rojmal	3.30–4.86	1.40	2.85	4.48–6.61	46.21–147.68
4		Sangasar	4.10–6.03	1.44	**2.77**	5.39–7.94	81.26–259.69
5		Suvarda	3.40–5.00	1.26	3.32	5.61–8.27	85.36–272.77
6		Vandhiya	2.90–4.27	1.36	2.97	4.67–6.88	51.32–164.01
7		Vadgam	2.20–3.24	1.43	2.78	4.68–6.90	53.35–170.48
8		Lodrani	3.70–5.44	1.20	3.52	4.56–6.72	44.98–143.76
9		Sinugra	3.50–5.15	1.15	3.76	4.71–6.94	48.74–155.77
10		Lamba	3.60–5.30	1.12	**3.92**	4.37–6.43	38.54–123.17
11		Dhrobana	2.70–3.97	1.43	2.79	4.65–6.85	51.97–166.09
12	Tamil Nadu	Kaluneerkulam	5.01–7.38	2.12	1.81	5.64–8.31	133.64–427.12
13		Kamagiri	4.35–6.40	1.74	2.21	4.91–7.23	71.50–228.49
14		Kanyakumari	5.59–8.23	1.19	3.57	6.20–9.14	112.69–360.13
15		Muttom	3.40–5.02	1.17	3.67	3.77–5.56	25.23–80.64
16		MS Puram	4.01–5.91	2.65	**1.52**	4.45–6.56	86.08–275.09
17		Servallar Hills	4.22–6.22	2.06	1.86	4.75–7.00	77.44–247.48
18		Agasthiampalli	3.64–5.36	1.07	4.19	4.00–5.90	29.32–93.72
19		Kalai Nagar	3.99–5.87	1.06	**4.26**	4.38–6.46	38.39–112.69
20		Kainankarai	3.55–5.22	1.27	3.26	3.95–5.83	30.04–96.01
21	Sikkim	Ravangla	4.51–6.65	1.12	**3.90**	4.98–7.34	57.34–183.24

wind speed 10 m above Earth's surface for specific locations [45]. NASA measured wind speed on a brown dwarf [46]. After that, WS data is evaluated at different heights up to 150 m in step size of 10m. Based on this evaluated dataset, CF, k, c, and wind power density (WPD) are assessed for each height level. Finally, the economic cost analysis for the cost of wind energy at different tower heights is performed, and the performance of the proposed approach is validated and demonstrated by using a dataset of twenty-one locations in India.

2.1. Cubic factor method

Eq. (1) demonstrates a clear correlation between the power produced by wind and three key factors: air density, the cube of wind speed, and the swept area of the wind turbine rotor.

$$\mathrm{P} = \frac{1}{2}\rho A v^3 \tag{1}$$

where v is the speed of the wind (m/s), ρ is the density of the air, A is the area swept by the rotor (m^2), and P is the power (watt).

2.2. Weibull model

The following formulas are used to compute probability distributions like Weibull (WDF) and Cumulative (CDF) density functions, as well as the frequency distribution of known wind speeds [47].

$$f(v) = \left(\frac{v}{c}\right)^{k-1}\left(\frac{k}{c}\right)\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{3}$$

where v = speed of the wind (m/s) is represented by the WDF and CDF, $f(v)$ and $F(v)$, respectively. The scale parameter, c, and the shape parameter, k is indicate the peak of the Weibull plot's distribution. It adopts a Weibull distribution when the shape parameter is smaller than 2. It is referred to as the Rayleigh distribution when it is precisely two; if it is more than three, it takes the Gaussian distribution.

2.3. Wind profile vertical

Eq. (4) defines the vertical wind profile as follows. Another name for it is power law. The power law is a valuable tool for estimating wind speeds about the hub heights required for wind turbines. The power law may be mathematically represented as [48].

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{4}$$

The wind speeds at heights h_1 and h_2 (measured in m) are represented by v_1 and v_2 (measured in m/s), respectively. The power exponent, denoted as α, has a value of 0.143. The shape parameter k represents the characteristics of wind, such as $1.5 \leq k \leq 1.99$ indicating a reasonably windy location, $k \leq 1.5$ indicates a wind speed that is highly variable or gusty, $k \geq 2$ indicates a moderate wind speed, and $k \geq 3$ denotes a consistent, steady wind speed.

The following formulae may be used to get the Weibull parameters:

Table 5
Developed correlation of WPD as a function of wind speed.

S. No.	State	Locations	Equations	R^2	RMSE
1	Gujarat	Khambhada	$y = 11.4x^2 - 60.1x + 104.6$	1	0.14
2		Mahidad	$y = 25.0x^2 - 117.7x + 182.7$	1	0.29
3		Rojmal	$y = 14.76x^2 - 54.72x + 65.6$	0.99	**1.89**
4		Sangasar	$y = 18.07x^2 - 91.47x + 152.9$	1	0.25
5		Suvarda	$y = 27.54x^2 - 115.4x + 159.6$	1	0.22
6		Vandhiya	$y = 22.76x^2 - 81.35x + 95.98$	1	0.13
7		Vadgam	$y = 41.12x^2 - 111.5x + 99.77$	1	0.13
8		Lodrani	$y = 12.26x^2 - 55.89x + 84.14$	1	0.11
9		Sinugra	$y = 14.84x^2 - 64.02x + 91.16$	1	0.12
10		Lamba	$y = 11.09x^2 - 49.22x + 72.09$	1	**0.10**
11		Dhrobana	$y = 26.6x^2 - 88.49x + 97.21$	1	0.13
12	Tamil Nadu	Kaluneerkulam	$y = 19.8x^2 - 122.4x + 249.6$	1	0.35
13		Kamagiri	$y = 14.1x^2 - 75.56x + 133.7$	1	0.18
14		Kanyakumari	$y = 13.44x^2 - 92.64x + 210.3$	1	0.29
15		Muttom	$y = 8.104x^2 - 34.04x + 47.2$	1	**0.06**
16		MS Puram	$y = 19.9x^2 - 98.52x + 161$	1	0.22
17		Servallar Hills	$y = 16.18x^2 - 84.26x + 144.8$	1	0.20
18		Agasthiampalli	$y = 8.249x^2 - 37.02x + 54.85$	1	0.07
19		Kalai Nagar	$y = 5.88x^2 - 14.55x + 1.928$	0.99	**2.38**
20		Kainankarai	$y = 8.839x^2 - 38.91x + 56.19$	1	0.07
21	Sikkim	Ravangla	$y = 10.49x^2 - 58.36x + 107.2$	1	0.14

$$k = 1 + \frac{3.69}{(CF)^2}, \tag{5}$$

Where CF =wind energy pattern factor

$$CF = \frac{V^{3^-}}{\upsilon^{-3}} \tag{6}$$

where V^{3^-} the average of cubes of wind speed, υ^{-3} is a cube of the average wind speeds.

$$c = \frac{\overline{v}}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{7}$$

The WPD is determined as,

$$\text{WPD} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{8}$$

WPD indicates the availability of energy at a particular site.

2.4. Error analysis

Root means square error (RMSE) analysis was used to assess the difference between the observed value and predicted value for n observations. The optimum RMSE value is always positive and near zero.

Table 6
Comparative analysis with other research.

Studies	Error	Highlights
Current study	RMSE varies from 0.06 to 2.38	Develop correlation provide best estimation.
Nymphas and Teliat [49]	RMSE varies between 0.008912 to 0.65615	Five numerical methods used for wind speed data analysis in Nigeria.
Al-Mhairat and Al-Quraan [55]	RMSE = 0.0176	The maximum likelihood method is the most effective approach for the nine sites in Jordan.
Yadav et al. [56]	RMSE = 0.13	Rayl give better estimation.
Al-Quraan et al. [57]	RMSE varies between 0.11 to 0.15	Quadratic model give highest correlation.
Al-Quraan et al. [58]	RMSE = 0.1	Exponential model present strong correlation.
Al-Quraan and Al-Mhairat [59]	RMSE < 0.2	For optimization, the whale optimization algorithm (WOA) is used.
Al-Quraan et al. [60]	RMSE varies between 0.01013 to 0.03222	Gamma model employing WOA proved best compared to Weibull and Rayleigh.
Al-Quraan et al. [61]	RMSE < 0.1	Microsoft Excel environment is used for estimation.
Imam et al. [62]	RMSE=0.022 for testing dataset	Support vector regression used for assessing the wind energy potential at various locations of Saudi Arabia.
Khchine and Sriti [63]	RMSE varies between 0.0083 to 0.0505	Modified maximum likelihood technique present better results than Weibull parameters.
Hasan et al. [64]	RMSE is 0.0453	Wind power potential investigated using Rayleigh and Weibull distribution functions.
Alrashidi [65]	RMSE varies between 0.0018 to 0.0182	Seven numerical methods used for wind speed data analysis in Saudi Arabia.
Kutty et al. [66]	RMSE varies between 0.1062 to 0.4255	Assessment of wind energy in Tonga utilizing eleven methodologies for estimating Weibull parameters.

The following formula is used to calculate the RMSE [49].

$$\text{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(OV_i - PV_i)^2\right]^{\frac{1}{2}} \tag{9}$$

where n = number of observations, OV= observed value and PV= predicted value.

2.5. Categorization of wind energy resource

The Wind Energy Resource Atlas of the United States provides estimates of regional wind resources. Table 1 shows how wind power density, wind speed, and wind class are expressed to evaluate wind resources.

2.6. Site description

The selected states (Gujarat, Tamil Nadu, and Sikkim) are shown in Fig. 3, and latitude and longitude details are given in Table 2. The monthly average WS at an altitude of 10 m for 21 sites, as estimated by NASA, is shown in Figs. S1–S3 (Supplementary Material). The aforementioned data points are computed as the mean value for each month during a span of 30 years, namely from January 1984 to December 2014. The WS for Gujarat, Tamil Nadu, and Sikkim varies from 2.20 to 4.28 m/s, 3.40 to 5.0 m/s, and 4.5 m/s, respectively. For most of the sites in Gujarat, WS is a minimum for January, December and a maximum for July; Tamil Nadu WS is a minimum for January, December and a maximum for May; Ravangla in Sikkim, WS is a maximum for March, November, and minimum for September due to mountainous region. These sites have good WS, but wind resource assessment has not been done.

Table 7
Wind speeds, average, minimum, and maximum, at 10 m of Gujarat sites.

Site	Average wind speed (m/s)	Maximum wind speed(m/s)	Minimum wind speed(m/s)	CF	K	Highlights	WPD (W/m^2) at 150 m	Wind class	Wind category
Khambhada	4.28	7.1 (June)	2.4 (Dec)	1.38	2.91	Moderate wind speed	179.32	1	Poor
Mahidad	**4.98**	**5.97 (June)**	**3.8 (Oct)**	**1.28**	**3.24**	**Regular steady wind speed**	**308.86**	**3**	**Moderate**
Vadgam	2.88	3.24 (May)	2.2 (Jan)	1.43	2.78	Moderate wind speed	170.48	1	Poor
Rojmal	4.32	4.86 (May)	3.3 (Dec)	1.40	2.85	Moderate wind speed	147.68	1	Poor
Dhrobana	3.54	3.97 (June)	2.7 (Oct)	1.43	2.79	Moderate wind speed	166.09	1	Poor
Vandhiya	3.80	4.27 (June)	2.9 (Nov)	1.36	2.97	Moderate wind speed	164.01	1	Poor
Sangasar	5.37	6.03 (May)	4.1 (Nov)	1.44	2.77	Moderate wind speed	259.69	2	Marginal
Lodrani	4.85	5.44 (May)	3.7 (Oct)	1.20	3.52	Regular steady wind speed	143.76	1	Poor
Sinugra	4.59	5.15 (May)	3.5 (April)	1.15	3.76	Regular steady wind speed	155.77	1	Poor
Lamba	4.72	5.30 (July)	3.6 (Sep)	1.12	3.92	Regular steady wind speed	123.17	1	Poor
Suvarda	4.46	5.00 (May)	3.4 (Oct)	1.26	3.32	Regular steady wind speed	272.77	2	Marginal

Table 8
Wind speeds, average, minimum, and maximum, at 10 m of Tamil Nadu sites.

Site	Average wind speed (m/s)	Maximum wind speed (m/s)	Minimum wind speed (m/s)	K	CF	Highlights	WPD (W/m^2) at 150 m	Wind class	Wind category
Kaluneerkulam	**6.58**	**7.38 (Aug)**	**5.01 (Nov)**	**1.81**	**2.12**	**Fairly windy site**	**427.12**	**4**	**Good**
Servallar Hills	5.55	6.22 (Sep)	4.22 (Dec)	1.86	2.06	Fairly windy site	247.48	2	Marginal
Muttom	4.47	5.02 (July)	3.40 (Oct)	3.67	1.17	Regular steady wind speed	80.64	1	Poor
Kanyakumari	7.33	8.23 (Aug)	5.59 (Nov)	3.57	1.19	Regular steady wind speed	360.13	3	Moderate
MS Puram	5.27	5.91 (July)	4.01 (Dec)	1.52	2.65	Fairly windy site	275.09	2	Marginal
Kamagiri	5.70	6.40 (July)	4.35 (Mar)	2.21	1.74	Moderate wind speed	228.49	2	Marginal
Agasthiampalli	4.77	5.36 (June)	3.64 (Oct)	4.19	1.07	Regular steady wind speed	93.72	1	Poor
Kalai Nagar	5.23	5.87 (May)	3.99 (April)	4.26	1.06	Regular steady wind speed	112.69	1	Poor
Kainankarai	4.65	5.22 (Aug)	3.55 (April)	3.26	1.27	Regular steady wind speed	96.01	1	Poor

Table 9
Wind speeds, average, minimum, and maximum, at 10 m of Sikkim site.

Site	Average wind speed (m/s)	Maximum wind speed (m/s)	Minimum wind speed (m/s)	CF	K	Highlights	WPD (W/m^2) at 150 m	Wind class	Wind category
Ravangla	5.92	6.65 (Mar)	4.51 (Sep)	1.12	3.90	Regular steady wind speed	183.24	1	Poor

2.7. Economic analysis

Capital and operational cost investments are used to determine the cost of wind power units. It is essential to decide on the price of a wind turbine generator (WTG) based on references before installing one [52, 53]. Eq. (10) defines the cost of energy (COE, $/kWh).

$$COE = \frac{C_{TAC}}{E_{AEO}} \tag{10}$$

where E_{AEO} = annual electricity generation of WTG (kWh), C_{TAC} = total annual cost ($).

The sum of a WTG's yearly capital repayments, operating costs, and maintenance costs equals the device's total annual cost. As an illustration, consider the following:

$$C_{TAC} = (r_d + 0.025)C_{ICC} \tag{11}$$

$$r_d = \frac{R}{1 - (1+R)^{-n}} \tag{12}$$

where n is the duration of the project, often assumed to be 20 years, the discount rate (%) is represented by R, which typically takes approximately 10 %, and the discount factor is represented by r_d. For a particular building, the initial capital cost (C_{ICC}; $) may be calculated using components cost by following equations [51].

$$Blade\ cost = 3.8118\left(\frac{D}{2}\right)^{2.5025} + 0.5582\left(\frac{D}{2}\right)^{2} - 955.24 \tag{13}$$

$$Hub\ cost = 4.05\ \times Mass\ of\ blade\left(\frac{D}{2}\right)^{2.9158} + 24141 \tag{14}$$

$$Mass\ of\ blade = 0.1452\left(\frac{D}{2}\right)^{2.9158} \tag{15}$$

$$Pith - system\ cost = 0.4802(D)^{2.6578} \tag{16}$$

$$Nose - cone\ cost = 103(D) - 2899 \tag{17}$$

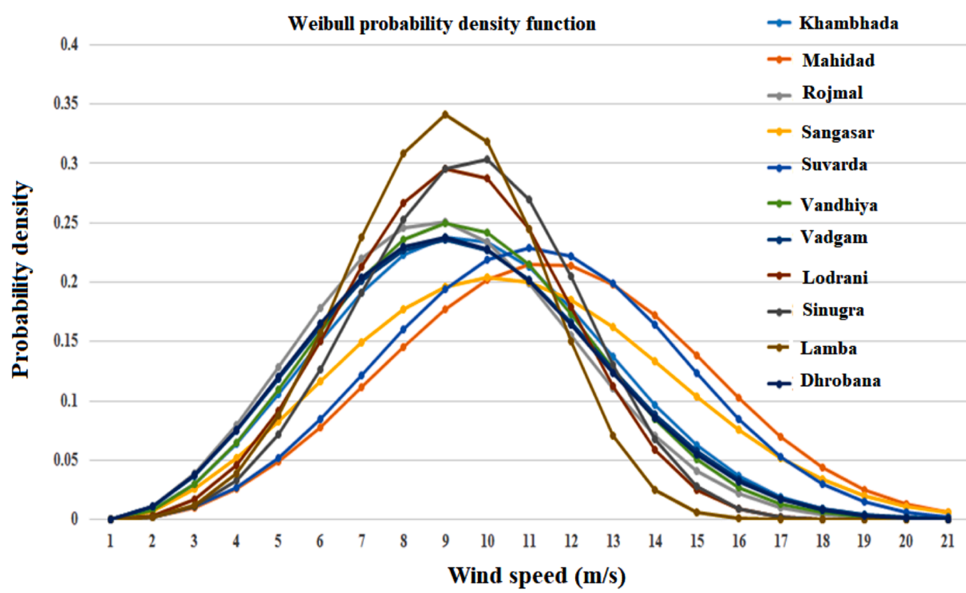

Fig. 4. Wind density functions at 10 m from Weibull distributions compared across all locations in Gujarat.

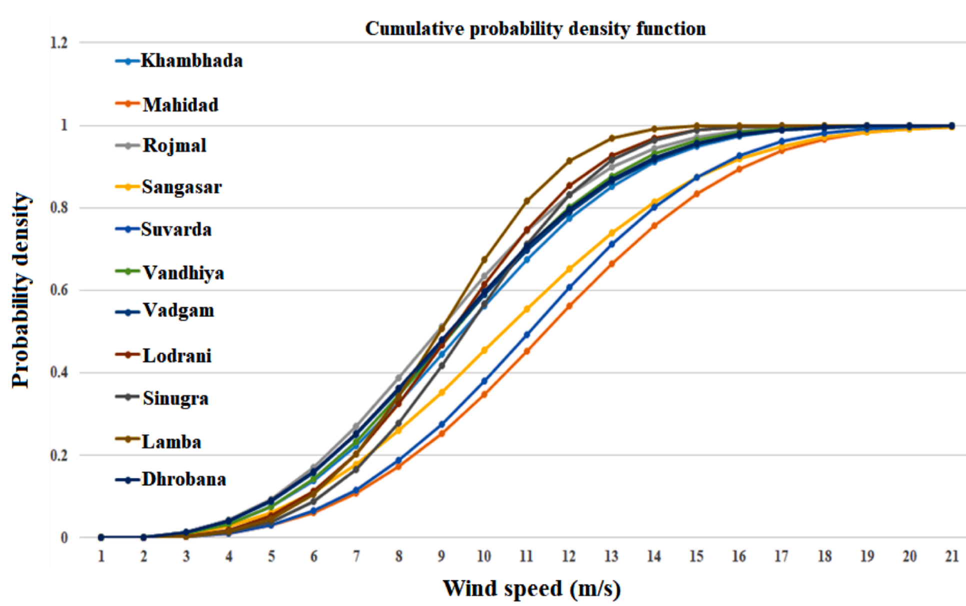

Fig. 5. Comparative analysis of cumulative probability wind density functions at 10 m across various locations in Gujarat.

$$Low-speed-shaft\ cost = 0.1(D)^{2.887} \quad (18)$$

$$Bearing-system\ cost = D^{2.5}(0.0043D - 0.011) \quad (19)$$

$$Gear-box\ cost = 16.45{N_p}^{1.249} \quad (20)$$

$$Electronics\ cost = 79N_p \quad (21)$$

$$Yaw-system\ cost = 0.0678(D)^{2.964} \quad (22)$$

$$Main-frame\ cost = 9.489(D)^{1.953} \quad (23)$$

$$Main-frame\ mass = 2.233(D)^{1.953} \quad (24)$$

$$Platform-and-railing\ cost = 1.09 \times Mass_{main-frame} \quad (25)$$

$$Hydraulic-and-cooling\ cost = 12N_p \quad (26)$$

$$Electrical-connection\ cost = 40N_p \quad (27)$$

$$Nacelle-cover\ cost = 11.537N_p + 3849.7 \quad (28)$$

$$Foundation\ cost = 303.24 \times (Area \times hub\ height)^a \quad (29)$$

$$Assembly-and-installation\ cost = 1.965 \times (D \times hub\ height)^b \quad (30)$$

$$Tower\ cost = (0.596 \times Area \times hub\ height) - 2121 \quad (31)$$

where N_p= nominal power (kW), D=rotor radius (m), b = 1.1736, a = 0.4037.

Table 3 shows the eight different kinds of wind turbines used to assess their appropriateness for 21 other sites in India [54].

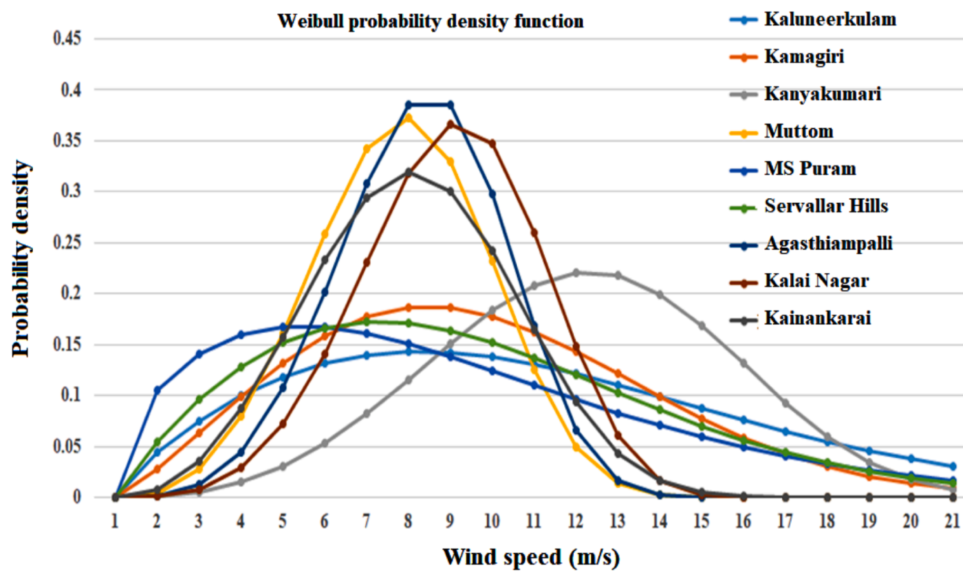

Fig. 6. Comparative analysis of Weibull probability wind density functions at 10 m across various locations in Tamil Nadu.

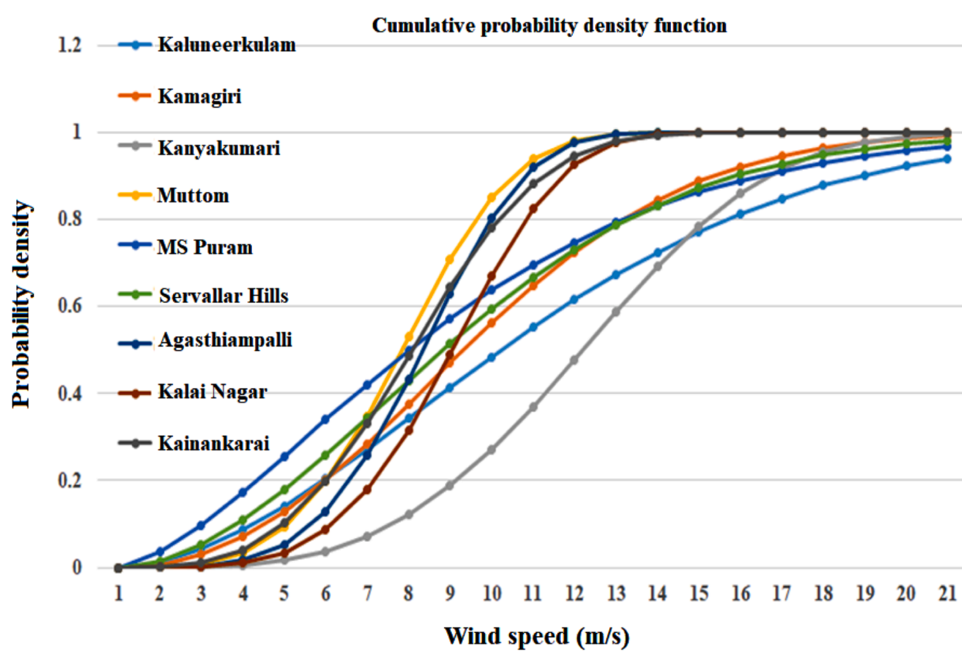

Fig. 7. Comparative analysis of cumulative probability wind density functions at 10 m across various locations in Tamil Nadu.

3. Results and discussions

The WPP assessment has been done for economic analysis of wind turbine installation at different heights, and its results are demonstrated in the following three subsections: A) Wind power density analysis at different heights, B) Weibull and cumulative wind speed distributions analysis, and C) Cost of wind energy analysis at different tower height. The proposed approach has been implemented and verified to demonstrate the performance analysis and validation for twenty-one locations in India (i.e., 11 sites in Gujarat, 9 sites in Tamil Nadu, and one site in Sikkim). The demonstrated results show that the proposed approach is extendable to other locations without any technical modification.

3.1. Wind power density analysis at different heights

At 10 m altitude, the WS measurements taken by the weather station are unsuitable for electricity production. Hence, for 21 sites in India, WPP evaluations are computed using the Power-law, Cubic Factor (CF) approach, and Weibull model up to a height of 150 m in 10-meter increments. The evaluated WPD for 11 sites of Gujarat (i.e., Khambhada, Mahidad, Rojmal, Sangasar, Suvarda, Vandhiya, Vadgam, Lodrani, Sinugra, Lamba, Dhrobana), 9 sites of Tamil Nadu (i.e., Kaluneerkulam, Kamagiri, Kanyakumari, Muttom, MS Puram, Servallar Hills, Agasthiampalli, Kalai Nagar, Kainankarai) and Ravangla in Sikkim are represented in Table 4.

The highest and lowest WPD are 308.86 W/m^2 and 123.17 W/m^2 in Gujarat for the Mahidad and Lamba locations, respectively. For Tamil Nadu, the highest WPD is 427.12 W/m^2 (Kaluneerkulam), and the lowest WPD is 80.64 W/m^2 (Muttom). The values of CF and K do not change with height, and c increases with height, which shows the significance of WPD. The shape value varies from 2.77 to 3.92 for Gujarat, 1.52 to 4.26 for Tamil Nadu, and 3.90 for Ravangla Sikkim, showing a

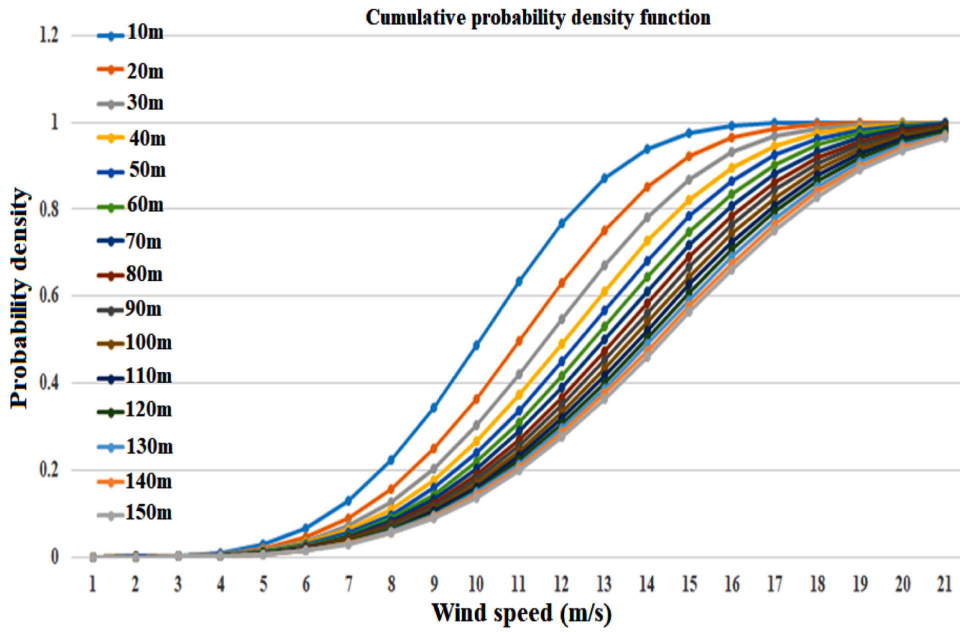

Fig. 8. Comparative analysis of cumulative probability wind density functions at different heights for Ravangla Sikkim.

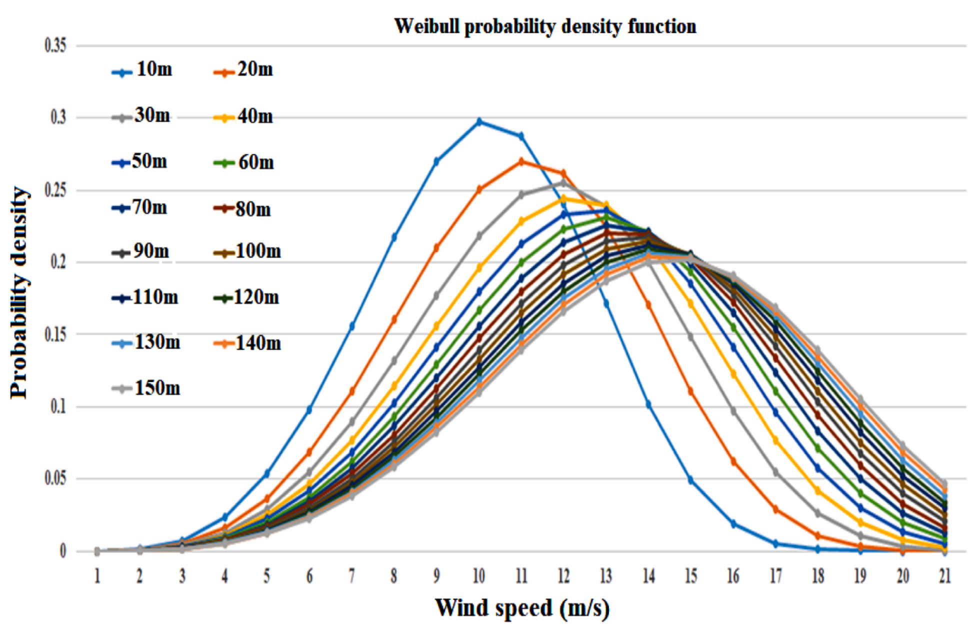

Fig. 9. Comparative analysis of Weibull probability wind density functions at different heights for Ravangla Sikkim.

normal distribution of WS variation from 10 m to 150m. The correlation between WPD (symbol: y) and WS (symbol: x) was developed to demonstrate the RMSE (root mean square error) and R^2 (correlation value) by using the regression analysis method. RMSE values ranging from 0.2 to 0.5 indicate that the model has a high level of accuracy in predicting the data. A high value for R^2, more than 0.75, indicates precision. The developed correlations are demonstrated in Table 5.

These equations are used to estimate WPD at 10 m to 150 m heights. R^2 for these equations are more than 0.99 showing developed correlation estimate WPD accurately. RMSE value varies from 0.10 to 1.89 for Gujarat, 0.06 to 2.38 for Tamil Nadu and 0.14 for Ravangla Sikkim showing equations relatively predict WPD accurately. The results of this study are validated through a comparison with various studies, as presented in Table 6. The findings indicate that RMSE aligns closely with the studies that have been reported.

3.2. *Weibull and cumulative wind speed distributions analysis*

The average, maximum and minimum wind speeds, CF, K, WPD at 150 m, wind class and wind category of different sites for Gujarat, Tamil Nadu and Sikkim are shown in Tables 7–9. In Gujarat, sites with a maximum value of wind speed are in May, June, July, and the minimum value of WS are in January, April, September, October and November Khambhada has a maximum value of WS. The maximum value of average WS is 5.37 m/s in Sangasar. As per WPD Khambhada, Rojmal, Vandhiya, Vadgam, Lodrani, Sinugra, Lamba, Dhrobana are in Wind Class 1 and Wind Category poor. Sangasar, Suvarda are in Wind Class 2 and Wind Category Marginal. Mahidad is in Wind Class 3 and wind category moderate. In Tamil Nadu sites having maximum wind speed value are in May, June, July, Aug, Sep and minimum value of WS are in March, April, September, October and November, Kaluneerkulam has a

Table 10
Variation of cost of energy ($/kWh) with different hub height of wind turbines.

	Locations	COE of WTG with Model No E53/800	COE of WTG with Model No E70/ 2300	COE of WTG with Model No E82/ 2000	COE of WTG with Model No E82/ 2300	COE of WTG with Model No E101/ 3000	COE of WTG with Model No E82/3000	COE of WTG with Model No YZ78/ 1.5	COE of WTG with Model No YZ82/1.5	COE of WTG with Model No YZ87/ 2.0
Gujarat	Khambhada	0.15–0.05	0.24–0.08	0.16–0.05	0.18–0.06	0.16–0.05	0.039–0.01	0.13–0.04	0.12–0.04	0.14–0.05
	Mahidad	0.09- 0.03	0.13–0.04	0.09–0.03	0.10–0.03	0.09–0.03	0.02–0.01	0.07–0.02	0.07–0.02	0.08–0.02
	Rojmal	0.18–0.06	0.29–0.09	0.19–0.06	0.22–0.07	0.19–0.06	0.04–0.02	0.16–0.05	0.15–0.05	0.17–0.06
	Sangasar	0.10–0.03	0.16–0.05	0.11–0.03	0.12–0.04	0.11–0.03	0.02–0.01	0.09–0.03	0.08–0.03	0.1–0.03
	Suvarda	0.10–0.03	0.15–0.05	0.10–0.03	0.12–0.04	0.10–0.03	0.02–0.01	0.08–0.03	0.08–0.02	0.09–0.03
	Vandhiya	0.17–0.06	0.26–0.08	0.17–0.06	0.20–0.06	0.17–0.06	0.04–0.01	0.14–0.05	0.13–0.04	0.15–0.05
	Vadgam	0.16–0.06	0.25–0.08	0.16–0.05	0.19–0.06	0.17–0.05	0.04–0.01	0.14–0.05	0.13–0.04	0.15–0.05
	Lodrani	0.19–0.07	0.30–0.10	0.20–0.06	0.22–0.07	0.20–0.06	0.04–0.02	0.16–0.05	0.15–0.05	0.18–0.06
	Sinugra	0.17–0.06	0.27–0.09	0.18–0.06	0.21–0.07	0.18–0.06	0.04–0.02	0.15–0.05	0.14–0.05	0.16–0.05
	Lamba	0.22–0.08	0.35–0.11	0.23–0.08	0.26–0.09	0.23–0.08	0.05–0.02	0.19–0.07	0.17–0.06	0.21–0.07
	Dhrobana	0.16–0.06	0.25–0.08	0.17–0.06	0.19–0.06	0.17–0.05	0.04–0.01	0.14–0.05	0.13–0.04	0.15–0.05
Tamil Nadu	Kaluneerkulam	0.06–0.02	0.10–0.03	0.06–0.02	0.07–0.02	0.06–0.02	0.010.007	0.05–0.02	0.05–0.01	0.06–0.02
	Kamagiri	0.12–0.04	0.18–0.06	0.12–0.04	0.14–0.04	0.12–0.04	0.03–0.01	0.10–0.03	0.09–0.03	0.11–0.03
	Kanyakumari	0.07–0.02	0.11–0.04	0.08–0.02	0.09–0.03	0.08–0.02	0.010.008	0.06–0.02	0.060.022	0.07–0.02
	Muttom	0.34–0.12	0.53–0.18	0.35–0.12	0.40–0.14	0.36–0.12	0.08–0.03	0.30–0.10	0.27–0.09	0.32–0.11
	MS Puram	0.10–0.03	0.15–0.05	0.10–0.03	0.12–0.04	0.10–0.03	0.02–0.01	0.08–0.03	0.08–0.02	0.09–0.03
	Servallar Hills	0.11–0.04	0.17–0.05	0.11–0.04	0.13–0.04	0.11–0.04	0.02–0.01	0.09–0.03	0.08–0.03	0.10–0.03
	Agasthiampalli	0.29–0.10	0.46–0.15	0.30–0.10	0.35–0.12	0.31–0.10	0.07–0.03	0.25–0.09	0.23–0.08	0.27–0.09
	Kalai Nagar	0.22–0.08	0.35–0.12	0.23–0.08	0.26–0.09	0.23–0.08	0.05–0.02	0.19–0.07	0.18–0.06	0.21–0.07
	Kainankarai	0.29–0.10	0.44–0.15	0.30–0.10	0.34–0.11	0.30–0.10	0.07–0.03	0.25–0.08	0.23–0.08	0.27–0.09
Sikkim	Ravangla	0.15–0.05	0.23–0.07	0.15–0.05	0.18–0.06	0.15–0.05	0.03–0.01	0.13–0.04	0.12–0.04	0.14–0.04

maximum value of WS. The maximum value of average WS is 7.33 m/s in Kanyakumari. As per WPD Muttom, Agasthiampalli, Kalai Nagar, Kainankarai are in Wind Class 1 and Wind Category poor. Kamagiri, MS Puram, Servallar Hills are in Wind Class 2 and Wind Category Marginal. Kanyakumari is in Wind Class 3 and wind category moderate. Kaluneerkulam is in Wind Class 4 and wind category good. Ravangla in Sikkim is in Wind Class 1 and Wind Category poor.

The comparison of Weibull, cumulative probability wind density functions for all different sites in Gujarat and Tamil Nadu are shown in Figs. 4–7. Comparison of cumulative and Weibull probability wind density functions at different heights for Ravangla Sikkim are shown in Figs. 8 and 9. These figures show WS follows the Weibull distribution. From Figs. 4 and 6 Sangasar, Mahidad, Khambhada, Kanyakumari follows right skewed curve and other sites follow normal distribution of WS.

3.3. Cost of wind energy analysis at different tower height

A wind turbine's initial investment is proportional to its size and hub height. Table 10 displays the results of this study's analysis of the cost of energy (COE) sensitivity at various hub heights for 21 sites in India. It is found that COE decreases with an increase in hub heights for all WTGs in all selected locations. It is found that the COE of WTG with Model No E82/3000 has the least for all considered sites.

The variation of COE ($/kWh) from 10 m to 150 m hub height in Gujarat sites are 0.0394–0.0179, 0.0229–0.0104, 0.0229–0.0104, 0.0272–0.0123, 0.0259–0.0117, 0.0431–0.0195, 0.0414–0.0188, 0.0491–0.0223, 0.0454–0.0206, 0.0574–0.026, 0.0425–0.0193 for Khambhada, Mahidad, Rojmal, Sangasar, Suvarda, Vandhiya, Vadgam, Lodrani, Sinugra, Lamba, Dhrobana respectively. From these sites, Khambhada has the least COE in Gujarat. The variation of COE ($/kWh) from 10 m to 150 m hub height in Tamil Nadu sites are 0.0165–0.0075, 0.0309–0.014, 0.0196–0.0089, 0.0876–0.0397, 0.0257–0.0116, 0.0285–0.0129, 0.0754–0.0342, 0.0576–0.0260, 0.0736–0.0333 for Kaluneerkulam, Kamagiri, Kanyakumari, Muttom, MS Puram, Servallar Hills, Agasthiampalli, Kalai Nagar, Kainankarai respectively. From these sites, Kaluneerkulam has the least COE in Tamil Nadu. COE variation ($/kWh) from 10 m to 150 m hub height is 0.0386–0.0175 for Ravangla Sikkim.

3.4. Discussion of the results

The current investigation has conducted an initial evaluation of the wind power capacity and economic analysis of wind turbine deployment in 21 locations across India. These locations encompass 11 sites in Gujarat (Khambhada, Mahidad, Rojmal, Sangasar, Suvarda, Vandhiya, Vadgam, Lodrani, Sinugra, Lamba, Dhrobana), 10 sites in Tamil Nadu (Kaluneerkulam, Kamagiri, Kanyakumari, Muttom, MS Puram, Servallar Hills, Agasthiampalli, Kalai Nagar, Kainankarai), and one site in Sikkim (Ravangla). This work is essential for India, where wind power potential is not fully harnessed. Economic analysis for wind turbine installation is not performed. The wind energy pattern factor and shape parameter are independent of heights. It is found that for Gujarat, Sangasar has a maximum average wind speed of 5.37 m/s and Vadgam has a minimum value of 2.88 m/s. For Tamil Nadu maximum and minimum values of average wind speed are for Kanyakumari (7.336 m/s) and Muttom (4.471 m/s). For Ravangla Sikkim, wind speed varies from 4.51 to 6.61 m/s. At 150 m height, wind power density varies from 123.17 W/m^2 to 308.86 W/m^2 in Gujarat and from 80.64 W/m^2 to 427.12 W/m^2 in Tamil Nadu.

The site for marginal wind category is Sangasar, Suvarda in Gujarat and Kamagiri, Servallar Hills, MS Puram in Tamil Nadu. The moderate wind category is Mahidad in Gujarat and Kanyakumari in Tamil Nadu. The good wind category is Kaluneerkulam in Tamil Nadu, and the rest other considered sites have come under the poor wind category. Research indicates that wind speeds have risen by roughly 10.28 % at a height of 20 m and by 47.19 % at a height of 150 m, relative to the recorded height of 10 m. Wind power density and wind speed exhibit exponential growth as altitude increases.

For an economic analysis of wind turbine generators, nine wind turbine models E53/800, E82/2000, E70/2300, E82/2300, E82/3000, E101/3000, YZ82/1.5, YZ78/1.5, and YZ87/2.0, are considered. It is found that turbine model E82/2300 has the least COE for all sites. The variation in COE of wind turbine model E82/2300 for considered locations from 10 m hub height to 150 m is 0.0229–0.026 $/kWh in Gujarat, 0.0165–0397 $/kWh in Tamil Nadu and 0.0386–0.0175 $/kWh in Sikkim, presenting Tamil Nadu has least COE variation followed by Gujarat and Sikkim. The analysis performed in this study benefits the renewable energy system designer for wind resource assessment and successful operation in the installation of wind turbine generators.

4. Conclusions

This study provides a comprehensive evaluation of wind power potential and an economic analysis of wind turbine installations across 21 locations in India. It highlights the variation in wind speeds and wind power density at different hub heights, with significant increases observed as height rises from 10 m to 150m. Tamil Nadu demonstrated the most favorable wind energy potential and the lowest cost of energy variation, followed by Gujarat and Sikkim. Among the turbine models analyzed, E82/2300 emerged as the most cost-efficient across all sites. The findings serve as a valuable resource for optimizing wind resource assessments and guiding the deployment of wind energy systems in India.

CRediT authorship contribution statement

Amit Kumar Yadav: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Vibha Yadav:** Writing – review & editing, Methodology, Formal analysis. **Ujawal Kumar:** Writing – review & editing, Formal analysis, Data curation. **Adarsh Ranjan:** Writing – review & editing, Formal analysis, Data curation. **Talluru Sai Vinil Kumar:** Writing – review & editing, Formal analysis, Data curation. **Rohit Khargotra:** Writing – review & editing, Methodology, Formal analysis. **Gusztáv Fekete:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis. **Tej Singh:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal 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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rineng.2024.103743.

Data availability

Data will be made available on request.

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