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Novel exploration of hub heights on economics and Weibull distribution methods for wind power potential in Indian sites

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Abstract. Wind energy is a clean and practical way to create electricity. It necessitates the assessment of Wind Power Potential (WPP) and its economic analysis at different heights. In this context, this study examines WPP assessment for 62 different locations of 12 states in India from 10 m to 150 m height using six methods. The effectiveness of each method was performed through the computation of Relative Power Density Error (RPDE). The results suggested that the best method to estimate the WPP is the Novel Energy Pattern Factor Method (NEPFM) followed by the Empirical Method of Mabchour (EMM), the Empirical Method of Justus (EMJ), and the Empirical Method of Lysen (EML). A technical assessment is also made using six different wind turbine Models, through the computation of their respective capacity factors, annual power, and energy outputs. Furthermore the economic feasibility of these wind turbines gave Cost of Energy (COE) variation from 0.28 to 15.31 \$/kWh at 10 m hub height of wind turbine and 150 m hub height of wind turbine COE varies from 0.10 to 3.53 \$/kWh. This study is useful for industry.

Keywords: Wind power density, Cost of energy, Weibull, Economics.

1 Introduction

The domestic wind energy sector in India is the most advanced and has made constant advancements. The growth of the wind sector has led to a robust ecosystem, project operating capabilities, and a base of manufacture of around 10 000 MW annually. With a total installed capacity of 38.62 GW (as of December 31, 2020) and 64.64 Billion Units produced from wind power during 2019–2020, the nation now has the fourth-greatest wind installed capacity in the world [1]. The country achieved wind power capacity of 44736.24 MW as on 31 December 2023. A wind atlas of India has been recently published by the author in [2] in which wind potential at 100 m and 120 m above ground level is given. Assessment of the wind resource is essential to determining whether a given location or area has the capacity for an economically successful wind farm. A variety of techniques that can be used to evaluate wind resources has been reported by various researchers worldwide. Her *et al.* [3] did a Wind Resource Assessment (WRA) for communities in the Arctic and suggested a 100 kW wind turbine with a Levelized Cost Of Energy (LCOE) of \$1.15/kWh and a capacity factor of 16.7% as an appropriate option. Dayal *et al.* [4] completed an evaluation of the wind resources in Fiji's Rakiraki, Nabouwalu, and Udu. For these sites, it was discovered that the Wind Speed (WS) and Wind Power Potential (WPP) are 7.6 m/s, 7.1 m/s, 7.0 m/s, and 401 W/m^2, 512 W/m^2, and 294 W/m^2 correspondingly. These locations have 97–98% wind efficiencies. In their spatial and economic examination of Nepal's wind potential, Neupane *et al.* [5] calculated that 1686 MW of wind energy might be captured. Provinces in Karnali and Gandaki have high WPP. For China WPP was estimated at 1783–39 000 TWh by Franke *et al.* [6]. Weather data set, land use, and wind turbine configuration all affect WPP. Vinhoza and Schaeffer [7] examined Brazil's offshore WPP. There are three potentials listed: 1064 GW of technical potential, 330 GW of environmental and social potential, and 1688 GW of gross potential. WPP was carried out for South Sudan by Ayik *et al.* [8]. It is discovered that at 10 m, WPP ranges from 128.36 to 14.39 W/m^2, while WS ranges from 5.08 to 2.36 m/s. For the Indian Tirumala region, Kumar *et al.*'s [9] study estimates Weibull parameters via multiverse optimization. The highest mean wind speeds recorded in December were 5.12 m/s at 10 m and 6.621 m/s at 65 m. Chandel *et al.* [10] presented Weibull for WPP at 30 m, 50 m, 80 m, and 100 m for the Western Himalayan Indian state of Himachal Pradesh.

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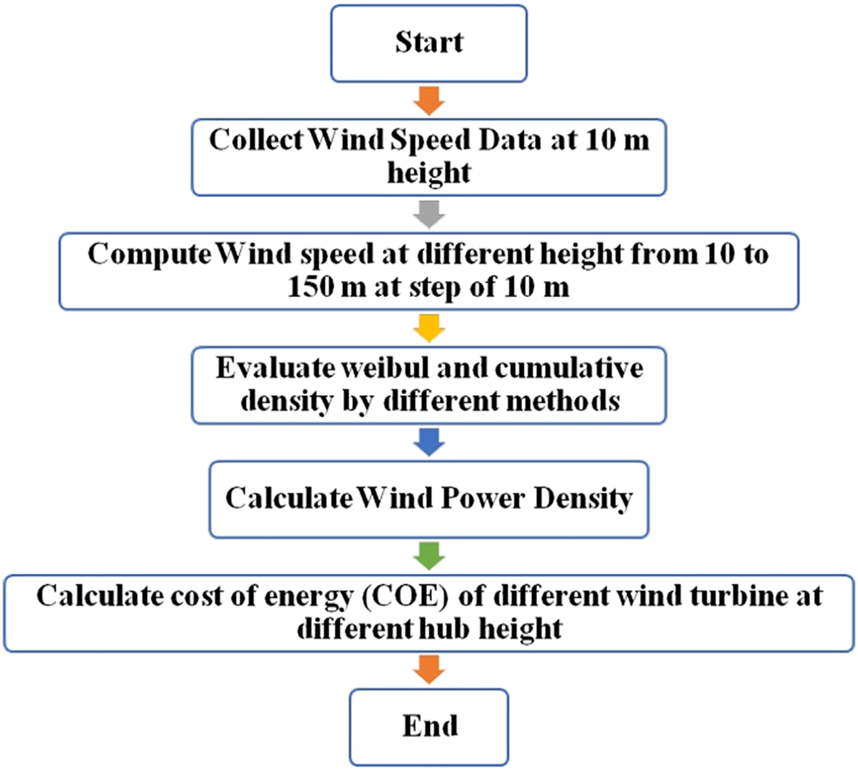


Figure 1. Proposed approach for wind power density evaluation and cost of energy at different tower heights.

The findings indicated that the wind speed is highest in the summer and lowest in the winter. In a different study, Chandel *et al.* [11] used WAsP to evaluate WPP at distances of 30 m, 50 m, 70 m, and 100 m and discovered that the Hamirpur location is most suitable for microturbines. For 10 Indian states at 90 m, Sangroya and Nayak [12] detected WPP using Weibull and determined that the wind's generation capacity was 21 268.3 MW as of May 2014. For the Uttara Kannada district, Karnataka State, India, Ramachandra *et al.* [13] estimated the preliminary WPP at 70 m utilizing geospatial tools including remote sensing and GIS. The average annual WS is discovered to be between 2.5 and 3.0 m/s. In order to identify WPP at 80 m for Indian sites, Hossain *et al.* [14] presented a Geographic Information System (GIS) 4 250 639.912 MW is found to be the predicted wind farm potential. Singh and Prakash [15] identified WPP using Weibull probability distribution at 10 m for Ranchi, Jamshedpur, Devghar, Lohardaga, and Chaibasa of Jharkhand in India. It is suggested that at 10 m in height is not suitable for the wind turbine to generate electricity. At 50 m Gadanki, India, Reddy *et al.* [16] statistical analysis for WPP detection. The yearly energy yield is 332.8 kWh/m^2 and the average WS is 2.9 m/s. WPP at 150 m height for Bheemunipatnam in northern Andhra Pradesh, India, was examined by Murthy and Rahi [17]. They discovered that the site had moderate and consistent wind speeds as well as a gusty wind speed of 13.3 m/s.

From preceding studies, there is no information, publically available regarding WPP and its economics at 150 m to allow enforce more development of wind energy use in different sites of India. This paper is the first effort to make publically available information about the WPP assessment with different methods and its economics at 150 m height for 62 Indian sites, it will allow to local population a valuable insight into the wind resource, its potential development, and its value to a utility utilization of individual use.

The objective of this paper is to present a very comprehensive WPP at different Indian sites using various methods. Section 2 describes briefly the analysis methods while Section 3 presents the results gathered and a discussion of their significance. The conclusions of this paper are given in Section 4.

2 Methodology

2.1 Research plan and program

The suggested method for assessing wind power generation capacity and performing an economic cost analysis for installing wind turbines at various tower heights is shown in Figure 1, which includes the step-wise-step procedure. Based on this and the equation given in the subsection computational analysis is performed.

2.2 Weibull parameters computation

2.2.1 Wind power

The amount of energy a wind turbine can convert to power depends greatly on the wind speed: The average wind speed's cube (the third power) affects the wind's energy

Table 1. Wind turbine details.

S. No	Manufacturer	Model	Power (KW)	Diameter (m)	Cut-in Speed (m/s)	Cut-out speed (m/s)	Rated Speed (m/s)	Maximum Cp
1	Enercon	E53/800	800	52.9	2.0	28.0	12.5	0.49
2	Enercon	E70/2300	2300	71.0	2.0	28.0	14.5	0.50
3	Enercon	E82/2000	2000	82.0	2.0	28.0	12.4	0.50
4	Enercon	E82/2300	2300	82.0	2.0	28.0	13.5	0.50
5	Enercon	E101/3000	3000	101.0	2.0	28.0	11.7	0.48
6	Enercon	E82/3000	3000	82.0	2.0	28.0	16.1	0.50

Table 2. Classification of wind energy resource.

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

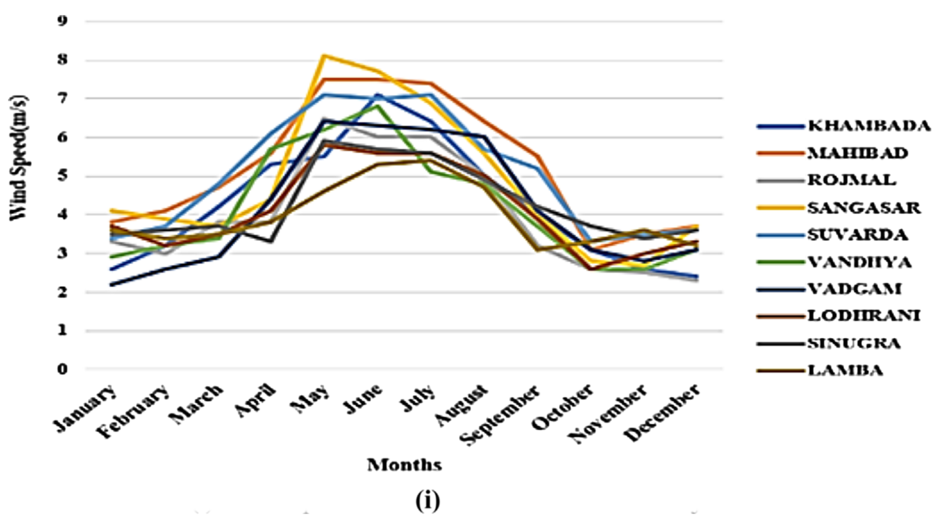


Figure 2. Wind speed profile of 62 Indian sites. a) Wind Speed for 10 different locations in Gujarat; b) Wind speed for 9 different locations in Karnataka; c) Wind Speed for 10 different locations in Tamil Nadu; d) Wind Speed for different locations in Andaman and Nicobar, Assam, Jammu and Kashmir and West Bengal; e) Wind Speed for 8 different locations in Madhya Pradesh; f) Wind Speed for 8 different locations in Maharashtra; g) Wind Speed for 9 different locations in Andhra Pradesh; h) Wind Speed for 4 different locations in Rajasthan.

content. As seen below, air density, the area swept by a wind turbine's rotor, and the cube of wind speed all directly relate to the amount of power that may be generated from the available wind.

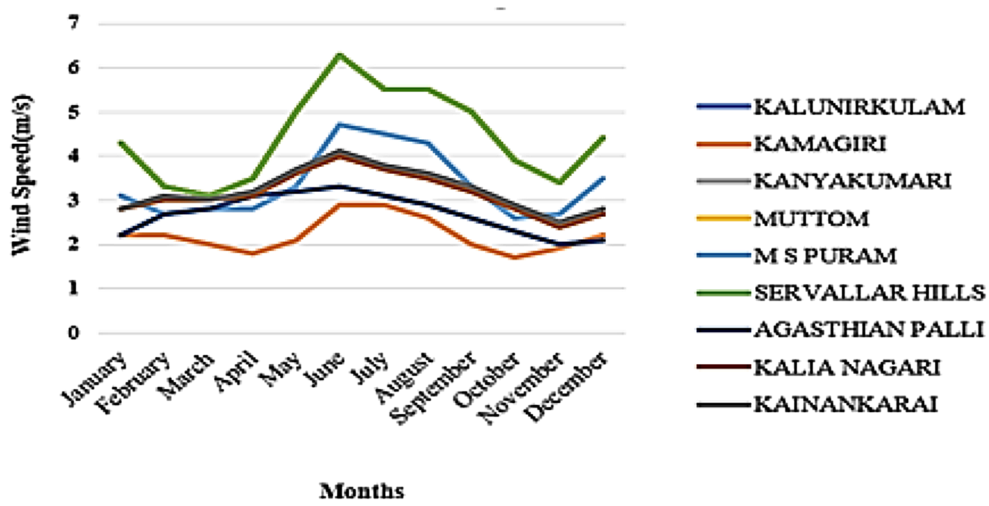
$$p = \frac{1}{2}\rho A v^3 \tag{1}$$

where A = rotor swept area, ρ = air density, v = velocity of wind in m/s.

2.2.2 Weibull model

Weibull and Cumulative Density Functions, or WDF and CDF, are two probability distributions that are used to compute the frequency distribution of known wind speeds [18].

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



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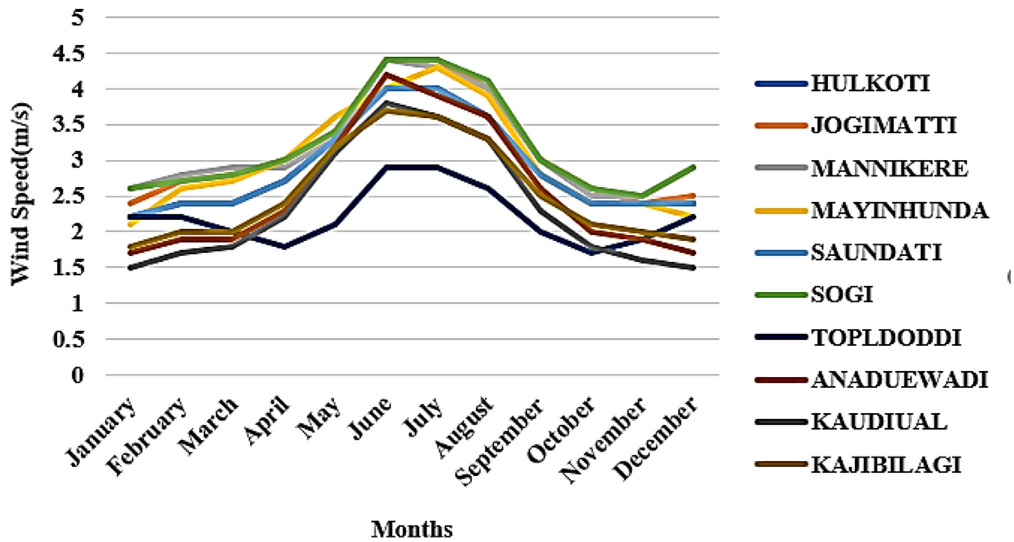

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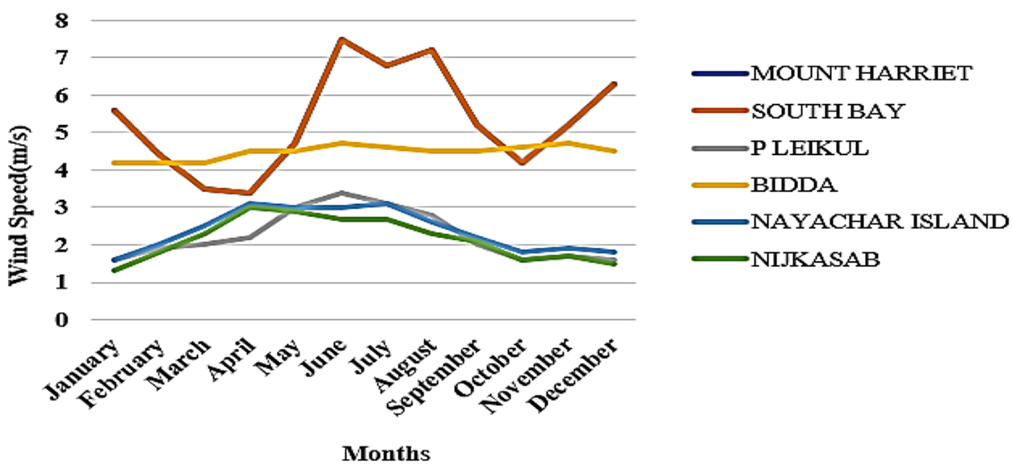

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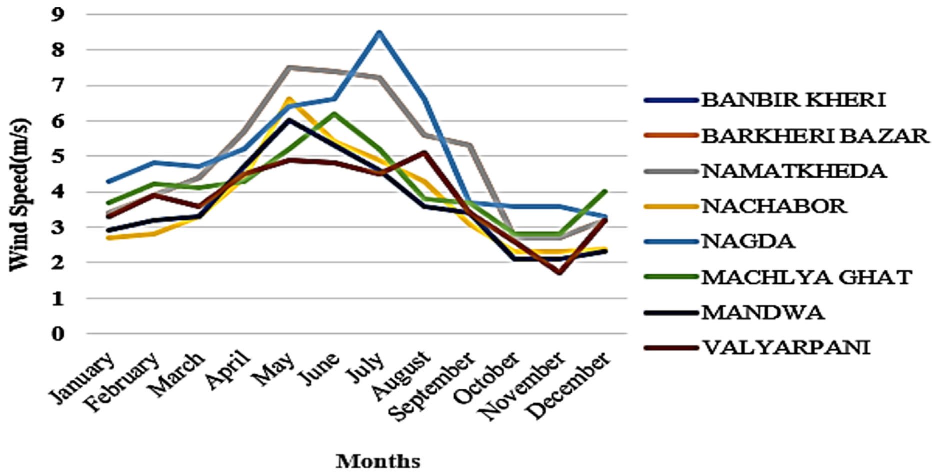

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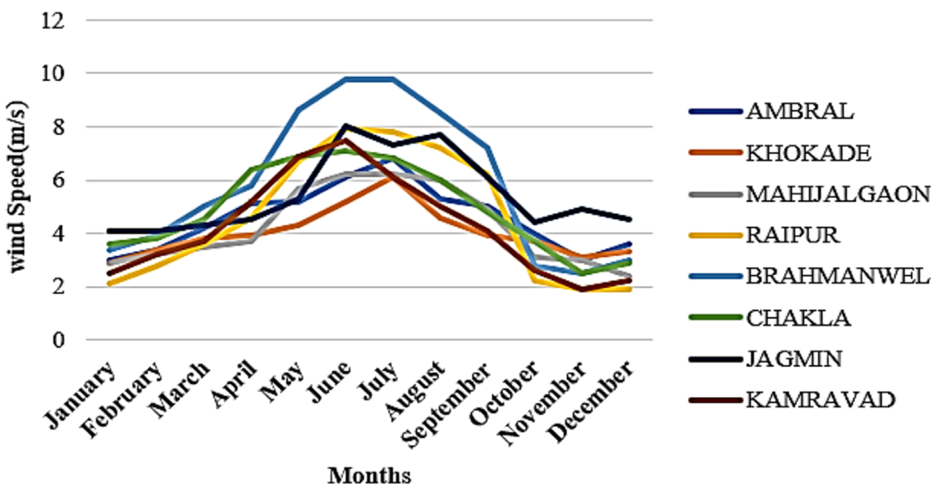

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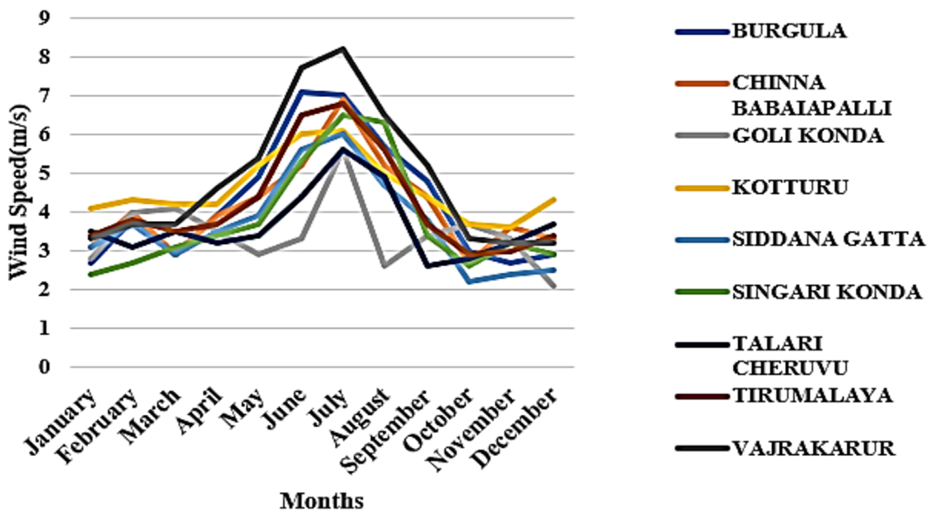

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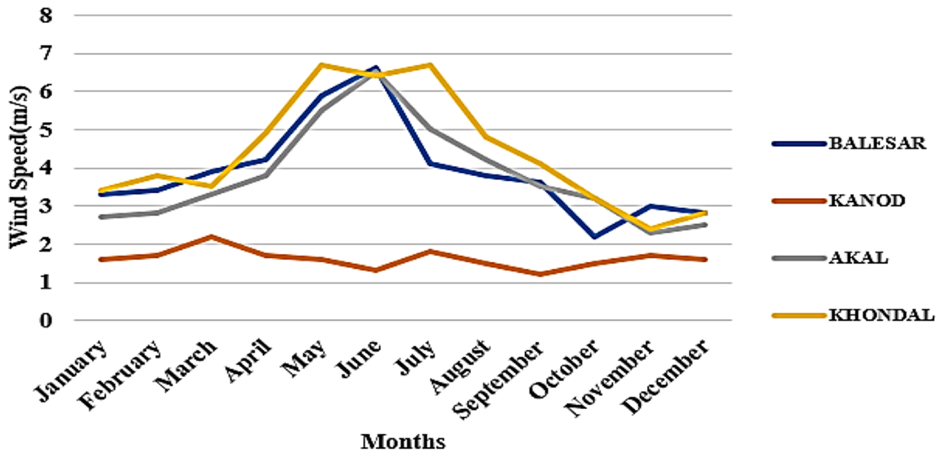

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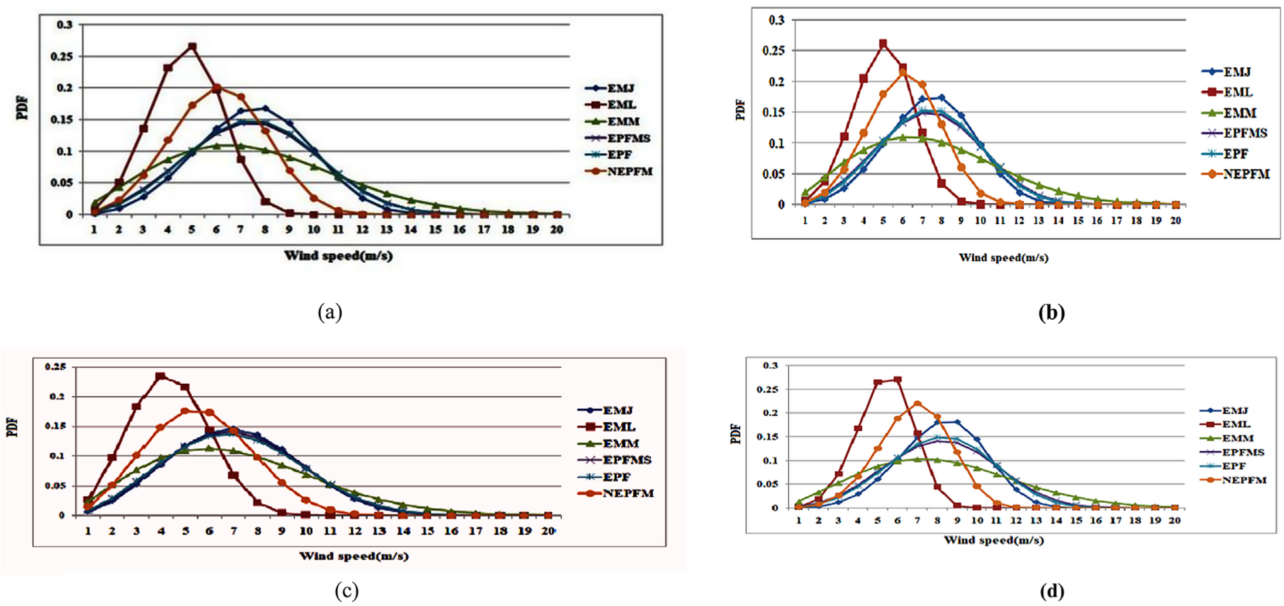


Figure 3. Comparison of Weibull probability density function with different methods. a) Fitting comparison methods of wind speed distribution of Mahidad hill location of Gujarat; b) Fitting comparison methods of wind speed distribution of Suvarda location of Gujarat; c) Fitting comparison methods of wind speed distribution of Sansagar location of Gujarat; d) Fitting comparison methods of wind speed distribution of Kanyakumari location of Tamil Nadu; e) Fitting comparison methods of wind speed distribution of Kainonkarai location of Tamil Nadu; f) Fitting comparison methods of wind speed distribution of Kalunirkulam location of Tamil Nadu; g) Fitting comparison methods of wind speed distribution of M.S.Puram location of Tamil Nadu; h) Fitting comparison methods of wind speed distribution of Sarvallar hill location of Tamil Nadu; i) Fitting comparison methods of wind speed distribution of Mount Harriet location of Andaman Nicobar; j) Fitting comparison methods of wind speed distribution of Barkheri bazaar location of Madhya Pradesh; k) Fitting comparison methods of wind speed distribution of Nagda location of Madhya Pradesh; l) Fitting comparison methods of wind speed distribution of Jagmin location of Maharashtra; m) Fitting comparison methods of wind speed distribution of Chakla location of Maharashtra; n) Fitting comparison methods of wind speed distribution of Raipur location of Maharashtra; o) Fitting comparison methods of wind speed distribution of Brahmanwel location of Maharashtra.

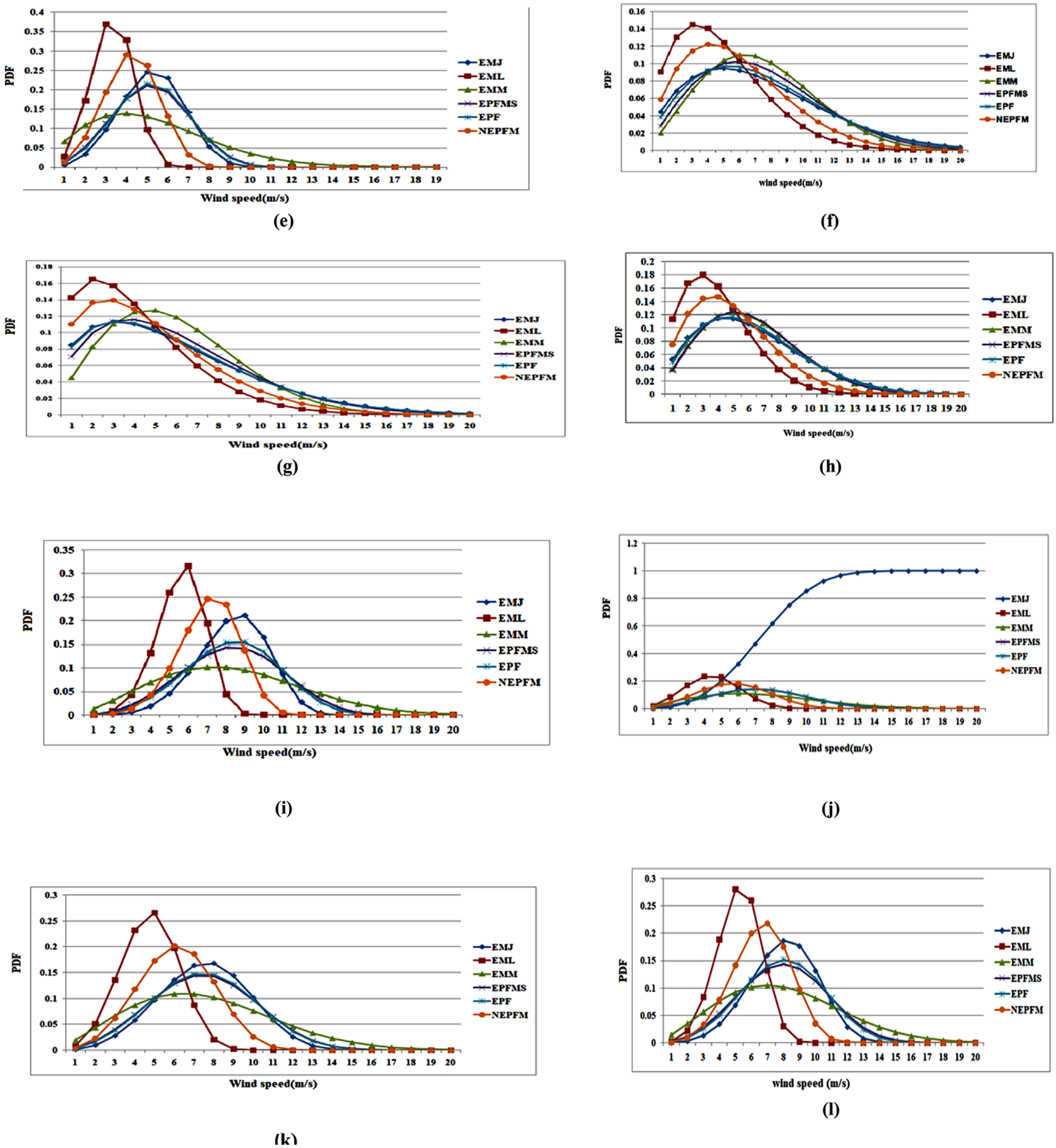


Figure 3. Continued.

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

where, $f(v)$ and $F(v)$ are the WDF and CDF corresponding to the wind speed v in m/s, K is the shape parameter which has no units and tells how to peak the distribution of the Weibull plot is, and C is the scale parameter.

2.2.3 Wind profile vertical

Research and applications in boundary layer meteorology, air quality, and numerical weather prediction all depend on wind profiles. The vertical wind profile is defined in equation (4). It is also known as power law. The power law is highly useful for calculating wind speeds in accordance with the necessary hub heights for wind turbines. Below is a mathematical illustration of the power law [19].

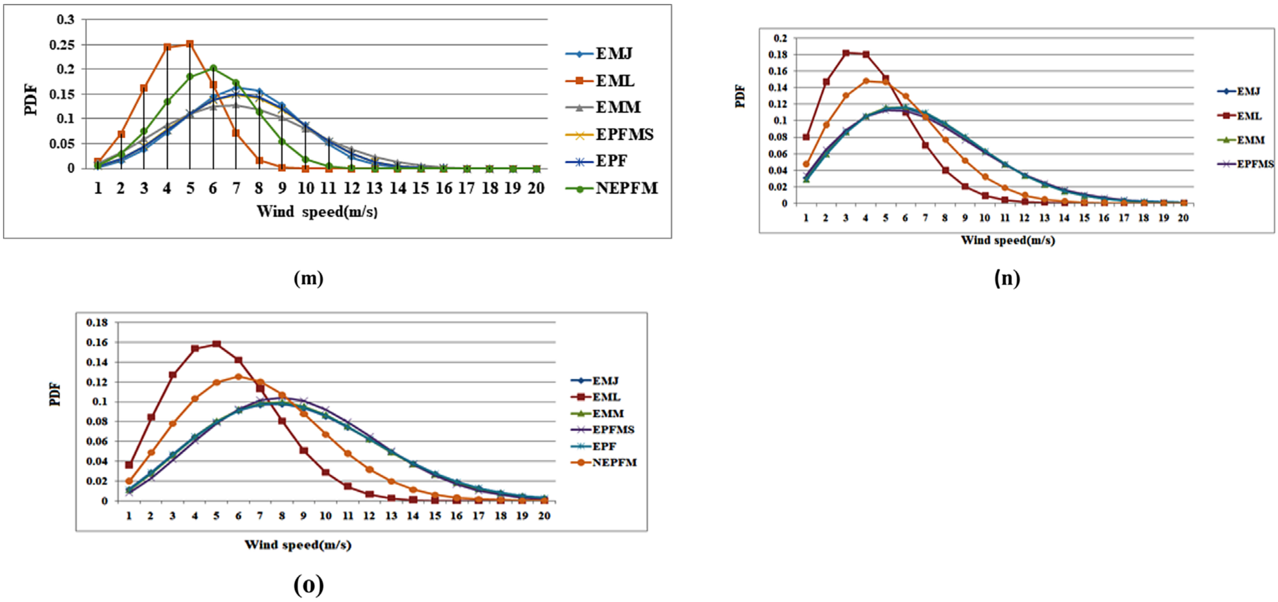


Figure 3. Continued.

Table 3. Wind category and class of different Indian sites.

State	Site	K	Highlights	WPD	Wind Class	Wind Category
Andaman and Nicobar	Mount Harriet	3.6169	Regular Steady Speed	311	3	Moderate
	South Bay	3.7710	Regular steady wind speed	337.04	3	Moderate
Madhya Pradesh	Barkheri Bazar	2.94	Moderate wind Speed	269.63	2	Marginal
	Nagda	3.35	Regular steady wind speed	303.64	3	Moderate
Maharashtra	Raipur	2.12	Moderate Wind Speed	275.50	2	Marginal
	Brahmanwel	2.43	Moderate Wind Speed	517.16	5	Excellent
	Chakal	3.13	Regular steady wind speed	260.25	2	Marginal
	Jagmin	3.35	Regular steady wind speed	333.24	3	Moderate
Rajasthan	Kanod	2.96	Regular steady wind speed	208.04	2	Marginal
Andhra Pradesh	Vajrakarur	2.84	Moderate wind Speed	233	2	Marginal
Tamil Nadu	Kalunirkulam	1.81	Fairly windy site	427.12	4	Good
	Kamagiri	2.21	Moderate wind speed	228.49	2	Marginal
	Kanyakumari	3.57	Regular steady wind speed	360.13	3	Moderate
	M.S. Puram	1.52	Fairly windy site	275.09	2	Marginal
	Servallar Hills	1.86	Fairly windy site	247.48	2	Marginal
Gujarat	Mahidad	3.24	Regular steady wind speed	308.86	3	Moderate
	Sangasar	2.77	Moderate wind speed	259.69	2	Marginal
	Suvarda	3.32	Regular steady wind speed	272.77	2	Marginal

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h1}\right)^{\alpha} \tag{4}$$

where, v_1 and v_2 are the wind speeds (in m/s) at corresponding heights h_1 and h_2 (in meters), and α is the power exponent, which is equal to 0.143. The shape parameter k represents the nature of the wind *i.e.* $1.5 \leq K \leq 1.99$ indicates fairly windy site, if $K \leq 1.5$ indicates highly variable or gust wind speed, if $K \geq 2$ means moderate wind, if $K \geq 3$ indicates regular steady wind speed.

The Weibull parameters can be computed by different methods given in Appendix A. The mean Wind Power Density (WPD) is calculated as,

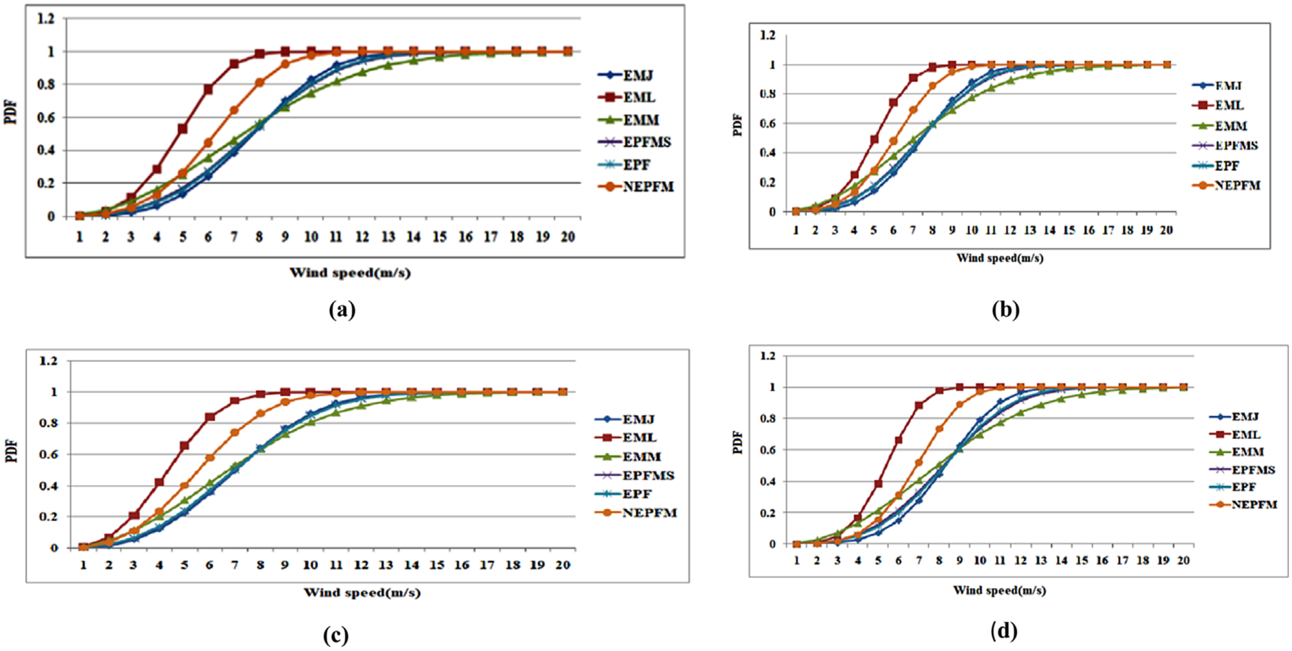


Figure 4. Comparison of cumulative wind distribution for different sites. a) Fitting comparison methods of cumulative wind distribution of Mahidad hill location of Gujarat; b) Fitting comparison methods of cumulative wind distribution of Suvarda location of Gujarat; c) Fitting comparison methods of cumulative wind distribution of Sansagar location of Gujarat; d) Fitting comparison methods of cumulative wind distribution of Kanyakumari location of Tamil Nadu; e) Fitting comparison methods of cumulative wind distribution of Kainonkarai location of Tamil Nadu; f) Fitting comparison methods of cumulative wind distribution of Kalunirkulam location of Tamil Nadu; g) Fitting comparison methods of cumulative wind distribution of M.S.Puram location of Tamil Nadu; h) Fitting comparison methods of cumulative wind distribution of Sarvallar hill location of Tamil Nadu; i) Fitting comparison methods of cumulative wind distribution of Mount Harriet location of Andaman Nicobar; j) Fitting comparison methods of cumulative wind distribution of Barkheri Bazar location of MP; k) Fitting comparison methods of cumulative wind distribution of Nagda location of Madhya Pradesh; l) Fitting comparison methods of cumulative wind distribution of Jagmin location of Maharashtra; m) Fitting comparison methods of cumulative wind distribution of Chakla location of Maharashtra; n) Fitting comparison methods of cumulative wind distribution of Jaipur location of Maharashtra; o) Fitting comparison methods of cumulative wind distribution of Brahmanwel location of Maharashtra.

$$P_{\mathrm{W}} = \frac{1}{2}\rho C^3 \gamma\left(1+\frac{3}{K}\right). \tag{5}$$

2.2.4 Statistical analysis

2.2.4.1 Relative power density error (RPDE)

RPDE is computed using the following formula proposed by Mohammadi *et al.* [27]:

$$\mathrm{RPDE} = \frac{(P_{\mathrm{pdf}} - P)}{P} \times 100 \tag{6}$$

where P_{pdf} represents the wind power density computed by the considered method and P is the power derived from the data. The best method in terms of power density will provide the smallest RPDE.

2.3 Economic analysis

The unit cost of wind power is calculated by investment in capital and operating costs. Before installation of a Wind Turbine Generator (WTG), it is crucial to find its cost based on references [28, 29]. The Cost Of Energy (COE, \$/kWh) calculation are given in Appendix B.

For analysis of the suitability of wind turbines for 21 locations in India, 8 different types of wind turbines are taken as shown in Table 1 [30].

2.4 Categorization of wind energy resource

Regional wind resource estimates can be obtained from the Wind Energy Resource Atlas of the United States. Wind resource assessment is expressed in terms of wind class, wind speed, and wind power density as shown in Table 2 [31].

2.5 Site selection

The monthly average wind speed at 10 m height for 62 locations measured by *National Aeronautics and Space Administration (NASA)* which is averaged for that month over the 30 years (January 1984–December 2014), is shown in Figure 2 [32].

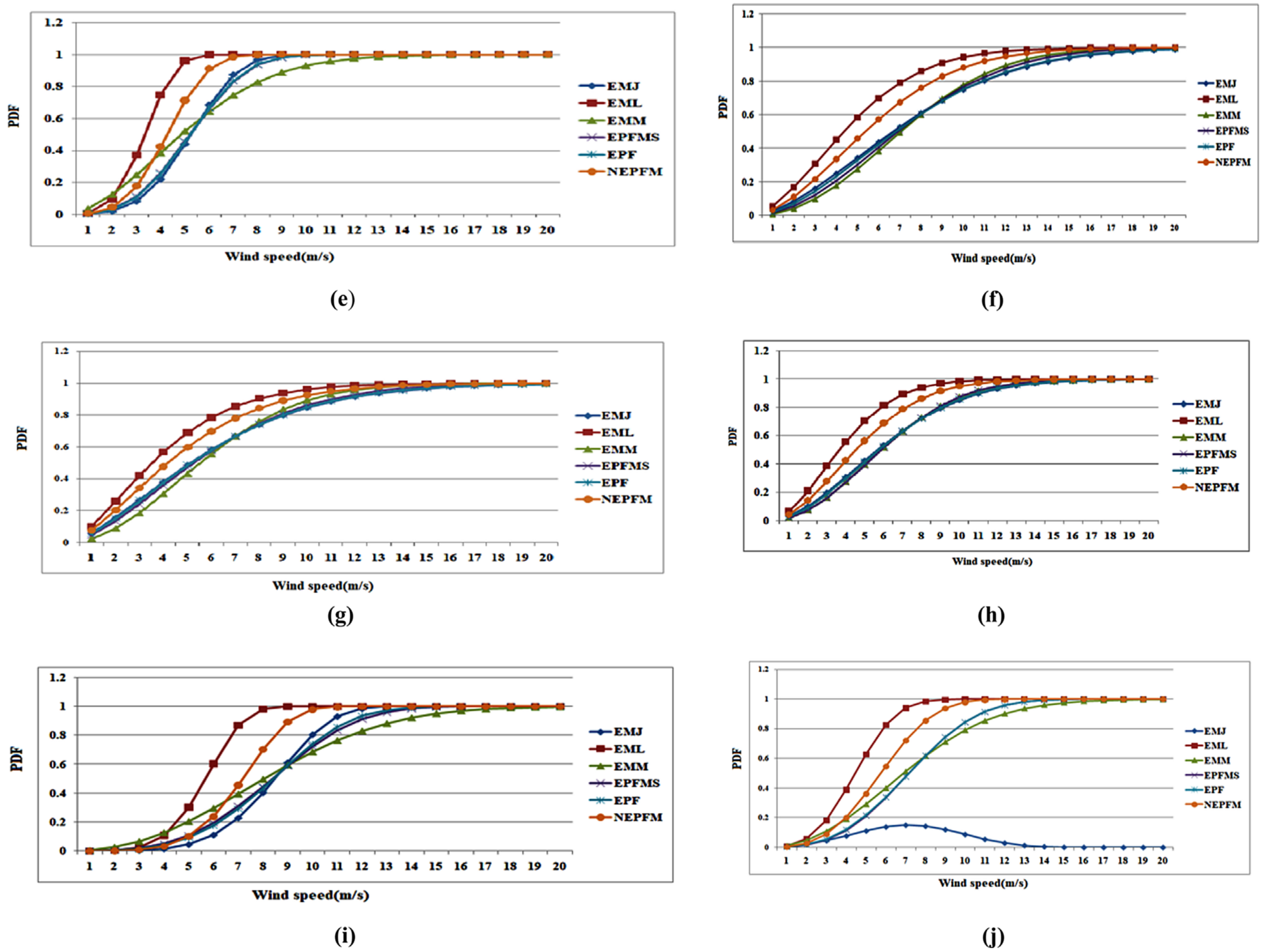


Figure 4. Continued.

3 Results and discussions

3.1 WPP Estimation at different heights

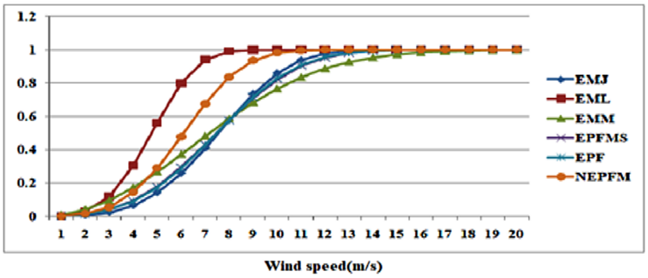
Wind classes of different sites are shown in Table 3. It is found that Barkheri Bazar of Madhya Pradesh, Raipur, Chakal of Maharashtra, Vajrakarur of Andhra Pradesh, Kamagiri, M.S. Puram, Servallar Hills of Tamil Nadu, Sangasar, Suvarda, of Gujarat comes under Wind Class 2, Mount Harriet, South Bay of Andaman and Nicobar, Nagda of Madhya Pradesh, Jagmin of Maharashtra, Kanyakumari of Tamil Nadu, Mahidad of Gujarat come under Wind Class 3, Kalunirkulam of Tamil Nadu under Wind Class 4 and Brahmanwel of Maharashtra fall under Wind Class 5. The rest sites come under Wind Class 1 which is not suitable for wind power generation.

3.2 Comparison of different methods to estimate wind power density

The results of each of the comparison of the methods for each of the 15 sites are presented below. Figure 3 presents the comparison of the Weibull Probability Density Function (PDF) obtained by each method and Figure 4 presents the comparison of the Weibull Cumulative Density Function (CDF) obtained by each method. Table 4 presents the best method for wind regime characteristics for each site. The rank is evaluated by RPDE to find out the best method. It is found that the NEPFM method estimates WPD better for Mahidad, Suvarda, Kanyakumari, Kalunirkulam, Mount Harriet, Barkheri Bazar, Nagda, Chakla. Empirical Method of Justus (EMJ) estimates WPD better for Sansagar, Jagmin. Empirical Method of Mabchour (EMM) estimates WPD better for Kamagiri, M.S. Puram, Savaller Hill, Raipur. Empirical Method of Lysen (EML) estimates WPD better for Brahmanwel.

3.3. Cost of energy evaluation for different wind turbines

The cost of energy is calculated using data shown in Table 1 of all the sites of different locations is shown in Table 5. The cost of energy (COE, \$/kWh) varies from 0.28 to 15.31 \$/kWh at the 10 m hub height of the wind turbine and at the 150 m hub height of the wind turbine, COE varies from 0.10 to 3.53 \$/kWh. Wind turbine E53/800



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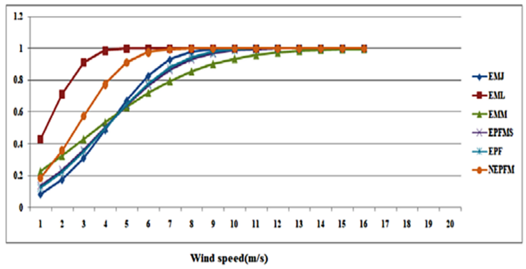

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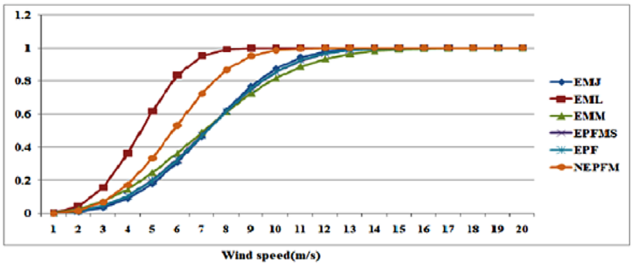

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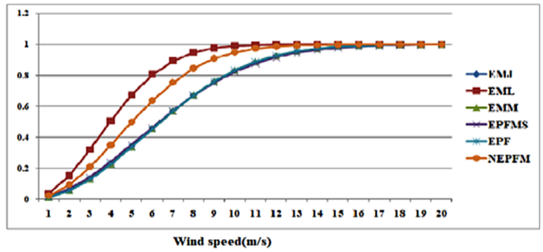

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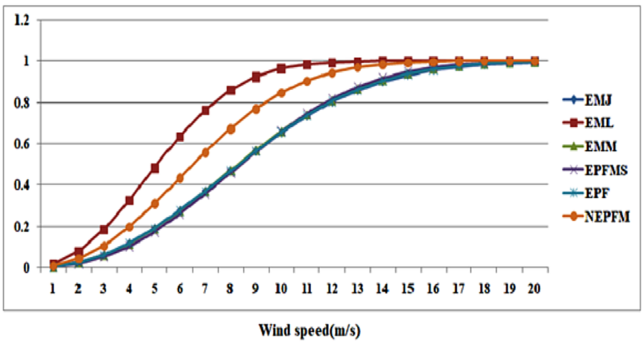

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Figure 4. Continued.

Table 4. Best methods and wind regime characteristics at 150 m height.

State	Site	Method	K	C (m/s)	Vm (m/s)	WPD (W/m^2)
Gujarat	Mahidad	NEPFM	3.63	6.94	7.70	190.57
	Sansagar	EMJ	2.96	7.92	7.07	302.04
	Suvarda	NEPFM	3.78	6.70	7.42	169.88
Tamil Nadu	Kanyakumari	NEPFM	4.38	7.50	8.23	231.62
	Kamagiri	EMM	1.86	5.90	5.22	147.96
	Kalunirkulam	NEPFM	1.80	6.56	7.38	256.24
	M.S.Puram	EMM	1.98	6.67	5.91	204.80
	Sarvallar Hill	EMM	2.03	7.01	6.22	234.28
Andaman Nicobar	Mount Harrient	NEPFM	5.21	7.70	8.37	246.53
Madhya Pradesh	Barkheri Bazar	NEPFM	3.10	6.47	7.24	162.10
	Nagda	NEPFM	3.56	6.77	7.52	177.55
Maharashtra	Jagmin	EMJ	4.35	8.78	8.00	372.09
	Chakla	NEPFM	3.42	6.50	7.24	159.05
	Raipur	EMM	2.11	7.59	6.73	289.89
	Brahmanwel	EML	2.32	5.99	8.62	151.14

Table 5. Cost of energy of different sites with different wind models.

States	Sites	Wind speed at 10m and 150m (m/s)	E53/800		E70/2300		E82/2000		E82/2300		E101/3000		E82/3000	
			COE 10m	COE 150m	COE 10m	COE 150m	COE 10m	COE 150m	COE 10m	COE 150m	COE 10m	COE 150m	COE 10m	COE 150m
Gujarat	Mahidad	3.80 and 5.59	1.04	0.36	3.04	0.99	5.09	1.63	5.10	1.64	11.16	3.54	5.14	1.65
	Sangasar	4.18 and 6.03	0.78	0.28	2.28	0.79	3.82	1.30	3.84	1.30	8.39	2.82	3.86	1.31
	Suvarda	3.42 and 5.00	1.43	0.50	4.17	1.38	6.98	2.28	7.00	2.29	15.31	1.54	7.05	2.30
Tamil Nadu	Kalunirkulam	5.01 and 7.38	0.45	0.15	1.33	0.43	2.22	0.71	2.23	0.71	4.87	1.54	2.24	0.72
	Kamagiri	4.35 and 6.40	0.69	0.24	2.02	0.66	3.39	1.09	3.40	1.09	7.44	2.36	3.43	1.10
	Kanyakumari	5.59 and 8.23	0.32	0.11	0.95	0.31	1.60	0.51	1.60	0.51	3.51	1.11	1.62	0.52
	M.S. Puram	4.01 and 5.91	0.88	0.30	2.58	0.84	4.33	1.38	4.34	1.38	9.50	2.99	4.38	1.39
	Servallar Hills	4.22 and 6.22	0.76	0.26	2.22	0.71	3.72	1.18	3.73	1.19	8.15	2.57	3.76	1.20
Maharashtra	Raipur	4.57 and 6.73	0.59	0.20	1.75	0.57	2.93	0.93	2.93	0.94	6.42	2.03	2.96	0.94
	Brahmanwel	5.86 and 8.54	0.28	0.10	0.83	0.28	1.39	0.46	1.39	0.46	3.04	0.99	1.40	0.46
	Chakal	4.91 and 7.24	0.48	0.16	1.41	0.45	2.36	0.75	2.37	0.75	5.17	1.63	2.38	0.76
	Jagmin	5.43 and 8.00	0.35	0.12	1.04	0.34	1.74	0.56	1.75	0.56	3.83	1.21	1.76	0.56
Madhya Pradesh	Barkheri Bazar	4.91 and 8.11	0.48	0.11	1.41	0.32	2.36	0.75	2.37	0.54	5.17	1.16	2.38	0.54
	Nagda	5.23 and 7.70	0.40	0.13	1.16	0.38	1.95	0.62	1.96	0.63	4.28	1.35	1.97	0.63
Andaman and Nicobar	Mount Harriet	5.33 and 7.85	0.37	0.13	1.10	0.36	1.84	0.59	1.85	0.59	4.05	1.28	1.86	0.60
	South Bay	5.50 and 8.11	0.34	0.11	1.00	0.32	1.68	0.53	1.68	0.54	3.68	1.16	1.70	0.54

has minimum COE variation and E101/3000 has maximum COE.

4 Conclusions

The WPP assessment with different methods and economics of wind power generation has been done for different locations in India. The most important outcomes of the study can be summarized as follows:

1. The best method to estimate the wind power density is NEPFM followed by EMM, EMJ, and EML.
2. Shape parameters and cubic factors do not change with the hub height of the wind turbine. The wind speed and wind power density increase exponentially with the heights.
3. Weibull shape parameter k ranges from 1.52 to 4.65 while the scale parameter c is between 2.39 m/s and 9.73 m/s.
4. It is found that Kalunirkulam of Tamil Nadu comes under the Wind Class 4 category and Brahmanwel of Maharashtra falls under Wind Class 5.
5. At 10 m hub height cost of energy varies from 0.28 to 15.31 \$/kWh whereas at 150 m hub height cost of energy varies from 0.10 to 3.53 \$/kWh, showing a decrease in COE from 64.28% to 76.94%.
6. The outcome of this study is important for the wind industry.

Future research work will be focused on the development and comparison of different forecasting models accuracy for wind speed in Indian diverse climatic conditions.

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Appendix A

A.1. Cubic factor (CF)

The Weibull parameters can be obtained as follows:

$$K = 1 + \frac{3.69}{(\mathrm{CF})^2} \tag{A.1}$$

where CF is the wind energy pattern factor

$$= \frac{\text{Average of cubes of wind speeds}}{\text{Cube of the average of wind speeds}} \tag{A.2}$$

$$C = \frac{v}{\Gamma\left(1 + \frac{1}{K}\right)}. \tag{A.3}$$

A.2 Empirical method of Justus (EMJ)

This approach was proposed by Justus *et al.* [20] in 1977. It present a direct solution based on average wind speed and standard deviation. It is a moment-based estimate of the form factor. This approach results in the Weibull shape factor being written as,

$$K = \left(\frac{Vm}{\sigma}\right)^{-1.086} \tag{A.4}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (V_i - Vm)^2}{n}} \tag{A.5}$$

$$C = \frac{Vm}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{A.6}$$

where Vm is average mean wind speed and V_i is a wind speeds.

Table A1. NEPFM coefficients.

Coefficients	Values	Coefficients	Values	Coefficients	Values
a0	−0.22037	b0	−12728	c0	0.225761
a1	3.27527	b1	3.6911	c1	0.134704
a2	−5.7896	b2	−2.6097	d0	−0.35144
a3	2.15143	b3	−0.8004	d1	0.711818
a4	0.90396	b4	0.9920		

A.3 Empirical method of Lysen (EML)

This approach also came from the Moment method. It uses equation (A.6) to determine K. C is computed as follows [21]:

$$C = Vm\left(0.568 + \frac{0.433}{K}\right)^{\frac{1}{K}}. \tag{A.7}$$

A.4 Empirical method of Mabchour (Mabch)

This approach was used to assess Morocco's potential for wind energy by Mabchour. K is expressed using the method of Mabchour [22, 23] as

$$K = 1 + (0.483(Vm - 2))^{0.51}. \tag{A.8}$$

Once K is calculated, C is obtained using equation (A.6).

A.5 Energy pattern factor method (EPF)

It is an easy method to estimate Weibull parameters. It is based on wind speed average. Once Epf is calculated, the value of K and C is given by the following equations [24]:

$$\mathrm{Epf} = \frac{\overline{V^3}}{Vm^3} \tag{A.9}$$

$$K = 1 + \frac{3.69}{\mathrm{Epf}^2}. \tag{A.10}$$

Once K is calculated, C is obtained using equation (A.7).

A.6 Energy pattern factor method of Sathyajith (EPFMS)

This method is another approximation method of estimating Weibull parameters based on the Epf. With this method, K is calculated as follows [25]:

$$K = 3.957 \times \mathrm{Epf}^{-0.898}. \tag{A.11}$$

A.7 Novel energy pattern factor method (NEPFM)

This method is also an approximation of the energy density method to determine the Weibull shape factor and the scale parameter. The parameters were determined using the following equations [26].

$$K = \frac{a4\mathrm{Epf}^4 + a3\mathrm{Epf}^3 + a2\mathrm{Epf}^2 + a1\mathrm{Epf} + a0}{b4\mathrm{Epf}^4 + b3\mathrm{Epf}^3 + b2\mathrm{Epf}^2 + b1\mathrm{Epf} + b0} \tag{A.12}$$

$$C = \frac{Vm(K^2 + c1K + c0)}{K^2 + d1K + d0}. \tag{A.13}$$

Appendix B

The COE (\$/kWh) can be defined by equation (B.1), where C_{TAC} is the total annual cost (\$) and E_{AEO} is the yearly electrical energy output of WTG (kWh):

$$\mathrm{COE} = \frac{C_{\mathrm{TAC}}}{E_{\mathrm{AEO}}}. \tag{B.1}$$

The total annual cost of a WTG is the sum of its operation, maintenance expenses and annual repayments on its capital. It can be demonstrated by the following:

$$C_{\mathrm{TAC}} = (b + 0.025)\,C_{\mathrm{ICC}} \tag{B.2}$$

$$b = \frac{c}{1 - (1 + c)^{-n}} \tag{B.3}$$

where c is the discount rate (%) and often takes about 10%; b is the discount factor; n is the lifetime of project, often taken to be 20 years; Initial capital cost of building in WTG (\$) (C_{ICC}) and is given by following equation:

$$C_{\mathrm{blade}} = 0.5582\left(\frac{D}{2}\right)^2 + 3.8118\left(\frac{D}{2}\right)^{2.5025} - 955.24 \tag{B.4}$$

$$\text{Mass of blade} = 0.1452\left(\frac{D}{2}\right)^{2.9158} \tag{B.5}$$

$$C_{\mathrm{hub}} = 4.05 \times \text{Mass of blade}\left(\frac{D}{2}\right)^{2.9158} + 24141 \tag{B.6}$$

$$C_{\text{pith system}} = 0.4802(D)^{2.6578} \tag{B.7}$$

$$C_{\text{nose cone}} = 103(D) - 2899 \tag{B.8}$$

$$C_{\text{low speed shaft}} = 0.1(D)^{2.887} \tag{B.9}$$

$$C_{\text{bearing system}} = D^{2.5}(0.0043D - 0.011) \tag{B.10}$$

$$C_{\text{gear box}} = 16.45{N_p}^{1.249} \tag{B.11}$$

$$C_{\text{electronics}} = 79N_p \tag{B.12}$$

$$C_{\text{yaw system}} = 0.0678(D)^{2.964} \tag{B.13}$$

$$C_{\text{main frame}} = 9.489(D)^{1.953} \tag{B.14}$$

$$\text{Mass}_{\text{main frame}} = 2.233(D)^{1.953} \tag{B.15}$$

$$C_{\text{platform and railing}} = 1.09 \times \text{Mass}_{\text{main frame}} \tag{B.16}$$

$$C_{\text{hydraulic and cooling}} = 12N_p \tag{B.17}$$

$$C_{\text{electrical connection}} = 40N_p \tag{B.18}$$

$$C_{\text{nacelle cover}} = 11.537N_p + 3849.7 \tag{B.19}$$

$$C_{\text{foundation}} = 303.24 \times (\text{Area} \times \text{hub height})^a \tag{B.20}$$

$$C_{\text{assembly and installation}} = 1.965 \times (D \times \text{hub height})^b \tag{B.21}$$

$$C_{\text{tower}} = (0.596 \times \text{Area} \times \text{hub height}) - 2121 \tag{B.22}$$

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