5. Identification of Optimum Wind Turbine Parameters for Varied Wind Climate using A Novel Turbine Performance Index

The Capacity Factor (*CF*) and Power Coefficient (C_p) are two essential wind turbine characteristics that play a vital role in defining its performance. *CF* predicts the duration of operation of the wind turbine in a year. On the other hand, C_p indicates the efficiency in the conversion of the wind power potential to the electric power generation **[194]**. The higher C_p is, the more efficiently the wind turbine converts the available wind energy into useful energy output. The optimization of these two wind turbine characteristics is essential before designing and installing wind turbines at a given site so that the feasibility of higher power generation and economic viability of the power plant can clearly be evaluated for the wind power plant (*WPP*). Several researchers **[60, 66, 111, 195-202]** have reported the use of statistical technique to predict the wind energy potential and assess the economic viability of the selected sites. Their conclusions are biased and focused only on maximizing *CF* and neglect the importance of C_p. A high *CF* can also be achieved using a wind turbine with a relatively large rotor size and a small generator size, as a result, its efficiency gets reduced, resulting in a lower electricity generation. In contrast, for the same rotor size a large generator leads to a higher efficiency, but the total duration of power generation gets reduced, i.e., *CF* is reduced. **Chang, *et al.* [28]** suggested that the best suitable wind turbine for a particular site is judged only when it yields a higher energy production for a longer duration of time, which results in the maximization of the energy output. Recently using real data from an urban environment, **Cooney, *et al.* [203]** used such a *CF* and C_p to assess the performance of a wind turbine.

From the literature review, it has been observed that the majority of researchers consider only *CF* as the judgment criterion to estimate the optimum speed parameters of the turbine. They have either neglected the importance of C_p or have considered it to be a constant. It is well known that the wind turbine C_p presents a maximum value for a particular wind speed, which decreases rapidly for all other wind speeds **[204]**. However, the average output power ($\overline{WPD}_{output}$) is defined as a function of both the *CF* and C_p along with the rated wind speed. Therefore, both *CF* and C_p are equally important when defining the optimal wind turbine parameters. The same observation has been revealed while plotting the *CF* and C_p against the normalized rated wind speed (V_r / s), as depicted in Figure 5.1, where the normalized rated wind speed has been varied from 0.1 to 4 with a step of 0.05. Here, *s* is a scale parameter, and the shape parameter (*k*) has been varied from 1.0 to 3.4 with a step of 0.4. Eqs. 5.1 and 5.2, which are elaborated in detail later, have been used to estimate the *CF* and C_p, respectively

$$CF = \left(\frac{V_c}{V_r}\right)^3 \exp\left(-\left(\frac{V_c}{s}\right)^k\right) + \frac{3}{k\left(\frac{V_r}{s}\right)^3}\left[\gamma\left(\left(\frac{V_r}{s}\right)^k, \frac{3}{k}\right) - \gamma\left(\left(\frac{V_c}{s}\right)^k, \frac{3}{k}\right)\right] - \exp\left(-\left(\frac{V_f}{s}\right)^k\right) \tag{5.1}$$

and

$$C_p = C_{pR} \times \frac{CF}{\Gamma(1+3/k)}\left(\frac{V_r}{s}\right)^3 \tag{5.2}$$

where $\gamma(a,x) = \int_0^x \exp(-t)t^{a-1}dt$ is the lower incomplete Gamma function; Γ is the complete Gamma function, and *p* and *q* are constants.

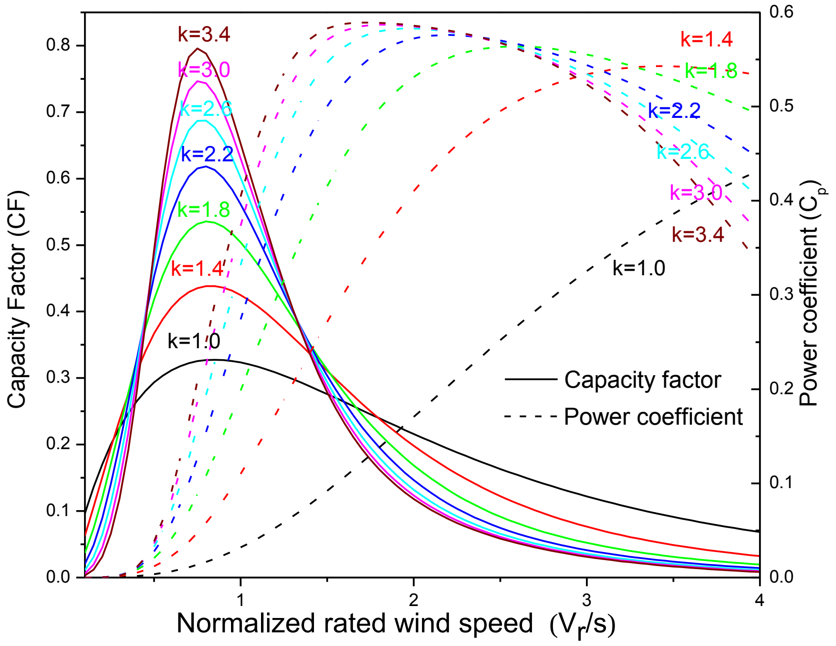

Figure 5.1: Capacity Factor and Power Coefficient curves.

Figure 5.1 reveals that the plots for the *CF* and C_p have peaks at different values of V_r / s for the same value of *k*. This implies that at a maximum *CF*, C_p is relatively low, which indicates that the conversion efficiency of the available wind potential into useful energy is lower. Conversely, at a maximum C_p, *CF* is relatively low, which indicates that the cost of the wind turbine generator equipment is higher since it is being used for less time. Thus, it is necessary to estimate the V_r / s, which simultaneously optimizes both *CF* and C_p to yield a higher energy production for a longer duration.

The normalized rated wind speed (V_r/s) is the ratio of the rated wind speed to the scale parameter of the *W.pdf*. The scale parameter can statistically be estimated from the wind climatic condition at a particular site. However, the rated wind speed is a turbine parameter that can be controlled by the manufacturer. Therefore, designing the wind turbine with optimum speed parameters, namely, the cut-in speed (V_c), rated speed (V_r), and cut-out speed or furling speed (V_f), is the prime requirement to maximize the wind energy harnessed at a particular site. Particularly, wind speeds that are rated too low lead to much energy lost for higher-speed winds.

In contrast, wind speeds that are rated too high lead to the turbine operating at its capacity, results in too much loss of energy at the lower-speed winds **[65]**. Therefore, the evaluation of optimum rated wind speed $V_{r,opt}$ is important for the turbine to yield higher energy at a higher *CF*.

To evaluate $V_{r,opt}$, **Janagmshetti, and Rau [205]** proposed a turbine performance index (*TPI*) based on optimizing *CF* and C_p, and they suggested a formula to estimate the speed parameters of the turbine, i.e., V_c, V_r, and V_f. This *TPI* was then used by **Abul'Wafa [65]** to perform research in Egypt. **Yeh, and Wang [67]** proposed another *TPI* based on optimizing *CF* and C_p to estimate the speed parameters V_c, V_r, and V_f of the turbine. However, these approaches are applicable only to the region or country where the wind climate is rather stable throughout the year or where data analyses are performed on an annual basis for power generation. Conversely, in the Indian subcontinent, the wind climate is fluctuating in nature; hence, the monthly analysis of the wind speed data is of the utmost importance. Consequently, previously suggested *TPI* has been deemed inapplicable in the cases where monthly analysis of the wind speed data is quite essential. The shortcoming of the other research, such as neglecting the importance of C_p or estimating speed parameters based only on the maximum *CF*, considered only the stable wind climate throughout the year. Therefore, in this work, a novel *TPI* has been proposed that considers monthly averages of the wind speed data and enables an estimation of the optimum speed parameters of the wind turbine for a given site that yields high-energy output.

The main objectives of this chapter are as follows:

i. To propose a novel *TPI* to estimate the optimum speed parameters of the turbine considering wide monthly variations in the wind climate.

ii. To estimate the optimum speed parameters of the turbine that would have the potential to optimize both *CF* and C_p simultaneously to yield a high-energy output.

iii. To determine the sites that have the highest probability of producing high wind energy output.

5.1 Significance of Analyses of Monthly Average Wind Speed Data

Variations in the wind speeds at any location are obvious; hence, **Kwon [206]** recommended conducting an uncertainty analysis to assess the wind energy potential. Unlike most of the European countries, the Indian subcontinent faces variable climatic change throughout the year **[207]**, which significantly govern the wind regime available at a given site. Analyzing wind data annually may lead to erroneous estimations of the wind power potential (*WPP*). However, to assess the economic viability of *WPP*, it is important to characterize the wind speeds correctly **[208]**. Therefore, to correctly estimate the *WPP*, a monthly analysis of the wind speed data is of paramount importance **[209, 210]**. Figure 5.2 depicts the plots of the monthly mean wind speed data for these three stations, showing the seasonal behaviour from the monthly average of the wind speed data. The figure shows that higher monthly mean wind speeds occur during the months between May and July, and lower monthly mean wind speeds occur during the months between October and January for all three stations.

Indian climatology is the windiest during the southwest monsoon season, i.e., during the months between May and September. During this season, the probability of higher wind speeds is much greater. However, the winter season in India is during the months between October and January, which has an increased probability of low wind speeds. The turbines are rarely operated during this season, as it is a season of low wind speeds.

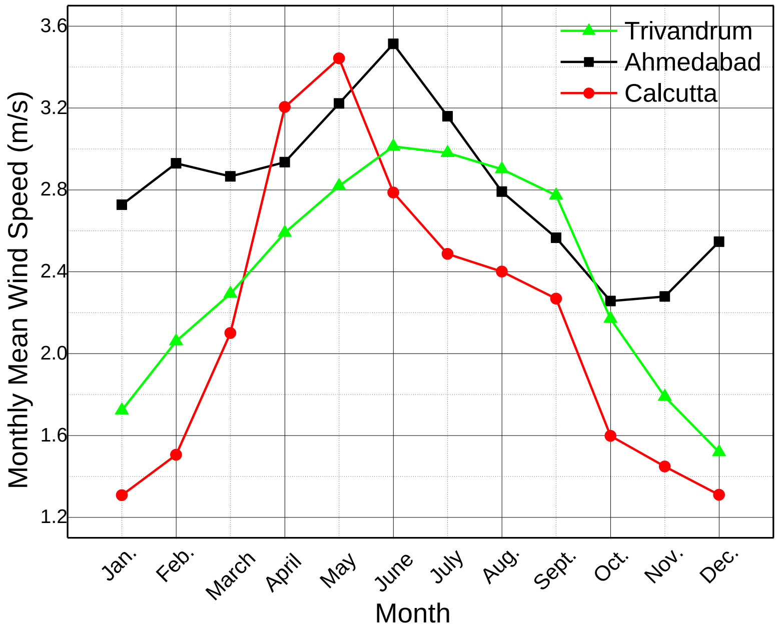

Figure 5.2: Plot of monthly average wind speed data.

5.2 Mathematical Analysis

5.2.1 Extrapolation of Wind Speed at Different Hub Heights

To estimate the wind energy potential, wind speed data at the hub height are necessary. However, the IMD measures the wind speed data at the anemometer height, i.e., 10 *m* above the ground level, which mandates using the so-called wind shear exponent. In this study, the formula proposed by **Allnoch [211]** to estimate the vertical wind shear exponent has been employed to determine the wind speed at the hub height.

The expressions to estimate the Hellmann exponent (α), shape parameter (k_z), and scale parameter (s_z) of the *W.pdf* and vertical mean wind profile ($\bar{v}_z$) at different heights (z) are given as:

$$\alpha = \frac{0.65 - 0.19\log s_a}{1 - 0.19\log\left(\frac{z_a}{z_{ref}}\right)} \tag{5.3}$$

$$k_z = k_a \frac{\left[1 - c\log\left(\frac{z_a}{z_{ref}}\right)\right]}{\left[1 - c\log\left(\frac{z}{z_{ref}}\right)\right]} \tag{5.4}$$

$$s_z = s_a\left(\frac{z}{z_a}\right)^{\alpha} \tag{5.5}$$

$$\bar{v}_z = \bar{v}_a\left(\frac{z}{z_a}\right)^{\alpha} \tag{5.6}$$

where z_a is the anemometer height (10m); z_{ref} is the reference height (18 m); z denotes the height at which the parameters are to be estimated; s_a is the scale parameter at the anemometer height; $\bar{v}_a$ is the mean wind speed at the anemometer height; and c is a constant with a value of 0.19.

5.2.2 Capacity Factor (CF) and Power Output of the Wind Turbine

The Capacity Factor (CF) is the ratio of the total energy generated during a given period to the total rated generation capacity during the same period **[194]**, which is expressed as:

$$CF = \frac{E_{output}}{E_{rated}} = \frac{P_{avg} \times T}{P_{rated} \times T} \tag{5.7}$$

where E_{output} is the total energy generated during a given period, and E_{rated} is the total energy generated at the rated speed for the same period. Here, E_{output} is the product of the average electrical power output (P_{avg}) for the period (T), whereas E_{rated} is the product of the rated electrical power output (P_{rated}) for the same period (T). The average electrical power output has been calculated as:

$$P_{avg} = CF \times P_{rated} \,. \tag{5.8}$$

In addition, the average electrical rated output power has been calculated as:

$$P_{rated} = \frac{1}{2}\rho A C_{pR} \eta_{mech} \eta_{ele} V_r^3 \tag{5.9}$$

where C_{pR} is the maximum power coefficient of the wind turbine, the value of C_{pR} is 16/27 (Betz limit), η_{mech} is the efficiency of the mechanical system, and η_{ele} is the efficiency of the electrical system. Hence, the expression for the average output power density ($\overline{WPD}_{output}$), measured in W/m^2, is:

$$\overline{WPD}_{output} = \frac{P_{avg}}{A} = CF \times C_{pR} \times \eta_{mech} \times \eta_{ele} \times \frac{1}{2} \times \rho \times V_r^3 \,. \tag{5.10}$$

To estimate $\overline{WPD}_{output}$, both η_{mech} and η_{ele} have been assumed to be 1 in the present study, as because, these efficiencies does not play any role in deciding the rated wind speed of the turbine. Therefore, the output power is a function of only three variables, namely, CF, C_p, and V_r, since the air density is constant. An analytical approach to estimate the CF based on the *W.pdf* has been used. The expression for CF is given as **[27, 63, 64]** :

$$CF = \frac{1}{V_r^3}\int_{V_c}^{V_r} v^3 f(v)dv + \int_{V_r}^{V_f} f(v)dv \,. \tag{5.11}$$

Eq. 5.11 can also be written as (see Appendix B for detail derivation):

$$CF = \left(\frac{V_c}{V_r}\right)^3 \exp\left(-\left(\frac{V_c}{s}\right)^k\right) + \frac{3}{k\left(\frac{V_r}{s}\right)^3}\left[\gamma\left(\left(\frac{V_r}{s}\right)^k, \frac{3}{k}\right) - \gamma\left(\left(\frac{V_c}{s}\right)^k, \frac{3}{k}\right)\right] - \exp\left(-\left(\frac{V_f}{s}\right)^k\right) \tag{5.12}$$

where V_c, V_r, and V_f are the cut-in, rated, and cut-out or furling wind speeds, respectively, of the wind turbine generator, expressed in m/s, and the ratio V_r / s is the normalized rated speed. In this study, the values of p and q for the simulation have respectively been taken as 0.275 and 1.85, respectively **[64, 204]**. While considering commercial wind turbines, p and q have been taken as the ratio of V_c/V_r and V_f/V_r, respectively.

5.2.3 Power Coefficient (C_p)

Power coefficient (C_p) is the ratio of power output from the wind turbine to the input power of the wind, which can be expressed as:

$$C_p = \frac{P_{avg}}{P_{total}} . \tag{5.13}$$

Eq. 5.13 can also be expressed as:

$$C_p = \frac{\overline{WPD}_{output}}{\overline{WPD}} \tag{5.14}$$

where P_{total} is the total power input, which is the product of the $\overline{WPD}$ and the swept area of the turbine blade (A), and P_{avg} is the average power extracted from the wind. Using equations 5.10 and 1.3, the analytical expression for C_p is given as:

$$C_p == \frac{\frac{1}{2}\rho A C_{pR} \times C.F. \times V_R^3}{\frac{1}{2}\rho A s^3 \Gamma\left(1+\frac{3}{k}\right)} , \tag{5.15}$$

which can also be expressed as:

$$C_p = C_{pR} \times \frac{C.F.}{\Gamma\left(1+\frac{3}{k}\right)} \times \left(\frac{V_R}{s}\right)^3 . \tag{5.16}$$

The $\overline{WPD}_{output}$ calculated from Eq. 5.10 is at rated wind speed (V_r) at which power coefficient is maximum, i.e., at C_{pR}. As we have seen from figure 5.1 that at maximum power coefficient, capacity factor is low. Therefore, we need an optimum rated wind speed at which the product of CF and C_p will be maximum. Thus, *TPI* has been proposed in this study and is discussed in detail in subsequent section.

5.2.4 Turbine Performance Index (TPI)

The ratio of the actual energy output to the maximum possible energy output is defined as the turbine performance index (*TPI*). In this work, the selection and design of a suitable turbine have been carried out using the site-dependent monthly wind speed data. Accordingly, the *TPI* has been evaluated from

$$TPI = \frac{\text{Actual Energy Output}}{\text{Maximum Possible Energy Output}}. \tag{5.17}$$

The actual energy output is depends on actual output wind power density ($\overline{WPD}_{actual,o/p}$), which is a function of *CF*, C_p and optimal rated wind speed ($V_{r,opt}$). The other parameters, such as η_{mech} and η_{ele} are assumed to be unity. Therefore, in this study, these quantities have been assumed to be constant.

whereas $\rho/2$ is assumed to be constant, which gives:

$$\overline{WPD}_{actual,o/p} = CF \times C_p \times V_{r,opt}^3. \tag{5.18}$$

However, in varied wind climate regions such as India, it may be advisable to analyze the wind speed data on a monthly basis. Therefore, to estimate the optimum rated wind speed of the turbine ($V_{r,opt}$), a new *TPI* has been proposed herein. The *TPI* serves as a tool to find the optimum rated wind speed ($V_{r,opt}$), which is most suitable for a given location. The rated wind speed (V_r), at which the maximum *TPI* has been obtained, can be considered as the optimal rated wind speed of the turbine ($V_{r,opt}$).

Based on the monthly CF_i and $(C_p)_i$ for a month (*i*) and the V_r, the cumulative actual energy output (*CAEO*) for each month in a year has been calculated as:

$$CAEO = \sum_{i=1}^{12} \left[CF_i \times (C_p)_i \times V_{r,opt}^3 \right]. \tag{5.19}$$

The maximum possible energy output (*MPEO*) over a year has been calculated based on the maximum value of the product of the *CF* and C_p, which is obtained at the optimal value of normalized rated wind speed, $(V_r / s)_{opt}$.The normalized rated wind speed, (V_r / s) varies from 0.1 to 4 in a step size of 0.1, which means that the (V_r / s) at which the product of *CF* and C_p is the maximum is the optimal value of the normalized rated wind speed, $(V_r / s)_{opt}$. The product of *CF*, C_p, and $(V_r / s)_{opt}^3$ with s^3 of a particular month has been used to estimate the monthly maximum possible energy output, and the summation of the monthly maximum possible energy output has been used to estimate the *MPEO*, such that

$$MPEO = \sum_{i=1}^{12} \left\{ \left[\left(CF \times C_p \right)_{\max} \times \left(\frac{V_r}{s} \right)_{opt}^3 \right]_i \times s_i^3 \right\}. \quad (5.20)$$

The ratio of the *CAEO* to the *MPEO* is the *TPI* for a given location. Thereby, the proposed novel formula to estimate the *TPI* based on the abovementioned monthly wind speed data analysis is given as:

$$TPI = \frac{\sum_{i=1}^{12} \left[CF_i \times (C_p)_i \times V_{r,opt}^3 \right]}{\sum_{i=1}^{12} \left\{ \left[\left(CF \times C_p \right)_{\max} \times \left(\frac{V_r}{s} \right)_{opt}^3 \right]_i \times s_i^3 \right\}}. \quad (5.21)$$

To estimate the *TPI* from the monthly estimated Weibull parameters, *i* has been taken as 1-12., whereas to determine the *TPI* from the annually estimated Weibull parameters, *i* has been taken as 1. In this study, the rated wind speed (V_r) has been varied from 8 to 15 *m/s*; subsequently, the *CAEO* and *TPI* have been calculated.

The V_r at which the maximum *TPI* has been obtained is the optimum turbine rated wind speed ($V_{r,opt}$) at that particular location.

5.3 Accuracy Judgment Criteria

To verify the degree of accuracy, i.e., whether the estimated probability function models can fit the observed data, four kinds of measure of goodness of fit have been employed as the judgment criteria. These *GOF* are the coefficient of determination, root mean square error, and Kolmogorov-Smirnov test, and percentage error in the wind power density. Among these *GOF*, the first three are discussed below. However, the expression for percentage error in wind power density has been discussed earlier (see Eq. 4.19)

5.3.1 Coefficient of Determination [R^2 (%)]

To verify the accuracy of the parameters estimated from the *MEPF* method of the *W.pdf*, the measure of the goodness of fit, R^2, has been performed. A value of R^2 more than 95% shows that there is less than a 5% level of significance between the observed and estimated data points, and thereby the estimated *W.pdf* has been found to be suitable to fit the observed data. The expression of R^2 for the wind speed and wind power density is represented as **[71, 139, 212]**:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(P_i - FF_i)^2}{\sum_{i=1}^{N}(P_i - \overline{FF})^2}\text{; for } i = 1,2,\ldots,N;$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(CDD_{observed} - CDD_{estimated})^2}{\sum_{i=1}^{N}(CDD_{observed} - \overline{CDD}_{estimated})^2}\text{; for } i = 1,2,\ldots,N \qquad (5.22)$$

where P_i are the values of the observed cumulative relative frequencies of the wind speed data; FF_i are the values of the estimated cumulative distribution functions of the wind speed data; and $\overline{FF}$ is the mean of the FF_i. Furthermore, N is the number of different observed wind data, and $CDD_{observed}$ and $CDD_{estimated}$ are the cumulative density distributions of the observed and calculated wind power density, respectively.

5.3.2 Root Mean Square Error (RMSE)

The root mean square error (*RMSE*) can be performed for both wind speed and wind power density using the following expressions **[70, 71]**:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - FF_i)^2}{DOF}} = \sqrt{\frac{\sum_{i=1}^{N}(P_i - FF_i)^2}{N - NPF}} \; ;$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(CDD_{observed} - CDD_{estimated})^2}{DOF}} \tag{5.23}$$

where *DOF* represents the degrees of freedom, which has been defined as the difference between the number of different wind speed data (*N*) and the number of parameters fitted (*NPF*). For the single distribution model, *NPF* = 2.

5.3.3 Kolmogorov-Smirnov Test (K-S)

To check the acceptability of a distribution obtained using the observed data, the Kolmogorov-Smirnov (*K*-*S*) test is performed. This test provides information about the suitability of a given distribution to describe the observed data. The *K*-*S* is defined as the maximum difference between the observed cumulative distribution function and the empirical cumulative distribution function **[7, 118]**. The expression of *K*-*S* for the wind speed and wind power density is represented as

$$K - S = \max\left|P_i - FF_i\right| ;$$

$$K - S = \max\left|CDD_{observed} - CDD_{estimated}\right| . \tag{5.24}$$

The critical value for the *K*-*S* test at a 95% confidence level is given as:

$$Q_{95critical} = \frac{1.36}{\sqrt{n}} \tag{5.25}$$

where *n* is the number of data points. If the Q_* value exceeds the critical value, then there is a significant difference between the observed and estimated distributions.

5.4 Results and Discussion

In this study, the optimum speed parameters of the modern Horizontal axis wind turbine with yaw controlling mechanism, which enables turbine rotor to rotate at any degree, have been determined using the new turbine performance index (*TPI*) to yield a high-energy output for longer durations. Different commercially available wind turbines with varying hub heights have been assessed to verify the applicability of the proposed approach. A detailed statistical study of the wind speed and wind power at 10, 30, and 60 *m* heights, as well as wind direction, have been conducted for three reference stations from distinct regions in India: (i) Trivandrum, (ii) Ahmedabad, and (iii) Calcutta. (see Table 4.1).

Tables 5.1-5.3 show the mean monthly and annual variation of the estimated Weibull parameters, both actual and estimated mean wind speed and wind power density at the anemometer height (10 *m*) for three selected stations, namely, Trivandrum, Ahmedabad, and Calcutta respectively. The wind speed data have been parameterized using the *W.pdf*. The method employed to estimate Weibull parameters is Modified Energy Pattern Factor Method (as discussed in Chapter 4).

Table 5.1: Mean monthly and annual variation of Weibull parameters, mean wind speed, and wind power density in Trivandrum at 10 *m* height.

Months	**Weibull Parameters**		**Mean Wind Speed (*m/s*)**		**Wind Power Density (*W/m²*)**	
	k	*s* (*m/s*)	Actual	Estimated	Actual	Estimated
Jan.	1.5462	1.9210	1.7225	1.7282	8.3527	8.2242
Feb.	1.5900	2.3019	2.0602	2.0650	13.6032	13.4929
Mar.	1.5040	2.5460	2.2928	2.2976	20.5654	20.1176
Apr.	1.4301	2.8565	2.5909	2.5951	30.4592	31.3039
May	1.3833	3.0952	2.8192	2.8265	45.1475	42.6775
June	1.4110	3.3126	3.0121	3.0155	50.5075	50.1825
July	1.4797	3.2992	2.9804	2.9834	46.3720	45.1277
Aug.	1.4583	3.2055	2.9011	2.9043	40.8206	42.5651
Sept.	1.4545	3.0627	2.7729	2.7758	35.6437	37.3095
Oct.	1.3936	2.3848	2.1705	2.1751	18.6369	19.2145
Nov.	1.4521	1.9811	1.7890	1.7959	10.5820	10.1314
Dec.	1.5106	1.6917	1.5185	1.5259	6.2667	5.8542
Annual	1.3523	2.7339	2.5062	2.5132	31.3486	29.857

Table 5.2: Mean monthly and annual variation of Weibull parameters, mean wind speed, and wind power density in Ahmedabad at 10 *m* height.

Months	**Weibull Parameters**		**Mean Wind Speed (*m/s*)**		**Wind Power Density (*W/m²*)**	
	k	*s* (*m/s*)	Actual	Estimated	Actual	Estimated
Jan.	1.5562	3.0716	2.7271	2.7312	26.9871	26.6199
Feb.	1.8726	3.3019	2.9298	2.9314	31.8472	31.5705
Mar.	1.8304	3.2244	2.8658	2.8652	30.2480	30.2374
Apr.	1.9208	3.3050	2.9349	2.9317	30.3443	30.7282
May	2.0089	3.6338	3.2218	3.2201	38.9050	38.8875
June	1.9455	3.9630	3.5128	3.5142	52.4394	52.2205
July	2.1107	3.5677	3.1593	3.1598	35.3788	35.0385
Aug.	2.0374	3.1505	2.7914	2.7912	25.3930	24.9781
Sept.	1.9014	2.8940	2.5658	2.5680	21.4011	20.8756
Oct.	1.6623	2.5310	2.2569	2.2619	17.4828	16.7146
Nov.	1.5562	2.5417	2.2789	2.2851	20.0883	18.8373
Dec.	1.7387	2.8633	2.5463	2.5511	23.0751	22.6669
Annual	1.8154	3.2230	2.8650	2.8668	30.5220	30.1952

Table 5.3: Mean monthly and annual variation of Weibull parameters, mean wind speed, and wind power density in Calcutta at 10 *m* height.

Months	**Weibull Parameters**		**Mean Wind Speed (*m/s*)**		**Wind Power Density (*W/m*^{2})**	
	k	*s* (*m/s*)	Actual	Estimated	Actual	Estimated
Jan.	1.3397	1.4334	1.3079	1.3162	5.0184	4.5488
Feb.	1.3246	1.6467	1.5052	1.5153	8.1065	7.0781
Mar.	1.3575	2.3009	2.100	2.1078	19.7439	18.2660
Apr.	1.4441	3.5306	3.2046	3.2030	54.9068	57.9693
May	1.4817	3.8045	3.4424	3.4397	65.4430	69.0146
June	1.3926	3.0605	2.7869	2.7917	41.4448	40.6738
July	1.4481	2.7457	2.4869	2.4901	27.1117	27.1207
Aug.	1.3380	2.6211	2.4008	2.4074	29.3249	27.8928
Sept.	1.2706	2.4543	2.2683	2.2775	26.3140	25.8983
Oct.	1.2403	1.7326	1.5979	1.6082	10.2019	9.5398
Nov.	1.3189	1.5831	1.4482	1.4579	6.4583	6.3524
Dec.	1.3020	1.4286	1.3096	1.3191	5.0117	4.8133
Annual	1.1832	2.3753	2.2426	2.2510	29.0362	26.0120

As seen from Tables 5.1-5.3, the month-wise estimated scale parameter is maximum in June for the western region stations (Trivandrum and Ahmedabad) in India; on the other hand it is maximum in May for the eastern zone station (Calcutta). As the mean wind speed and wind power density are proportional to the scale parameter (*s*) and a cube of the scale parameter, respectively, the mean wind speed and wind power density show the similar profile as that of the scale parameter. The plot of the monthly mean wind speed as shown in Figure 5.2 confirmed the conclusion made in this study. Among the three selected stations, the annual value of the scale parameter is the highest for Ahmedabad, followed by Trivandrum, and the minimum has been found for Calcutta.

The histograms of annual data along with the fitted Weibull probability density functions as well as corresponding cumulative distribution functions for both the wind speed and wind power density are shown in Figure 5.3, where the *W.pdf*s have been found in good agreement with the observed distributions. Similarly, the *W.pdf* representing the monthly probability density functions, wind power density, and corresponding cumulative distribution function for Trivandrum, Ahmedabad, and Calcutta as shown in Figure 5.4.

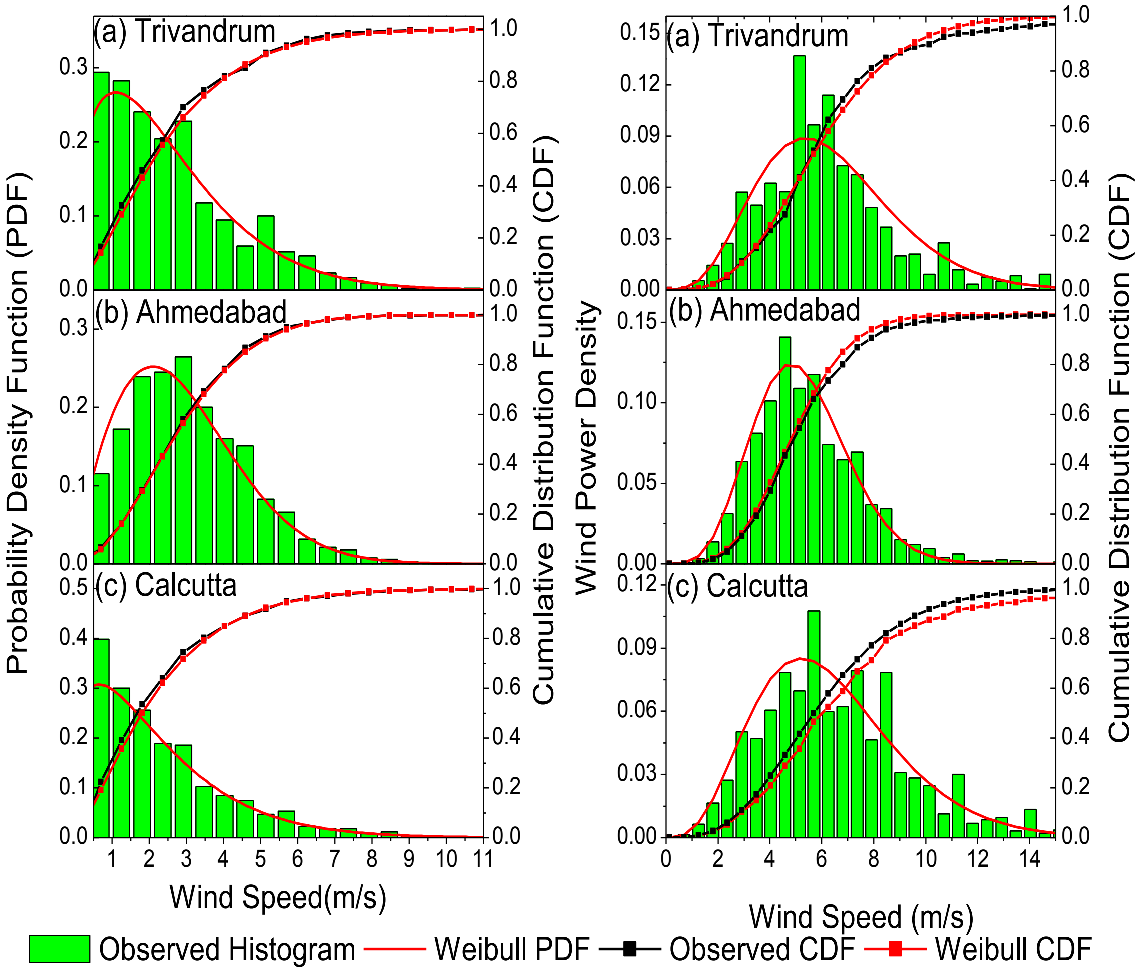

Figure 5.3: Weibull function representing annual wind speed probability density function, corresponding cumulative distribution function, wind power density, and corresponding cumulative distribution function for (a) Trivandrum, (b) Ahmedabad, and (c) Calcutta.

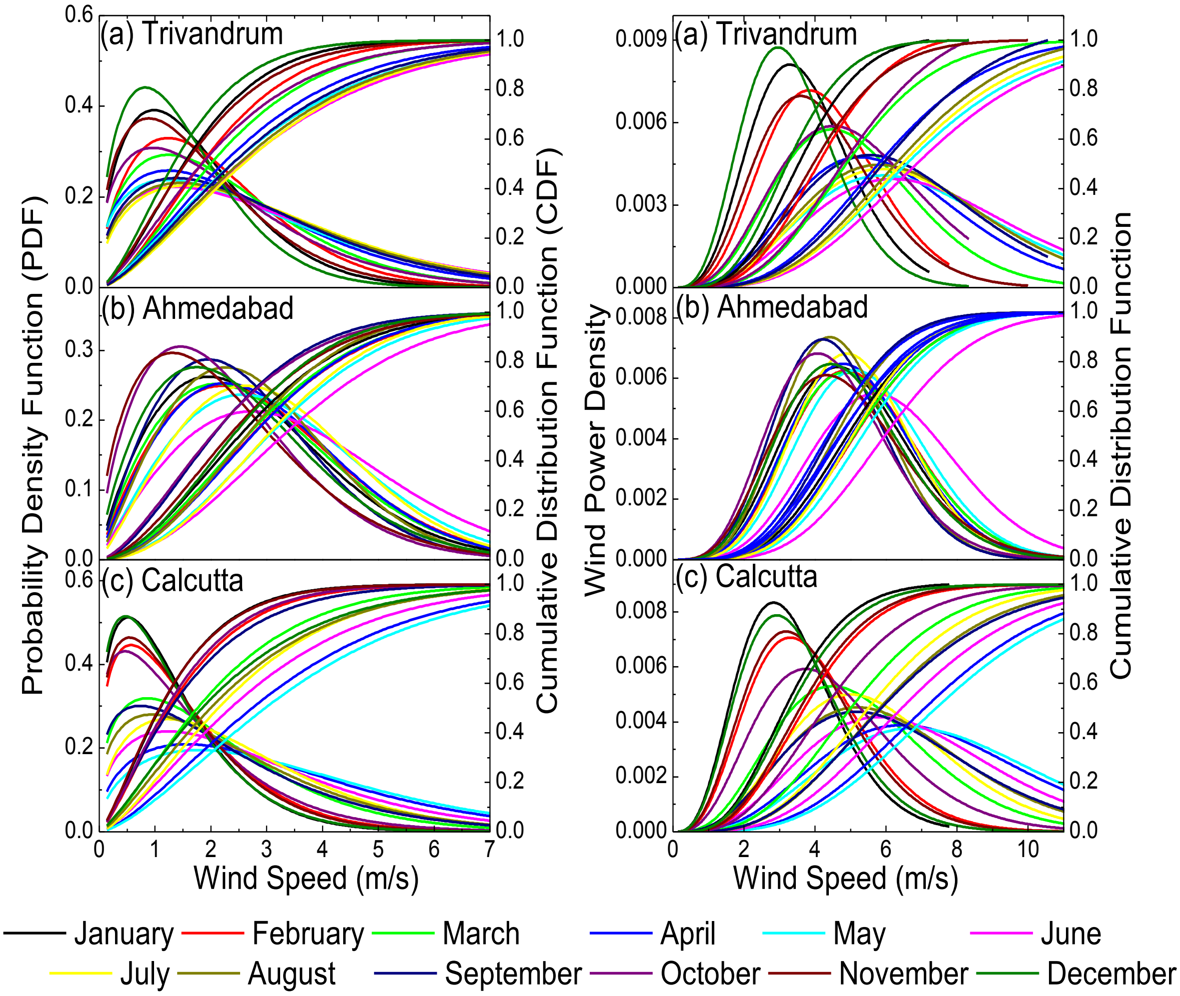

Figure 5.4: Weibull function representing monthly wind speed probability density function, corresponding cumulative distribution function, wind power density, and corresponding cumulative distribution function for (a) Trivandrum, (b) Ahmedabad, and (c) Calcutta.

The results of the goodness of fit statistics, i.e., R^2, *RMSE*, and *K-S* test, and *Error* (%) for both the wind speed and wind power densities at the anemometer height, respectively for these three selected stations namely, Trivandrum, Ahmedabad, and Calcutta are given in Tables 5.4-5.6 respectively. These characterization techniques have been used to define the effectiveness of the estimated Weibull parameters in describing the actual wind speed and wind power densities.

Table 5.4: Monthly and annually estimated goodness of fit for wind speed and wind power density in Trivandrum at 10 *m* height.

Months	**Wind Speed**			**Wind Power Density**			
	R^2 (%)	***RMSE***	***K-S ($Q_{95critical}$)***	***R^2 (%)***	***RMSE***	***K-S***	***Error(%)***
Jan.	98.23	0.0374	0.1019 (0.2667)	99.35	0.0322	0.0853	1.54
Feb.	98.78	0.0330	0.0809 (0.2570)	99.18	0.0356	0.1219	0.81
March	99.26	0.0182	0.0871 (0.1520)	98.96	0.0349	0.0900	2.18
April	99.11	0.0254	0.0839 (0.2005)	98.62	0.0478	0.1277	2.77
May	99.40	0.0188	0.0725 (0.1650)	97.41	0.0591	0.1313	5.47
June	99.49	0.0165	0.0684 (0.1466)	99.32	0.0301	0.0744	0.64
July	99.57	0.0156	0.0560 (0.1502)	98.35	0.0458	0.0810	2.68
Aug.	99.27	0.0243	0.0648 (0.2050)	98.31	0.0535	0.1220	4.27
Sept.	99.15	0.0267	0.0710 (0.2206)	98.68	0.0461	0.1020	4.67
Oct.	98.56	0.0333	0.0908 (0.2483)	98.95	0.0399	0.1222	3.10
Nov.	98.38	0.0320	0.0969 (0.2266)	98.93	0.0403	0.1514	4.26
Dec.	97.85	0.0370	0.1072 (0.2480)	97.58	0.0604	0.1645	6.58
Annual	99.28	0.0178	0.0758 (0.1466)	99.55	0.0236	0.0560	3.37

Table 5.5: Monthly and annually estimated goodness of fit for wind speed and wind power density in Ahmedabad at 10 *m* height.

Months	**Wind Speed**			**Wind Power Density**			
	R^2 (%)	***RMSE***	***K-S ($Q_{95critical}$)***	***R^2 (%)***	***RMSE***	***K-S***	***Error (%)***
Jan.	99.56	0.0207	0.0459 (0.2150)	99.76	0.0196	0.0517	1.36
Feb.	99.66	0.0186	0.0428 (0.2050)	99.80	0.0178	0.0489	0.87
March	99.69	0.0170	0.0354 (0.1963)	99.89	0.0135	0.0323	3.5021×10^{-2}
April	99.70	0.0212	0.0388 (0.2150)	99.77	0.0199	0.0670	1.27
May	99.73	0.0216	0.0439 (0.2050)	99.89	0.0133	0.0377	4.5013×10^{-2}
June	99.75	0.0199	0.0545 (0.1786)	99.92	0.0112	0.0334	0.42
July	99.72	0.0197	0.0612 (0.1625)	99.82	0.0160	0.0388	0.96
Aug.	99.63	0.0231	0.0582 (0.1923)	99.46	0.0286	0.0641	1.63
Sept.	99.57	0.0235	0.0668 (0.1850)	99.29	0.0319	0.0647	2.46
Oct.	99.42	0.0247	0.0518 (0.1963)	98.14	0.0509	0.0921	4.39
Nov.	99.43	0.0218	0.0519 (0.1785)	97.45	0.0578	0.1041	6.23
Dec.	99.49	0.0258	0.0488 (0.2150)	99.76	0.0197	0.0483	1.77
Annual	99.53	0.0178	0.0481 (0.1625)	99.84	0.0146	0.0412	1.07

Table 5.6: Monthly and annually estimated goodness of fit for wind speed and wind power density in Calcutta at 10 *m* height.

Months	**Wind Speed**			**Wind Power Density**			
	R^2 (%)	***RMSE***	***K-S ($Q_{95critical}$)***	***R^2 (%)***	***RMSE***	***K-S***	***Error(%)***
Jan.	96.12	0.0435	0.1338 (0.2570)	98.44	0.0486	0.1027	9.36
Feb.	97.46	0.0307	0.1101 (0.1923)	96.10	0.0674	0.1017	12.68
March	99.07	0.0206	0.0719 (0.1700)	98.46	0.0451	0.0859	7.48
April	99.55	0.0181	0.0560 (0.1727)	98.42	0.0502	0.1362	5.58
May	99.63	0.0168	0.0508 (0.1713)	98.49	0.0502	0.1301	5.46
June	99.52	0.0166	0.0558 (0.1625)	99.78	0.0177	0.0625	1.86
July	99.43	0.0185	0.0652 (0.1755)	99.87	0.0140	0.0556	3.31×10^{-2}
Aug.	99.30	0.0194	0.0664 (0.1755)	98.98	0.0377	0.0846	4.88
Sept.	99.23	0.0161	0.0720 (0.1388)	98.61	0.0473	0.1093	1.58
Oct.	97.80	0.0266	0.0992 (0.1755)	97.35	0.0591	0.1260	6.49
Nov.	97.73	0.0276	0.0976 (0.1851)	99.28	0.0291	0.0621	1.64
Dec.	97.13	0.0275	0.1028 (0.1755)	98.30	0.0470	0.0810	3.96
Annual	99.03	0.0177	0.0748 (0.1388)	99.15	0.0314	0.0616	8.24

As seen from these Tables 5.4 – 5.6 that the values of R^2 for monthly and annually have been found to be greater than 95%. This indicates that with 95% confidence level, the estimated wind speed and wind power densities follow actual wind speed and wind power densities for all three selected stations. The estimated *K-S* values for each month are less than the critical *K-S* ($Q_{95critical}$) (see Tables 5.4 – 5.6). Hence, it has been concluded that the *W.pdf* is a suitable model to fit the wind speed data for all the three selected stations in India. The low value of *Error* (%) indicates that there is a marginal difference between the actual wind power density and the estimated Weibull wind power density. Therefore, the wind turbine design can use the Weibull wind power density as an input power for its functioning. In addition to this, the mean absolute percentage error for twelve months is quite less than the percentage error estimated annually. For Trivandrum, Ahmedabad, and Calcutta the mean absolute percentage errors have been found respectively to be 3.24, 1.78, and 5.08, which are quite less than the annual percentage error for Trivandrum (3.37) and Calcutta (8.24), and is comparable with Ahmedabad (1.07). Trivandrum lies on the south-west coast, and Ahmedabad lies on the inland area of the west coast of India where severe storms are less predominant yielding stability in the wind climate. On the other hand, Calcutta lies on the east coast of India where storms are frequent and annual wind climate is not at all stable. That is why the difference of error between monthly and annual has been found to be quite higher for Calcutta rather than Trivandrum and Ahmedabad. However, considering the variation of the wind climate from one month to another, the monthly analysis of wind speed data can be preferred over annual wind speed to estimate the optimal design parameters of the wind turbine. The month-wise variations of the estimated *CF* and C_p for three different stations at the height of 30 *m* from the ground are shown in Figure 5.5.

The rated speed has been varied from 8 to 15 *m/s*. The cut-in and furling wind speeds have been taken as 0.275 and 1.85 times of the rated wind speed, respectively.

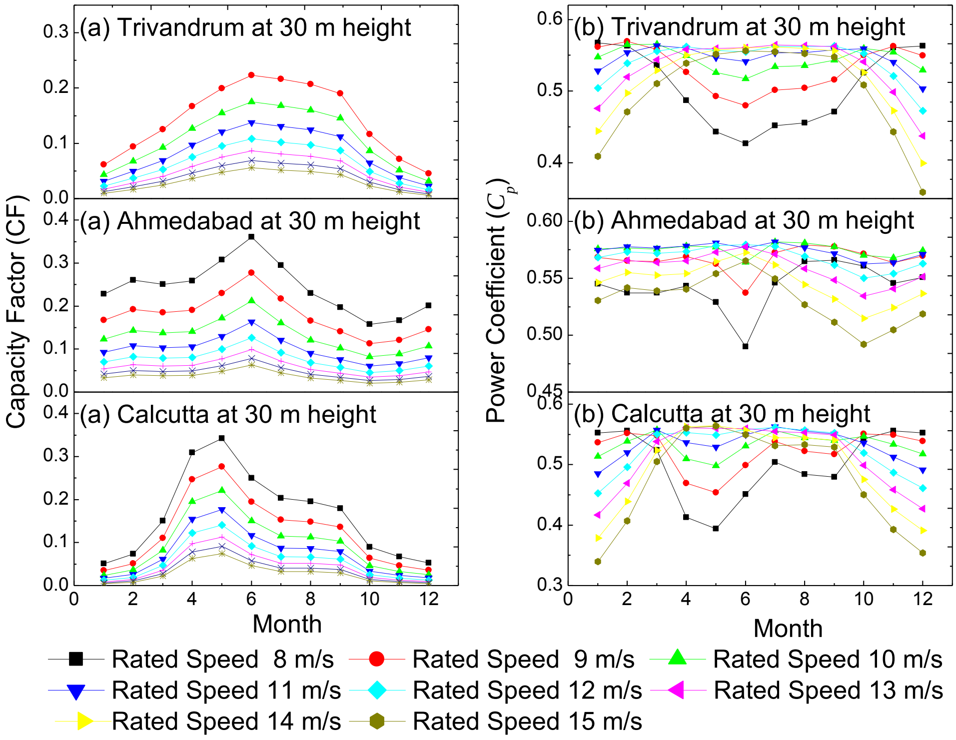

Figure 5.5: Month-wise variation of (a) Capacity Factor and (b) Power Coefficient at different rated wind speeds for Trivandrum, Ahmedabad, and Calcutta at 30 *m* height.

Figure 5.5 reveals that the month-wise *CF* is the highest for $V_r = 8$ *m/s* for all the months and it decreases as the rated wind speed increases for all three stations. However, Figure 5.5 reveals that the C_p has a concave profile at $V_r = 8$ *m/s* with observed deeps from April till September, and as the rated speed increases the profile of the C_p converts into the convex shape with the peaks from April till September.

Figure 5.6 shows the similar trends with the *CF* and C_p at the height of 60 *m* for three selected stations.

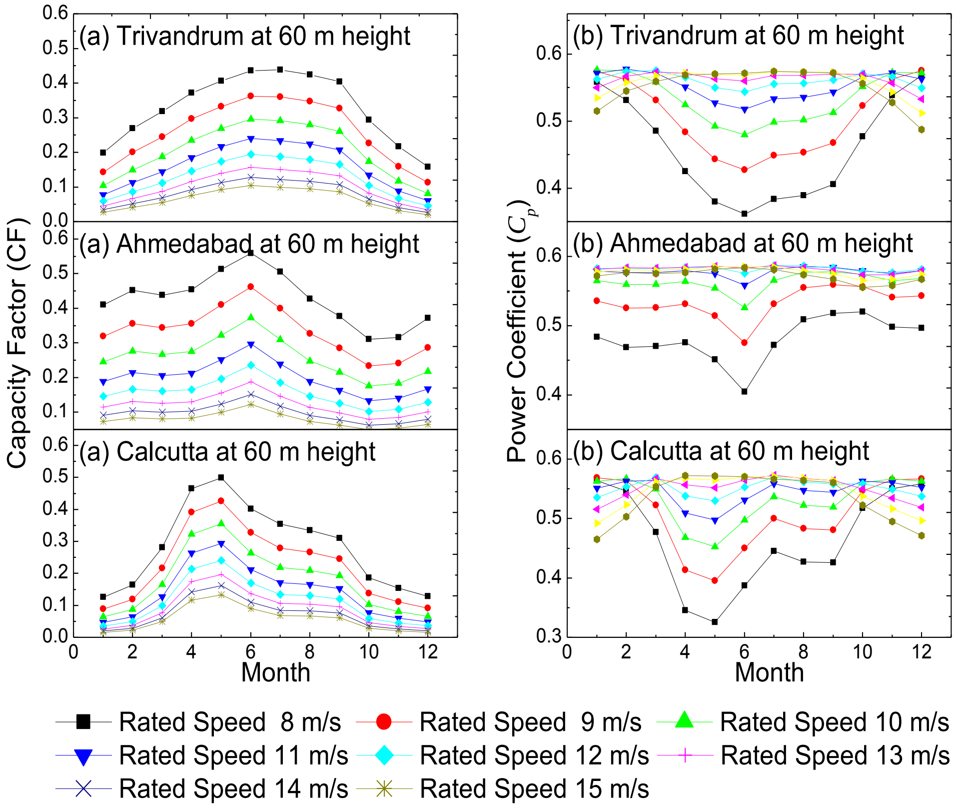

Figure 5.6: Month-wise variation of (a) Capacity Factor and (b) Power Coefficient at different rated wind speeds for Trivandrum, Ahmedabad, and Calcutta at 60 *m* height.

It is difficult to predict from these plots, the optimum rated wind speed that simultaneously maximizes both the *CF* and C_p, which is the utmost desirable objective for increasing the power generation. In estimating the rated wind speed, both the *CF* and C_p are equally important that maximize the average output power density, $\overline{WPD}_{output}$. Earlier, Figure 5.1 reveals that both the *CF* and C_p are not maximized at a single normalized rated wind speed. Moreover, it is difficult to predict the $V_{r,opt}$ based on the analysis of the monthly wind speed data, as each is having a different trend in the *CF* and C_p.

In view of these major difficulties, the proposed novel *TPI* has an advantage that it takes into account monthly average wind data, and is directly related to the $\overline{WPD}_{output}$. The rated wind speed with high *TPI* will give high $\overline{WPD}_{output}$. Thus, it enables in predicting reasonably rated wind speed for the particular location in fluctuating wind climate. The $\overline{WPD}_{output}$ and *TPI* for the three selected stations namely, Trivandrum, Ahmedabad, and Calcutta are given in Tables 5.7 and 5.8. The rated wind speed has been varied from 8 to 15 *m/s* and corresponding $\overline{WPD}_{output}$ and *TPI* have been calculated at both 30 and 60 *m* hub heights. Further, it is seen from Figures 5.5 and 5.6 that at V_r = 8 *m/s*, the *CF* is the highest for all months; however, the $\overline{WPD}_{output}$ and *TPI* is low, which implies that the *CF* alone cannot be taken as a judgment criterion for estimating the design rated wind speed.

Table 5.7: Average output power density and turbine performance index for the three stations at 30 *m* hub height.

Rated Speed, V_r (*m/s*)	**Trivandrum**		**Ahmedabad**		**Calcutta**	
	Output Power (*W/m*^{2})	***TPI* (%)**	**Output Power (*W/m*^{2})**	***TPI* (%)**	**Output Power (*W/m*^{2})**	***TPI* (%)**
8	345.0538	73.33	504.5185	86.89	289.6150	69.21
9	398.5333	84.69	542.5933	95.51	338.1179	80.80
10	432.7244	91.96	562.0481	98.94	371.2022	88.70
11	449.9652	95.62	563.2096	99.14	389.9311	93.17
12	453.7762	96.43	553.7725	97.47	396.6459	94.78
13	447.6785	95.14	537.5481	94.62	394.2141	94.20
14	434.5755	92.35	516.1333	90.85	385.1400	92.03
15	416.5726	88.53	490.0725	86.26	371.4562	88.76

Table 5.7 shows that at 30 *m* height, Ahmedabad shows the maximum $\overline{WPD}_{output}$ at 11 *m/s* rated wind speed with the highest *TPI* of 99.14. Trivandrum and Calcutta show the maximum $\overline{WPD}_{output}$ at 12 *m/s* rated wind speed and the *TPI* of 96.43 and 94.78, respectively. Among the three, Ahmedabad shows the highest $\overline{WPD}_{output}$ followed by Trivandrum and it is the least for Calcutta. At 30 *m* height, for Ahmedabad the wind turbine with rated wind speed of 11 *m/s* is the most suitable; and for Trivandrum and Calcutta, the wind turbines with 12 *m/s* rated wind speed are the most suitable.

Table 5.8: Average output power density and turbine performance index for the three stations at 60 *m* hub height.

Rated Speed, V_r (*m/s*)	**Trivandrum**		**Ahmedabad**		**Calcutta**	
	Output Power (*W/m²*)	***TPI* (%)**	**Output Power (*W/m²*)**	***TPI* (%)**	**Output Power (*W/m²*)**	***TPI* (%)**
8	540.6333	57.01	764.4444	66.14	457.8778	54.61
9	675.5555	71.44	948.1481	81.93	574.1711	68.48
10	782.2222	82.70	1066.6666	92.17	669.6296	79.68
11	859.2592	90.50	1131.8518	97.46	734.8148	87.78
12	900.7407	95.15	1155.5555	99.40	776.2962	92.90
13	924.4444	97.24	1155.5555	99.43	800	95.44
14	924.4644	97.38	1143.7037	98.39	805.9259	95.97
15	912.5925	96.13	1120	96.67	794.0740	94.98

From Table 5.8, it may be noted that at 60 *m* height, 13 and 14 *m/s* rated wind speeds show the highest $\overline{WPD}_{output}$ of 1.9463×10^3, 1.5584×10^3, and 1.3578×10^3 W/m^2 respectively for Ahmedabad, Trivandrum, and Calcutta, and corresponding high *TPI* of 99.43, 97.38, and 95.97 in descending order. At 60 *m* height, for Ahmedabad the wind turbine with rated wind speed of 13 *m/s* is the most suitable; and for Trivandrum and Calcutta the wind turbines with 14 *m/s* rated wind speed are the most suitable.

As a case study, some commercially available wind turbines have been considered to check the appropriateness of the proposed *TPI* for maximizing the energy output. Table 5.9 shows the characteristics of the commercially available wind turbines at both 30 and 60 *m* hub heights.

Table 5.9: Characteristics of the commercially available selected wind turbines.

Order	**Diameter (*m*)**	**No. of Turbine Blades**	**Rated Power (*kW*)**	**Cut-In Speed (*m/s*)**	**Rated Speed (*m/s*)**	**Cut-Out Speed (*m/s*)**
Hub Height = 30 *m*						
A	38	3	100	2	8	25
B	27	3	150	3	10	25
C	25	3	200	3.5	14	25
D	29	3	250	4	15	25
E	29	3	300	3	12	25
F	34	3	400	4	13.5	20

Table 5.9: Continued

Order	**Diameter (*m*)**	**No. of Turbine Blades**	**Rated Power (*kW*)**	**Cut-In Speed (*m/s*)**	**Rated Speed (*m/s*)**	**Cut-Out Speed (*m/s*)**
Hub Height = 60 *m*						
I	58	3	850	3	12.5	20
J	54	3	1000	3.5	15.5	25
K	62	3	1300	3	14.5	22.5
L	77	3	1500	3.5	12	20
M	66	3	1750	3.5	16	25
N	80	3	2000	3.5	14.5	25

The alphabetically ordered wind turbines considered here are commercially available, having specified diameter, a number of turbine blades, rated power, V_c, V_r, and V_f. They are commonly designated as the Order-Diameter/Rated Power. The selected turbines for operation at 30 *m* height has rated power variation ranging 100-400 kW and that selected for 60 *m* height has a variation ranging 850-2000 kW. Furthermore, it has also been noted that the rated wind speeds of such wind turbines vary from 8 to 15 *m/s*. Table 5.10 shows a comparison of the six commercially available wind turbines at both 30 and 60 *m* hub heights along with its calculated *TPI* for the three selected stations.

Table 5.10: Average output power density and turbine performance index of the selected wind turbines for the three stations at 30 *m* and 60 *m* hub heights.

Commercial Wind Turbines	**Trivandrum**		**Ahmedabad**		**Calcutta**	
	Output Power (*W/m*^{2})	***TPI* (%)**	**Output Power (*W/m*^{2})**	***TPI* (%)**	**Output Power (*W/m*^{2})**	***TPI* (%)**
Hub Height = 30 *m*						
A-38/100	325.71	79.27	495.77	86.05	294.26	68.49
B-27/150	423.73	92.63	553.23	99.08	362.89	89.37
C-27/200	457.41	94.86	543.11	94.26	404.78	94.02
D-29/250	426.22	89.81	502.49	88.00	379.52	89.86
E-29/300	467.86	97.02	568.29	98.63	409.39	95.29
F-34/400	421.41	92.38	502.28	89.71	372.98	91.49
Hub Height = 60 *m*						
I-58/850	936.29	96.12	1149.62	99.56	811.85	94.22
J-54/1000	960	98.12	1161.48	98.63	841.48	97.20
K-62/1300	977.77	98.74	1179.25	99.66	859.25	97.75
L-77/1500	894.81	95.37	1143.70	99.45	770.37	93.03
M-66/1750	960	98.01	1161.48	98.48	847.40	97.16
N-80/2000	954.07	98.17	1161.48	98.99	835.55	97.01

From these results, it has been observed that E-29/300 produces the highest $\overline{WPD}_{output}$, and has high *TPI*; consequently, it is a suitable wind turbine for the three selected stations in India at 30 *m* height. The wind turbine, E-29/300 has rated wind speed of 12 *m/s*, which also matches with the rated wind speed showing high *TPI* in Table 5.7. Similarly, from the commercially available wind turbines, as mentioned in Table 5.10, K-62/1300 is the most suitable wind turbine at 60 *m* height for the three selected stations in India. The rated wind speed of K-62/1300 wind turbine is similar to the rated wind speed showing high *TPI* and a high $\overline{WPD}_{output}$ in Table 5.8. The rated wind speed of the commercially available wind turbine matches well with the optimum rated wind speed estimated in Table 5.8. Thus, it can be concluded that the novel *TPI*-based approach proposed herein is a suitable tool to estimate the optimum rated wind speed, which ensures delivering high output energy. If this *TPI* would be employed at the planning and development stage for installation of the wind farm, it will serve as a useful tool to make a judicious choice of a wind turbine generator that yields higher energy output for a longer duration of time.

5.5 Summary

Optimum wind turbine parameters have been identified in this study for fluctuating wind climate in the Indian subcontinent using a novel turbine performance index (*TPI*). The proposed *TPI* takes into account monthly average of the wind speed data and enables in evaluating the optimum rated turbine speed for a given site. A detailed statistical study of the wind speed and wind power at 10, 30, and 60 *m* heights for three stations in India namely, Trivandrum, Ahmedabad, and Calcutta have been presented. The following points are drawn from the study as:

1. The Indian subcontinent experiences a wide variation in the climate throughout the year. Therefore, the monthly analysis of the wind speed data becomes important in the design of the wind turbines. The proposed turbine performance index (*TPI*) serves as a useful tool to estimate the optimum rated wind speed ($V_{r,opt}$) that takes into account the long-term monthly average data.
2. The southwest monsoon plays a dominant role in deciding the installation of the wind farm in India for generating electricity. The leading path for installation of the wind farm for Ahmedabad is the southwest direction; for Trivandrum, it is the northwest direction; and for Calcutta, it is the south direction. Among these stations, taken as a reference at three onshore corners of India, Ahmedabad appears to be the most suitable site for installation of the wind farm followed by Trivandrum and Calcutta.
3. It is concluded that at 30 *m* height, the rated wind speed (V_r) of around 11-12 *m/s* and at 60 *m* height, the V_r of around 13-14 *m/s* are the optimum design rated wind speeds ($V_{r,opt}$). Such $V_{r,opt}$ shows high *TPI* and a high average output power density ($\overline{WPD}_{output}$) for the selected stations from three distinct zones of India.

4. Comparison of the six types of commercial wind turbines has shown that the E-29/300 (V_r = 12 *m/s*) and K-62/1300 (V_r = 14 *m/s*), respectively for 30 and 60 *m* hub heights, are most suitable for these three selected stations in India, showing higher *TPI* and $\overline{WPD}_{output}$. These two commercially available wind turbines possess a rated wind speed same as the optimum rated wind speed ($V_{r,opt}$) calculated in this study.