4. Methods Employed to Estimate Weibull Parameters

Methods employed to estimate 2-parameter *W.pdf* play a crucial role in the accurate assessment of wind resources. A slight difference in estimation of Weibull parameters leads to the high difference in estimation of wind power potential at a given site. Therefore, the selection of appropriate method is utmost important for accurate estimation of Weibull parameters. The ideal method to estimate Weibull parameters should have following necessary and sufficient criteria:

(i) The method should be accurate for estimating the Weibull parameters.

(ii) The formulation of the method should be simple and explicit.

(iii) The solution should be efficient in terms of calculations, and preferably do not involve any iterative procedures.

(iv) The method should be free from the binning problem.

Binning problem is of major concern while estimating the parameters of Weibull distribution. The two conventional methods such as LSM, and MMLM are influenced by the binning problem. In both LSM and MMLM, higher weight is given to lower tail of the wind speed data. The two major drawback of binning is that, firstly, it is difficult to predict the optimum size of each bin. As too high bin size results in information loss, and too low bin size results in sampling errors. Secondly, within each bin, the choice of the middle or upper value of bin taken for estimation of Weibull parameters is still of major concern. The improper choice of value results in an underestimation of Weibull parameters [161]. The proposed method has an advantage that there is no such requirement to classify data into bins for the calculation of Weibull parameters like MOM and its formulation is also explicit unlike MOM.

In this study, a new Modified Energy Pattern Factor (*MEPF*) method has been proposed to estimate the parameters of the 2-parameter *W.pdf*. This *MEPF* method has the advantage that is simple, robust, efficient in terms of calculations, free from the binning problem and does not require any iterative procedures. Our new proposed method has the additional advantage that it takes into account the wind speed variability, i.e., the moments calculated from the parameters estimated from the *MEPF* method are very close to the empirical moments. The performance of the *MEPF* is compared with the available six methods, namely *LSM*, EM, *MOM*, *PDM*, *MLM*, and *MMLM*. This comparison will be based on simulated data of varying sample size from 100-100,000 for a fixed seed value. The well-performing *MEPF* has been used to estimate the Weibull parameters for real wind data from three sites in India.

The chapter is organized as follows. Section 4.1 describes the locations as well as wind data that are going to be analyzed. The various mathematical methods used in the present paper are presented in Section 4.2, while Section 4.3 contains both a simulation study to compare the various Weibull estimation methods to our new *MEPF* method and a detailed analysis of the wind data at the three sites in India in terms of wind speed, load, and power. The final Section 4.4 provides the overall summary of this chapter.

4.1 Geographical Condition and Observation Period

The IMD, Pune, recorded the long-term hourly mean wind speed data in *km/h* at 10 *m* height above the ground level with a dyne pressure tube anemograph. Among the 40 locations that are discussed in chapter 3 (see Table 3.1). In this study, three locations were taken as a reference sites to carried out the further research work. These sites were Calcutta (42809), Ahmedabad (42647) and Trivandrum (43371). Calcutta is located on the east coast of India whereas Trivandrum is located on the south-west coast and Ahmedabad is located on the inland area of the west coast. Figure 4.1 shows the map of India with locations of the three stations and Table 4.1 shows the latitude, longitude, altitude, observation periods and a total number of observations of these stations. For India, the choice of appropriate class width is of prime importance as the wind speed data supplied by IMD Pune were in integer *km/h*. The hourly wind speed histogram for 1 *km/h* class width will induce error in the histograms, and the histograms are not at all stable. Hence, a class width of 2 *km/h* has been opt (as discussed in section 3.1, chapter 3). The calm hours are not considered in order to avoid potential wrong wind speed measurements.

Figure 4.1: Map of India with the location of the three stations **[192]**.

Table 4.1: Description of the stations.

Stations	**Latitude (*°N)***	**Longitude (*°E)***	**Altitude (*m)***	**Observation period**	**Total No. of data**
Ahmedabad	23.0300	72.5800	53.00	Jan.1969-Oct.1998	145834
Trivandrum	8.4875	76.9525	4.90	Jan.1973-Dec.2005	121251
Calcutta	22.6200	88.4200	7.00	Jan.1969-Dec.1994	147608

4.2. Mathematical Models

The *W.pdf* is a flexible distribution that is widely used to describe unimodal frequency distributions like the wind regime at a particular location. The probability density function *f(v)* and cumulative distribution function *F*(*v*) are respectively given by

$$f(v) = \left(\frac{k}{s}\right)\left(\frac{v}{s}\right)^{k-1} \exp\left[-\left(\frac{v}{s}\right)^{k}\right] \quad (4.1)$$

and

$$F(v) = 1 - \exp\left[-\left(\frac{v}{s}\right)^{k}\right] \quad (4.2)$$

for $v > 0$ and $k, s > 0$, where *v* is the reference wind speed, *k* is the non-dimensional shape parameter, and *s* is the scale parameter whose dimension coincides with that of *v* (*m/s*). The brief description of six distinct existing methods to estimate the Weibull parameters, and then introduce our new *MEPF* method has been given in subsequent section. The observed data have been written as $v_1, v_2, v_3, ..., v_n$.

4.2.1 Least Square Method or Graphical Method (LSM)

Estimation of the *W.pdf* parameters can be made graphically. Taking the double logarithms of Eq. (4.2) (after a small manipulation of that equation) yields

$$\ln\ln\left(\frac{1}{1-F(v)}\right)=k\ln v\ -k\ln s \tag{4.3}$$

The plot of $\ln\ln\left(\frac{1}{1-F(v)}\right)$ against ln v has been used to estimate the Weibull parameters by fitting a straight line for the data $v_1, v_2, v_3, ..., v_n$. It is to be noted that one has to use for $F(v)$ the empirical distribution function of the data in Eq. (4.3).

The Weibull parameter k is the slope of the best-fitted straight line and $-k \ln s$ is its vertical axis intercept. Although a line may be fitted graphically using eye-estimation, fitting the straight line using least-squares regression is preferred for the accuracy of estimation.

4.2.2 Method of **Moments** *(MOM)*

The Method of Moments is a very common statistical estimation technique to estimate parameters of any distribution. The idea consists in comparing the theoretical Moments of distribution to their empirical counterparts, the latter being only based on data $v_1, v_2, v_3, ..., v_n$. The first and second order Weibull theoretical Moments are respectively given by

$$\mu=\int_{-\infty}^{\infty}(v)f(v)dv=s\Gamma\left(1+\frac{1}{k}\right) \tag{4.4}$$

$$\sigma=\sqrt{\int_{-\infty}^{\infty}(v-\mu)^2 f(v)dv}=s\left[\Gamma\left(1+\frac{2}{k}\right)-\Gamma^2\left(1+\frac{1}{k}\right)\right]^{1/2} \tag{4.5}$$

Its empirical counterpart is given by

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{4.6}$$

$$sd = \left[\left(\frac{1}{n-1}\sum_{i=1}^{n}(v_i - \bar{v})\right)\right]^{1/2} \tag{4.7}$$

A clever way to isolate *k* consists in considering the theoretical coefficient of variation (*CV*):

$$CV = \frac{\sigma}{\mu} = \frac{\sqrt{\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{4.8}$$

and to equate it with its empirical counterpart. Once the value of *k* is estimated, Eq. (4.9) has been used to estimate the value of *s* where $\bar{v}$ is the observed mean wind speed:

$$s = \frac{\bar{v}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{4.9}$$

4.2.3 Empirical Method (EM)

The Empirical Method is a special case of the Method of Moments to estimate Weibull parameters. **Justus [156]** proposed the following estimation for *k*:

$$k = \left(\frac{sd}{\bar{v}}\right)^{-1.086} \tag{4.10}$$

Once *k* is estimated *s* can be found using Eq. (4.9).

4.2.4 Maximum Likelihood Method (MLM)

Stevens, and Smulders [159] suggested the use of the Maximum Likelihood Method for estimating the Weibull parameters. The *MLM* is probably the most popular parameter estimation method in statistics. The aim is to find those parameter values that maximize the likelihood function of the data, in other words, those values rendering the observed data most likely. Straightforward calculations yield the following expressions for the Weibull shape and scale parameters:

$$k = \left[\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n} \right]^{-1} \quad (4.11)$$

$$s = \left[\frac{1}{n} \sum_{i=1}^{n} v_i^k \right]^{1/k} \quad (4.12)$$

From Eq. (4.11) it can be seen that the parameter k appears on both sides of the equality and cannot be isolated, hence numerical approximation methods are required to determine k. Once k is calculated, the value of s is easily obtained from Eq. (4.12).

4.2.5 Modified Maximum Likelihood Method (MMLM)

When the wind speed data are available under frequency distribution format (in other words, classified into bins because of repetitive values), the Modified Maximum Likelihood Method is used to estimate the Weibull parameters. These are then calculated as follows **[28]**:

$$k = \left[\frac{\sum_{i=1}^{n} v_i^k \ln(v_i) P(v_i)}{\sum_{i=1}^{n} v_i^k P(v_i)} - \frac{\sum_{i=1}^{n} \ln(v_i) P(v_i)}{P(v \geq 0)} \right]^{-1} \tag{4.13}$$

$$s = \left[\frac{1}{P(v \geq 0)} \sum_{i=1}^{n} v_i^k P(v_i) \right]^{1/k} \tag{4.14}$$

where $P(v_i)$ is the frequency of the class in which v_i is the wind speed central to the bin and $P(v \geq 0)$ is the total frequency for wind speed equal to or exceeding zero. The detail description to solve Eqs. 4.13 and 4.14 have been discussed in Appendix A.

4.2.6 Power Density Method (PDM)

Akdag, and Dinler [139] suggest a method to estimate the Weibull parameters that is useful when the mean wind speed and wind power density are available. The wind power density depends directly on the third Moment of the *W.pdf* $\int_0^\infty v^3 f(v)dv$ and hence also on the empirical version $\overline{v^3}$, the mean of the wind speed cube. The ratio of the mean of the wind speed cube to the cube of the mean wind speed $\left(\frac{\overline{v^3}}{\overline{v}^3} \right)$ is defined as Energy pattern factor (E_{pf}). Equating the theoretical and empirical expressions for E_{pf} thus leads to

$$E_{pf} = \frac{\overline{v^3}}{\overline{v}^3} = \frac{\frac{1}{n}\sum_{i=1}^{n} v_i^3}{\left(\frac{1}{n}\sum_{i=1}^{n} v_i \right)^3} = \frac{\Gamma\left(1+\frac{3}{k}\right)}{\left[\Gamma\left(1+\frac{1}{k}\right)\right]^3} \tag{4.15}$$

Weibull shape parameters can be estimated by solving Eq. (4.15) or approximately by using the simple expression suggested by [139]:

$$k = 1 + \frac{3.69}{E_{pf}^2} \tag{4.16}$$

The above expressions need just the mean of the wind speed cube and the cube of the mean wind speed to estimate the E_{pf}, and consequently, the shape parameter of the *W.pdf* can be estimated. The scale parameter can be determined using Eq. (4.9). As the estimated k from Eq. (4.16) is only an approximated value as mentioned by **Akdag, and Dinler [139]**, the accuracy of this method is in doubt. As a response, a more accurate and simple-to-use way to estimate the Weibull parameters from E_{pf} has been proposed in the subsequent section. This new method has been called as Modified Energy Pattern Factor Method.

4.2.7 Our New Proposal: The Modified Energy Pattern Factor Method (MEPF)

As defined earlier, E_{pf} is the ratio of the mean of the wind speed cube to the cube of the mean wind speed. From Eq. (4.15) it is observed that E_{pf} is a function of only the shape parameter. However, Eq. (4.15) is rather difficult to solve. In order to overcome this problem and avoid inaccuracy issues as in the *PDM*, the following new process has been adopted. Let the k value vary from 1 to 15 because earlier findings indicate that, in the wind regime of India, k is never less than 1 **[8]**. The plot k *vs.* E_{pf} has been plotted with E_{pf} on the abscissa and k on the ordinate. The variation between E_{pf} and k is Modelled using curve fitting techniques. Table 4.2 shows the three different rational functions M1, M2, and M3 that were used to fit the variation between k and E_{pf}. The reason for the selection of these rational formulae is that the graph of k vs. E_{pf} is horizontally asymptotical at $k \neq 0$ and the function $f(\infty)$ = constant. Therefore, the rational function should be such that the degree of the numerator should be equal to the degree of the denominator. That is why these three rational functions which have equal degrees of numerator and denominator have been opted. The one showing a minimum sum of squared error is the most suitable rational function to describe the variation between k and E_{pf}. Our findings indicate that M3 is the most suitable function. Figure 4.2 shows the graphical representation of k *vs.* E_{pf} and the best fitted rational function M3. The rational function coefficients a_n, and b_n are determined using the nonlinear Least Square Method with the Levenberg-Marquardt algorithm.

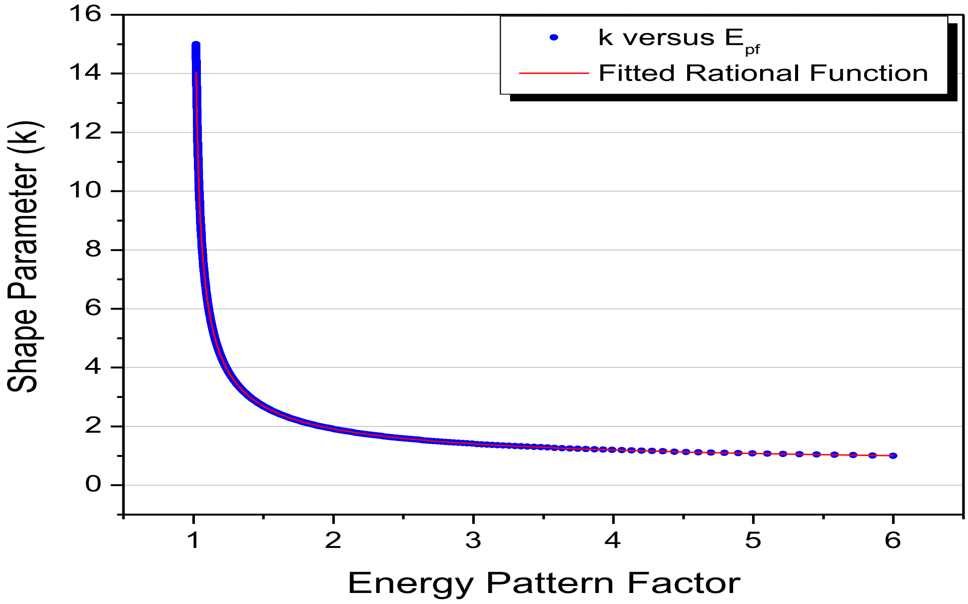

Figure 4.2: Variation of k versus E_{pf} and best fitted rational function.

Table 4.2: Comparison of rational formulae for the Modified Energy Pattern Function.

Methods	Shape Parameter	SSE (%)
M1	$k=\frac{a_2E_{pf}^2+a_1E_{pf}+a_0}{b_2E_{pf}^2+b_1E_{pf}+b_0}$	**31.58**
M2	$k=\frac{a_3E_{pf}^3+a_2E_{pf}^2+a_1E_{pf}+a_0}{b_3E_{pf}^3+b_2E_{pf}^2+b_1E_{pf}+b_0}$	**4.1x10^{-2}**
M3	$k=\frac{a_4E_{pf}^4+a_3E_{pf}^3+a_2E_{pf}^2+a_1E_{pf}+a_0}{b_4E_{pf}^4+b_3E_{pf}^3+b_2E_{pf}^2+b_1E_{pf}+b_0}$	**6.5x10^{-4}**

Table 4.3: Modified Energy Pattern Factor coefficient for both shape and scale parameters.

Coefficient for Shape Parameter	
a_0 = -0.2204	b_0 = -1.2728
a_1 = 3.2753	b_1 = 3.6912
a_2 = -5.7896	b_2 = -2.6097
a_3 = 2.1514	b_3 = -0.8005
a_4 = 0.5904	b_4 = 0.9920

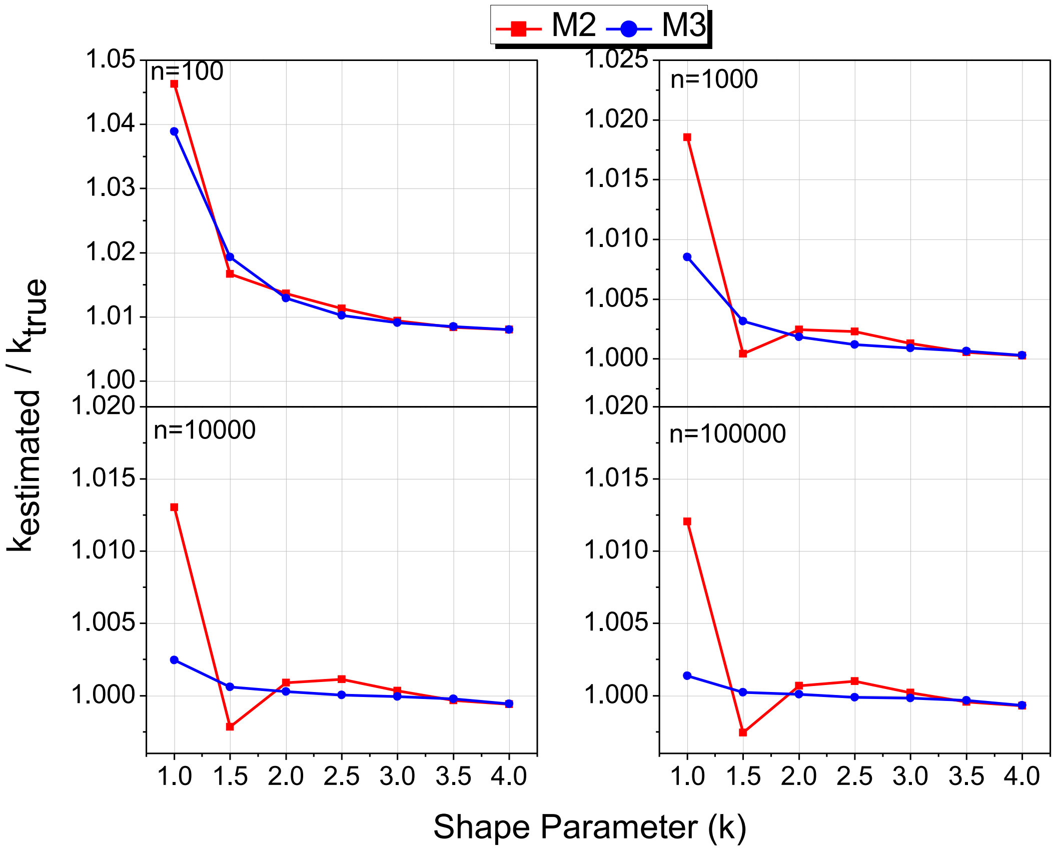

Figure 4.3: Comparison of M2 and M3 methods based on the ratio of estimated Shape parameter to Shape Weibull parameter versus shape parameter for different sample sizes.

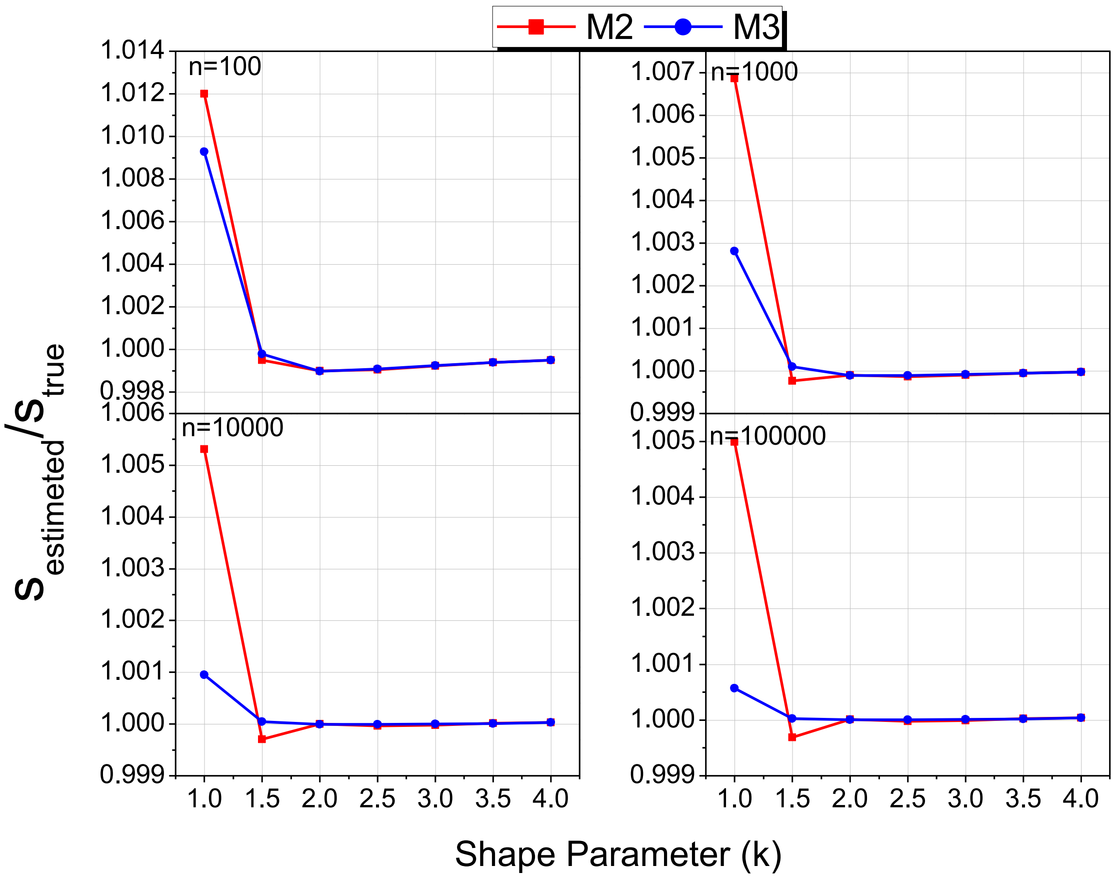

Figure 4.4: Comparison of M2 and M3 methods based on the ratio of estimated Scale parameter to Scale Weibull parameter versus shape parameter for different sample sizes.

A special comparison of M2 and M3 has been done by plotting the ratio of estimated Weibull parameters to true Weibull parameters (for k = 1-4 and s = 2-15 *m/s*) as a function of the true shape parameters for various sample sizes (100-100,000), (see Figures 4.3 and 4.4). A visual inspection of Figures 4.3 and 4.4 confirms the better fit provided by M3. Therefore, it can be concluded that M3 can be used to model the variation of k vs. E_{pf} as shown in Figure 4.2. The values of the coefficients for M3 are given in Table 4.3. Once k has been estimated, s can be determined from Eq. (4.9).

4.2.8 Random Variable Generation of the Weibull Distribution

In view of simulation study conducted at Section 4.1, the procedure for generation of random variables following a specified *W.pdf* has been described. The random variables have been generated to compare different methods to estimate the parameters of *W.pdf.* To this end, the sample sizes varying from 100 to 100,000 in multiples of 10 with a fixed seed value have been considered. Therefore, to model wind speed, *W.pdf* with shape parameter (k) varying from 1 to 4 with a step size of 0.5 and scale parameter (s) varying from 2 to 15 in a step size of 1 have been generated. These Weibull parameters are referred to as true Weibull parameters, and how well the different methods can estimate them has been investigated. The equation used to generate wind speed data with such *W.pdf*s is given by

$$v = s\left[\ln\left(\frac{1}{1-R_N}\right)\right]^{1/k} \tag{4.17}$$

where R_N is a random variable uniformly distributed on [0,1], and v is the targeted Weibull random variable.

4.2.9 The Weibull Quantile Function and the Detection of Extreme Wind Data

The wind speed data are asymmetric (skewed) data. Not all the supplied wind speed data are eligible to fit the *W.pdf*, hence a method to detect the most extreme values is needed. This will be done by following a quantile-based method suggested by **Tukey [193]**. From Eq. (4.17) the general Weibull quantile function (here q_a = right-hand side of Eq. (4.17) with R_N replaced by a) has been derived as:

$$q_a = s\left[\ln\left(\frac{1}{1-a}\right)\right]^{1/k} \tag{4.18}$$

where q_a is the quantile of order a of the *W.pdf* with parameters k and s. This yields directly the expressions for the first Quartile (a = 0.25)

$$q_1 = s\times\left(\left(\ln(4)-\ln(3)\right)^{(1/k)}\right) \tag{4.18(a)}$$

the second Quartile (a = 0.5)

$$q_2 = s\times\left(\left(\ln(2)\right)^{(1/k)}\right) \tag{4.18(b)}$$

and the third Quartile (a = 0.75)

$$q_3 = s\times\left(\left(\ln(4)\right)^{(1/k)}\right) \tag{4.18(c)}$$

With these expressions in hand, a value lower than q_1 - 3H or higher than q_3 + 3H, has been considered as extreme, where H is the inter-quartile range, i.e., $H = q_3 - q_1$ [240]. The purpose of using 3 times the Inter quartile range (H) is to identify the maximum data point beyond which data are considered as an extreme outliers. Eliminating such extreme data will lead to identify the data that can be modeled by Weibull distribution so that the stability of the remaining data is maintained without much loss of information from the data.

4.3 Results and Discussion

4.3.1 Comparison of Different Methods to Estimate the Weibull Parameters Based on Simulated Data

The best way to see which estimation method works best in which circumstances consist in simulating data from a *W.pdf*, as we then know the true values of the shape and scale parameters and can compare the estimates to these true values. Therefore, various simulation scenarios have been considered with sample sizes varying between 100 and 100,000. In each case, the Weibull parameters have been estimated using the seven different methods described in Section 4.2, namely *LSM, EM, MOM, MLM, MMLM, PDM,* and *MEPF*, and the estimated values have been compared with the true Weibull parameters from the simulated data. Different values of the shape parameter can have marked effects on the behaviour of the *W.pdf*. The shape parameter *k* is determinant for the nature of the *W.pdf*. Therefore, it has been selected as the abscissa for the visual comparison of the distinct methods. Figure 4.5 shows the comparison of seven different methods based on the ratio of estimated Weibull parameter to true Weibull parameter versus shape parameter for different sample sizes. Figure 4.5 (a) shows the ratio of estimated to true shape parameters versus the shape parameter. Figure 4.5 (a) reveals that for the sample size n = 100 and at $k = 1$, the *LSM* method underestimates the true shape parameter whereas *PDM* overestimates the true Weibull parameter followed by *MEPF, EM,* and *MOM*. As *k* increases, the estimated Weibull parameters from *MEPF, MOM,* and *EM* approach towards the true Weibull parameters. With increasing sample size n the performances of *LSM,* and *MEPF* are remarkably improved, and all methods lead to good estimates except for *PDM* followed by *EM*. At $n = 100{,}000$, among the seven methods compared. It can be seen that *LSM, MOM, MLM, MMLM,* and *MEPF* show equal behaviour, whereas *PDM* performs less well, followed by *EM*.

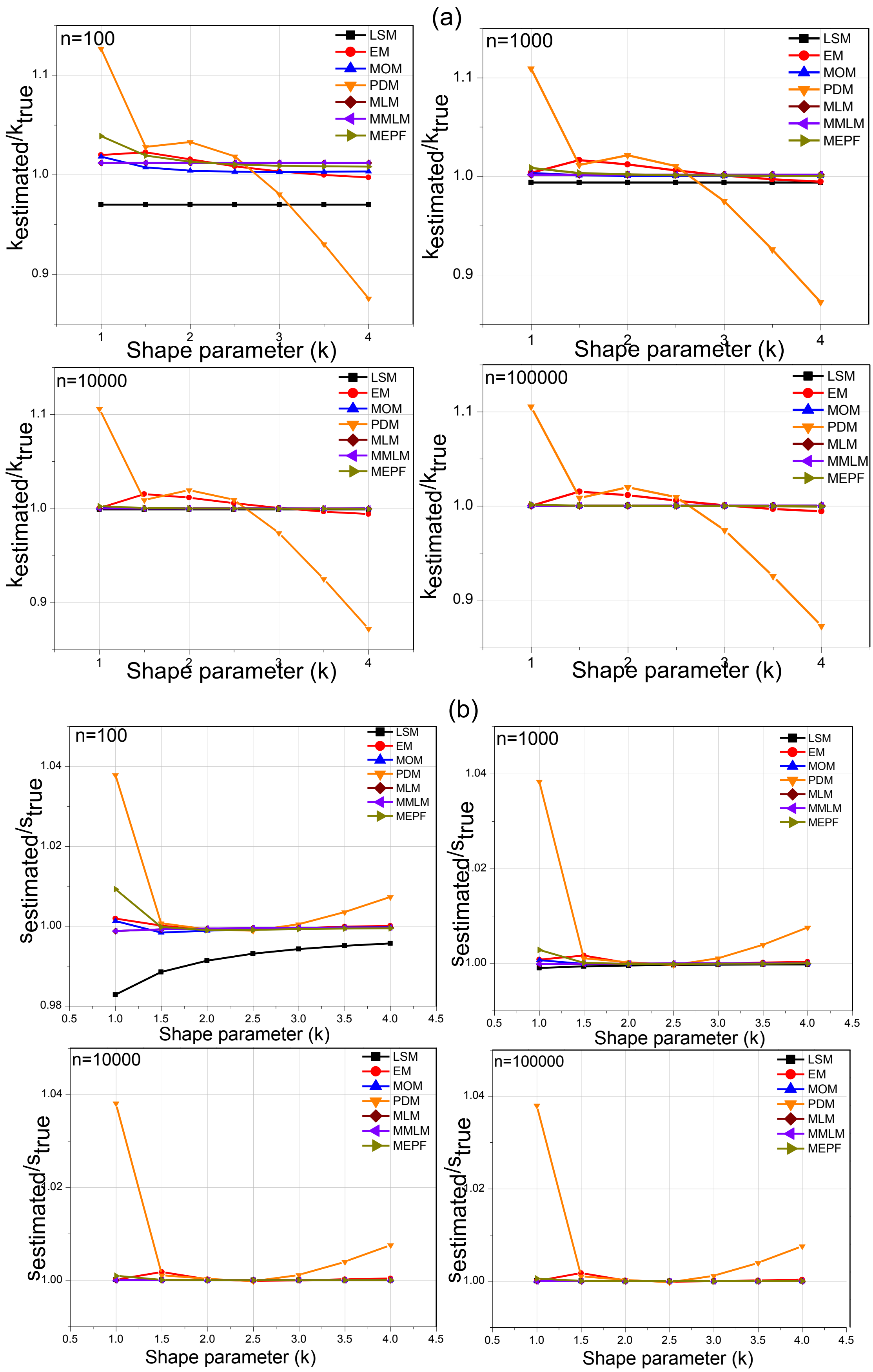

Figure 4.5: Comparison of seven different methods based on the ratio of estimated Weibull parameter to true Weibull parameter versus shape parameter for different sample sizes.

Figure 4.5 (b) shows the ratios of estimated scale parameter to true scale parameter versus the shape parameter. Similarly to our previous conclusions, it has been seen that for n = 100 and at k = 1, *PDM* overestimates the scale parameter followed by *MEPF* and EM, whereas *LSM* underestimates the true scale parameter. Remarkably, in the range of k = 1.5 to 3, the *PDM* estimates approach towards the true values while beyond k = 3 there is again overestimation. As n increases, the performances of all the methods improve, with extraordinary improvement for *LSM*. For n = 100,000, all methods show a similar behaviour to what it have been discussed for the shape parameter. From the above discussion, it has been observed that the proposed *MEPF* performs equally well in estimating the Weibull parameters as *LSM*, *MOM*, *MLM*, and *MMLM* provided the sample size is large enough. For a smaller sample size and a low value of k, the *MOM*, *MLM*, and *MMLM* perform best. For large n, *PDM* performs less well than the other methods, followed by *EM*.

On the basis of this simulation study, it has been concluded that the *MEPF* clearly outperforms its antecedent *PDM* and is a competitive method to estimate the parameters of the *W.pdf*. To further ensure about the performance of the proposed *MEPF* method, a comparison of all seven methods based on the absolute percentage error in mean wind power density ($\overline{WPD}$) at different values of shape parameters have ben cried out (see Figure 4.6).

The expression for the calculation of absolute percentage error in mean wind power density is given as:

$$error(\%) = \left| \frac{\overline{WPD}_{estimated} - \overline{WPD}_{true}}{\overline{WPD}_{true}} \right| \times 100 \tag{4.19}$$

where

$$\overline{WPD}_{estimated} = s^3_{estimated}\Gamma\left(1+\frac{3}{k_{estimated}}\right); \qquad \overline{WPD}_{true}{}^{1} = s^3_{true}\Gamma\left(1+\frac{3}{k_{true}}\right)$$

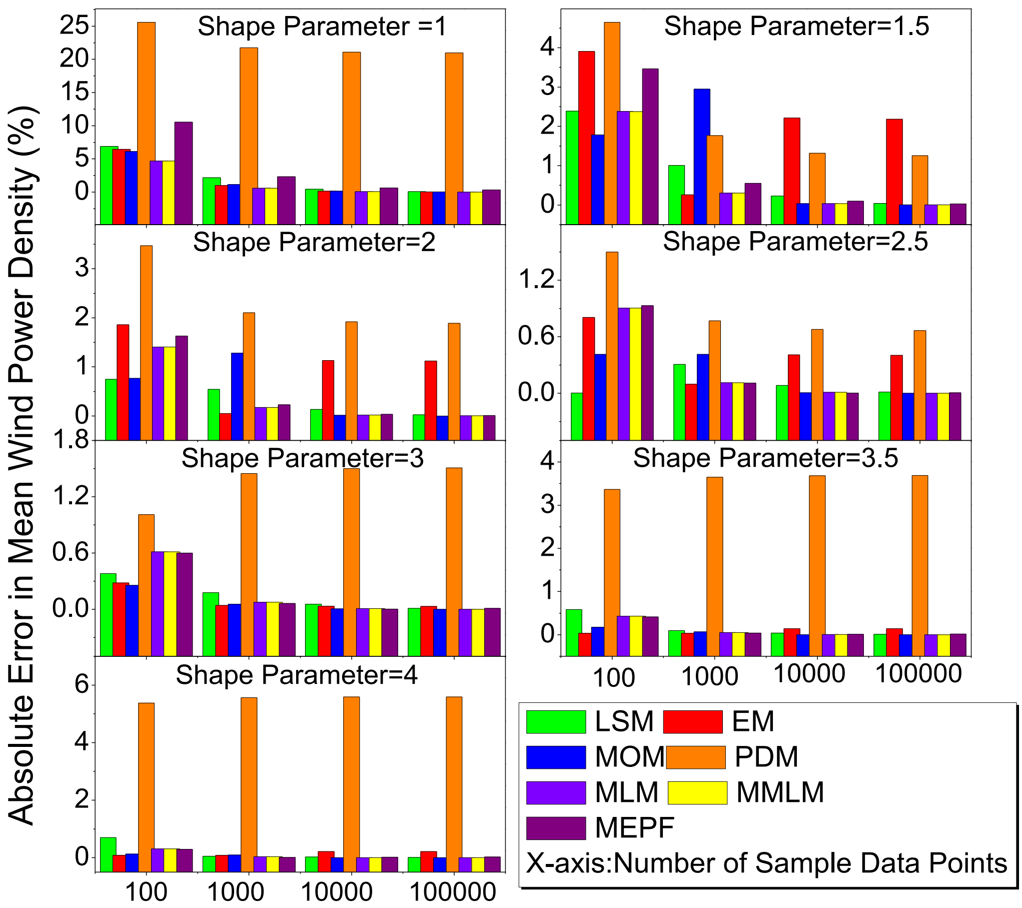

Figure 4.6: Comparison of seven different methods based on the absolute error in mean wind power density versus sample size for different shape parameters.

[1] $\overline{WPD}_{true}$ can be calculated empirically using Eq. 1.2

It is seen from the Figure 4.6 that a very strong improvement in terms of percentage error in mean wind power density between the *MEPF* and the *PDM*. However, the *MEPF* is equivalently good in estimating the true mean wind power density as compared to *LSM*, *MOM*, *MLM*, and *MMLM*. Therefore, this new method has been used for further analysis of wind speed data at the three different locations Ahmedabad, Trivandrum, and Calcutta.

4.3.2 Step 1 of Wind Data Analysis: Do the Observed Data Follow a Weibull Distribution?

The wind speed data supplied by IMD Pune contain wide ranges of hourly mean wind speed data. To be confident about the estimated Weibull parameters, the authors first measure the extent to which the wind speed data actually follow a *W.pdf*. In this chapter, upper extreme wind speed data are detected using the Weibull quantile function mentioned in Eq. (4.18). The total number of extreme wind speed data for the three stations Ahmedabad, Trivandrum, and Calcutta are 44, 136 and 427 in numbers, respectively. The trend of supplied wind data and wind data after elimination of extreme wind speed are graphically represented using Quantile-Quantile plots. The Q-Q plot is a graphical technique for determining whether the data set under investigation follows a given distribution. On the abscissa theoretical quantiles of the given distribution and on the ordinates the empirical quantiles of given data have been plotted. A 45^0 reference line is plotted to check whether the data follow that distribution. The points should fall approximately along this reference line. The greater the departure from this reference line, the greater the evidence that the data do not follow the given distribution. Figure 4.7 shows the graphical representation of Q-Q plots of *W.pdf*s with parameters estimated via the *MEPF* method with and without extreme data for the three stations, and the corresponding estimated Weibull parameters are provided in the captions of each figure. Figure 4.7 (a) shows the deviation of the observed data from the theoretical

Weibull line. After elimination of the extreme data, it can nicely be seen from Figure 4.7(b) that the wind data follow the theoretical Weibull line for all three stations.

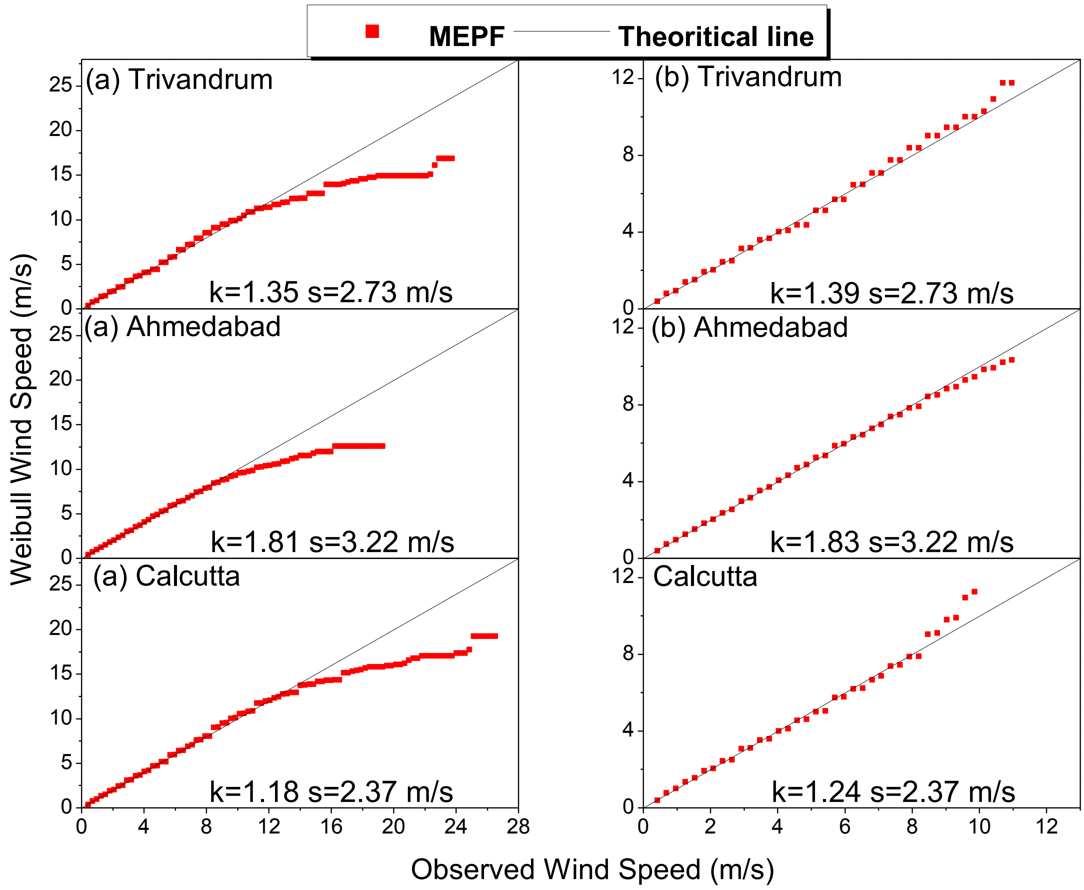

Figure 4.7: Q-Q plot of wind speed data (a) with and (b) without extreme data for three stations.

4.3.3 Step 2 of Wind Data Analysis: MEPF Estimates for Wind Speed, Wind Load, and Wind Power

The wind speed data without the extreme observations have been detected in the previous section. Figures 4.8-4.10 show the histograms of wind speed, and Figure 4.11 shows the histograms of load, and power together with the superimposed best-fitting Weibull density obtained via the *MEPF* method for the three stations of Trivandrum, Ahmedabad, and Calcutta. The left ordinate of the graph represents the probability density function, and the right ordinate represents the cumulative distribution function. The respective estimated parameter values are indicated in the captions of each figure.

Figure 4.8 shows the wind speed histogram of the Ahmedabad station. The peak of the Weibull function is approximately on the mean wind speed, i.e., 2.8637 *m/s*, implying that wind flows more likely around the mean wind speed. The Ahmedabad station lies in the western region of India, and hence the probability of getting higher wind speed is much pronounced, due to the onset of the southwest monsoon season. Moreover, it is the largest city of Gujarat, which is the 2nd leading state of wind power generation in India.

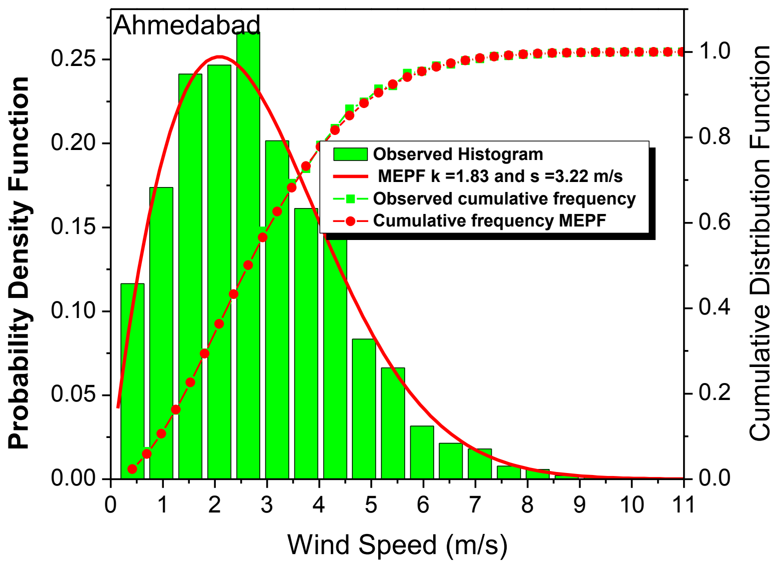

Figure 4.8: Histogram of wind speed together with the corresponding Weibull density and cumulative distribution function. The parameters have been estimated via the *MEPF* method at the Ahmedabad station

Figure 4.9 shows the wind speed histogram of the Trivandrum station. It reveals that the slope of the observed histogram decreases gradually. Trivandrum lies in the southwest region of India, located near the coastal region where sea breeze is most prominent, and the southwest monsoon enters India from this zone. Therefore, chances of low and medium range wind speeds are more pronounced. This may be the possible reason for the gradual decay of the slope for the Trivandrum station.

The peak of the Weibull function is on the left-hand side of the mean wind speed, meaning that the wind speeds are more likely to be lower than the mean. This makes Trivandrum a probable site for the installation of the wind farm. As per "Agency for Non-Conventional Energy and Rural Technology" Ramakkalmedu in Idukki district of Kerala is the second most suitable place in India for setting up a wind farm.

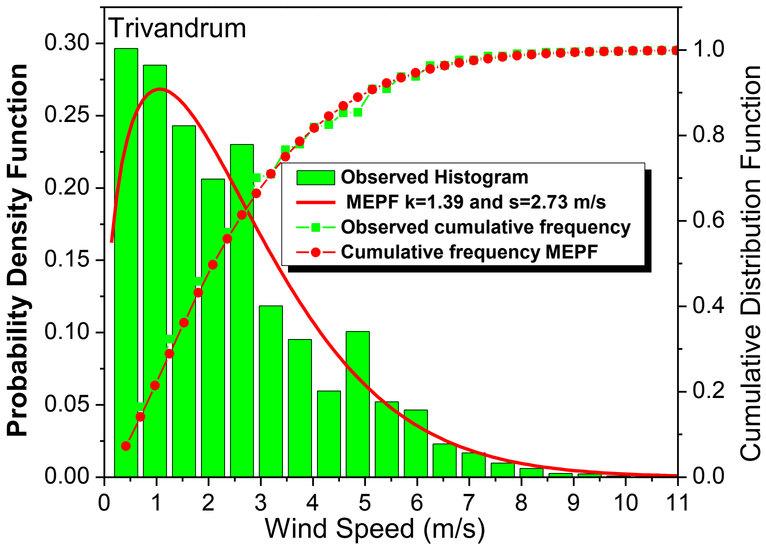

Figure 4.9: Histogram of wind speed together with the corresponding Weibull density and cumulative distribution function. The parameters have been estimated via the *MEPF* method at the Trivandrum station.

Figure 4.10 shows the wind speed histogram of the Calcutta station. It has been observed that the histogram shows a pattern of steep decay, which in turn reveals that the peak of the Weibull function is less than the mean wind speed (2.2133 *m/s*). Calcutta is a station that lies at the eastern part of India with the Bay of Bengal at its southern zone, the sea breeze from the Bay of Bengal flows over Calcutta. According to the West Bengal Renewable Energy Department (*WBRED*), Sagar island and Frazerganj are the two sites located at the south of Calcutta that are the most probable for the installation of a wind farm and *WBRED* is planning to install the wind farm at these two sites.

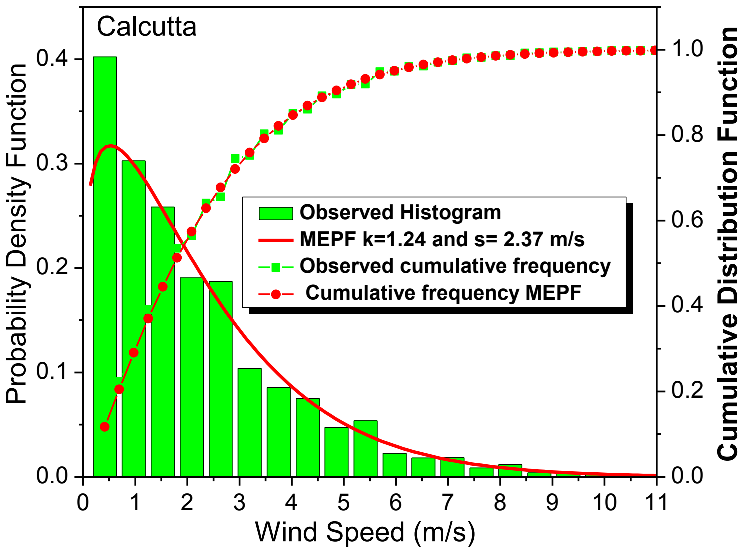

Figure 4.10: Histogram of wind speed together with the corresponding Weibull density and cumulative distribution function. The parameters have been estimated via the *MEPF* method at the Calcutta station.

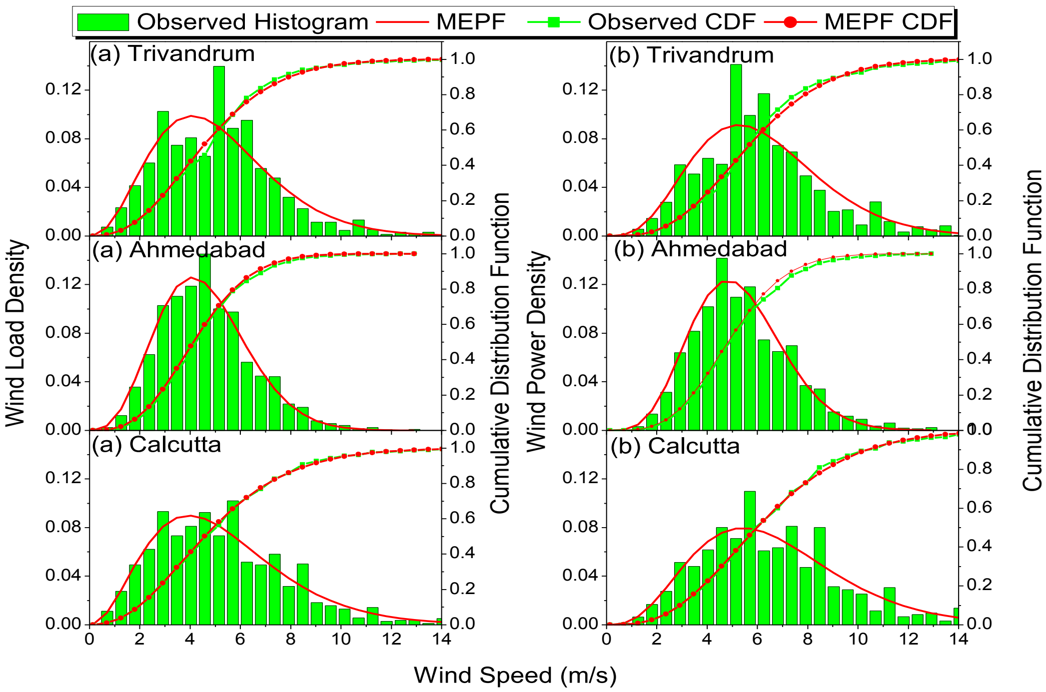

Figure 4.11: Histogram of (a) wind load and (b) wind power together with the corresponding Weibull density and cumulative distribution function. The parameters have been estimated via the *MEPF* method for all three stations.

4.4 Summary

In this chapter, the proposed Modified Energy Pattern Factor Method is compared to six different Weibull parameter estimation methods proposed in the literature. The simulation study revealed that the *MEPF* is a suitable alternative to these methods, and it clearly outperforms in terms of precision and simplicity its antecedent, the Power Density Method of **Akdag, and Dinler [139]**. Compared to the other methods *MEPF* has an advantage that it is robust, efficient in calculation, free from binning problems and does not require any complicated calculation for its solution as may be the case with other methods such as the Least Square Method, Method of Moments, and Maximum Likelihood Method. It has much higher precision in estimating parameters of the *W.pdf* than the Empirical Method. Moreover, it has the additional advantage that it takes into account the wind speed variability, that enables the accurate assessment of wind power density. The *MEPF* method has been used to estimate the Weibull parameters for the wind data that has been available from three stations in India.