Evaluation of Wind Energy Potential and Estimation of Wind Turbine Characteristics

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ABSTRACT
In this study a novel distribution function is discussed to study the wind speed characteristics and wind turbine characteristics. This paper focuses on the study of estimation of wind resource potential and wind turbine characteristics at higher hub height. A detailed wind resource assessment analysis and selection of wind turbine are discussed for estimating capacity factor and harnessing maximum wind power at Mamatkheda. The selection procedures of the efficient wind turbine (WT) of (class II) for the site, according to IEC 61400, are fully investigated. This study also reveals that the Mamatkheda has a high wind potential which result in significant increase in AEP.

Keywords: Probability distribution functions, wind power density, Weibull parameters, statistical analysis, wind frequency distribution.

I INTRODUCTION

Wind energy is an interminable and renewable source of electricity generation and has proved its potential in combating climate change. For the successful and economic development, it is necessary to install a wind turbine in a windy area along with suitable selection of wind turbine. However wind is highly intermittent so it is important to understand the different meteorological parameters with time and region. Estimation of wind speed characteristics is therefore an essential factor in assessing wind power potential and performance of wind energy conversion system [1]. The wind direction is less important because modern turbines have yaw control mechanism but the wind power is cubically proportional to the wind speed therefore it is essential to characterize the probability distribution of wind speed. The statistical explanation is simple when a measured histogram can be correctly fitted by an analytical probability density function (PDF) consisting few parameters [2]. Abbreviation symbols used are tabulated at end of this paper as legend.

II LITERATURE SURVEY

There are various methods of modeling the wind speed PDF which are available in literature. The most common method is based on Rayleigh and the more steadfast Weibull distribution [3-7]. However, over land the Weibull fit of empirical data have low quality which encouraged the researchers to suggest various alternative analytical distributions, such as inverse Gaussian [8], lognormal [9], extended exponential functions [10], square root normal [11], inverse Weibull [12], maximum entropy principal [13], generalized gamma [2]. In the recent past years several studies has been conducted to assess wind power potential using single and mix distribution [8-13].

Kiss and Imre [2] tested the performance of Rayleigh, binormal, Weibull, lognormal and gamma distributions for the modeling of wind speed over land and sea both. They found that Weibull functions does not perform well at many location over land whereas generalized gamma distribution provides an adequate and unified distribution everywhere. A. Garcia et al. [14] used lognormal and Weibull distribution function to fit wind speed distributions. Carta et al. [15] used WW-PDF to estimate wind speed distribution in which there was an indication of unimodality, bimodality or bitangentiality. Subarto Kumar Ghosh et al. [16] used Weibull distribution function to assess the wind energy potential of five different coastal areas in Bangladesh. Vaishali Sohoni et al. [17] carried a detailed analysis of three functions Raleigh, Weibull and gamma for the description of wind regimes and identified that the Weibull distribution was best for the sites with moderate wind speed whereas gamma distribution performed best for low and high wind speed sites. Stewart and Essenwanger [18] and Tuller and Brett [19] used a 3- parameter Weibull (W3) model with an added location parameter and founded a better fit compared to normal W2. Nkongho Ayuketang Arreyndip et al. [20] employed generalized extreme distribution to study the wind energy variation and wind energy potential of Debuncha, South-West Cameroon.

To account for parametric model, numbers of non-parametric models were also suggested by the authors. This model has the advantage of considering null wind speed. The most accepted distributions are derived from maximum entropy principle [21, 22]. Zhang et al. [23] adopted non-parametric model using the kernel density concept approach in a numerous distribution model. In the recent past various mixture distributions were found accurate in describing wind energy characteristics as well as in assessing the wind energy potential. Akdag et al. [24] found better fit with two-component mixture Weibull distribution (W3) against ordinary two-parameter Weibull distribution (W2). Akpinar et al. [25] employed the

mixture of truncated normal distribution and traditional Weibull distribution to model wind speed.
In the Indian Peninsula limited numbers of studies have been performed to model the distribution of wind speed [26-28]. In all these studies the 2 parameter Weibull distribution function and Rayleigh distribution is employed for modeling wind speed. The Weibull distribution is most common, traditional accepted and has a number of advantages but it cannot represent every wind regimes found in nature, in particular for bimodal distribution and wind speed distribution with high fraction of null wind speed. Subsequently various model have been suggested in the literature which includes hybrid distributions, standard distributions, mixed distributions. As far as wind energy literature is concerned Weibull distribution occupied a prominent position in the recent literature for site assessment.

III NOVEL APPROACH TO ANALYSE WIND SPEED CHARACTERISTICS

In this study a novel approach is discussed to analyse the wind speed characteristics and wind turbine characteristics. The hourly wind speed is modelled using Weibull distribution. Furthermore, this paper focuses on the study of estimation of wind resource potential and wind turbine characteristics at higher hub height. A detailed wind resource assessment analysis is performed for the site at higher hub-heights. The wind speed, wind power density, Weibull parameter is extrapolated at higher height and different wind characteristics are calculated. In addition the selection of wind turbine is discussed for estimating capacity factor and harnessing maximum wind power at Mamatkheda. The outcome of this research investigation will provide significant information of wind resources potential at higher elevation and selection of wind turbine model for selected terrain.

The rest of this paper is organized as: Section IV shows the site details. Section V presents the selection of wind turbine model. Section VI shows method for estimating wind energy potential and capacity factor and also discusses the goodness of fit. The results are discussed in Section VII and finally conclusions in Section VIII

IV SITE DETAILS AND WIND SPEED DATA

Madhya Pradesh has good reserves of wind power, as per C-WET (presently National Institute of Wind Energy) data there are various sites of potential in Madhya Pradesh at 80 m and 50 m respectively. The 60 % of the total power generated from renewable resources in the state is the wind power [28]. Because of its geographical location it is called as 'Heartland of India'. It extends to an area about 3, 08,252 sq. km stands second place in India in terms of area. The Mamatkheda is located in Ratlam district of Madhya Pradesh at 23^0 41' N Latitude and 75^0 03' E Longitude at a mean sea level of 560 m (Fig 1). The time series Wind speed data was collected at height of 10 m and 25 m for a year. The statistical description of wind speed data is shown at Table 1.

Fig No. 1 Geographical location of sites

Table No. 1
Descriptive statistics of wind speed data

Height (m)	Station	Maximum (m/s)	Mean (m/s)	Standard deviation (m/s)	Skewness	Kurtosis
10 m	Mamatkheda	19.03	6.21	4.231	0.142	-0.275
25 m	Mamatkheda	33	7.12	5.694	0.264	-0.397

V SELECTION OF THE WIND TURBINE

The IEC 61400 describes the minimum design criteria for wind turbines (WTs), the external environmental conditions to be considered during design are dependent on the type of site for the installation of Wind Turbines. The basic parameter for wind turbine machines classes are discussed in Table 2 [26].

Table No. 2
Parameters for Wind Turbines classes

WTs Class	I	II	III	IV
V_{ref} (m/s)	50	42.5	37.5	30
V_{avg} (m/s)	10	8.5	7.5	6
A I_{15} (-)	0.18	0.18	0.18	0.18
a (-)	2	2	2	2
B I_{15} (-)	0.16	0.16	0.16	0.16
a (-)	3	3	3	3

VI METHOD FOR ESTIMATING WIND ENERGY POTENTIAL AND CAPACITY FACTOR

(a) Wind speed distribution modelling - The modeling of wind speed distribution requires a time series wind data. The most important tools for assessing the wind speed characteristic is probability density function. In the present study Generalised Gamma distribution and two parameters Weibull distribution is used to describe wind speed characteristics.

(i) Weibull distribution - The most commonly accepted and used model for wind speed probabilities is a two parameter Weibull probability distribution [29, 36]:

$$f(v,k,c_{zk}) = \frac{z}{z_{\rho}v} \frac{k}{z_{\rho}v} [^{zz(zn} \times \exp[\,0\,(\frac{z}{z_{\rho}v})^{z}] \quad (1)$$

where k and c_0 represent shape and scale parameter (m/s) respectively. The Weibull shape and scale parameter is computed using the maximum likelihood method which is determined by equation [3]:

$$k = 0\frac{\cdots}{\cdots}\,0\,\frac{\cdots}{z}\,0^{z(zn} \quad (2)$$

$$c_{zk} = \frac{z}{z}\,\frac{z}{zz})(v_z)^{z}\frac{\rho a}{\rho}(\quad (3)$$

where n is the number of data points and v_i is the wind speed measured at time step i. An iterative technique is used to evaluate Equation 3. Since, the Weibull distribution does not describe a good description of wind speeds universally [2] therefore this paper focuses on the application of other distribution.

(b) Estimation of Wind Energy Potential - Once the probability distribution of wind speed is obtained, the wind energy potential can be determined accordingly.

(i) Wind Speed at Higher Hub Height - The wind speed data was recorded at 10 m and 25 m height above ground level at both sites. The power law method is generally used to extrapolate the wind speed from one level to another level. The power law can be mathematically written as [30]

$$\frac{z_{\rho a}}{z_{\rho c}} = (\frac{z_{\rho a}}{z_{\rho c}})^{\alpha} \quad (4)$$

where V_1 and V_2 represents the wind speeds (m/s) at heights H_1 and H_2 (m) and ü is a power law coefficient. The values of ü varies from 0.1 to 0.32 representing the degree of roughness. In this study, ü is considered 1/7.

Similarly, the Weibull parameter is also extrapolated at higher heights using the following equation [31]

$$k_z = \frac{z_{\rho\rho\rho}}{znz(zkz(z(z\rho z))} \quad (5)$$

$$c_z = c_{zzz}\left(\frac{z_\rho}{z_{\rho\rho\rho}}\right)^z \quad (6)$$

$$n = 0.37\ 0\ 0.088\ \ln(c_{zzz})$$

where k_h, c_h and k_{ref} and c_{ref} are Weibull shape and scale parameters at desired height and required height respectively.

(ii) **Capacity Factor-** The study of usefulness of using a suitable wind turbine at a site is represented by capacity factor and it can be defined as percentage of average output power to the rated power output and mathematically it can be written as [27]

$$CF = \left(\frac{z_{\rho\rho\rho}}{z_\rho} \times 100\ \%\right) \quad (7)$$

$$CF = \frac{zzz\,[z((\frac{\rho\rho}{\rho})^\rho]z(zzz[z((\frac{\rho\rho}{\rho})^\rho]}{(\frac{\rho\rho}{\rho})^\rho\quad z(\ (\frac{\rho\rho}{\rho})^\rho}\ 0\ \exp[0\ (\frac{z_\rho}{z})^z] \quad (8)$$

where, P_{zzz} is a average output power of the wind turbine in kW, P_z is a rated power output of a wind turbine in kW, V_z is a wind velocity (cut-in) in m/s, V_z wind velocity (rated) in m/s and V_z is a wind velocity (cut-out) in m/s respectively.

(iii) **Annual Energy Production -** The AEP is determined using the turbine output from turbine power curve and the observed wind speed distribution, generally assumed a Weibull distribution. The energy produced at each single wind speed is turbine output power multiplied by the time that occurs in a year. By considering the energy production at all wind speeds, the AEP is evaluated. The accuracy depends upon the measured time-series wind data. Mathematically it can be written as [31]

AEP = P_{tot} x 8760 kWhrs/ year

The AEP can also be estimated by simple approximate method by using swept area of the turbine, which is shown below

AEP = 0.5 x] x A x V^3 x CF x 8760 kWhrs/ year (9)

(iv) **Wind Characteristics-**The most probable wind speed (V_{mp}) and maximum energy carrying wind speed (V_{me}) signifies the wind characteristics. The wind speed probability peak is represented by the most probable wind speed, whereas the wind power probability distribution peak is represented by maximum energy carrying wind speed. Mathematically it can be evaluated from the below equations [24, 25]

$$V_{mp} = c\,(1-\frac{z}{z})^{z\eta z}\theta_z \quad (10)$$

$$V_{me} = c\,(1+\frac{z}{z})^{z\xi z}\theta_z \quad (11)$$

(v) **Wind power density estimation -** Power (P) in the wind can be calculated using the following relation, where A is the area swept by turbine blades,] is the air density, V is the velocity of wind [36]

$$P = \frac{z\eta}{zr}\,\mathrm{l\!A}V^{zv} \quad (12)$$

As Betz already proved that all the available power in the wind cannot be extracted, only 16/27[th] portion can be extracted. In practice the wind power captured by the wind turbines is far less from that the Betz criterion.

$$P = C_z\,\frac{z\eta}{zr}\,\mathrm{l\!A}V^{zv} \quad (13)$$

Where]z is the performance coefficient, Wind Power Density is defined as power available per unit area swept by the turbine blades.

$$WPD = C_z\,\frac{z\eta}{zr}\,\mathrm{(l}V^{zv}$$

$$WPD = \frac{z\eta}{zr}\int_{zk}^{\infty}(\mathrm{l}v^{z}\mathrm{f}(v)\ dv \quad (14)$$

Wind power density in terms of Weibull parameters can be expressed as,

$$\mathrm{WPD} = \frac{zn}{zr}\int_{zk}^{\infty}\left(kv^{zv}\frac{z}{z_{\rho}v}\frac{\lambda}{z_{\rho}v}\right)^{z\lambda}\left[\left(zn \times e^{z\left(\frac{\lambda}{\rho_{\rho}v}\right)^{q}}\right] - dv \quad (15)$$

$$\mathrm{WPD} = \frac{zn}{zr}\left(k_{zk}^{zv}H-1\right) + \frac{zv}{z} - \left[\quad (16)$$

(c) **Goodness of fit test -** To measure the deviation between observed data and the predicted data using probability distribution function goodness of fit test is performed. In this study two statistical error analyses are used to evaluate the fitness of probability density function.

(i) **Root mean square error:** RMSE provides a comparison of actual difference between observed probability and predicted probability. A lower value of RMSE shows a best fit distribution model. It is expressed as [3]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - x_i\right)^2}{N-n}} \quad (17)$$

(ii) **R^2 test:** It measure the correlation between predicted cumulative probability and observed cumulative probability of a wind speed distribution. The higher value of R^2 signifies a better fit of a predicted cumulative distribution. R^2 can be calculated using [3]:

$$R^2 = \frac{\sum_{i=1}^{n}\left(y_i - z_i\right)^2 - \sum_{i=1}^{n}\left(y_i - x_i\right)^2}{\sum_{i=1}^{n}\left(y_i - z_i\right)^2} \quad (18)$$

where N is the number of observations, $]_z$ is the frequency of observation, $]_z$ is the frequency of Weibull/Generalized Gamma, $]_z$ is the mean wind speed, n is number of constants used.

VII RESULTS AND DISCUSSION

(a) **Wind Speed Modelling and Analysis -** Several comparisons have been made based on measured data to illustrate the suitability of presented probability distribution function at both the regions. Table 3 lists the values of relevant parameter computed for distribution functions for the stations.

Table No. 3
Computed parameter of Weibull distribution functions at 25 m

Month	Mamatkheda (25m)	
	k	c_0(m/s)
July	3.93	9.43
August	4.48	8.00
September	2.34	11.48
October	2.08	8.26
November	2.53	8.51
December	3.40	9.79
January	2.66	7.27
February	2.94	7.77
March	2.67	8.18
April	3.47	8.55
May	4.32	9.57
June	4.33	9.69

The Table 3 shows the monthly estimated Weibull parameters for Mamatkheda. The least value of Weibull shape parameter is found to be 2.08 in October and reached up to 4.48 in August whereas the Weibull scale parameter is minimum in January with 7.27 m/s and reached maximum in December with a value of 9.79 m/s. In Weibull distribution the slope of the curve is dependent on the shape parameter. On generalizing Weibull distribution the constraint on the both tails of the Weibull peak are eliminated. In Figure 2 the Weibull distribution are compared with the measured data for locations. The improvement is particularly observed at the right tail (high wind speed) side which is correctly fitted at the locations this is due to shape flexibility which allows to fit any number of wind speed with reasonable accuracy. Similarly Figure 3 shows the plot of cumulative distribution function fit of Weibull distribution function with the measured values.

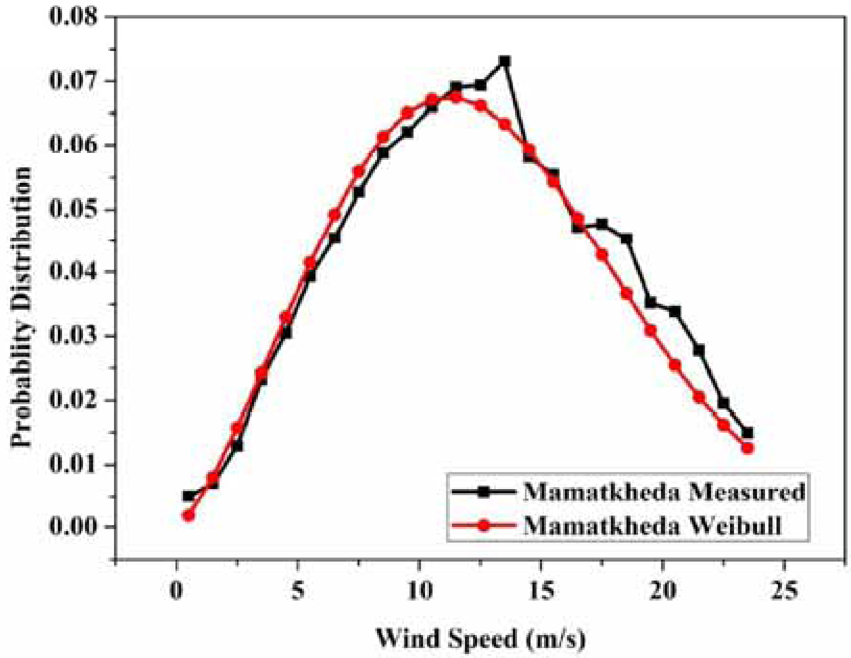

Fig No. 2 Comparison of Probability Distribution Function at 25 m

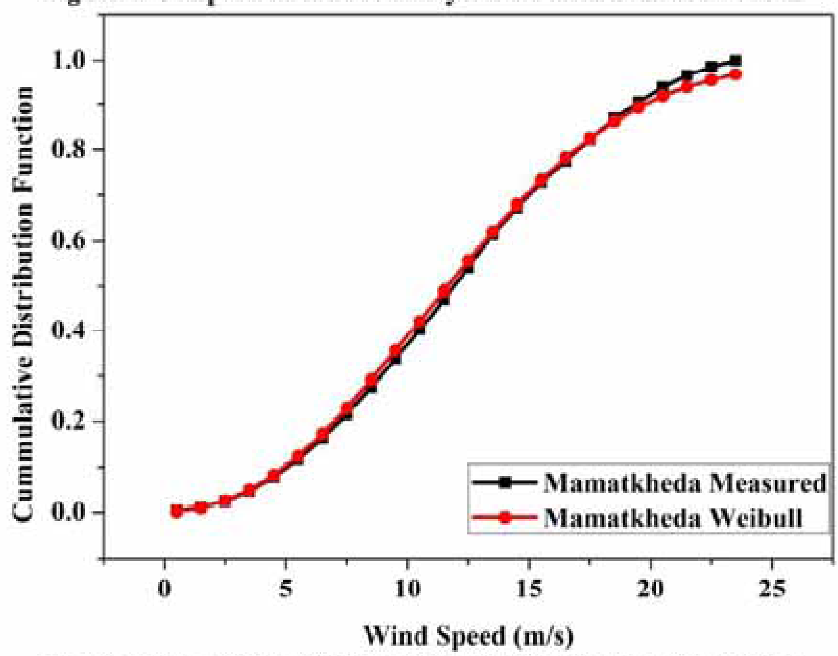

Fig No. 3 Comparison of Cumulative Distribution Function at 25 m

The calculated parameters for the statistical analysis for the measured wind speed data at both locations are presented in Table 4.

Table No. 4
Statistical analysis for wind speed data

Months	Mamatkheda	
	Weibull	
	RMSE	R^2
July	0.0083	0.9338
August	0.0087	0.9583
September	0.0147	0.4516
October	0.0095	0.9379
November	0.0110	0.9335
December	0.0099	0.9564
January	0.0100	0.9087
February	0.0160	0.8298
March	0.0086	0.9088
April	0.0127	0.7951
May	0.0141	0.8671
June	0.1201	0.8761

The higher value of R^2 and lower value of RMSE (highlighted bold) indicate that the distributions function is better in describing this set of wind speed data. The Table 4 above shows a comparison of monthly computed R^2 and RMSE values for the wind speed, which indicates that the values shows the more appropriate and better fit result to estimate wind energy potential at this location.

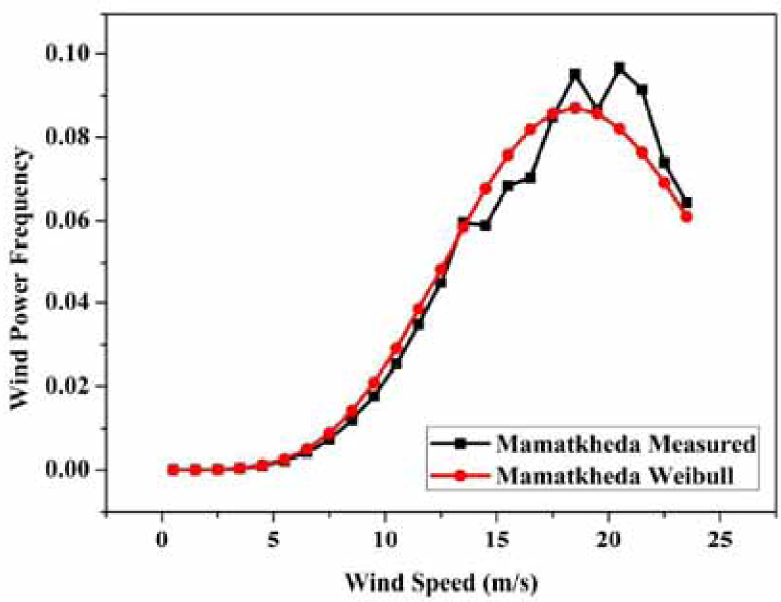

Fig No. 4 Comparison of Wind Power Density frequency at 25 m

The Figure 4 above shows the distribution of wind power at location from figure it is observed that Weibull distribution fits well to the measured distribution.

Table No. 5
Statistical analysis of wind power density (W/m^2) at 25 m

Months	Mamatkheda	
	Weibull	
	RPE	RMSE
July	0.0304	1.2610
August	0.0589	1.0952
September	3.3897	70.2959
October	5.4113	22.6379
November	1.4747	5.9807
December	0.0104	0.0574
January	1.8218	16.6883
February	0.2974	2.9794
March	0.8642	15.9516
April	4.2229	93.2787
May	5.6673	9.0346
June	39.3864	18.2749

The Table 5 shows the result of statistical analysis of computed wind power density for the distributions. The lower value of RMSE and RPE (highlighted bold) indicate that the two parameter Weibull distribution fits approximately well in estimating wind power density.

(b) Estimated Wind Energy Resource at Higher Height - This section shows the extrapolated wind resource at higher heights to extract the maximum wind energy from the site. The Mamatkheda has a highest wind potential and it is seen from the table that the annual mean wind speed increases with the increased height. The wind speed data were extrapolated using power law discussed above. The Table 6 below shows the statistics of extrapolated wind speed data. The average wind speed increases to 10.49 % at 50 m height and 6.94 % at 80 m height respectively.

Table No. 6
Descriptive statistics of wind speed at higher heights

Height (m)	Station	Annual mean wind speed (m/s)	Standard deviation (m/s)
50 m	Mamatkheda	7.867	4.336
80 m	Mamatkheda	8.413	6.653

The extrapolated Weibull parameters determined at required higher heights of 50 m and 80 m has been presented in Table 7 below.

Table No. 7
Descriptive statistics of Weibull parameter at higher heights

Height (m)	Station	Shape factor (k)	Scale factor (c_0) (m/s)
25 m	Mamatkheda	2.90	9.57
50 m	Mamatkheda	3.08	10.77
80 m	Mamatkheda	3.21	11.61

From the above Table 7, it is seen that both k and c_0 increases with height, which reveals the availability of greater wind resource at higher height. The magnitude of scale factor increases due to decrease in turbulence at higher height which results in increase in wind speed. Similarly, the shape of wind increases at higher heights which increases the value of shape factor.

Table No. 8
Estimated characteristics of wind speeds

Height	Characteristics of wind speeds (m/s)	
	Mamatkheda	
	V_{mp}	V_{me}
25 m	8.271	11.462
50 m	9.481	12.671
80 m	10.335	13.500

The Table 8 above shows the value of V_{mp} and V_{me}, technically, in order to extract higher energy the rated speed of wind turbine should be close to the maximum energy carrying wind speed and the most probable wind speed provides useful information for the structural design of wind turbines. The values of most probable wind speed for ranges from 8.271 m/s at 25 m to 10.335 m/s at 80 m, while maximum energy carrying wind speed ranges (V_{me}) between 11.462 m/s at 25 m to 13.500 m/s at 80 m respectively.

(c) **Wind Turbine Characteristics** - The overall cost benefit wind power project depends on the selection of wind turbines in accordance with the condition of wind at a site. The wrong selection of wind turbine results in a financial loss. An efficient wind turbine means that more energy can be converted per cross-section area of the prevailing wind. This can help to mitigate the challenges related to the cost. On the basis of achieved results:

(i) The average wind speed at height of 80 m and 50 m is 8.413 m/s and 7.86 m/s which match the specification of class II wind turbine.

(ii) Weibull fit to the wind speed distribution shows a 'k' value 3.36 that is high compared with the standard value in IEC 61400-1 Edition 2.

The most appropriate wind turbine for Mamatkheda it is classified under class II. The selected wind turbine for Mamatkheda has a power rating of 2 MW (VESTAS V90), a diameter of 90 m, and a hub-height of 80 m. Its corresponding power curve is depicted in Figure 6 below and the Table 9 shows the technical specification of selected wind turbine [34].

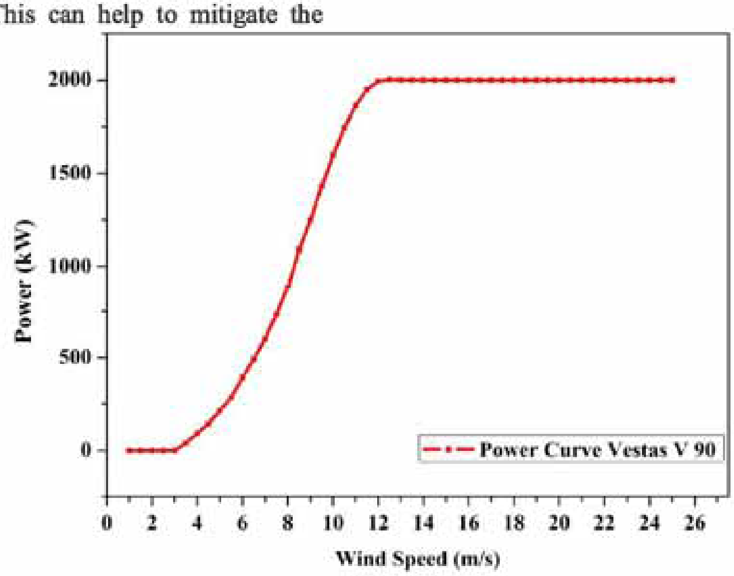

Fig No. 6 Power curve (Vestas V90)

Table No. 9
Technical specification Vestas V90

Parameter	Value/Dimension
Rated power	2000 kW
Rotor diameter	90 m
Hub-height	80 m
Swept area	6362 m^2
Blade length	44 m
Cut-in wind speed	3.5 m/s
Cut-out wind speed	25 m/s
Rated wind speed	12.5 m/s
Wind class	IEC IIA

After selecting the wind turbine for a site, capacity factor at 50 m and 80 m for Mamatkheda is calculated considering Equation 10. At 50 m the capacity factor is found to be 0.49 while at 80 m capacity factor increases by 12.2 % attaining a value of 0.55. The capacity factor increases due to the increase in average distribution of wind speed. The maximum capacity factor results in the higher efficiency of wind turbine at the site. The annual energy production is directly proportional to the capacity factor. On the basis of capacity factor annual energy production is determined using Equation 11 at both heights for the site. The AEP at 50 m and 80 m are 8143.8 GWhrs/year and 11179.4 GWhrs/year. The AEP increases by 37.3 % at 80 m as compared to 50 m due to wind turbine capacity to operate efficiently at the site. A larger wind turbine and increased average wind speed at higher hub-height result in significant increase in AEP. The increased AEP can fulfil the electricity demand by generating considerable amount of unit of electricity through wind energy.

VIII CONCLUSION

The investigation of wind resource potential is a primary step for developing a wind farm. Moreover, empirical equations are used to evaluate wind speed at higher height by measuring at different lower heights which arises uncertainty in measurement. The appropriate selection of wind turbines for the regions was also examined, providing a theoretical foundation for local wind energy resources. The following major conclusion are drawn from the study

(a) The annual average wind speed at Mamatkheda was found to be 6.21 m/s at 10 m and 8.41 m/s at 80 m height which shows a 35.47 % increase in wind speed.

(b) The most appropriate wind turbine for Mamatkheda is classified under class II. Therefore, it is recommended that site is feasible for the extraction of wind energy at higher height.

(c) The capacity factor is found to be 0.49 at 50 m height while at 80 m capacity factor increases by 12.2 % attaining a value of 0.55, due to the increase in average distribution of wind speed.

(d) The AEP at Mamatkheda increases by 37.3 % at 80 m as compared to 50 m which may result in fulfilling considerable amount of unit of electricity through wind energy.

Legend

Nomenclature	
Root mean square error	RMSE
Coefficient of determination	R^2
Shape parameter of Weibull distribution	k
Scale parameter of Weibull distribution (m/s)	c_0
Generalized Gamma distribution	GG
Probability distribution function	pdf
Wind power density (W/m^2)	WPD
Wind speed (m/s)	V
Number of observations	n
Wind speed measured at the interval i.	v_i
Frequency for wind speed ranging within bin i	$f(v_i)$
Cumulative distribution function	F(v)
Weibull, probability density function	f(v)
Mean wind speed (m/s)	ɋ
Power in the wind (Watt)	P
Swept Area (m^2)	A
Coefficient of performance	Cp
Capacity Factor	CF
Annual Energy Production	AEP
Cut-in wind speed	V_c
Rated wind speed	V_r
Cut-out wind speed	V_f
Greek letters	
Density of surrounding air (kg/m^3)	(l
Gamma function	H
Standard deviation	'
Shape flexibility	∫
Order of Moment	t

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