Research Journal of Engineering and Technology
Vol. 1 (2), pp. 30-40, August, 2015
ISSN 2467-8597
Review
http://pearlresearchjournals.org/journals/jsre/index.html

Statistical Analysis for Wind Energy Estimation over Gadanki, India

G. Karthick Kumar Reddy[1], S. Venkatramana Reddy[1*], B. Sarojamma[2] and T. K. Ramkumar[3]

Accepted 13-8-2015

[1]Department of Physics, Sri Venkateswara University, Tirupati-517502, India.
[2]Department of Statistics, Sri Venkateswara University, Tirupati-517502, India.
[3]National Atmospheric Research Laboratory, Department of Space, Government of India, Gadanki-517112, India.

ABSTRACT

The wind resource is sustainable and will be available as long as there is uneven heating from the sun on the surface of the Earth. The wind speed is extremely important for the amount of energy, a turbine can convert wind energy to electricity and is directly proportional to the cubic power of the wind speed. Wind speeds are affected by the friction against the surface of the earth. The objective of this paper is to assess statistically the wind speed distribution and to determine the wind power density (WPD) at Gadanki region using Weibull, Rayleigh and Gamma parameters. To determine the suitability of this site for wind energy generation, the mean wind speed, the shape and scale parameters of the site are estimated at 50 m height. The predicted wind values are tested with the actual wind distribution for the lowest values of χ^2, Root Mean Square Error (RMSE) and Power density error. Based on Weibull distribution parameters, the most probable and the maximum wind speeds are calculated to select the preferable wind turbine to the site.

Key words: Gamma Distribution, Power Density, Rayleigh Distribution, Weibull Distribution, Wind Energy, Wind Turbines.

*Corresponding author. E-mail:drsvreddy123@gmail.com.

INTRODUCTION

Winds are caused by the uneven heating of the atmosphere by sun, irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, water bodies, and vegetative cover. Wind speed is the most important parameter to calculate the wind energy (Yilmaz and Çelik, 2008). Wind energy when harvested by wind turbines, can be used to generate electricity. Wind turbines are used to convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for grinding grains, pumping water and electricity generation to households, industries etc. In terms of wind power installed capacity, India is ranked 5th in the World. Today India is a major player in the global wind energy market. Wind speed characteristics and distribution of a particular site is important for sitting the wind farm. Selection of suitable site for assessment of the wind resources such as the wind speed and its prevailing direction, turbulence intensity, the shape and scale parameters, the wind distribution, WPD and classes etc are important in evaluation of wind energy potential at that site (Olaofe and Folly, 2012).

Based on probability density function a number of studies have been conducted for modeling the wind speed.

Wind speed varies with vertical height from ground and to predict the wind speed at particular height, the most common expression used is the power law. Wind shear ‘α’ at a particular height is given by the surface roughness coefficient, which is the necessary factor to express the atmospheric instability. The wind shear value varies with increasing heights, time and season, nature of the terrain, weather effect, etc. In most cases it is assumed to be 0.143 (or 1/7) (Olaofe and Folly, 2012; Ayodele et al., 2012). The statistical probability density functions for the analysis are Weibull, Rayleigh, Gamma, Lognormal, Exponential, Inv. Gaussian, etc. The Weibull function is widely used in the wind farms as the preferable model for energy assessment due to its wide range of versatility, flexibility, and usefulness for describing the wind speed variation (Olaofe and Folly, 2012; Yilmaz et al., 2005). There are many statistical tests for validating the accuracy of the predicted wind speed. Some of the tests commonly performed are RMSE, Chi-Square Test (χ^2), Coefficient of Determination (COD), and Percentage of Error for wind power (Olaofe and Folly, 2012; Yilmaz et al., 2005). After estimating wind distributions and parameters from the statistical density distributions, the evaluation of wind resources is conducted on the known distribution for accurate sizing of the wind energy systems. Power curve for a particular site is developed from the obtained wind distribution, the power curve of the wind generator (WG) and the site parameters.

This basic data information enables the turbine designers to optimise the output of their turbines at the lowest generating cost. Wind power investors utilize the information to estimate possible income from their investment, and it also serves as a control tool to reduce threats to the security of the power system as a result of variation in wind speed. Wind energy is one of the most alternative renewable energy technologies at present. From the recent years, the amount of energy produced by wind-driven turbines has increased rapidly due to its significant turbine technologies and making wind power economically compatible with conventional sources of energy (Poongavanam and Ramalingam, 2013).

The power-generating efficiency of a wind turbine can be significantly raised if the turbine’s operation is controlled based on the collected data of wind speed and wind direction at the turbine location.

The wind speed data for the study in hourly mean time series data format are collected for the period 2007 to 2012 at station name: ISRO 01, station Id: AF800874 located in Gadanki, India. The data is obtained from the ISRO AWS data from NARL, Gadanki. Wind speeds are recorded using an anemometer at height of 4.5 m above the ground level for Automatic weather station (AWS). This time series wind data are continuously measured by the wind acquisition systems sampled at every second (1s) and stored as hourly mean wind data. The wind data collected includes the mean wind speed and direction, temperature, atmospheric pressure and air humidity.

THEORETICAL ANALYSIS

Wind Speed Variation with Height

The wind speed varies continuously as a function of time and height, and requires an equation that predicts the wind speed at a height in terms of the measured speed at another. The most common expression for the variation of wind speed with height is the power law.

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{1}$$

$$v_2 = v_1 \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{2}$$

Where ‘v_1’ and ‘v_2’ are the mean wind speeds at heights ‘h_1’ and ‘h_2’ respectively. The exponent ‘α’ depends on the factors such as surface roughness and atmospheric stability. Numerically, it lies in the range 0.05 to 0.5, most frequently ‘α’ value being 0.143 (or 1/7) and applicable for low surfaces and well exposed sites (Olaofe and Folly, 2012; Ayodele et al., 2012; AlBuhairi, 2006; Oyedepo et al, 2012; Argungu et al., 2013; Ahmeda and Mahammeda, 2012; Karthick et al., 2014). The surface roughness coefficient ‘α’ for various sites can be determined from the following expression (Oyedepo et al, 2012).

$$\alpha = [0.37 - 0.88\ln(V_0)] \big/ \left[1 - 0.088 ln\left(\frac{h_0}{10}\right)\right] \tag{3}$$

Where V_0, h_0 are the initial wind speed and height at surface level, respectively. The wind shear value varies with increasing heights, time and season, nature of the terrain, weather effect, etc.

Air Density Variation with Altitude

The air density is an important parameter for estimating both the wind power and density. The wind power production is proportional to the air density at a height (h), as a function of the atmospheric pressure and air temperature, and is given by

$$\rho(h) = \frac{P}{RT} e^{-\left(\frac{gh}{RT}\right)} \tag{4}$$

where ‘$\rho(h)$’ is the varied air density as a function of height (kg/m³), ‘P’ is the atmospheric pressure (hPa), ‘R’ is the molar gas constant (287.05 J/kg/K), ‘T’ is the temperature (K), ‘g’ is the gravitational constant (9.81m/s²), and ‘h’ is the height above ground level.

Modeling of the Wind Speed

The wind speed variation at a site is usually described using the wind distribution. The suitable statistical distributions for describing the wind speed variation are the Weibull, Rayleigh, Gamma, Lognormal, Inverse Gaussian etc. However, the Weibull, Rayleigh and Gamma functions are the widely accepted and extensively used statistical models for wind energy application. In this study, three distribution functions are considered and they are the Weibull function, the Rayleigh function, and the Gamma function.

Weibull Function

Wind speed is a stochastic process and its descriptive parameters mean and standard deviation can be obtained as (2).

$$v_m = \frac{1}{N}\sum_{i=1}^{N} v_i \qquad (5)$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(v_i - v_m)^2} \qquad (6)$$

The probability density function of the Weibull distribution is given by (Olaofe and Folly, 2012; AlBuhairi, 2006; Oyedepo et al, 2012; Argungu et al., 2013; Ahmeda and Mahammeda, 2012; Karthick et al., 2014; Youm et al., 2005).

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v_i}{c}\right)^{k-1} exp\left[-\left(\frac{v_i}{c}\right)^k\right] \qquad (7)$$

where, ‘*f* (*v*)’ is the probability of observing wind speed ‘*v*’; ‘*c*’ is the Weibull scaling parameter and ‘*k*’ is the dimensionless Weibull shape parameter. The corresponding cumulative probability function of the Weibull distribution is given by (Olaofe and Folly, 2012; AlBuhairi, 2006; Oyedepo et al, 2012; Argungu et al., 2013; Ahmeda and Mahammeda, 2012; Karthick et al., 2014; Youm et al., 2005; Odo et al, 2012).

$$F(v) = 1 - exp\left[-\left(\frac{v_i}{c}\right)^k\right] \qquad (8)$$

The monthly and annual values of Weibull parameters are calculated using standard deviation method. This method is useful where only the mean wind speed and standard deviation are available and it gives better results than graphical method. The shape and scale factors for weibull distribution are computed as (Ayodele et al., 2012; Oyedepo et al, 2012; Argungu et al., 2013; Karthick et al., 2014; Youm et al., 2005; Odo et al, 2012; Pradhan and Kundu, 2011).

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086} \qquad (9)$$

$$c = \frac{V_m}{\Gamma\left(1+\frac{1}{k}\right)} \qquad (10)$$

Where Γ( ) is the gamma function. The shape parameter is denoted by ‘*k*’, represents the nature of the wind (variability or stability of the wind). For most fairly wind site, the value of ‘*k*’ ranges between 1.51 to 1.99. Smaller values of *k* correspond to highly variable or gust wind, whereas *k=2* corresponds to moderate wind and indicates regular, steady wind.

Rayleigh Function

The next accepted distribution function, which is extensively used in modeling the wind speed is the Rayleigh function. The Rayleigh distribution is a special case of the Weibull distribution in which the shape parameter ‘*k*’ takes the value 2. From Weibull equation the probability density function for the Rayleigh distribution can be simplified as (Olaofe and Folly, 2012; Ahmeda and Mahammeda, 2012).

$$f(v) = \left(\frac{2v_i}{c^2}\right) exp\left[-\left(\frac{v_i}{c}\right)^2\right] \qquad (11)$$

The corresponding cumulative probability function of the Rayleigh distribution is given by

$$F(v) = 1 - exp\left[-\left(\frac{v_i}{c}\right)^2\right] \qquad (12)$$

The mean of Rayleigh distribution function is defined as

$$V_m = c\sqrt{\frac{\pi}{4}} \qquad (13)$$

$$V_m = 0.8862\, c \qquad (14)$$

The scale parameter for Rayleigh distribution function is given by

$$c = \sqrt{\frac{1}{2N}\sum_{i=1}^{N} {v_i}^2} \qquad (15)$$

Gamma Function

The probability density function of a Gamma distribution is defined as (Olaofe and Folly, 2012; Pradhan and Kundu, 2011).

$$f_g = \frac{v^{k-1}}{c^k \Gamma(k)} \exp\left[-\left(\frac{\mathrm{v}}{\mathrm{c}}\right)\right] \mathrm{dt} \qquad \text{and } k, c > 0 \tag{16}$$

Where *'c'*, *'k'* and *'f_g'* are the scale, shape parameters and probability density function of a Gamma distribution, respectively and are defined as

$$k = \frac{{v_m}^2}{\sigma^2} \tag{17}$$

$$c = \frac{V_m}{\sigma^2} \tag{18}$$

The cumulative distribution function is defined as

$$F_g = \frac{v^{k-1}}{c^k \Gamma(k)} \int_0^v t^{k-1} exp\left(-\left(\frac{t}{c}\right)\right) dt \tag{19}$$

Where F_g, Γ(k) are the Gamma cumulative distribution and Gamma function of (k), respectively. The gamma distribution function can be found applicable in the modeling of low wind speed data and modeling errors in multi-level Poisson regression models.

Goodness of Fit

There are several tests used for validating the predicted wind distribution from various statistical functions. The tests are performed for the wind distributions to indicate whether they are fitted for wind speed or failed to model the data for a given site. For the accuracy test, an independent wind speed datasets are chosen for the statistical distribution functions in modeling the wind speed at the particular site. Some of the tests for validating the goodness-of-fit to the statistical distribution functions are explained below.

Chi-Square Test (χ^2)

The Chi-Square method is used for testing the predicted wind distribution with respect to the actual wind distribution. The mathematical expression for the Chi-square test "χ^2" is defined as (Yilmaz and Çelik, 2008; Olaofe and Folly, 2012; AlBuhairi, 2006; Argungu et al., 2013):

$$\chi^2 = \left(\sum_{i=1}^{N} (y_i - x_i)^2\right) \frac{1}{N - n} \tag{20}$$

Where 'x_i' is the *i_{th}* actual wind distribution, 'y_i' is the *i_{th}* predicted wind distribution, 'N' is the number of the wind speed dataset and 'n' is the number of constant wind data.

Root Mean Square Error (RMSE)

The RMSE has been used for comparison of the deviation between the predicted and the measured values. The root mean square error value is defined by equation (Olaofe and Folly, 2012; AlBuhairi, 2006; Argungu et al., 2013).

$$RMSE = \left[\left(\sum_{i=1}^{N} (y_i - x_i)^2\right) \frac{1}{N}\right]^{\frac{1}{2}} \tag{21}$$

Where 'x_i' is the *i_{th}* actual wind distribution, 'y_i' is the *i_{th}* predicted wind distribution from anyone of the Weibull, Rayleigh, and Gamma functions etc. and '*N*' is the number of the wind speed dataset.

Estimation of WPD

Weibull power density P_W

The power of the wind at speed 'V' through a blade sweep area 'A' increases as the cube of its velocity and is given by (Olaofe and Folly, 2012; AlBuhairi, 2006; Oyedepo et al, 2012; Argungu et al., 2013; Karthick et al., 2014).

$$P(v) = \frac{1}{2} \rho A V^3 \tag{22}$$

The mean WPD is defined as

$$P_D = \frac{P(v)}{A} = \frac{1}{2} \rho {V_m}^3 \tag{23}$$

Where 'ρ' is the mean air density (1.225 kg/m^3 at 15°C), which depends on altitude, air pressure, and temperature. The expected monthly or annual WPD per unit area of a site based on a Weibull probability density function can be expressed as follows (Olaofe and Folly, 2012; Ayodele et al., 2012; Oyedepo et al, 2012; Argungu et al., 2013; Ahmeda and Mahammeda, 2012; Karthick et al., 2014).

$$P_W = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{24}$$

Where '*k*' and '*c*' are shape and scale parameters of the Weibull distribution and 'P_W' is the Weibull power density.

Rayleigh Power Density P_R

The Rayleigh WPD 'P_R' is estimated (Olaofe and Folly, 2012; Ahmeda and Mahammeda, 2012) as

$$P_R = \frac{3}{\pi}\rho\left(c\sqrt{\frac{\pi}{4}}\right)^3 \qquad (25)$$

Where 'c' is scale parameter of the Rayleigh distribution.

Gamma Power Density P_G

The WPD using the Gamma distribution is estimated (Olaofe and Folly, 2012; Pradhan and Kundu, 2011) as

$$P_G = \frac{1}{2}\rho c^3[k(k+1)(k+2)] \qquad (26)$$

Where 'k'and 'c' are the shape and scale parameters, respectively. The wind power potential for a region is usually classified according to its wind power class. The wind power range lies in between 1 to 7 depending on the prevailing wind resources. Each wind power class represents a range of mean WPD and its equivalent mean wind speed (m/s) at different heights (Olaofe and Folly, 2012). The percentage error (%) of the WPD is expressed as

$$Error(\%) = \frac{P_{W,R,G} - P_A}{P_A} * 100\% \qquad (27)$$

Where '$P_{W,R,G}$', are the wind power densities of the Weibull, Rayleigh, Gamma distributions, respectively, and 'P_A' is the actual wind power density (Olaofe and Folly, 2012; AlBuhairi, 2006; Argungu et al., 2013; Ahmeda and Mahammeda, 2012; Karthick et al., 2014; Youm et al., 2005). In addition to the mean wind speed, the two significant wind speeds for wind energy estimation are the most probable wind speed, 'V_F' (m/s), and the wind speed carrying the maximum energy, 'V_E' (m/s). The most probable wind speed is the most frequent wind speed for a given wind probability distribution using Weibull 'k' and 'c' parameters. These wind speeds are expressed (Ayodele et al., 2012; Oyedepo et al, 2012; Argungu et al., 2013) as

$$V_F = c\left(\frac{k-1}{k}\right)^{1/k} \qquad (28)$$

$$V_E = c\left(\frac{k+2}{k}\right)^{1/k} \qquad (29)$$

The most probable wind speed corresponds to the peak of the probability density function, and the wind speed carrying maximum energy can be used to estimate the wind turbine design or rated wind speed. Wind turbine system operates most efficiently at its rated wind speed and is closer to the wind speed carrying maximum energy.

Wind Turbine Selection

The wind turbine choice is made on the basis of the wind profile of the site. If the most probable and the maximum wind speeds are known then the wind turbine operating range can be estimated (Ayodele et al., 2012) as

$$\mathrm{V_E} \le \mathrm{V_{co}} \le (2 \text{ to } 4)\mathrm{V_E};\ (1.5 \text{ to } 3)\mathrm{V_F} \le \mathrm{V_{rated}} \le (2 \text{ to } 4)\mathrm{V_{co}};\ 0.3\ \mathrm{V_F} \le \mathrm{V_{ci}} \le 0.8\ \mathrm{V_F} \qquad (30)$$

where 'V_{co}' is the wind speed at which the wind turbine shuts down (cut out wind), 'V_{ci}' is the wind speed at which the wind turbine starts to produce power known as cut in wind speed and 'V_{rated}' is the wind speed at which the wind turbine operates at full rating. The power output performance curve of a wind turbine varies from one wind turbine to another. The equation for simulating the power output of a wind turbine can be expressed (Ayodele et al., 2012) as

$$\mathrm{PD(V)} = \begin{cases} P_{rated}\frac{v^k - v_{ci}^k}{v_{rated}^k - v_{co}^k} & (v_{ci} < v < v_{rated}) \\ P_{rated} & (v_{rated} \le v \le v_{co}) \\ 0 & v < v_{ci}\ and\ v > v_{co} \end{cases} \qquad (31)$$

The mean energy density (ED) over a period of time T is the product of the mean power density and the time T, and is expressed as

$$E_D = \frac{1}{2}\rho V^3 T \qquad (32)$$

Weibull mean energy density

$$E_W = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right)T \qquad (33)$$

Rayleigh mean energy density

$$E_R = \frac{3}{\pi}\rho\left(c\sqrt{\frac{\pi}{4}}\right)^3 T \qquad (34)$$

Gamma mean energy density

$$E_G = \frac{1}{2}\rho c^3[k(k+1)(k+2)]T \qquad (35)$$

RESULTS AND DISCUSSION

The wind resource at Gadanki region has been statistically analysed at ground level (4.5 m) and 50 m

Table 1. Wind speed mean and standard deviation at ground (4.5 m) and 50 m height levels.

	At 4.5 m		At 50 m	
	V_m	σ	V_m	σ
2007	3.1	0.87	5.6	1.59
2008	2.9	0.85	5.5	1.60
2009	3.2	1.05	6.0	1.93
2010	3.1	1.00	5.8	1.84
2011	3.1	0.96	5.8	1.77
2012	3.0	0.85	5.6	1.59

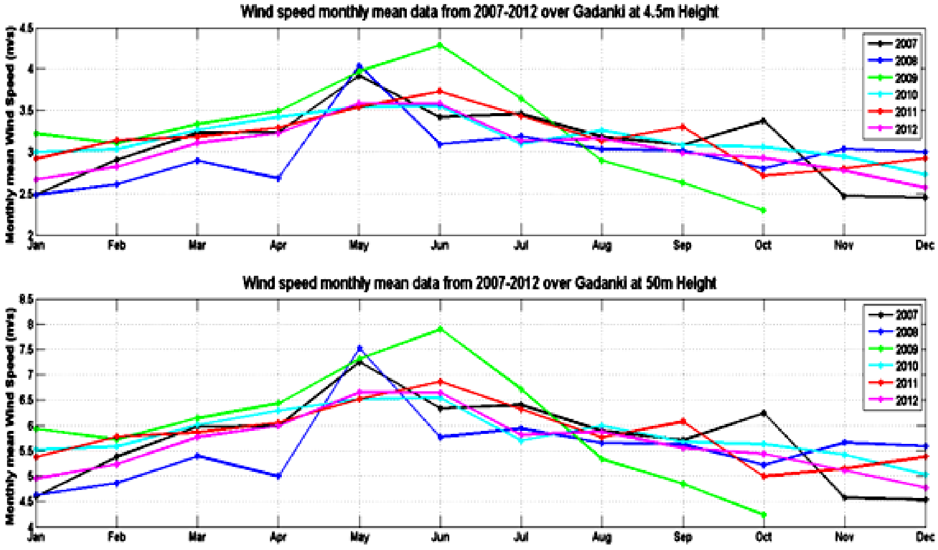

Figure 1. Monthly mean wind speeds from 2007 to 2012.

Table 2. Annual surface roughness coefficient ‘α’ and air density ‘ρ’ kg/m^3.

	α	ρ
2007	0.256	1.127
2008	0.258	1.127
2009	0.251	1.120
2010	0.253	1.124
2011	0.253	1.124
2012	0.257	1.123

heights for the wind energy assessment, evaluation and production. The annual mean wind speed and standard deviation for 2007 to 2012 years at ground and estimated at 50 m heights are shown in Table 1. where ‘V_m’ is the annual mean wind speed in m/s and ‘σ’ is the annual mean standard deviation. The mean wind speed and the standard deviation are the important parameters for determining the wind turbulence at different hub heights. The monthly mean wind speeds at ground and 50 m height levels are shown in the Figure 1. The mean wind speed and standard deviation at ground level for six years is ranging from 2.9 to 3.1 m/s and 0.85 to 1.05, respectively. Wind speeds are extrapolated for 50 m height level by using the power law and estimating the surface roughness coefficient factor ‘α’ for the Gadanki region. The annual roughness coefficient and air densities are shown in Table 2. From the table the surface roughness coefficient is almost same for 2007 to 2012. The small change in the coefficient is seen as the seasonal variation and the value indicates the area to be forestry with bush and scrubs and it is alike.

The shape and scale parameters of the Weibull, Rayleigh and Gamma distribution functions are estimated. The parameters are used to obtain the wind distributions at

Table 3. Statistical distribution parameters at ground (4. m) level.

	Weibull		Rayleigh		Gamma	
	k	c	k	c	k	c
2007	4.3	3.4	2	3.5	15.5	0.24
2008	4.1	3.3	2	3.3	14.7	0.25
2009	4.0	3.6	2	3.7	14.4	0.35
2010	3.5	3.5	2	3.5	10.5	0.32
2011	3.7	3.5	2	3.5	11.9	0.30
2012	4.1	3.3	2	3.4	14.4	0.24

Table 4. Statistical distribution parameters at 50 m height level.

	Weibull		Rayleigh		Gamma	
	k	c	k	c	k	c
2007	4.1	6.2	2	6.3	14.2	0.46
2008	4.1	6.1	2	6.2	14.7	0.47
2009	4.0	6.7	2	6.8	14.4	0.65
2010	3.5	6.4	2	6.5	10.5	0.59
2011	3.7	6.4	2	6.5	11.9	0.55
2012	4.1	6.2	2	6.3	14.2	0.46

Table 5. χ^2 and RMSE values.

	Weibull		Rayleigh		Gamma	
	RMSE	χ^2	RMSE	χ^2	RMSE	χ^2
2007	0.19	0.03	0.20	0.04	0.19	0.03
2008	0.17	0.03	0.18	0.03	0.17	0.03
2009	0.20	0.04	0.21	0.04	0.20	0.04
2010	0.17	0.03	0.18	0.03	0.17	0.03
2011	0.17	0.03	0.18	0.03	0.17	0.03
2012	0.17	0.03	0.18	0.03	0.17	0.02

ground and 50 m heights and are shown in Tables 3 and 4. For Weibull distribution, k<2 means deviation is greater from the mean wind speed and k>2 means small variation from the mean wind speed; in case of Rayleigh distribution the shape parameter ‘k’ is 2. As the value of k increases, the probability curve becomes peaked indicating small variation from the mean wind speed. Chi-square (χ^2) test is used for goodness of fit, whereas RMSE is chosen to ascertain which model is better among Weibull, Rayleigh and Gamma distributions. The distribution which possess least RMSE values among Weibull, Rayleigh and Gamma distributions is the best model for a given data. Weibull, Rayleigh and Gamma distributions are good fit for data because all χ^2 calculated p-values are greater than 0.01 that is, χ^2 at 1% level of significance. Calculated p-values of χ^2 lies between 0.02 to 0.04 and RMSE values lies between 0.17 to 0.21 for three distributions. Both Weibull and Gamma distributions are equally good fits for the years 2007 to 2012 than Rayleigh distribution and are given in Table 5. At the 50 m height, the Weibull and Gamma function prove to be good for modeling of the wind speed data and prediction of the wind power density.

Power density errors are calculated using the statistical distribution functions and compared with the actual distribution. They are shown in the Table 6. The power density for Weibull distribution varies from 20 to 30%, for Rayleigh distribution it varies from 90 to 91% and for Gamma distribution it varies from 21 to 32%. From these distributions we conclude that Weibull distribution function is the best suitable distribution to estimate the power for the specified location.

Wind Energy Estimation for Specified Location Using Weibull Distribution

The monthly variation of the mean wind speed characteristics (V_F and V_E), mean power density and mean energy density as well as the annual values of these parameters at ground and 50 m height level are presented in Tables 7 and 8. The annual mean wind

Table 6. Power density errors for statistical distribution functions.

	Weibull	Rayleigh	Gamma
2007	0.24	0.90	0.25
2008	0.20	0.91	0.21
2009	0.30	0.91	0.32
2010	0.30	0.91	0.32
2011	0.28	0.91	0.29
2012	0.23	0.91	0.24

Table 7. Most probable (V_E) and maximum wind speed (V_F), Power density (P_D), wind energy (E_D) at 4.5 m.

Year	Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2007	V_E	2.76	3.46	3.94	4.07	5.12	4.39	4.35	3.85	3.80	4.46	2.84	2.77	3.82
	V_F	2.60	3.02	3.32	3.28	3.88	3.43	3.51	3.29	3.16	3.32	2.58	2.57	3.16
	P_D	8.78	14.0	18.9	18.9	33.4	22.3	23.1	18.1	16.4	21.7	8.64	8.47	17.76
	E_D	0.81	2.82	6.30	6.47	8.72	6.30	7.84	5.05	3.27	2.48	0.29	0.43	50.76
2008	V_E	2.76	3.00	3.56	3.13	5.59	3.85	4.10	3.69	3.70	3.47	3.88	3.60	3.70
	V_F	2.60	2.73	2.97	2.79	3.82	3.16	3.20	3.12	3.10	2.86	3.06	3.10	3.04
	P_D	8.82	10.1	13.6	10.7	36.7	16.5	18.1	15.6	15.4	12.4	15.9	15.5	15.81
	E_D	0.81	1.77	2.67	1.86	11.9	5.58	6.56	4.11	3.42	1.37	4.34	3.86	48.26
2009	V_E	3.95	3.92	4.23	4.80	5.46	5.79	4.81	3.43	3.11	2.50	0.00	0.00	4.20
	V_F	3.31	3.14	3.36	3.33	3.78	4.14	3.58	3.01	2.73	2.40	0.00	0.00	3.28
	P_D	19.2	17.0	20.8	23.7	34.5	43.7	26.9	13.5	10.1	6.85	0.00	0.00	21.66
	E_D	5.53	3.91	5.98	7.86	12.8	16.0	2.13	0.83	0.85	0.16	0.00	0.00	56.18
2010	V_E	3.59	3.71	4.11	4.47	4.66	4.71	3.85	4.18	3.99	3.84	3.88	3.25	4.02
	V_F	3.11	3.12	3.31	3.39	3.50	3.49	3.16	3.27	3.07	3.10	2.91	2.83	3.19
	P_D	15.5	15.8	19.5	22.1	24.6	24.9	16.7	19.4	16.4	16.1	14.5	11.6	18.13
	E_D	3.00	4.46	6.55	7.99	9.25	8.97	4.41	5.00	3.20	2.97	2.37	2.10	60.27
2011	V_E	3.45	3.83	3.97	4.18	4.79	5.01	4.45	3.95	4.17	3.21	3.36	3.44	3.99
	V_F	3.03	3.23	3.25	3.32	3.42	3.62	3.42	3.17	3.34	2.82	2.89	3.04	3.21
	P_D	14.3	17.7	18.2	19.9	24.6	28.8	22.2	17.1	20.2	11.2	12.5	14.4	18.46
	E_D	3.55	4.59	5.16	7.63	8.58	10.4	7.35	5.19	2.12	1.48	2.48	2.34	60.96
2012	V_E	3.12	3.28	3.77	4.03	4.68	4.60	3.85	3.96	3.71	3.69	3.27	2.88	3.74
	V_F	2.78	2.94	3.21	3.29	3.56	3.59	3.21	3.22	3.06	2.97	2.89	2.69	3.12
	P_D	10.8	12.7	16.8	18.7	25.5	25.4	17.1	17.7	15.0	14.2	12.2	9.71	16.36
	E_D	2.63	2.85	5.35	5.97	6.81	9.89	5.30	5.45	3.05	2.23	1.52	1.37	52.42

speed varies between 2.9 m/s in 2008 to 3.2 m/s in 2009 at ground level and 5.5 m/s in 2008 to 6.0 m/s in 2009 for Gadanki location. The annual mean power density varies between 15.81 W/m^2 in 2008 to 18.46 W/m^2 in 2011 at ground level and varies between 102.26 W/m^2 in 2008 to 135.51 W/m^2 in 2009 at 50 m height. Therefore, based on Pacific Northwest Laboratory (PNL) wind power classification scheme, the annual mean power density at ground level mostly falls into class I (PD ≤ 100), whereas for 50 m height it falls into class II (100< PD ≤ 150). The annual Weibull shape factors ‘k’ for Gadanki region from 2007 to 2012 are 4.1, 4.1, 4.0, 3.5, 3.7 and 4.1, respectively.

The annual Weibull scale parameters ‘c’ from 2007 to 2012 are 6.2, 6.1, 6.7, 6.4, 6.4 and 6.2, respectively. The most probable wind speed, ‘V_F’ (m/s), and the wind speed carrying the maximum energy, ‘V_E’ (m/s) are calculated from the shape and scale parameters of the Weibull function and the values are shown in Table 7 and 8 at ground and 50 m heights, respectively. The wind speeds cut-in, cut-out and rated will enhance the capacity factor of the wind turbine and are estimated as 2.0, 28.0 and 9.0m/s, respectively. The probability density function curves give the information on how much time the wind speed prevails at a location and peak of the curve indicates the most frequent velocity. The cumulative density function curves are used for estimating the time for which wind speed is within a certain speed limit. Cut-in wind speeds greater or equal to 2.5 m/s have frequencies greater than 95.0% for all years from 2007 to 2012. The monthly probability density frequency and cumulative density curves of wind speed at ground and

Table 8. Most probable (V_E) and maximum wind speed (V_F), power density (P_D), wind energy (E_D) at 50 m.

Year	Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2007	V_E	5.10	6.40	7.30	7.52	9.47	8.12	8.05	7.13	7.04	8.25	5.26	5.13	7.06
	V_F	4.81	5.58	6.14	6.07	7.18	6.35	6.49	6.08	5.84	6.14	4.78	4.75	5.85
	P_D	55.6	88.7	120	119	211	141	146	115	104	137	54.7	53.7	112.54
	E_D	5.12	17.8	39.9	40.9	55.2	39.9	49.6	32.0	20.7	15.7	1.81	2.74	321.70
2008	V_E	5.14	5.60	6.64	5.84	10.4	7.17	7.63	6.88	6.90	6.47	7.22	6.71	6.88
	V_F	4.84	5.08	5.52	5.20	7.12	5.88	5.95	5.81	5.77	5.33	5.69	5.78	5.67
	P_D	57.0	65.3	88.2	69.5	237	106	117	101	99.9	80.7	103	100	102.26
	E_D	5.25	11.4	17.3	12.0	77.0	36.1	42.4	26.5	22.1	8.89	28.1	24.9	312.13
2009	V_E	7.27	7.22	7.80	8.84	10.1	10.6	8.87	6.32	5.73	4.60	0.00	0.00	7.74
	V_F	6.09	5.79	6.20	6.14	6.96	7.64	6.60	5.54	5.03	4.42	0.00	0.00	6.04
	P_D	120	106	130	148	216	273	168	84.9	63.6	42.8	0.00	0.00	135.51
	E_D	34.7	24.5	37.5	49.3	80.6	100	13.4	5.27	5.35	1.03	0.00	0.00	352.85
2010	V_E	6.61	6.83	7.56	8.22	8.58	8.67	7.08	7.68	7.35	7.07	7.13	5.98	7.40
	V_F	5.72	5.73	6.09	6.23	6.44	6.42	5.82	6.01	5.66	5.71	5.35	5.21	5.87
	P_D	96.7	98.9	121	138	153	155	104	120	102	100	90.7	72.6	113.04
	E_D	18.6	27.8	40.8	49.7	57.6	55.9	27.4	31.2	19.9	18.5	14.7	13.1	375.69
2011	V_E	6.35	7.05	7.30	7.69	8.81	9.22	8.19	7.27	7.66	5.91	6.19	6.33	7.33
	V_F	5.58	5.94	5.97	6.10	6.30	6.66	6.30	5.82	6.15	5.19	5.32	5.60	5.91
	P_D	89.0	110	113	124	153	179	138	106	125	70.3	78.1	89.8	114.94
	E_D	22.1	28.5	32.1	47.4	53.4	65.3	45.7	32.3	13.2	9.21	15.4	14.5	379.54
2012	V_E	5.79	6.08	6.99	7.47	8.68	8.54	7.15	7.34	6.88	6.84	6.12	5.35	6.94
	V_F	5.15	5.46	5.95	6.10	6.60	6.66	5.95	5.97	5.67	5.51	5.29	4.99	5.78
	P_D	69.4	81.7	107	119	162	162	109	113	95.8	90.7	76.0	62.0	104.34
	E_D	16.8	18.2	34.1	38.1	43.5	63.1	33.8	34.8	19.4	14.2	9.51	8.74	334.56

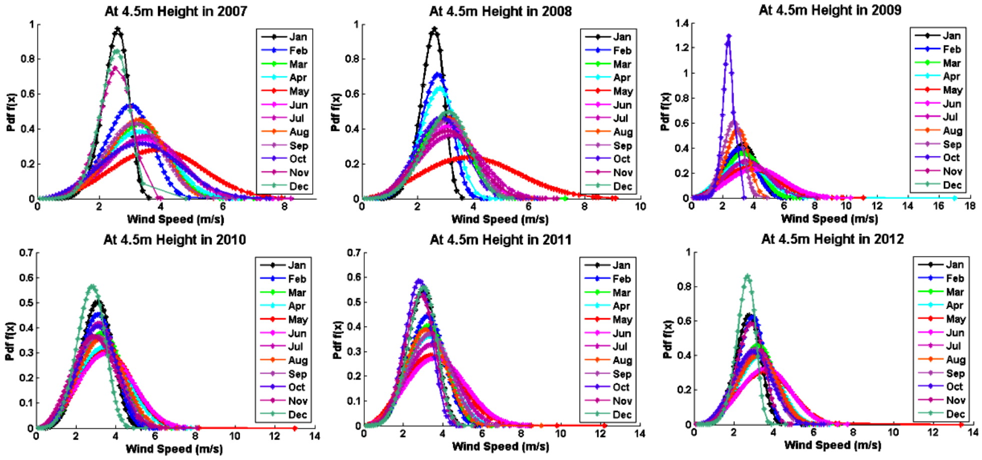

Figure 2. Weibull Probability Density Function curves for wind speed at ground level height.

50 m height levels for the Weibull density function are shown in Figures 2, 3, 4 and 5, respectively.

The Annual Wind Energy densities from 2007 to 2012 are 321.70, 312.13, 352.85, 375.69, 379.54 and 334.56 Wh/m^2 respectively at 50 m height. The wind turbines are selected which are suitable and preferred on the estimated wind speeds at 50 m height. M/S Aeolos wind turbine is a manufacturer of small wind turbines, and some of the specifications which are suitable for the analysed site are given in Table 9. M/S C and F Green Energy is another manufacturer of small and medium sized wind turbines with a mission to make wind energy affordable and accessible to everyone. C and F Green Energy manufacturer provides and installs high yield, efficient and low noise wind turbines.

CONCLUSION

The annual mean wind speeds estimated at Gadanki region for six years at 50 m height are 5.6, 5.5, 6.0, 5.8, 5.8 and 5.6 m/s, respectively. The mean surface

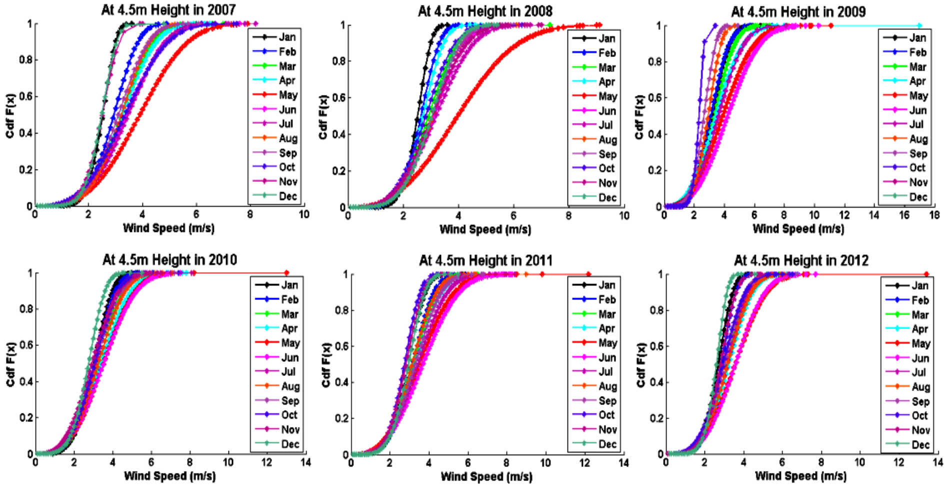

Figure 3. Weibull cumulative density function curves for wind speed at ground level height.

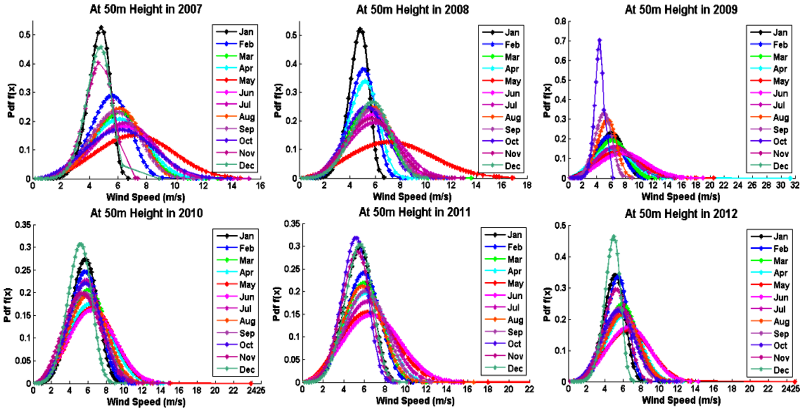

Figure 4. Weibull probability density function curves for wind speed at 50 m level height.

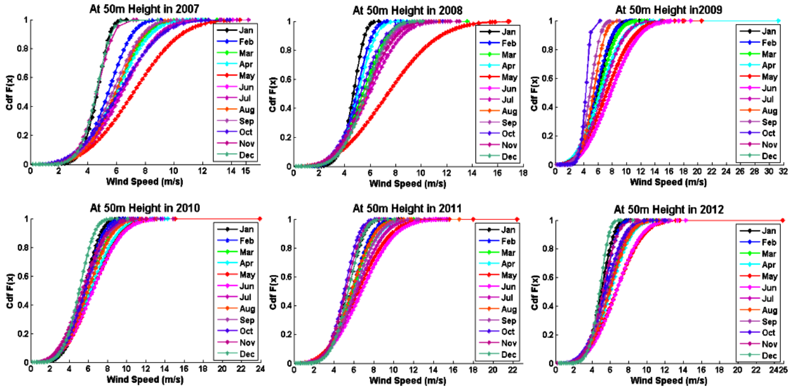

Figure 5. Weibull cumulative density function curves foe wind speed at 50m level height.

roughness coefficient ‘α’ for the Gadanki region for six years is 0.255 and Air density ‘ρ’ is 1.125 kg/m^3. The surface roughness coefficient ‘α’ is 0.25 and from the roughness table, it indicates that the site is agricultural

Table 9. Specifications of wind turbines.

	CF75-25	CF 51-21	CF 100	Aeolos-V	Aeolos-H
Rotor diameter	25.4 m	20.8 m	25.4 m	3.0 m	8 m
Max. power	75k W	51 kW	100 kW	10 kW	10 kW
An. yield @ ~ 7m/s	309,000 kWh	220,000 kWh	356,000 kWh	--	--
Rated wind speed	9.5 m/s	9.5 m/s	9.5 m/s	10 m/s	10 m/s
Cut-in wind speed	2.2 m/s	2.8 m/s	2.2 m/s	1.5 m/s	3.0 m/s
Cut-out wind speed	35 m/s	35 m/s	35 m/s	50 m/s	45 m/s

land with many houses, shrubs and plants, or 8 metre tall sheltering hedgerows, forests and very rough and uneven terrain. The Gadanki region is surrounded by hills, forest and so the roughness coefficient is considerable from estimation. The annual mean power densities at 50 m height fall in the class II (100<PD≤150) category. So, these wind energies can preferably be produced by small and moderate wind turbines. Statistical test for three wind distributions show that they are good fit to data and the power density error test shows that Weibull distribution is good among three of the functions to estimate closer to the actual data.

Based on Weibull distribution parameters the most probable and the maximum wind speeds are calculated to select the preferable wind turbine to the site. The annual most probable and the maximum wind speeds for 2007 to 2012 at 50 m level are 5.85, 6.88, 6.04, 5.87, 5.91 and 5.78 m/s and 7.06, 6.88, 7.74, 7.40, 7.33 and 6.94 m/s, respectively. From the most probable wind speed ‘V_F’ (m/s), and the wind speed carrying the maximum energy ‘V_E’ (m/s), we can estimate cut-in, rated and cut-off wind speeds. The wind speeds cut-in, cut-out and rated will enhance the capacity factor of the wind turbine; the estimated values from Weibull distribution are 2.0, 28.0 and 9.0m/s, respectively. The wind speed at hub height is based on the surface roughness factor assumption, and actual measurement at hub height is necessary to estimate the exact power density of the site. From the predicted wind distribution, the results show that the wind site is suitable for small to utility scale energy applications.

ACKNOWLEDGEMENT

Authors are thankful to the University Grants Commission (UGC), New Delhi, India for providing the necessary financial assistance under UGC-RFSMS program. The authors wish to express their gratitude to Dr. T. Narayana Rao, Sci/Engr. 'SF' for providing the Automatic Weather Station (AWS) data from 2007 to 2012 available at NARL, Gadanki, Andhra Pradesh, India and Prof. Y. Prabhakara Reddy (Retd.), Department of Physics, Sri Venkateswara University, Tirupati, Andhra Pradesh, India for his valuable discussions and suggestions while interpreting the data and his generous support.

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