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Wind Power Density Analysis for Micro-Scale Wind Turbines

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ABSTRACT

Wind, solar, and biomass are three emerging renewable sources of energy and replace conventional fuels in distinct areas. Now-a-days wind energy production increases rapidly due to its significant turbine technologies, compatible with conventional sources of energy and environment friendly in reducing Carbon emissions. The present study represents a statistical analysis for time varying wind resources at Gadanki, India for wind energy assessment. Weibull distribution function is considered and fitted to wind speed data at 50m heights above ground level for the year 2011 to identify and describe the wind speed variation for power production. The main purpose of this paper is to present results of an investigation on the wind energy potential at Gadanki, India. The data from selected stations is analyzed using the two-parameter Weibull distribution function. Annual mean wind speed of 2.8 m/s, energy of 332.8kWh/m^2, hourly Power 38W could be extracted and 57% hours in the year are utilized for the production of energy. It is ascertained that this wind energy in these locations is useful for water pumping; also it can be used for electrical appliances requiring small power. The present study is also an attempt to study the wind energy profile in Gadanki and to create prospective Wind Atlas.

KEYWORDS: *Power Curve, Weibull Distribution function, Wind Power Density, Wind Speed, Wind Turbines.*

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I. INTRODUCTION

Wind energy is one of the most alternative renewable energy technologies at present to sustain the increasing energy demand, whereas the Fossil fuels combustion increases negative effects on the environment. Wind speed measurement is the important parameter to calculate the wind energy which is harvested by wind turbines to generate electricity. Kinetic energy of the wind is converted into mechanical power by wind turbines for daily purpose like grinding grains, pumping water, generation of electricity and related industrial applications. The amount of wind energy production has rapidly increased due to its significant turbine technologies, compatible with conventional sources of energy [1] and represents an important component of environment in reducing Carbon Dioxide emissions [2, 3]. Wind energy conversion systems using micro/small-turbines face significant challenges due to the complexities associated with the urban and forest terrain and there is a need to assess the wind energy resource in 'rural' locations [4, 5]. Wind flow depends on the topographical and roughness features of the locations and causes wind shear. Appropriate estimations of wind shear show significant error in estimating the wind speed, which may lead to even greater errors in energy estimation especially in complex terrains [6]. Wind speed increases with vertical height from ground, Power law is the most common expression used to extrapolate the wind speed to a desired hub height of the wind turbine [7-9]. Numerically, wind shear 'α' in power law at a particular height lies in the range 0.05–0.5; most frequently 'α' value being 0.143 (or 1/7) and depends on terrain of the site [10-18].

Wind resources such as the wind speed and its prevailing direction, turbulence intensity, the shape and scale parameters, the wind distribution, wind power density and classes, etc are important in evaluation of wind energy potential at that site [19]. Power in the wind depends upon the wind speed probability density function and not with the statistical mean. Based on probability density function a number of studies have been conducted for modeling the wind speed [7]. Some of these density functions include the Weibull, Rayleigh, Gamma, Lognormal, Exponential, and Gaussian etc [20-22].

There are many statistical tests for validating the accuracy of the predicted wind speed. Some of the tests commonly performed are Root Mean Square Error (RMSE), Chi-Square Test (χ^2), Coefficient of Determination (COD), Percentage Error for wind power [1, 12, 23], the maximum likelihood method, least square techniques and method of moment [24-25]. Two-parameter Weibull distribution gives a better fit for wind speed data when compared to other families of distribution. The probability of observing various wind speeds has been compared for both Weibull and Rayleigh's distribution [13-15, 26-35]. This Weibull distribution function is widely used in the wind industry as the preferred approach for modeling of the wind speed for energy assessment due to its wide range of versatility, flexibility, and usefulness for describing the wind speed variation [36-38]. 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 (k) and scale (c) factors for Weibull distribution are calculated from the mean and standard deviation of wind [12-17, 29, 33, 39]. Smaller values of *k* correspond to highly variable or gust wind, whereas *k* =2 corresponds to moderate wind and indicates regular, steady wind. The corresponding cumulative probability function of the Weibull distribution has been taken to consider wind speed rating parameters to design wind turbines over the site [13-19, 33].

The expected monthly or annual wind power density per unit area of a site based on a Weibull probability density function has been studied earlier [12-14, 19, 40-41]. The power of the wind at speed 'V' through a blade sweep area 'A' with an air density 'ρ' increases as the cube of its velocity [41-44]. The mean air density 'ρ' (1.225 kg/m^3 at 15°C) is an important parameter for estimating both the wind power and density, which depends on altitude, air pressure, and temperature. The most probable wind speed, v_{mp} (m/s), and the wind speed carrying the maximum energy, v_{max} (m/s), can be determined using the Weibull parameters k and c [5, 12, 14, 16, 17, 45]. Once the most probable and the maximum wind speeds are known, the wind turbine operating range can be estimated [46]. The equation for simulating the power output of a wind turbine has been studied by various authors [12, 16, 39]. The mean energy density (ED) over a period of time T is the product of the mean power density and the time T [12]. According to the Betz limit, the maximum possible conversion coefficient of a wind rotor is 59% [47, 48, 9] and is helpful in wind turbine diameter selection based on power curve performance [49]. The actual power curve may deviate from the nominal one due to site-specific factors [50], complex wind regimes [51], or changes in component conditions. Using a 0.36kW wind turbine, the average monthly water produced by a rotodynamic pump assumption [17]. In the present work, it is suggested to install small/micro wind systems which can bring associated benefits such as increasing security of electricity supply for non-grid connected machines, some protection against electricity price rises and savings on electricity transmission and power station losses. Tall building individual houses and offices can use turbines ranging from 0.1 kW to 15 kW in the site.

The primary focus of this paper is to correlate the wind resource above a forest surface and wind observations made at a nearby site at 50m level from ground for suitability of wind energy generation. Micro scale turbines in this article are referred to as 100W-15kW and Small-scale turbines are below 50kW-75kW and Large-scale turbines are higher than 100kW.

II. METEOROLOGICAL DATA FOR MONITORING SITE

The wind data between Jan 2011 to Dec 2011 has been collected at 50m weather station at a height of 50m above ground level and temperature, pressure, Wind speed data from Automatic weather station at ground height (5m) for predicting and comparison with actual data. The time series wind data has been continuously measured by the wind acquisition systems at the weather station, sampled at every second (1s) and stored as 4-minute mean wind data for 50m and hourly for ground level heights. NARL (National Atmospheric Research Laboratory) Gadanki, a tropical rural station is located at 13.5^{o}N and 79.2^{o}E in the southern part of India. It is situated at 370 m above the mean sea level and complex terrain surrounded by forest, hillocks varying from 200–300 m in the radius of 1 km. Hill's altitude also extend to 700 m in the radial distance of 10 km, the site experiences a nominal wind speed at 50m. Three dimensional terrain heights over Gadanki region in and around NARL, gives an idea on roughness class and wind flows paths [52]. The annual mean wind speed recorded at 50m height shows the suitability of the wind resources at this site for micro and small scale wind energy systems.

III. OBSERVATION AND RESULTS

The diurnal variations for hourly average data in a month for the year 2011 at Gadanki site are plotted and are shown in Fig. 1. This comparison of the daily diurnal patterns leads to the identification of the maximum and required wind speed for the power production.

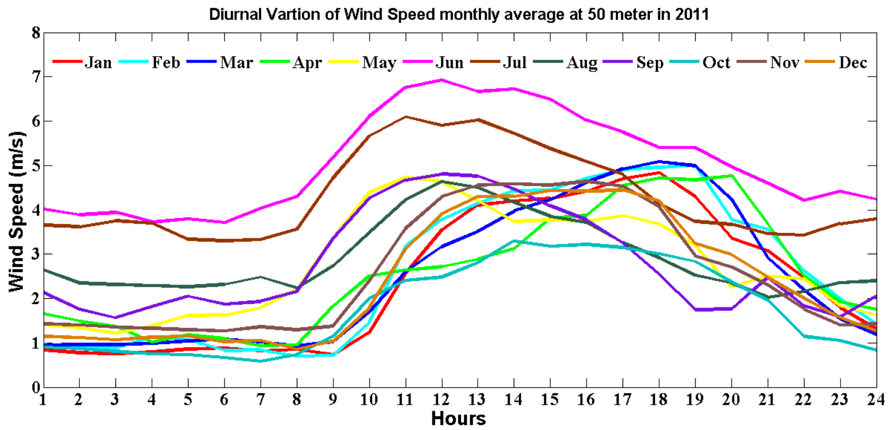

Figure 1. Diurnal variation of Wind speed hourly average in a month for 2011.

The maximum wind speeds are observed for the station during the warm period at midday, nominal wind speed (2 m/s) is extended up to late evening hours and the observations are shown in Fig. 1. From the Fig. 1, in the months of June-September, the nominal wind speeds are observed throughout the day.

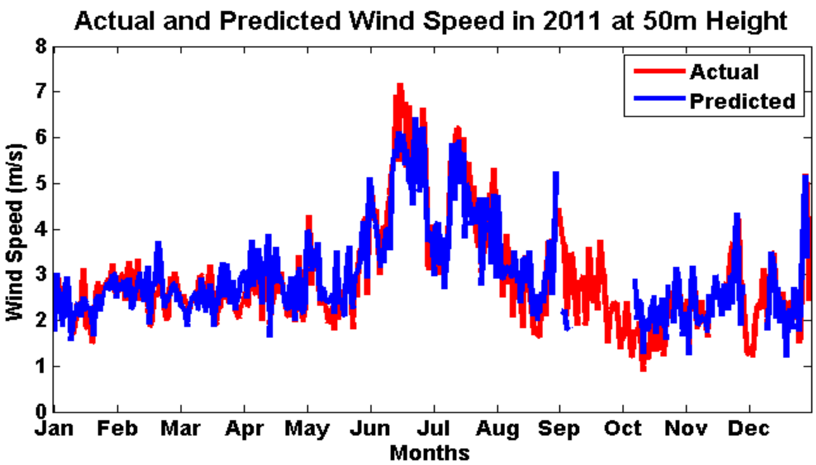

Figure 2. Daily mean wind speed for Actual and Predicted data at 50 m height.

The daily mean wind speeds for the actual measurement and predicted wind speed using Weibull distribution function for 50m level from the ground station in the year 2011 are shown in Fig. 2. Considering the surface roughness coefficient for every data values, the predicted wind speed data is matching with the actual measurement with slight deviation and acceptable for wind energy estimation over the site.

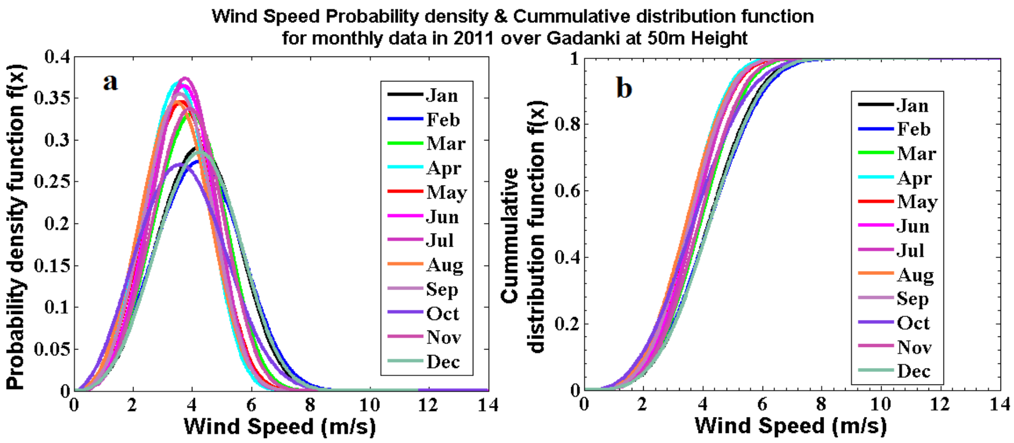

Figure 3. Weibull a) Probability density function and b) Cumulative distribution function.

Wind Power can be extracted from the Weibull distribution function shape and scale parameters knowing the mean speed and its variance. The probability density function from the Fig. 3(a) shows that the wind distribution for the site is smaller and the mean for the distribution is about 3.5m/s and the maximum wind speed spreads up to 8 m/s. The cumulative distribution function from Fig. 3(b) shows that the wake up wind speed for turbine power production is about 1.5 m/s and the rated wind speed is about 5-7m/s for different months. The useful information to optimise the design of wind turbines for the site can be estimated from the two plots in Fig. 3.

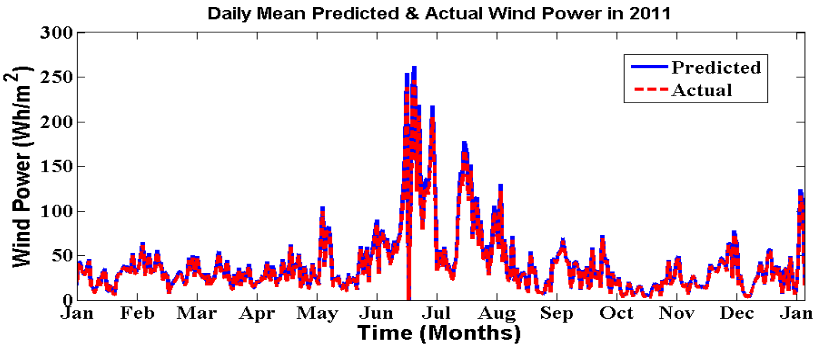

Figure 4. Daily mean power density for Predicted and Actual wind data.

The daily average power for actual and predicted wind speeds in 2011 for the Gadanki site at 50m level from the ground is shown in Fig. 4. The value varies from 15Wh/m^2 to 270Wh/m^2 in the year and annual mean value is about 38Wh/m^2. This value is very small for the commercial wind turbines and falls in wind power class-I. However, this is good for the small scale power home appliances and battery storage devices.

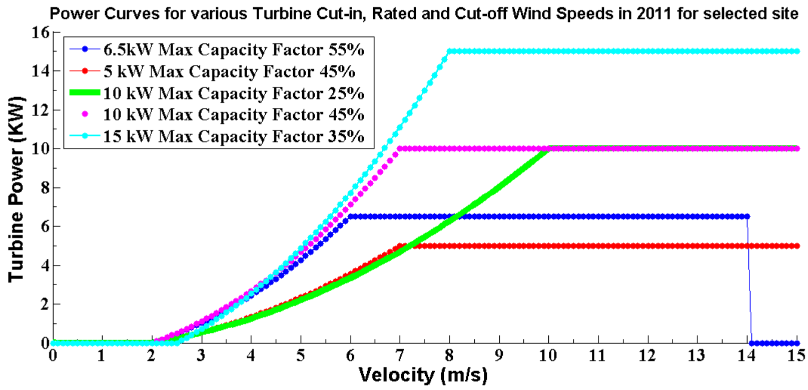

Figure 5. Power curve for different Power rated wind turbines.

The power curve is the key concept for the wind turbine and indicates the efficiency of turbine at different wind speeds. Various rated turbine power curves are shown in Fig. 5 with their maximum efficiency for the wind data at Gadanki in the year 2011 at 50m level from ground. The capacity factor is about 55% for 6.5kW turbine with 2m/s, 6m/s and 14m/s cut-in, rated and cut-off wind speeds respectively. The surface roughness coefficient for the site is high due to forest terrain, so the wind speeds at 50m height is not desirable for large turbines.

IV. DISCUSSIONS

Utility of low speed winds is relatively a low-cost method of micro-renewable electricity generation and reducing carbon dioxide pollution on the site. In addition small or micro wind systems can bring associated benefits such as increased security of electricity supply for non-grid connected machines, some relief against electricity price rises and savings on electricity transmission and power station losses. Individual houses and offices are usually using turbines ranging from 0.1 kW to 15 kW. In order to choose the preferable wind turbine for energy saving, we need to carry out the analysis for the selected site to install micro or small or large turbines. The daily diurnal variation pattern gives the knowledge on the preferable wind speed hours for the power production and diurnal wind speed in the year 2011 for all the months over the region are shown in Fig.1. This behavior is due to the increased downward turbulent mixing of momentum during the day and combined effect of roughness and stability changes on momentum transfer in the atmosphere [53]. Therefore, the diurnal cycle of the surface wind speed probability density function and its physical controls are important for estimating wind energy [54, 55]. This daily evolution characteristic is a consequence of the increased solar radiation on the land surface.

From the Fig. 2, the highest wind speed values are observed in the months of June and July. This means that these months have highest potential for wind energy generation at this site. The monthly mean value of wind speed in 2011 is greater than 2.5m/s and maximum to 8.3m/s, which are the wake up and rated wind speeds for the small scale wind turbines. Power law is the most important and common expression used in the analysis to estimate the wind speeds at various vertical heights [7, 8, 9]. Surface roughness coefficient is extracted from the measured wind data over the height of the location and it varies seasonally. The extrapolation is done with the ground level data to any height based on the power law and roughness coefficient. In Fig. 2, it is shown that the predicted data is more or less well matching with the actual measured data at 50m level in Gadanki for the year 2011. This implies that the prediction can be prospective to higher heights so that the winds may reach to maximum values and can be preferable to install large wind turbines.

The shape (k) and scale (c) parameters of Weibull distribution function are calculated to determine the stability and amount of the wind available to generate energy. Fig. 3a explains the characteristic of wind speed distribution and stability of the site. Distribution from the Fig. 3a maximizes to 8-9 m/s, which implies that the site is having lower wind speeds to the prospective measurement height. The most probable wind speed 'v_{mp}' (m/s) and the wind speed carrying the maximum energy 'v_{max}' (m/s) from Weibull parameters k and c [16] are applied to estimate the wind turbine design parameters (Cut-in, rated and cut-off wind speeds) and also analysed from the Fig. 3. The plots from Fig. 3b conclude that the cut-in/wake up wind speed for the turbine to be 1.5m/s and rated wind speed is 5m/s. In practical, these kinds of ratings are available only to micro-scale wind turbines and the site is not suitable for large scale wind turbines. The power of the wind at speed 'V' through a blade sweep area 'A' increases as the cube of its velocity and is taken as actual wind power for corresponding air density 'ρ' which is calculated from temperature and pressure data. Weibull power density is estimated from the shape and scale parameters. Fig. 4 shows the actual and calculated Weibull power density and agree fairly with each other, and the Two-parameter Weibull distribution is good fit and acceptable for the site to estimate the wind energy when compared to other statistical methods [19, 9, 43, 41, 44].

The wind turbine choice is made on the basis of the wind profile of the site. In Fig. 5, some of the rated wind turbines are simulated for the data in 2011 and efficiency are calculated. Among them 6.5kW with 2m/s, 6m/s and 14m/s rated parameters gives 55% and other rated turbines give 45%, 35% and 25% only (Fig. 5). Annual mean wind speed of 2.8 m/s, an annual energy of 332.8kWh/m^2, annual hourly 38W could be extracted and 57% hours in the year are utilized for the production of energy. Small and Micro scale wind turbines are manufactured, with a mission to make wind energy affordable and accessible to everyone with high yield, efficient and low noise**.** The power-generating efficiency of a wind turbine can be significantly raised if the turbine's operation is controlled based on the wind speed direction.

V. SUMMARY AND CONCLUSION

From the diurnal variations of hourly wind speed monthly mean values are evaluated: these values indicate that the winds are having nominal speed with the maximum peak value in midday (8-9m/s rated speed). This site is preferably good in energy production whole month in June & July, where the mean wind speed is 4.2m/s which is well suited for micro/small-scale wind turbines. These turbines are suggested for use in house holds and office electrical/electronic appliances which are placed on tall building and which need less power. The distinct diurnal variation of the wind speed attains above average conditions during the daylight hours, whilst dropping below average during the night. The Weibull distribution is well suited for this selected site for the calculation of parameters relevant to wind power generating systems.

The annual average wind speeds in Gadanki region are nominal, based on data from the 50m height. The average wind speed is 2.9 m/s and an annual energy of 332.8 kWh/m^2 could be extracted. The wake up/cut-in wind speed is 1.5 m/s and rated wind speed is 5.7m/s; turbines with this rated are needed for wind-electric generation, but wind powered water pumping applications appear to be a viable option. With this rating, the turbine design leads to utilize more than 75% hours for production of energy, which is very helpful in micro systems. The installation of proper turbines and practical initialization of the power generated by them will be under taken in due course of time.

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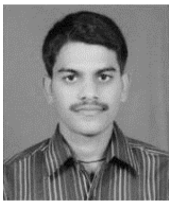

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