INVESTIGATION OF WIND ENERGY CHARACTERISTIC AND ITS POTENTIAL FOR THE HISTORICAL TIME SERIES DATA

SARAVANA VENKATESH.G
Assistant Professor, Department of EEE, Renganayagi Varatharaj College of Engineering, Sivakasi, Tamil Nadu,India,+91 9884471869, saravenki80@gmail.com

Dr. R. RENGARAJ,
Associate Professor, Department of EEE, S.S.N College of Engineering, Kalavakkam, Tamil Nadu, India, rengaraj811@gmail.com

Abstract: *The main objective of this paper is to check the feasibility of constructing the wind turbine by studying the wind speed characteristic and wind power estimation for the five years (2007-2011) historical NREL (National Renewable Energy Laboratory) time series data. The analysis of wind speed with respect to wind direction and various turbine output powers were carried out. Time series analysis of diurnal, monthly wise, annual and seasonally was investigated to characteristic the wind speed. Later the net mean power, net annual energy pattern and net capacity factor at the 80 meter hub height of various commercially available wind turbines were estimated. Finally wind power class is rated seasonally according to the wind power density. For the five years historical data, maximum wind speed occurs at 270° direction, 18:00-19:00 time period, June 2011, and Windtec DF-2000 turbine. Also wind power class is rated as outstanding class in summer season.*

Key words: *Wind energy, Wind power, Wind speed frequency distribution, Wind turbine.*

1. Introduction

Rapidly increasing energy consumption and depletion in fossil fuels reserve stocks along with its environmental problems made a considerable attention to renewable energy sources like solar energy, wind energy and Tidal energy. Especially wind energy is one among several energy source, which has given more preference due to its abundant availability, inexhaustible and clean nature. Recent research and development has been implemented in wind energy technologies such as bigger turbines, larger rotor diameter, generation of power in reduced costs, thereby making wind energy to compete with other type of energy sources [1]. The factors like mean wind speed, power density, wind speed distribution, turbine hub height, turbine rated power, shape of power curve, air density and turbulence intensity determines the output power of the wind turbine [2]. Among those, the wind speed characteristic is a vital parameter for to evaluate the wind energy potential estimation and assessment process. There are several density functions such as Weibull distribution, Rayleigh distribution and Gamma distribution functions to find the wind speed frequency distribution. The Weibull distribution function can perform better than other distribution function because of flexibility and simplicity. Also it can fit the wide collection of measured wind speed data [3]. The Weibull parameters can be found out by maximum likelihood method, modified maximum likelihood method, least square method, moment method, alternative maximum likelihood method, Justus moment method and WAsP algorithm.

S.A.Akdag and Guler analyzed the wind energy potential using Weibull distribution at Turkey location [4].Sultan Al –Yahyai et al carried out their wind shear estimation in Oman location from the weather stations data [5]. Meanwhile, Bonfils safari and Jimmy Gasore had done the wind shear analysis at Rwanda location [6]. In 2010, J.N Kamau et al determine the average wind speed of 14m/s with respect to the wind direction at the hub height of 100 meter in Marsabit, Kenya location for six years wind data [1].David Watts and Danilo Jara carried out the statistical analysis of wind energy potential for diurnal, monthly and annually in Chile [7]. In 2015, analysis in wind direction is carried out at Los Taques Venezuela [8]. Z.R Shu et al performed the statistical estimation in finding the wind speed carrying maximum wind energy in Hong Kong [9]. Similarly wind speed characteristics are studied in various parts of the world. In this paper, the wind data set collected at Colorado, United States of America is considered for characterizing the wind speed in terms of wind direction, time series analysis and wind turbines. For that purpose, the required Weibull parameters are calculated from least square method, maximum likelihood method and WAsP algorithm of Windographer software.

2. Wind Speed Characteristics:

2.1. Data Recovery Rate (DRR):

The datasets of various parameters like Wind speed, Wind direction, Temperature, Humidity and Air pressure are collected. Then these parameters are processed and analyzed by using Windographer software to remove the invalid records, missing records and suspect records due to data logger mal function. The remaining valid records are considered for next stage of statistical analytical process. The datasets measured at NREL for every 10 minutes time interval of the 10 meter hub height which was placed above the ground level are collected and considered for analysis. The Data Recovery Rate is calculated from [8] as,

$$\text{Data Recovery Rate} = \frac{\text{Data records collected}}{\text{Data records available}} \text{ X } 100\ \% \tag{1}$$

2.2. Wind Speed Distribution:

The models for describing the wind speed frequency distribution are Weibull and Rayleigh distribution function. The Weibull distribution is applied for constantly varying wide range of reliable skewed data. Rayleigh distribution gives the original shape for wind speed curve since it is related to the directional components. The statistical methods applied for analyzing these distribution functions are Probability and Cumulative density functions. For Weibull and Rayleigh distribution functions, these are calculated respectively as [10], [11], [12].

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left(\frac{-v}{c}\right)^{k} \tag{2}$$

$$F(v) = 1 - \exp\left(\frac{-v}{c}\right)^{k} \tag{3}$$

and

$$f(v) = \frac{\pi}{2}\left(\frac{v}{v_{avg}^{2}}\right) \exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{v_{avg}}\right)^{2}\right] \tag{4}$$

$$F(v) = 1 - exp\left[-\left(\frac{\Pi}{4}\right)\left(\frac{v}{v_{avg}}\right)^{2}\right] \tag{5}$$

Where c is the scale parameter in m/s,

k is the shape parameter,

v is the wind speed in m/s,

v_{avg} is the average wind speed in m/s

For Weibull distribution function, k takes the value from 1 to 10 and for Rayleigh distribution function, k=2.

2.3. Wind power density (WPD):

Wind Power density is the measure of the wind energy in a particular area of interest and is calculated from as [13],

$$WPD = \frac{1}{2}\rho c^{3}\, \Gamma\left(1 + \frac{3}{K}\right) \tag{6}$$

Where, ρ is the Air Density in kg/m^3 and Γ is the Gamma function.

2.4. Wind energy density (E):

The wind energy density and can be represented as [13],

$$E = T\int_{0}^{\infty} P(v)\, F(v) dv \tag{7}$$

Where, $P(v) = \frac{1}{2}\rho v^{3} A_{T}$ is the wind power in Watt

F (v) is the cumulative distribution function

and A_T gives the swept area of wind turbine blades in m^2.

2.5. Energy Pattern Factor (EPF):

In order to calculate the total amount of power in the wind, energy pattern factor is required and is find out from [15],

$$E_{pf} = \frac{(V^{3})_{avg}}{(V_{avg})^{3}} \tag{8}$$

2.6. Most Probable wind speed (V_{mp}):

This gives the average wind speed from a given probability density function by [16],

$$V_{mp} = c\left(1 - \frac{1}{k}\right)^{1/k} \tag{9}$$

2.7. Maximum energy carrying wind speed (V_{max}):

The wind speed that carries maximum energy can be calculated by [16],

$$V_{max} = c\left(1 + \frac{2}{k}\right)^{1/k} \tag{10}$$

3. Methods for determining k and c parameters:

The distribution can be represented by a graph with the help of the two parameters k and c. The parameters k and c used in Weibull and Rayleigh distribution functions can be calculated using least Square Method, maximum Likelihood Method and WAsP (Wind Atlas analysis and application Program) algorithm of Windographer software.

3.1. Least square method:

The parameters k and c are determined by using the concept of least squares. A straight line is fitted to wind data; thereby the datas are sorted in to bins [17],

$$k = a; \quad c = e^{\left(\frac{-b}{k}\right)} \tag{11}$$

Where a and b are the slope and intercept.

3.2. Maximum likelihood method:

In this method, parameters k & c can be calculated by following equation iteratively [14],

$$k = \left(\frac{\sum_{i=1}^{N} v_i^k \ln Vi}{\sum_{i=1}^{N} v_i^k} - \frac{\sum_{i=1}^{N} \ln(v_i)}{N}\right)^{-1}; \tag{12}$$

$$c = \left(\frac{1}{N}\sum_{i=1}^{N} v_i^k\right)^{1/k} \tag{13}$$

where N is the total number of wind speed measurements and v_i is the measured wind speed value for i^{th} measurement.

3.3. WAsP Algorithm:

It represents the program for predicting wind climates and wind resources that was obtained from wind turbines [16],

$$-\ln X = \Gamma\left(\frac{1}{K} + 1\right)^k \tag{14}$$

$$c = \sqrt[3]{\frac{\sum Vi^3}{N\Gamma\left(\frac{3}{K}+1\right)}} \tag{15}$$

3.4 Prediction performance:

The correlation coefficient R^2 determines the best method suitable for calculating the parameters k and c and is calculated from [14],

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - Z)^2 - \sum_{i=1}^{N}(x_i - Z)^2}{\sum_{i=1}^{N}(yi - Z)^2} \tag{16}$$

where y_i is the i^{th} actual data x_i is the predicted data, Z is the mean of actual data and N is the number of observations. High R^2 value determines the better model.

4. Results and Discussion:

4.1. Calculating Data Recovery Rate:

The five year datasets between 2007 and 2011 was taken from NREL website. The valid data points and data recovery rate are calculated after removing the invalid data points as per the equation (1) as shown in Table 1.

4.2. Wind Rose Analysis:

A wind rose diagram is a polar plot, representing average wind speed and wind direction on a single graph. This analysis is required for installing the turbines according to the direction of the wind energy. It was observed that the wind speed is maximum in the direction 270° (Figure 1).

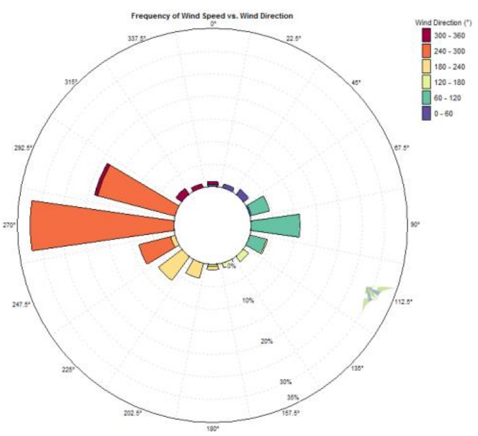

Fig. 1. Frequency of wind speed vs. Wind direction

Table 1: Analysis of Data Recovery Rate

S.No	Year	Possible Data Points	Valid Data Points	Recovery Rate (%)
1	2007	52560	52326	99.55
2	2008	52704	52673	99.94
3	2009	52560	51221	97.45
4	2010	52560	52296	99.5
5	2011	52560	52560	100
	Over all	262944	261076	99.29

4.3. Wind Shear analysis:

The wind shear analysis determines the variation of wind speed with turbine height. This variation of wind speed is directly proportional to the turbine height. Generally, datas are recorded at the hub height of 10 meter above the ground level, but the commercial wind turbines are fixed at various hub heights of 20m, 30m, 50m, 80m, 100m and 120m. So, by using power law, the wind speed is calculated for the various hub heights. The power law expression is given as [17],

$$\left(\frac{V_2}{V_1}\right) = \left(\frac{H_2}{H_1}\right)^{\propto} \quad (17)$$

Where V_1 and V_2 are the mean wind speeds at heights of H_1 & H_2 respectively.

The value α depends on surface roughness and atmospheric stability. It should be within the range of 0.05 - 0.5. Assume α value to be 0.4. Starting from the known wind speed at 10m height, the wind speeds for hub heights of 10m, 30m, 50m and 80m are found out from the above power law expression.

The parameters k and c needed for the wind speed characteristics are calculated from least square method, maximum likelihood method and WAsP algorithm of Windographer software. From the condition of high R^2 value, table 2 shows the maximum likelihood method seems to be the best method.

It is also verified that the curve of wind speed calculated from the parameters k and c of the maximum likelihood method perfectly fits with the actual wind speed data for all the hub heights of 10m, 30m, 50m and 80m (Figure 2). So the value of the parameters k and c calculated from the maximum likelihood method are applied to analyze the wind speed characteristics for the 10m, 30m, 50m and 80m hub heights (Table 3).

Table 2. Wind Shear analysis

Height (m)	Parameter k	Parameter c	Mean wind speed (m/s)	Power Density (W/m^2)	R^2 Value	Methods	Best Method
10	1.963	6.674	6.314	246.9	0.99847	Maximum Likelihood	Maximum Likelihood
	1.714	6.917	6.582	326.1	0.97025	Least Square Method	
	1.942	6.669	6.311	249.3	0.99787	WAsP Algorithm	
30	1.963	7.783	6.9	391.6	0.99832	Maximum Likelihood	Maximum Likelihood
	1.714	8.068	7.194	517.5	0.96958	Least Square Method	
	1.942	7.78	6.89	395.5	0.9977	WAsP Algorithm	
50	1.967	8.393	7.45	490.2	0.99892	Maximum Likelihood	Maximum Likelihood
	1.72	8.69	7.753	645	0.97687	Least Square Method	
	1.938	8.38	7.43	495.8	0.99833	WAsP Algorithm	
80	1.971	8.99	7.98	602.2	0.99866	Maximum Likelihood	Maximum Likelihood
	1.725	9.32	8.31	790.5	0.9764	Least Square Method	
	1.937	8.97	7.96	609.3	0.99794	WAsP Algorithm	

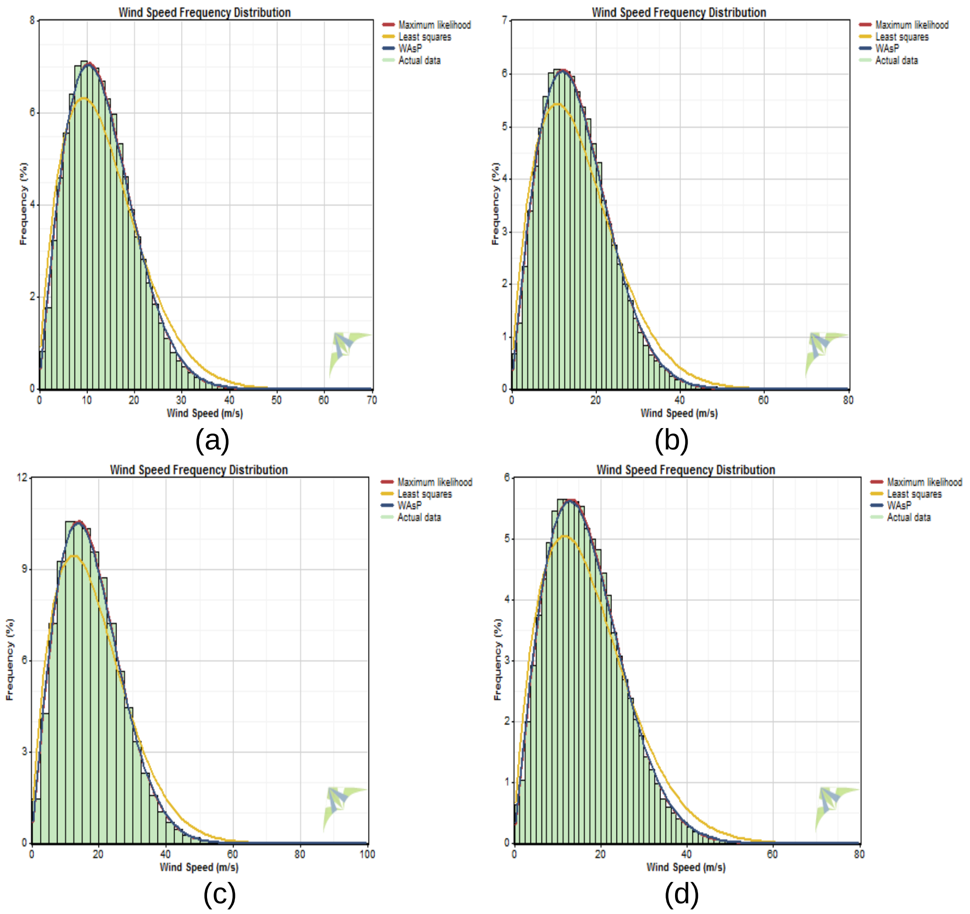

Fig. 2. Hub heights of a) 10 meter, b) 30 meter, c) 50 meter, d) 80 meter

Table 3: Various parameter analysis for different hub heights

Hub Height (m)	Mean Wind Speed (m/s)	Parameter K	Parameter c (m/s)	Mean Power Density (W/m^2)	Mean Energy Content (KWH/ m^2/Year)	Energy Pattern Factor	Most Probable wind Speed(m/s)	Most energy Carrying wind Speed (m/s)
10	5.916	1.963	6.674	232	2031	1.966	1.829	3.761
30	6.9	1.963	7.783	368	3222	1.966	1.976	4.068
50	7.437	1.967	8.39	460	4030	1.964	2.054	4.212
80	7.961	1.97	8.984	564	4940	1.962	2.127	4.349

4.4. Time series wind speed analysis:

4.4.1. Diurnal wind speed analysis:

The diurnal wind profile represents the average wind performance during the day for the 10m hub height. Wind speeds is low in day time and gradually increases in the evening time periods and finally attains a maximum value at the time period of 18:00-19:00 as 6.987(m/s) (Figure 3).

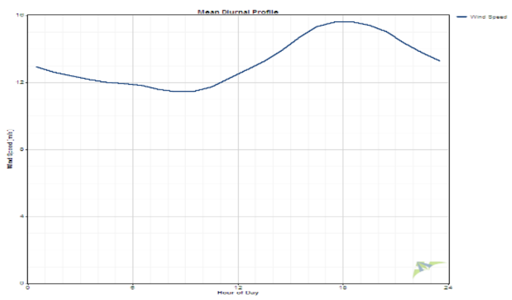

Fig. 3. Diurnal Wind speed analysis

4.4.2. Monthly wind speed analysis:

Wind speed is analyzed for every month of five years from 2007 to 2011 at the hub height of 10m (Figure 4). As an average, from Table 4, the lowest mean wind speed of 4.76 m/s was registered in the month of October 2007 and the highest on June 2011 as 7.224 m/s.

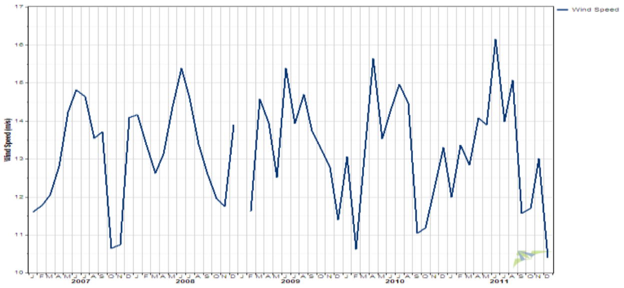

Fig.4. Monthly wind speed analysis

Table 4. Monthly Wind speed Analysis

Month	Mean Wind Speeds (m/s)				
	2007	2008	2009	2010	2011
January	5.191	6.331	6.438	5.84	5.363
February	5.267	5.982	5.199	4.848	5.976
March	5.392	5.643	6.518	5.825	5.744
April	5.724	5.872	6.238	6.995	6.297
May	6.367	6.426	5.593	6.05	6.215
June	6.627	6.884	6.88	6.403	7.224
July	6.543	6.526	6.231	6.693	6.249
August	6.059	5.987	6.572	6.472	6.74
September	6.135	5.636	6.144	4.942	5.171
October	4.761	5.347	5.932	4.998	5.231
November	4.806	5.255	5.714	5.468	5.819
December	6.302	6.215	5.096	5.949	4.854

4.4.3. Annual wind speed analysis:

Data over the period of 5 years from 2007 to 2011 was analyzed. The lowest average annual mean wind speed occurred during the year of 2007 is 5.77 m/s and that of highest in the year 2009 as 6.05 m/s. The mean wind speeds recorded in the subsequent years from 2007 to 2011 are 5.77 m/s, 6.01 m/s, 6.05 m/s, 5.873 m/s and 5.91 m/s respectively (Figure 5)

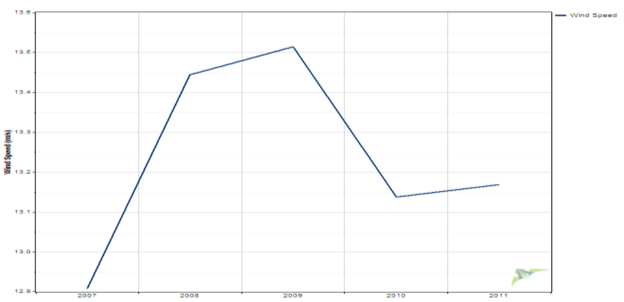

Fig. 5. Annual wind speed analysis

4.3.4 Seasonal wind speed Analysis:

The wind speed analysis is performed seasonally as Spring season of March, April, May, Summer season of June, July, August, Autumn season of September, October, November and Winter season of December, January, February from 2007 to 2011. From Table 5, the lowest mean wind speed is recorded during the autumn season as 5.231 m/s and the highest during the summer season as 6.732 m/s.

Table 5: Seasonal wind speed analysis

Season	Mean Wind Speed (m/s)				
	2007	2008	2009	2010	2011
Summer	6.407	6.461	6.558	6.524	6.732
Winter	5.603	6.18	5.495	5.529	5.309
Spring	5.829	5.982	6.116	6.282	6.083
Autumn	5.231	5.412	5.93	5.534	5.405

4.4. Wind Power analysis according to the wind turbines:

For the various turbine wind speeds at the specified hub height of 80 m, mean net power, Annual Energy Pattern (AEP) and Net Capacity Factor (NCF) are calculated as shown in Table 6. Based on this analysis, turbine Windtec DF 2000-WB shows the better results. The power curves for the various wind turbines (Figure 6).

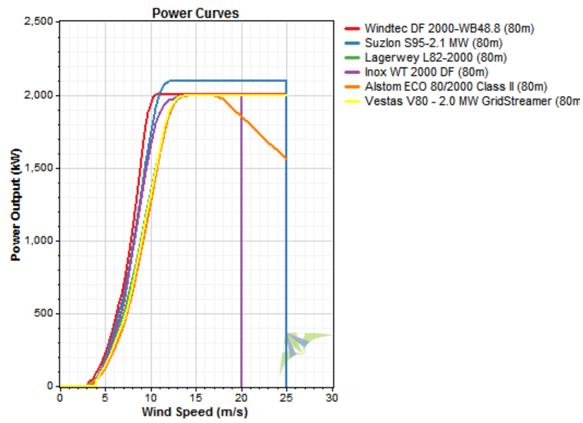

Fig. 6. Wind turbine power curves

4.5. Wind power class:

The wind power classes are classified in to seven types of 1 to 7 rating from poor to very outstanding [18] with respect to wind power density and wind speed (Table 7).

Table 6. Analysis of output power for different wind turbines at 80 m hub height

Wind Turbine Type	Rotor Diameter (m)	Simple mean Net Power (KW)	Simple mean Net AEP (kwh/year)	Simple mean Net NCF %
Windtec DF 2000-WB 48.8(80m)	100	812.7	71,19,143	40.63
Suzlon S95-2.1 MW	95	773.6	67,76,807	36.84
Lagerwey L82-2000	82.5	643	56,32,452	32.15
Inox WT 2000 DF	93	718.4	62,93,446	35.92
Alstom ECO 80/2000 Class II 80m	80	617.5	54,09,298	30.87
VESTAS V80 2.0MW Grid Streamer 80m	80	638.6	55,93,882	31.93

Table 7. Wind power class analysis

Wind Power Class	Description	Wind Power Density (W/m^2)	Wind Speed (m/s)
1	Poor	<200	<5.6
2	Marginal	200-300	5.6/6.4
3	Fair	300-400	6.4/7.0
4	Good	400-500	7.0/7.5
5	Excellent	500-600	7.5/8.0
6	Outstanding	600-800	8.0/8.8
7	Superb	>800	>8.8

The wind power class was identified for various hub heights with respect to wind power density factor (Table 8). Among the various hub heights, the wind power class at 80 m hub height for various seasonal data of autumn, summer, spring and winter are 4, 6, 5 and 5 respectively.

Table 8. Wind power class analysis for various seasons

Height (m)	Wind Power Density (W/m^2)			
	Autumn	Summer	Spring	Winter
10	187	253	232	230
30	302	406	377	391
50	374	503	468	485
80	455	613	570	591
Wind Power Class	4 (Good)	6 (Outstanding)	5 (Excellent)	5 (Excellent)

5. Conclusions

In this study article, five years 2007 - 2011 historical time series data from NREL has been analyzed with the help of Windographer software. From the correlation co-efficient value (R^2), parameters k and c obtained through maximum likelihood method gives the better solution for all the turbine heights (10, 30, 50, 80m). From the analysis of the historical time series data, wind speed is maximum in the direction of 270° for the time period of 18:00-19:00. Also, it was maximum during summer season particularly in the month of June 2011. Finally for the hub height of 80 meter, wind turbine Windtec DF 2000-WB provides high net mean power, annual energy pattern and net capacity factor. Also wind power class was rated as outstanding category for the summer season. From these results, the feasibility of constructing the wind turbine was clearly studied according to the historical time series data taken in the hill region. As a future work, this analysis are planned to extend for the data sets of the coastal regions.

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Saravana Venkatesh G. received BE (EEE) degree from Manonmanium Sundaranar University, Tirunelveli, India, and M.E. Power Electronics & Drives from Anna University, Chennai, India and presently pursuing Ph.D. from Anna University, Chennai, in the field of Renewable Energy. He is currently working as assistant professor in the Department of Electrical and Electronics Engineering, Renganayagi Varatharaj College of Engineering, Affiliated to Anna University Chennai, India.

Rengaraj. R. Associate Professor in the Department of Electrical and Electronics Engineering, SSN College of Engineering, Chennai, India. He received his B.E (EEE) degree first class with distinction from Manonmaniam Sundaranar University, M.E. Power Systems engineering from the Anna University Chennai and Ph.D. from the Anna University Chennai. He has also received TATA Rao Gold Medal from Institution of Engineers (India) for the publication of best paper in Electrical Engineering Divis ion.