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Prediction of wind power potential by wind speed probability distribution in a hilly terrain near Bhopal, Madhya Pradesh

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ABSTRACT : Daily wind speed data in metre per second and its direction of flow in degree were obtained from the records of the India Meteorological Department for a site near the Bhopal Airport for the period of ten years from 1998 to 2008. These records pertain to two heights of 10 m by a wind monitoring mast and 70 m by weather balloons. The influence of roughness of the terrain, obstacles and topography in terms of contour for the area were also taken into consideration. These data were analysed using WAsP programme and regional wind climate of the area was determined. Using the well known 1/7 power law, annual wind power potential were obtained at 50, 70 and 120 m heights. The geographical coordinates of the site under consideration were 77° 35' east longitude and 23° 28' north latitude. The site had an elevation of 530 m above mean sea level. It is seen from the analysis of the wind speed data and keeping the topographical variation of terrain, exploitable wind speed is experienced at 50 m or more. Also from the monthly average of wind speed, it can safely be recommended that a wind turbine generator with a cut in speed of 4 m/s would be able to achieve economical levels of wind energy generation.

Keywords : Weibull distribution, Regional wind climate, wind atlas, orography, roughness, wind monitoring, cut in speed and annual energy generation

I. INTRODUCTION

Wind data measurements over a period of ten-years are required to obtain an accurate assessment of the wind regime of an area [1]. The methodologies adopted to ultimately determine the annual energy production potential of a site must be carefully determined and documented [2]. Methodologies on wind farm design rely on data from the nearest measuring station and careful analysis of wind flow, which takes into account the topography and the roughness level of the surrounding land. Unless the data on wind speed, direction, topographical features and roughness classes are accurate calculations may result in significant errors in estimating the wind speed, which may lead to even greater errors in energy estimation especially in complex terrains [3]. In all of above cases, the first step is to estimate the mean value of the wind speed that is expected on a site and afterwards, the wind energy that a proposed wind farm would produce in an average year, is estimated.

India has a gross wind power potential of over 45195 MW, and the technical potential of 13390 MW depending upon land availability and grid penetration. India has made rapid strides in harnessing wind power. The gross generation capacity towards the end of 2008 was 8757 MW [4]. Exploration of newer sites to assess the wind energy potential is an ongoing process and many more wind monitoring stations are being installed to collect time series data on wind speed and direction. The present work is based on the time series wind data collected over a period of 10 years at two mast heights of 10 and 70 m located at 77°35′E Longitude and 23°28' N Latitudes at the height of 530 m above mean sea level near Bhopal. Wind speed data in metre per second and the direction in degrees were obtained from the India Meteorological Department for the site. Procedures and methodology to be adopted for the assessment and determination of the wind energy are explained and also the observed wind climate for different months have been calculated. Objectives of the study are :

(*i*) Recording wind speed data including direction.

(*ii*) Preparation of vector map.

(*iii*) Classification of terrain features.

(*iv*) Analysis of wind data and determination of observed wind climate.

II. DESCRIPTION OF THE MONITORING SITE

The topography map No.55 E/7 has been obtained from the Geological Survey of India in which the contours of the site near Bhopal are shown. This site has been chosen for the study (Fig.1). The site under consideration covers an area of approximately 256 square kilometres in undulating topography, interspersed with water bodies, cultivated and barren land and semi urban dwellings. A satellite image of the area is shown in (Fig.2). These areas were marked off separately in the vector map giving roughness values as defined by WAsP and given in Table 1. The map of the whole area was digitised with elevation contours at 5 m intervals.

Fig.1. Topography map of the area.

Fig.2. Satellite images of the area.

Table 1 : Roughness class and terrain surface characteristics.

z_0 [m]	Terrain surface characteristics
0.50	Suburbs
0.20	many trees and/or bushes
0.10	farmland with closed appearance
0.005	bare soil (smooth)
0.0001	water areas (lakes, open sea)

A. Preparation of vector map

Mortensen *et. al.,* have reported that it is possible to obtain accurate assessment of stable wind speed which are close to the measured values with maps of 8 × 8 sq. km and the influence of contour interval on the accuracy of wind speed prediction [5]. Prediction errors can be reduced with smaller contour intervals with a contour interval of 20 m or less. In the present study the hilly site near Bhopal covering an area of 16 × 16 sq. km. has been considered.

The topography map has been obtained from Geological Survey of India and the detailed surface features based on aerial photography conducted by the National Remote Sensing Agency were available as 2 × 2 sq. km tiles in the AutoCAD dwg format. These 6 layer map provide contours at 1 m intervals, trees, buildings, temples, tombs, electric and telegraph poles, waterways, marshy areas, roads, footpaths etc in different layers. Information relevant to WAsP, namely contours, open areas, farmlands, water bodies and urban and semi urban areas were retained by switching off the unwanted layers. Such tiles were joined together in the AutoCAD software and saved as dxf files (drawing exchange format), which could be imported into the WAsP Map Editor. In this study, contour intervals at 5 m were retained and imported into the WAsP Map Editor for calculating the wind energy density throughout the area. The map was transformed to the Universal Transverse Mercator (UTM) projection with the datum of WGS 1984. The area falls in Zone 43 with the central meridian of +75° E. There are 280 height contours in the map with elevation ranging from a low of 450 m to a high of 570 m. The total number of digitised points was 215000, thus giving reasonably smooth contour lines as shown in Fig.3.

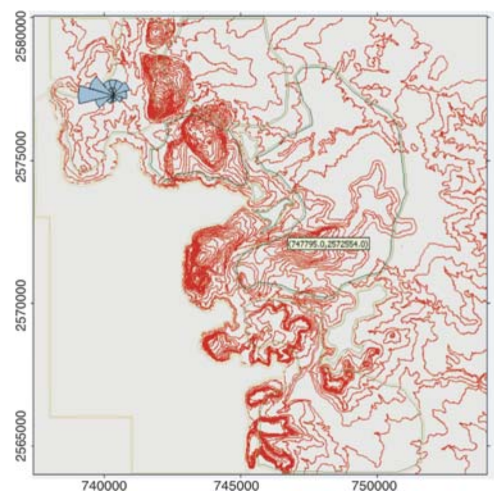


Fig.3. Digital contour map of the area under study Bhopal airport.

B. Specifying obstacles near measuring site

Each obstacle present near the measuring site affect the wind data collected and it depends upon porosity and roughness of the terrain. Obstacles are considered by WAsP as "boxes" with a rectangular cross-section and footprint. Each obstacle must be specified by its position relative to the site and its dimensions and must be assigned a poro sity value. The position of an obstacle is specified in a local, polar coordinate system. Angles (bearings measured with a compass) are given clockwise from north; distance is the radial length from the site to the corner of the obstacle (measured with a measuring tape or a range finder). The list and location of obstacles for the wind monitoring station for incorporation as a WAsP obstacle file is shown in Table 2 and the plot shown in Fig.4.

As a general rule, the porosity can be set equal to zero for buildings and ~ 0.5 for trees. A row of similar buildings with a separation between them of one third the length of a building will have a porosity of about 0.33. For windbreaks the characteristics defined in WAsP may be applied. The porosity of trees changes with the level of foliation, i.e. the time of year and similar to the roughness length, the porosity should be considered as a climatologically influenced parameter.

Table 2 : Obstacles at the site.

Obstacle	A1 [°]	R1 [m]	A2 [°]	R2 [m]	Height [m]	Depth [m]	Porosity
1	35	99	41	92	10	10	0
2	66	117	70	112	6	10	0
3	74	72	83	78	10	15	0.75
4	217	186	295	135	15	20	0.5
5	338	159	352	115	10	20	0

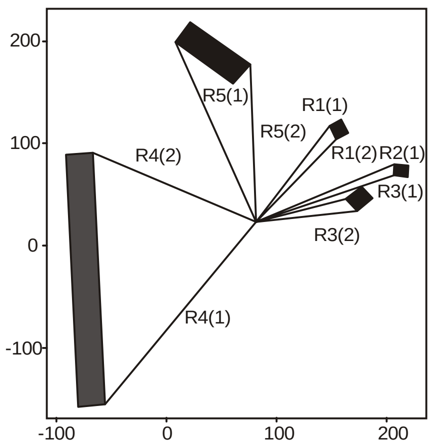


Fig.4. Location of obstacles near Bhopal airport.

III. WIND DATA ANALYSIS

Standard meteorological wind data are regularly collected by the India Meteorological Department near airports and towns for weather prediction and civil aviation requirements. Meteorological aspects of utilization of wind for the extraction of power have been well documented [6]. Wind speed data in knots and the direction in degrees were recorded from the station near airport site located at 77°35′E Longitude and 23°28' N Latitudes for a period of 10 years from 1998 to 2008 at two heights using pressure tube anemometer (Dines anemometer) at 10 m height and the other by hydrogen balloon at 70 m. The measurement site lies at an elevation of 530 m above mean sea level.

A. Vertical wind speed gradient

The wind speed at the surface is zero due to friction between the air and the surface of the ground. The wind speed increases with height most rapidly near the ground, increasing less rapidly with greater height. Measurement of wind speed at different heights is a prerequisite for the extrapolation of wind speed to the desired hub height of the proposed wind turbine. The power law equation is used to determine the value of α (power law index) which is subsequently used for the extrapolation of wind speed to the desired height of hub. The power law equation is given by,

$$\frac{V_2}{V_1} = \left(\frac{Z_2}{Z_1}\right)^{\alpha} \qquad ...(1)$$

Where V_2 and V_1 are the wind speeds at heights Z_2 and Z_1 respectively and α is the empirical wind shear exponent. Therefore, the value of α can be determined. A high value of a often results in changes in stress across the turbine disc [7]. This value of a was used to extrapolate the wind speed to the hub height of the proposed wind turbine. α is determined by the relation,

$$\bar{\alpha} = \frac{\log \frac{V_2}{V_1}}{\log \frac{Z_2}{Z_1}} \qquad ...(2)$$

If the hub height of a wind turbine is Z_2, then the extrapolated wind speed V_2corresponding to Z_2 is given by,

$$V_2 = V_1\left(\frac{Z_2}{Z_1}\right)^{\alpha} \qquad ...(3)$$

The vertical variation of the wind speed profile can be determined to describe the change in mean wind speed with different hub heights of 50m, 60m, and 120m based on experimental data is shown in Table 3. Fig.5 shows the mean monthly wind speeds for the period of 10 years from 1998 to 2008 for the study site at the heights of 50m, 60m and 120m.

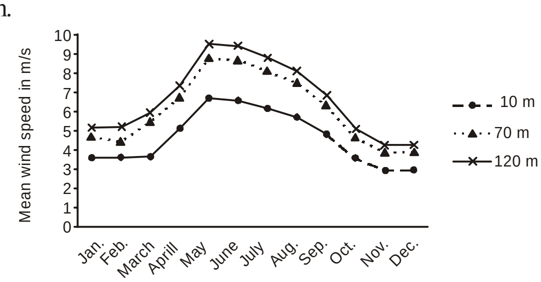


Fig.5. Mean monthly wind speed from 1998-2008.

B. Power in the wind

Wind is the moving mass of air and as such, has kinetic energy. A portion of the kinetic energy is exploited to drive a wind turbine. The energy available in wind is given by :

$$p_w = \frac{1}{2}\frac{1}{2}\rho A u^3 \qquad ...(4)$$

Where, p_w is the energy in the wind,

ρ is the density of the air, taken as 1.225kg/m^3,

A is the cross section of the area through which it flows (m^2).

Table 3 : Mean monthly wind speed and extrapolated wind speed, m/s.

Month	a	10 m	50 m	60 m	70 m	120 m
January	0.142	3.60	4.53	4.65	4.76	5.14
February	0.141	3.67	4.61	4.47	4.48	5.22
March	0.140	3.70	4.64	4.768	5.51	5.94
April	0.144	5.12	6.46	6.64	6.79	7.33
May	0.139	6.71	8.40	8.62	8.81	9.49
June	0.142	6.60	8.30	8.52	8.71	9.40
July	0.142	6.15	7.74	7.95	8.13	8.77
August	0.140	5.72	7.17	7.36	7.53	8.12
September	0.139	4.85	6.07	6.23	6.37	6.86
October	0.139	3.65	4.50	4.61	4.71	5.07
November	0.142	2.97	3.74	3.84	3.93	4.24
December	0.140	3.00	3.76	3.86	3.95	4.25

u is the velocity of the wind (m/s).

It is not possible to extract all the energy available in the wind, since it has to move away from the disc of the turbine and be replaced by the incoming mass. Therefore equation (4) is replaced by

$$P_E = \frac{1}{2} C_p \eta \rho A u^3 \quad ...(5)$$

P_E is the extractable energy,

C_p is the coefficient of the power, which will always be less than 0.59, as determined by Betz,

η is the power coefficient of wind turbine.

It has been found by experience that the power coefficient of a wind turbine is in the range of 0.4 to 0.5, the lower value usually obtainable.

C. Weibull wind speed distribution and energy extraction from wind

Power in the wind depends upon the wind speed probability density function and not just the statistical average. Wind speed data for a potential site is collected at a monitoring station and wind speed variation is closely modeled according to the two-parameter Weibull density function, expressed by,

$$F(u) = \exp\left[-\left(\frac{u}{A}\right)^k\right] \quad ...(6)$$

Where *F(u)* gives the probability of the wind speed exceeding the value u. The two Weibull parameters thus defined are called the scale parameter *A,* (m/s) and the shape parameter k. Wind speed and direction are measured at frequent intervals in order to obtain the average wind speed over a time period T. This is determined by the relation,

$$\bar{u} = \frac{1}{T}\int_0^T u(t)\partial t \quad ...(7)$$

where, $\bar{u}$ indicates the mean value of u. The wind power density available over this time period T is given by

$$P = \frac{1}{2}\rho u^3 = \frac{1}{2}\frac{1}{T}\int_0^T \rho u^3(t)\partial t \quad ...(8)$$

In equation (6) the air density may be taken as 1.225 kg/m^3 and simplified as

$$P = \frac{1}{2}\rho u^3 \quad ...(9)$$

Where ρ is the mean density of air, u^3 is the mean value of the third power of wind and $F(u)$ is the estimated Weibull distribution. It is reported by Justus *et. al.*, that the Weibull distribution produces smaller route mean square errors than the normal square root distribution when fitting actual distributions of observed wind speed data [8]. By the end of 2008, 598 wind monitoring stations were installed and 225 sites were found to have wind energy potential of 200 W/m^2 or more. Out of these, six are located in Madhya Pradesh. The details of these sites are given in Table 4 [9]. The time series wind data were analysed and Weibull parameter examined for the whole period as shown in Table 5. Mean monthly wind speed of the last 10 years at 70 m height have been calculated and shown in Table 6.

Table 4 : Prospective Windy Sites of Madhya Pradesh with WPD of more than 200 W/m^2.

Station	District	Latitude N		Longitude E		Altitude Msl, (m)	Mean Wind Power Density at 20/25m, W/m^2	Mean Wind Power Density at 50m, W/m^2
		Deg.	Min.	Deg.	Min.			
Jamgodrani	Dewas	22	59	76	10	560	130	222
Kukru*	Betul	21	30	77	29	1118	157	255
Mahuriya*	Shajapur	23	50	76	06	504	171	217
Mamatkheda	Ratlam	23	41	75	03	560	169	255
Sendhhva*	Khargon	21	38	75	03	540	163	215
Valiyarpani*	Barwani	21	40	74	57	510	191	287

*Micro survey report available with C-WET [12].

Table 5 : Weibull Parameter of last 10 years at 70 m height.

Year	K	c, m/s	u, m/s	E, W/m^2
1998	1.35	5.2	4.78	216
1999	1.7	7	6.27	346
2000	1.67	7.2	6.43	381
2001	2.09	6.4	5.64	202
2002	1.99	7.1	6.25	288
2003	1.74	6.8	6.09	307
2004	1.35	5.1	4.7	210
2005	1.36	5.4	4.78	220
2006	1.76	5.5	4.86	154
2007	1.56	5.5	4.92	187
2008	1.78	5.6	5.01	167

K Shape parameter, c: Scale parameter, u: Average wind speed, E: Wind power density

Table 6 : Mean Monthly Wind Speed (m/s) of last ten years.

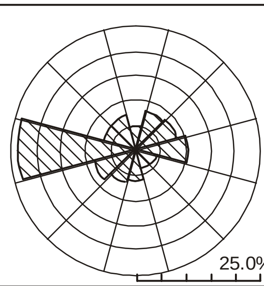
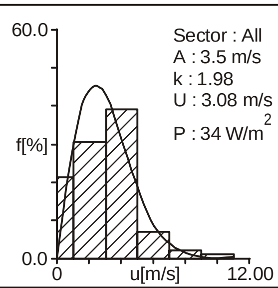
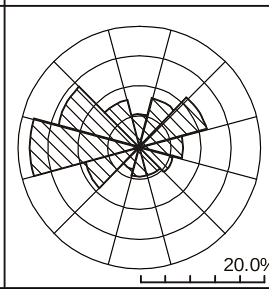
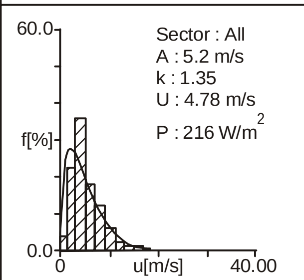
Year	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1998	4.06	4.62	5.77	6.63	12.78	7.94	8.71	7.33	5.8	4.67	3.86	3.31
1999	4.12	4.07	5.13	5.86	7.11	11.01	9.59	7.62	8.24	5.34	3.99	3.27
2000	5.31	6.72	6.76	7.92	7.96	7.74	7.65	8.48	6.46	4.31	3.97	3.34
2001	4.04	4.77	5.41	5.51	7.71	8.166	8.68	7.57	5.5	4.56	4.39	3.69
2002	5.41	4.51	4.51	7.4	7.96	7.95	8.72	7.65	7.31	4.99	3.72	4.05
2003	4.89	5.05	5.29	6.74	8.41	8.22	6.89	7.93	6.215	4.32	3.69	3.8
2004	3.72	4.33	4.7	6.2	6.26	6.46	5.82	5.8	4.4	3.37	3.3	3.28
2005	4.32	4.61	4.5	5.19	8.28	8.88	6.796	6.74	6.05	4.64	3.11	3.925
2006	3.7	4.36	4.53	5.1	6.41	6.84	6.02	6.18	6.05	4.24	3.09	3.53
2007	3.76	4.61	4.7	6.2	7.62	7.24	5.46	4.77	4.26	3.37	2.9	3.8
2008	4.3	4.5	3.8	5.11	7.6	6.7	6.98	5.24	3.38	3.32	3.32	3.49

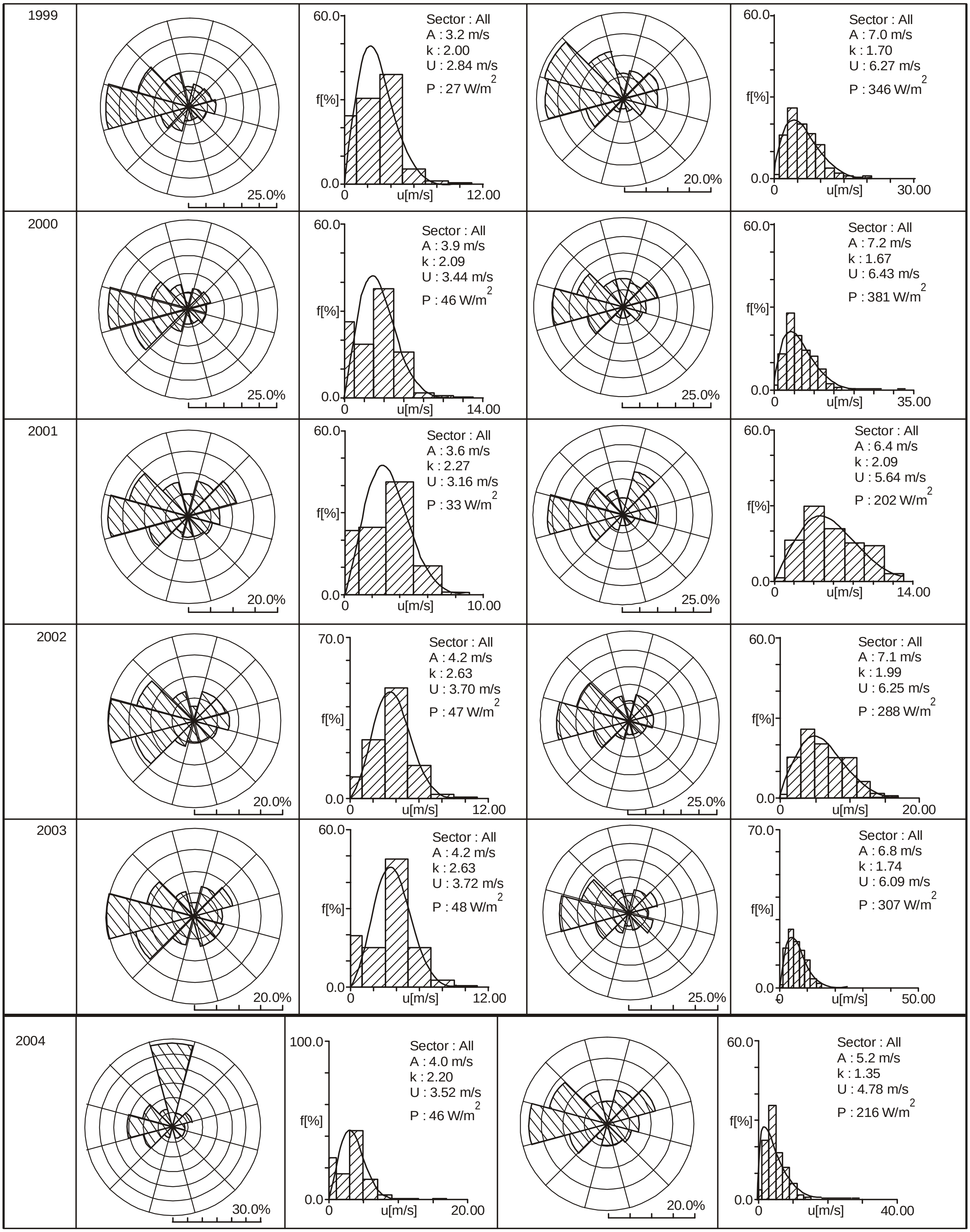
D. Observed wind climate

The detailed time series wind data recorded at the wind monitoring station have been analyzed and the observed wind climate determined by using WAsP. These are shown for the two hub heights of 10 and 70 m in Fig.7.

IV. OBSERVATION AND CONCLUSIONS FROM THE STUDY

It is seen from the analysis of observed wind climate for the site that the site is endowed with good wind power potential with the wind power density in the range of 154-381 W/m^2 from the year 1998 through 2008. However, it is also seen that the average wind speed calculated for different years does not indicate corresponding wind power density owing to uneven wind speed distribution. It is also seen from the wind roses that wind flows predominantly from the West-North West indicating a strong influence of the monsoon in the Indian sub-continent. Also there are many lull period in the winter month which gradually gain momentum as the climate warm up towards the approach of summer. The typical monthly variation in wind speed from January to December for a representative year average for the study period is shown in Fig 6. Exploitable wind speed is experienced only at the hub height of 50 m or more. Therefore, a wind turbine generator with a cut-in speed of 4 m and cut-out speed in the range of 20-25 m/s is recommended for the area.

Year	Wind Direction at 10 m	Frequency Distribution at 10 m	Wind Direction at 70 m	Frequency Distribution at 70 m
1998				


1999
25.0%
60.0
f[%]
0.0
0
u[m/s]
12.00
Sector : All
A : 3.2 m/s
k : 2.00
U : 2.84 m/s
P : 27 W/m2
20.0%
60.0
f[%]
0.0
0
u[m/s]
30.00
Sector : All
A : 7.0 m/s
k : 1.70
U : 6.27 m/s
P : 346 W/m2
2000
25.0%
60.0
f[%]
0.0
0
u[m/s]
14.00
Sector : All
A : 3.9 m/s
k : 2.09
U : 3.44 m/s
P : 46 W/m2
25.0%
60.0
f[%]
0.0
0
u[m/s]
35.00
Sector : All
A : 7.2 m/s
k : 1.67
U : 6.43 m/s
P : 381 W/m2
2001
20.0%
60.0
f[%]
0.0
0
u[m/s]
10.00
Sector : All
A : 3.6 m/s
k : 2.27
U : 3.16 m/s
P : 33 W/m2
25.0%
60.0
f[%]
0.0
0
u[m/s]
14.00
Sector : All
A : 6.4 m/s
k : 2.09
U : 5.64 m/s
P : 202 W/m2
2002
20.0%
70.0
f[%]
0.0
0
u[m/s]
12.00
Sector : All
A : 4.2 m/s
k : 2.63
U : 3.70 m/s
P : 47 W/m2
25.0%
60.0
f[%]
0.0
0
u[m/s]
20.00
Sector : All
A : 7.1 m/s
k : 1.99
U : 6.25 m/s
P : 288 W/m2
2003
20.0%
60.0
f[%]
0.0
0
u[m/s]
12.00
Sector : All
A : 4.2 m/s
k : 2.63
U : 3.72 m/s
P : 48 W/m2
25.0%
70.0
f[%]
0.0
0
u[m/s]
50.00
Sector : All
A : 6.8 m/s
k : 1.74
U : 6.09 m/s
P : 307 W/m2
2004
30.0%
100.0
f[%]
0.0
0
u[m/s]
20.00
Sector : All
A : 4.0 m/s
k : 2.20
U : 3.52 m/s
P : 46 W/m2
20.0%
60.0
f[%]
0.0
0
u[m/s]
40.00
Sector : All
A : 5.2 m/s
k : 1.35
U : 4.78 m/s
P : 216 W/m2

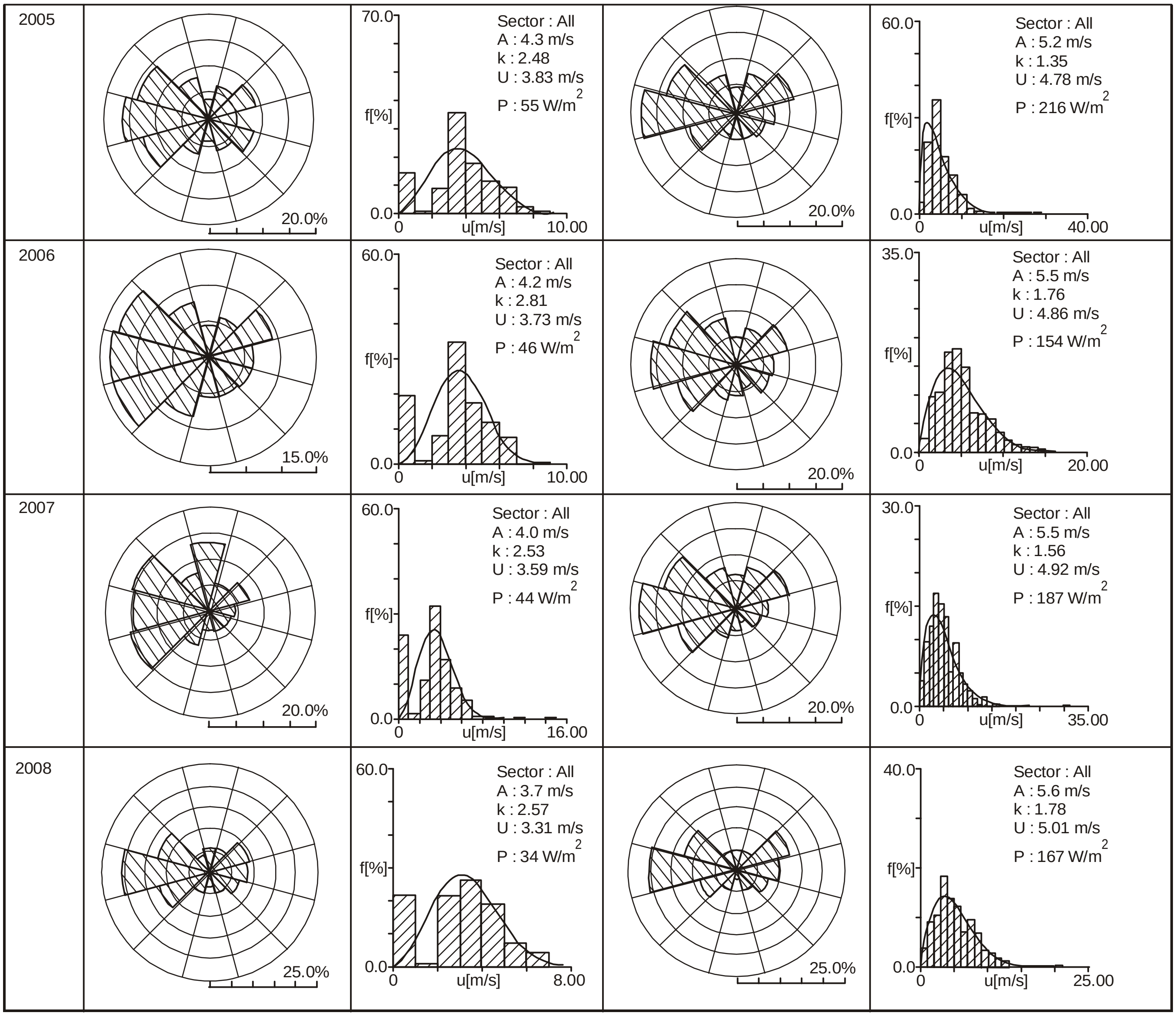


Fig.7. Observed wind climate of last ten year.

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