An Investigation of Wind Power Potential at Kati Bandar - Sindh

1. **Introduction:**

Wind energy is the fastest growing renewable energy source today. A continued interest in wind energy development worldwide has produced steady improvements in technology and performance of wind power plants. New wind power projects have proven that wind energy not only is cost competitive but also offers additional benefits to the economy and the environment.

A steady supply of reasonably strong wind is necessary requirement for utilizing the power in the wind. Development of wind energy depends upon a clear understanding of wind resources. Site location, turbine performance and physical effects of turbulence and energy extraction represent a few of the issues that must be addressed by anyone interested in developing wind energy.

As such any plan to develop wind energy must begin by understanding the wind resource. Where are the best potential wind sites located? How much energy could be extracted from the wind at those sites?

1.1 **Characteristic of wind:**

The global winds are caused by pressure differential across the earth's surface. The amount of solar radiation absorbed at the earth's surface is greater at the equator than at the poles. This variation in incoming heat sets up convective cells in the lowest layer of the atmosphere. In the simplest form air rises at the equator and sinks at the poles. However the rotation of the earth complicates this simple heat transfer. A series of circulations are set up in both northern and southern hemispheres.

The areas of the globe where air is descending are zones of high pressure and where the air is ascending, low-pressure zones are formed. The pressure gradient drives the flow of air from high to low pressure, thus causing the wind. The wind is then acted on the corriolis force due to the earth's rotation. The resultant wind is turned easterly or westerly. On a smaller scale, wind is created because of temperature difference between land and sea and mountains and valleys. The local topographical features and roughness of the terrain also cause air movements.

2.0 **Wind Mapping Project of Pakistan Meteorological Department:**

As any plan to develop wind energy must begin by understanding the wind resources. Where are the best potential wind sites located? How much energy could be extracted from the wind at those sites? Will the wind turbine performance be affected by the turbulence or other wind resource characteristics?

To answer these questions and to provide wind resource database for the different potential parts of the country, Pakistan Meteorological Department prepared a phased programme. Government of Pakistan, Ministry of Science and Technology provided the necessary funding for undertaking the Phase I. First phase covers the coastal areas of Sindh and Balochistan Provinces.

2.1 Study Area:

The project area for the wind mapping is 1100 kilometers along Sindh and Balochistan coast spreading over latitude 25°N approximately and up to 100 kilometers deep northward over land from the coast.

Forty-one stations for collecting wind data have been installed to study the wind regime as shown in figure-1.

The list of stations located along Sindh and Balochistan coast is given below.

Aghore, Basol, Bella, Gaddani, Gawadar, Hoshab, Hub Chowki, Jiwani, Liari, Makola, Managi, Mand, Nasirabad, Nelunt, Ormara, Othal, Pasni, Phore, Pishukhan, Ramra, Tump, Turbat, Winder, Badin, Baghan, Chuhar Jamali, Gharo, Golarchi, Hawks Bay, Hyderabad, Jati, Kadhan, Karachi, Kati Bandar, Matli, Mirpur Sakro, Nooriabad, Sajawal, Shah Bandar, Talhar, Thanu Bula Khan.

2.2 Data source:

To undertake this study 30-meter high towers are erected at the locations mentioned above. On each of these high towers two wind speed anemometers are installed at the height of 10 meters and 30 meters, respectively; wind vane for recording wind direction is installed at 30 meters height. Temperature sensors are also installed at 10 meters height. Automatic data loggers developed locally have been installed to record data at each site. These data loggers are recording, one-minute average wind speed at both levels, five-minute average wind direction, five-minute average temperature and 10-minute average minimum and maximum wind speed. While selecting the above-mentioned locations for wind monitoring; the main objective was to identify potentially windy areas that also possess other desirable qualities of wind energy developed site. Further following guidelines as far as possible were also kept in mind while choosing an exact location for monitoring towers.

- Towers are placed as for as possible away from the local obstruction to the wind
- Selected location should be representative of the majority of the site.

Since sating a tower near obstructions such as trees or building can adversely affect the analysis of the site's wind characteristics such as magnitude of wind resource, wind shear and turbulence levels the tower in most cases are placed as for as possible away from local obstructions to the wind. But where this rule could not be followed, the tower was placed at horizontal distance of 10 times the height of the obstruction in the prevailing wind direction as required internationally. The following parameters have been recorded during the study.

i. Wind speed one minute average at 10 & 30 meters
ii. Maximum wind speeds during 10 minutes
iii. Minimum wind speeds during 10 minutes
iv. Wind direction five minutes average at 30 meters
v. Temperature 5 minutes average in °C

Every month a team of observers and Maintenance Engineers visits these sites to inspect the instruments and to download the data on a laptop. Finally, the data is compiled and analyzed at Renewable Energy Research Cell established at Meteorological Complex, Karachi.

3.0   **Methodology; Analysis & Discussion:**

3.1   **Wind speed variation with height:**

Wind speed tends to increase with height in most locations, a phenomenon known as wind shear. The degree of wind shear depends mainly upon on two factors, atmospheric mixing and the roughness of the terrain.

Atmospheric mixing typically follows a daily cycle driven by solar heating. At the hub height of a wind turbine, this cycle often causes wind speeds to increase in the daytime and decrease at night. However, the range of variation between night and day typically diminishes as hub height increases. At a height of approximately 50 meters, it weakens or may even disappear in some cases.

Terrain roughness also affects wind shear by determining how much the wind is slowed near the ground. In areas with a high degree of roughness, such as forests or cities, near-surface wind speeds tend to be low and wind shear high, whereas the converse is true in areas of low roughness such as flat, open fields. Wind shear may be greatly reduced or eliminated where there is an abrupt change in terrain height such as a sea cliff or mountain ridge.

To save money wind measurements sometimes are taken at a lower height than the wind turbine tower. In that case, it is essential to measure wind shear at different times of day in different seasons to accurately predict the performance of a wind power plant. The shear can be measured by monitoring wind speeds at two or three heights on a tower. Since wind turbines produce much more power in stronger winds, wind turbine designers try to put turbines on the tallest possible towers. At some point, however, the increased cost of towers outweighs the benefits. With current wind turbine technology, the optimum tower height for large wind machines appears to be approximately 40 to 50 meters.

For saving money in this survey also the wind has been recorded at 10 & 30 meters and for calculating the wind speed at 50 meters the following two methods has been used in this study.

3.1.1   *Log Law:*

The turbulent mixing in the atmosphere may be considered in a similar way to molecular mixing (this is called k theory). Assuming the mixing is dominated by mechanical mixing due to shear forces a relationship of wind speed with height is derived.

$$u \; = \; \frac{u_*}{k} \ln \left(\frac{z - D}{z_o} \right)$$

Where

u_* is the friction notify
k is the von Karman constant
Z_o is the roughness length
D is the displacement height

The von Karman constant is generally taken as 0.4. The roughness length Z_o is related to the vegetation cover of the area. The values of roughness length are given in Table-1. The displacement height D is the height above the roughness elements where the flow is free. For most vegetation it is small and is generally treated as zero. For large roughness elements like trees and building in towns it is not negligible and is the order of the average height of the elements. The **log law** may only be used for heights above D. Turbines are rarely sited in forests or towns, so D is usually taken as zero.

The wind speed at any height z can then be computed provided that the wind speed at a height Z_R is known. Thus:

$$\frac{u}{u_R} = \frac{\ln\left(\frac{z}{z_o}\right)}{\ln\left(\frac{z_R}{z_o}\right)}$$

Where

    U_R is the wind speed at reference height Z_R

The reference height is usually 10m or 30m as this is the height at which mean wind data is generally collected.

3.1.2 *Power Law:*

Engineers often prefer to use a Power Law to describe the increase in wind speed with height, as it is easier to evaluate.

$$\frac{u}{u_R} = \left(\frac{z - D}{z_R}\right)^{\alpha}$$

Where:

    α is the power law exponent
    u_R is the wind speed at reference height z_R

The power law exponent typically varies between 0.1 and 0.32 depending upon the landscape type. A value of 1/7 is often quoted as a reasonable value for the power law exponent in countryside. The exponent can be calculated from the roughness length.

$$\alpha = \frac{\ln\left(\frac{\ln\left(\frac{z}{z_o}\right)}{\ln\left(\frac{z_R}{z_o}\right)}\right)}{\ln\left(\frac{z}{z_R}\right)} \approx \frac{1}{\ln\sqrt{\frac{z \cdot z_R}{z_o}}}$$

Where:

    Z is the measurement height
    Z_R is the reference height
    Z_0 is the roughness length

The power law exponent therefore varies with the interval between the two measurement heights. The power law should be carefully employed since it is not a physical representation of the surface layer and does not describe the flow nearest to the ground very well. Both the log law and the power law are simplified expressions of the <u>wind profile.</u> They

are valid in flat homogeneous terrain. So they do not include the effects of topography, obstacles or changes in roughness or stability.

Table 1: Typical values of surface roughness length Z_O and power law exponent α for various types of terrain

Type of terrain	Z_0	α
Mud Flats, Ice	10^{-5} to $3x\ 10^{-5}$	
Calm Sea	$2x10^{-4}$ to $3x10^{-4}$	
Sand	$2x10^{-4}$ to 10^{-5}	0.01
Mown Grass	0.001 to 0.01	
Low Grass	0.01 to 0.04	0.13
Fallow Field	0.02 to 0.03	
High Grass	0.04 to 0.1	0.19
Forest and Woodland	0.1 to 1	
Built up area, Suburb	1 to 2	0.32
City	1 to 4	

3.2   Average Wind Speed:

By using above mentioned above methods the wind speed at 50 meters has been computed and monthly average of these wind speed at 50 meters height have been given in Fig 2 in graphical as well as tabular form.

Fig-2 also shows monthly average wind speed at height of 10m & 30m in addition to 50meters. At 30 meters height, the average wind speed is above 5m/s during 8 months period from March to September where as maximum average wind speed of 10.4m/s at this height is during July. At 50meters the average wind speed is above 5m/s during 9 months from February – September with highest average wind speed of 11.3m/s is observed during July.

Fig-2   Monthly Arerage Wind Speed at KetiBandar (m/s)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AWS10m	2.88	3.26	3.48	5.30	7.59	6.45	8.62	5.76	5.66	2.70	2.07	2.80
AWS30m	4.02	4.90	5.05	7.31	9.52	8.09	10.41	6.93	7.05	4.27	3.56	4.03
AWS50	4.80	5.77	5.96	8.46	10.58	9.03	11.30	7.68	7.91	5.21	4.41	4.82
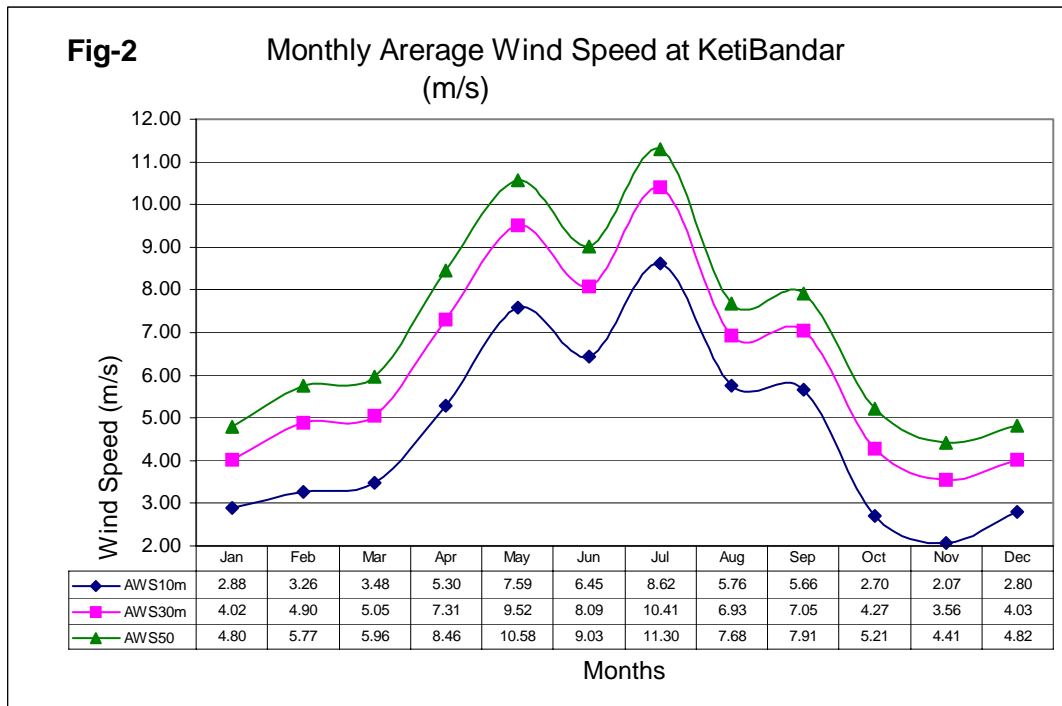
At this height even during January and December the wind speed is close to 5m/s. which means that average wind speed data at 50meters height indicate that there is a good wind power potential during at least eleven months in a year at Kati Bandar.

3.3 **Diurnal Wind speed Variation:**

Fig-3 shows the annual wind speed variations at Kati Bandar. The wind speed is generally lower during night and after sunrise it start picking up and reaches maximum around 3 – 4 p.m. which is around 7m/s and 8m/s at 30 meters and 50 meters height respectively. Then after sunset it starts generally decreasing. Figures 4 to 7 shows seasonal diurnal variation of wind speed. In first two figures the maximum wind speed during day times reaches to 9.6m/s during March to May (Fig-4) period and 10.6m/s during June to August (Fig-5).

Fig-3 Annual Diurnal variation wind speed at Kati Bandar

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
WS30	4.1	4.1	4.1	4.1	4.1	4.0	4.0	4.1	4.5	4.9	5.0	5.1	5.2	5.3	5.4	5.6	5.6	5.3	5.0	4.7	4.4	4.4	4.3	4.2
WS100	5.8	5.8	5.9	5.9	6.0	5.9	5.8	6.0	6.0	6.0	6.1	6.2	6.4	6.6	6.8	7.0	7.1	6.9	6.6	6.4	6.2	6.0	6.0	5.8
WS 50m	6.6	6.7	6.9	7.0	7.1	7.0	6.8	6.9	6.7	6.7	6.9	7.0	7.1	7.3	7.6	7.9	8.1	7.9	7.6	7.3	7.1	6.9	6.8	6.7

Source:Pakistan Meteorological Deptt   PST(Hours)
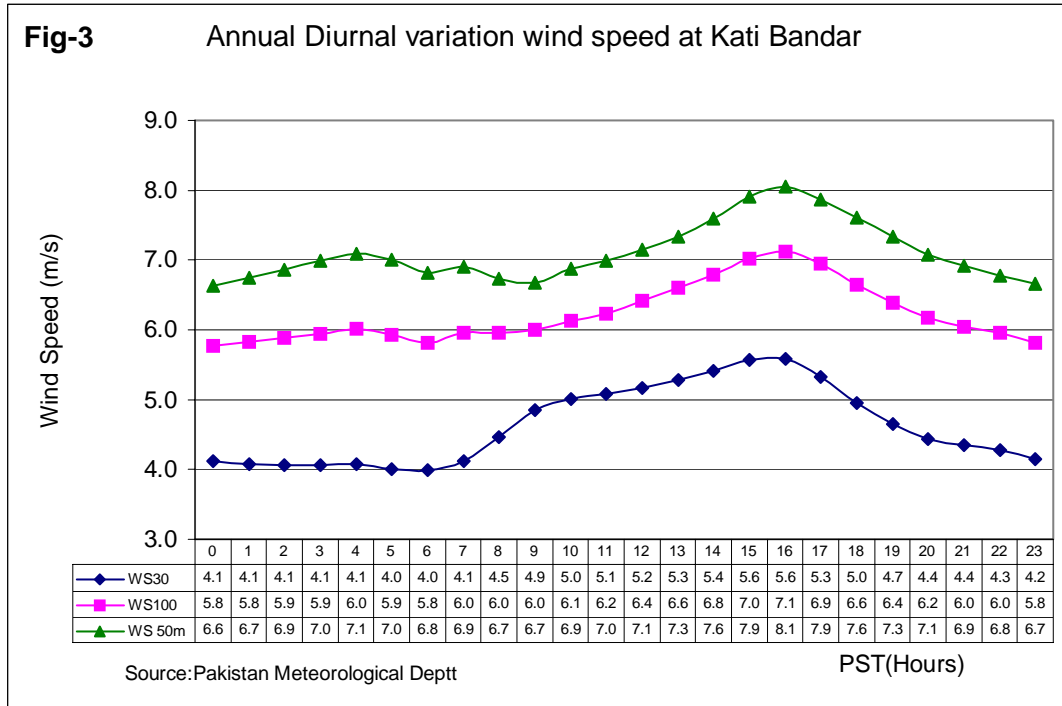
Fig-4 Diurnal variation wind speed at Kati Bandar Mar To May

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
WS 10m	4.9	4.7	4.6	4.5	4.3	4.2	4.1	4.5	5.0	5.2	5.2	5.3	5.5	6.0	6.4	6.7	6.7	6.6	6.2	5.8	5.5	5.4	5.2	5.0
WS 30m	6.9	6.8	6.7	6.7	6.6	6.5	6.4	6.6	6.7	6.7	6.5	6.7	7.0	7.5	8.1	8.4	8.4	8.4	8.0	7.6	7.3	7.2	7.1	6.8
WS 50m	7.7	7.7	7.9	8.1	7.9	7.8	7.7	7.5	7.4	7.4	7.5	7.7	7.7	8.2	9.0	9.5	9.6	9.4	9.1	8.5	8.0	8.0	7.6	7.5

Source:Pakistan Meteorological Deptt   PST(Hours)
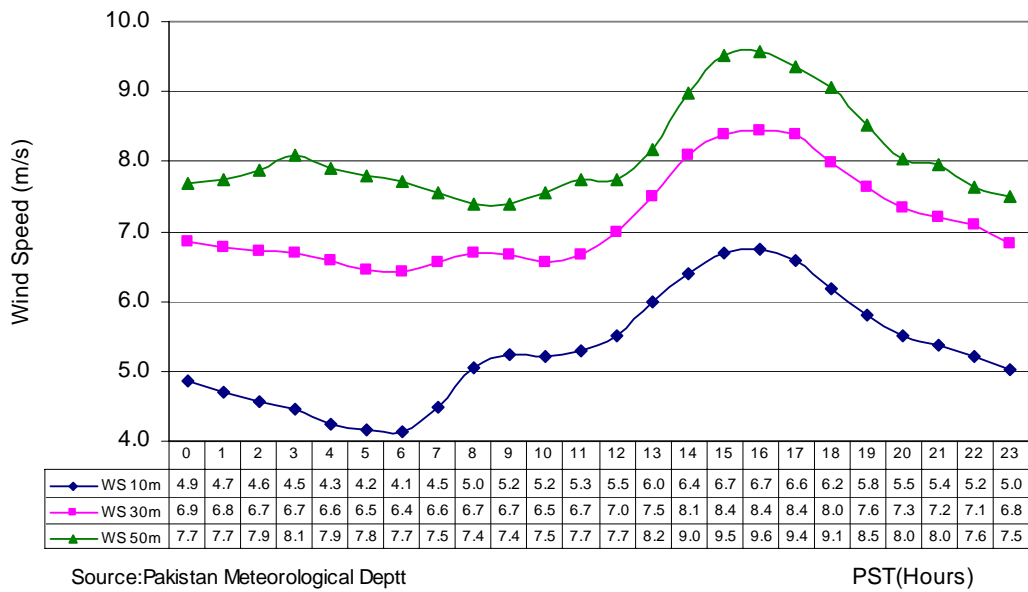
Fig-5 Diurnal variation wind speed at Kati Bandar Jun To Aug

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
WS 10m	6.6	6.6	6.5	6.5	6.4	6.3	6.3	6.4	6.7	7.0	7.1	7.2	7.4	7.5	7.6	7.8	7.9	7.9	7.7	7.5	7.1	6.8	6.6	6.6
WS 30m	7.9	7.9	7.9	7.9	8.0	7.9	7.9	8.0	8.2	8.5	8.8	8.9	9.2	9.4	9.5	9.6	9.6	9.5	9.1	8.9	8.4	8.1	8.0	7.9
WS 50m	8.6	8.7	8.7	8.7	8.8	8.8	8.7	8.8	9.1	9.4	9.7	9.8	10.3	10.5	10.6	10.6	10.6	10.4	9.9	9.7	9.2	8.8	8.7	8.7

Source:Pakistan Meteorological Deptt   PST(Hours)

Fig -6 Diurnal variation wind speed at Kati Bandar Sep To Nov

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
WS 10m	2.7	2.7	2.7	2.8	3.0	3.0	3.0	3.2	3.2	3.6	3.9	4.0	4.0	4.0	4.2	4.3	4.3	4.0	3.6	3.2	3.0	3.0	3.0	2.7
WS 30m	4.3	4.5	4.7	4.8	5.0	4.8	4.7	5.0	4.7	4.7	5.0	5.1	5.1	5.1	5.4	5.6	5.8	5.6	5.3	4.9	4.8	4.7	4.7	4.5
WS 50m	5.2	5.5	5.7	5.8	6.0	5.8	5.7	6.0	5.5	5.4	5.7	5.7	5.7	5.8	6.0	6.4	6.6	6.4	6.2	5.9	5.7	5.6	5.6	5.4

Source:Pakistan Meteorological Deptt

PST(Hours)

Fig- 7 Diurnal variation wind speed at Kati Bandar Dec to Feb

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
WS 10m	2.3	2.4	2.5	2.5	2.6	2.6	2.5	2.5	2.9	3.6	3.8	3.8	3.8	3.7	3.4	3.5	3.4	2.9	2.3	2.1	2.1	2.2	2.3	2.3
WS 30m	4.0	4.1	4.3	4.4	4.5	4.5	4.2	4.3	4.2	4.1	4.1	4.3	4.4	4.4	4.2	4.5	4.7	4.4	4.2	4.1	4.2	4.2	4.1	4.1
WS 50m	5.0	5.1	5.3	5.4	5.7	5.6	5.2	5.3	4.9	4.5	4.5	4.7	4.8	4.9	4.8	5.1	5.4	5.3	5.3	5.3	5.4	5.3	5.1	5.0

Source:Pakistan Meteorological Deptt
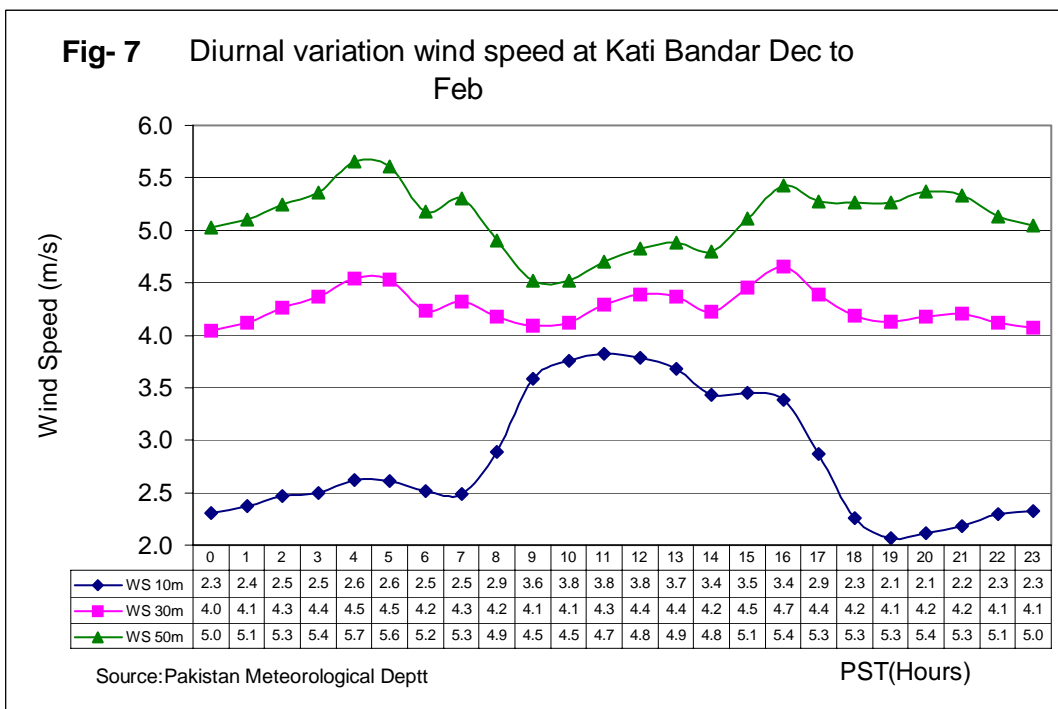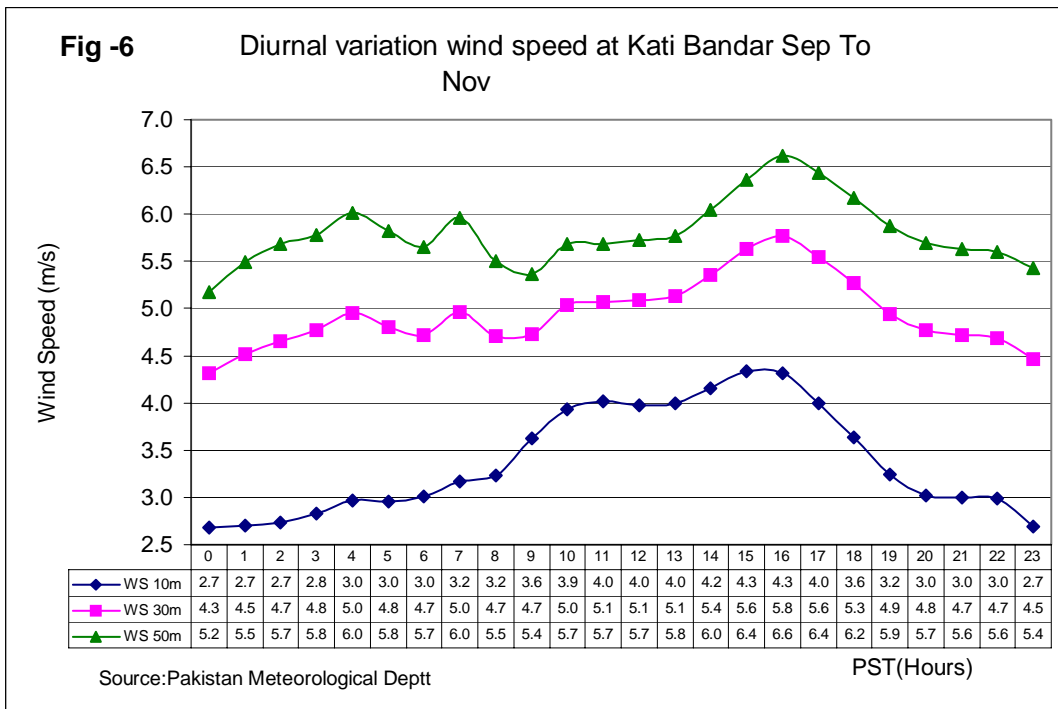
PST(Hours)

Fig-6 shows the diurnal variation during September to November and during this period the maximum wind speed is 6.6 m/s at 50 meters height and 5.8 m/s at 30 meters. Fig-6 shows this variation during the period December to February. Here the maximum wind speed is reduced to 5.4 m/s at 50 meters and 4.7 m/s at 30 meters height. This is the period when the wind speeds are generally not strong enough for power generation.

3.4 **Wind speed Frequency Distribution:**

Wind speed frequency distribution can simply be obtained by plotting the different wind speeds against their frequencies/related frequencies. For obtaining frequency distribution the following two procedures are necessary.

3.4.1 *Binning of Data:*

The sorting of the data into narrow wind speed bands is called binning of the data. In our case a bin width of 1m/sec has been used e.g.; a measured wind speed of 3.5 m/sec would be placed in 3<X<=4 m/sec bin. The central value of each bin i.e. 0.5 m/sec, 1.5 m/sec etc has been used in calculations and frequency distribution group.
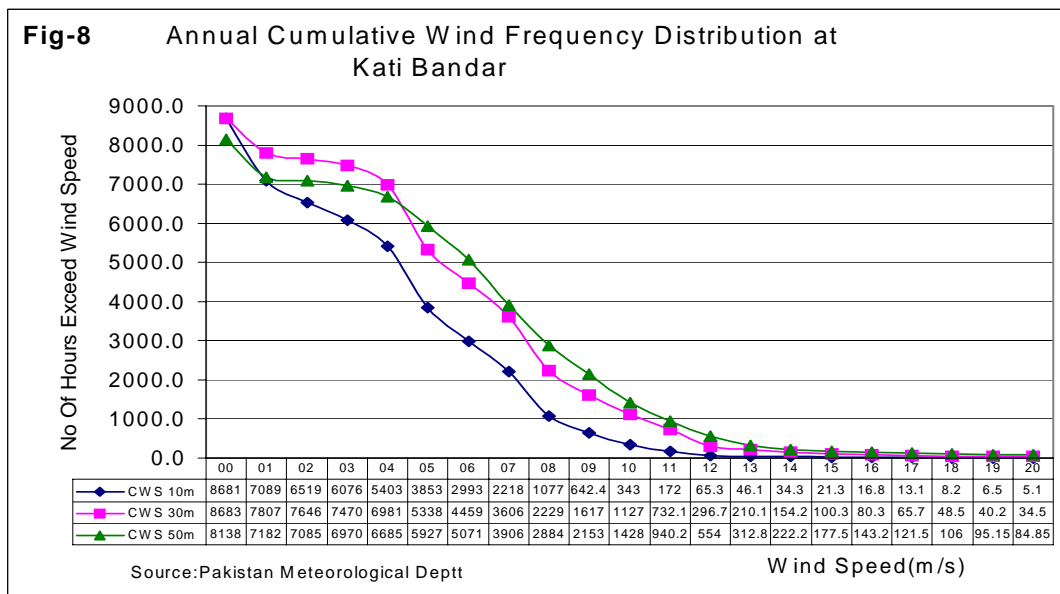
3.4.2 *Relative Frequency:*

It is proportion wind speed in each bin. It can be reviewed as the estimated of probability of given wind speed in the bin. Relative frequency is defined as

R .F = probability P (V_i) = Frequency of given wind speed / Total period

3.4.3 *Annual Cumulative Wind Frequency:*

Fig-8 shows the annual cumulative Wind Frequency distribution at three heights 10, 30 and 50 meters. The analysis indicate that in a year at a height of 30 meters during 5338 hours the wind speed is greater than 5 meters per sec which generally is enough to generate the electric power. Whereas at 50 meters in a year during 5927 hours the wind speed is equal or greater than 5m/s.

Fig-8 Annual Cumulative Wind Frequency Distribution at Kati Bandar

	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20
CWS 10m	8681	7089	6519	6076	5403	3853	2993	2218	1077	642.4	343	172	65.3	46.1	34.3	21.3	16.8	13.1	8.2	6.5	5.1
CWS 30m	8683	7807	7646	7470	6981	5338	4459	3606	2229	1617	1127	732.1	296.7	210.1	154.2	100.3	80.3	65.7	48.5	40.2	34.5
CWS 50m	8138	7182	7085	6970	6685	5927	5071	3906	2884	2153	1428	940.2	554	312.8	222.2	177.5	143.2	121.5	106	95.15	84.85

Source:Pakistan Meteorological Deptt   Wind Speed(m/s)

3.4.4 *Wind Frequency Distribution:*

Fig-9 shows the annual frequency distribution. We can see that at 50 meters during 883 hours wind speed is 6 m/s, 1288 hours speed is 7 m/s, 1127 hours speed is 8 m/s, 842 hours speed is 9 m/s and during 775 hours the wind speed is 10m/s and so on. This also indicates good wind potential in this area.
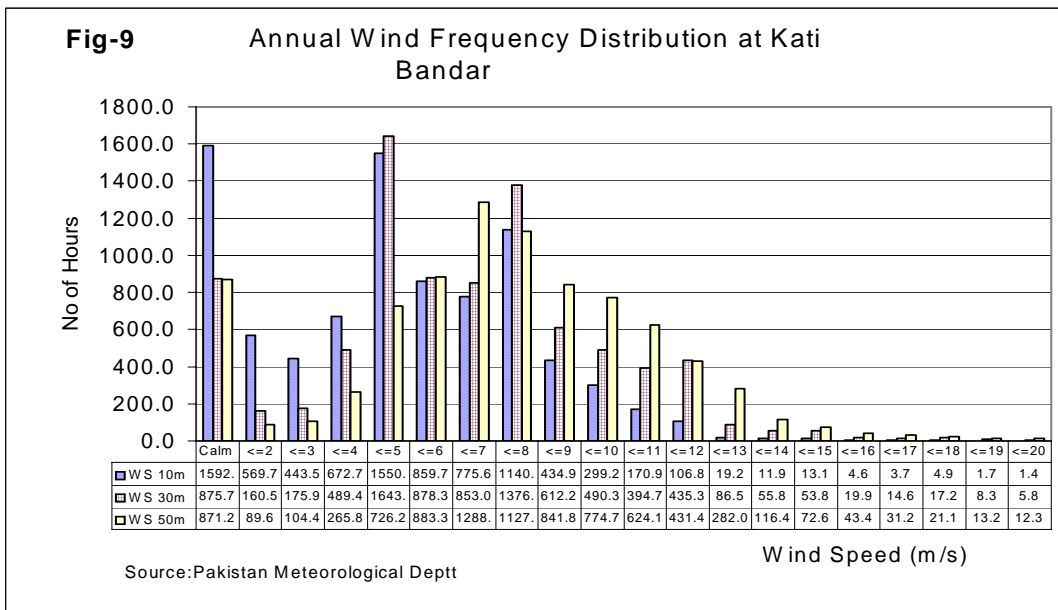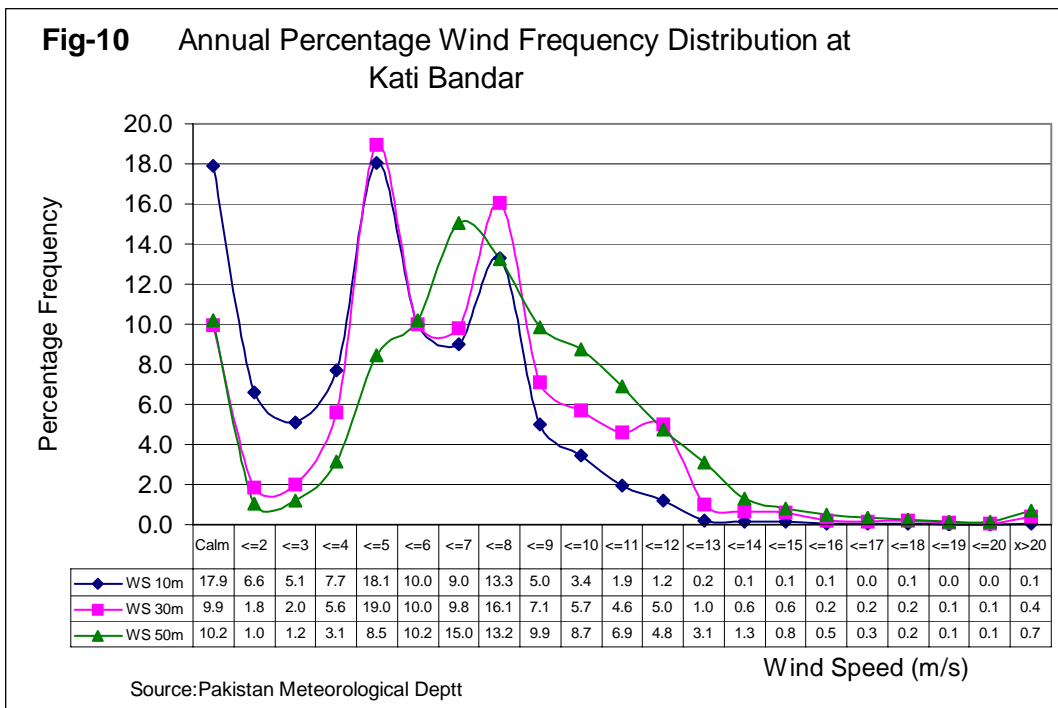
Fig-9 Annual Wind Frequency Distribution at Kati Bandar

	Calm	<=2	<=3	<=4	<=5	<=6	<=7	<=8	<=9	<=10	<=11	<=12	<=13	<=14	<=15	<=16	<=17	<=18	<=19	<=20
WS 10m	1592.	569.7	443.5	672.7	1550.	859.7	775.6	1140.	434.9	299.2	170.9	106.8	19.2	11.9	13.1	4.6	3.7	4.9	1.7	1.4
WS 30m	875.7	160.5	175.9	489.4	1643.	878.3	853.0	1376.	612.2	490.3	394.7	435.3	86.5	55.8	53.8	19.9	14.6	17.2	8.3	5.8
WS 50m	871.2	89.6	104.4	265.8	726.2	883.3	1288.	1127.	841.8	774.7	624.1	431.4	282.0	116.4	72.6	43.4	31.2	21.1	13.2	12.3

Wind Speed (m/s)

Source: Pakistan Meteorological Deptt

Fig-10 gives this frequency distribution in percentage. At 30 meters we find that during 19% of time wind is 5m/s, 16.1% time 8m/s. whereas at 50 meters height we get 15% of the time wind speed 7m/s and 13.2% times 8m/s and 9.9% of the time 10m/s. This appears to be reasonably enough to generate power from the wind.
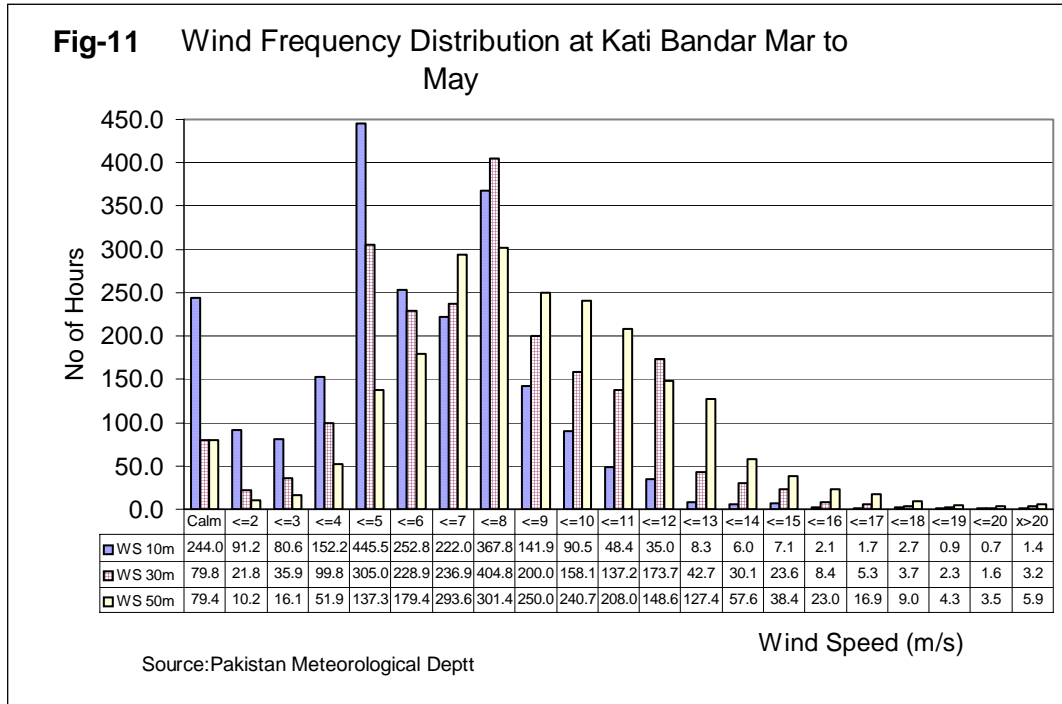

Fig-10 Annual Percentage Wind Frequency Distribution at Kati Bandar

	Calm	<=2	<=3	<=4	<=5	<=6	<=7	<=8	<=9	<=10	<=11	<=12	<=13	<=14	<=15	<=16	<=17	<=18	<=19	<=20	x>20
WS 10m	17.9	6.6	5.1	7.7	18.1	10.0	9.0	13.3	5.0	3.4	1.9	1.2	0.2	0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.1
WS 30m	9.9	1.8	2.0	5.6	19.0	10.0	9.8	16.1	7.1	5.7	4.6	5.0	1.0	0.6	0.6	0.2	0.2	0.2	0.1	0.1	0.4
WS 50m	10.2	1.0	1.2	3.1	8.5	10.2	15.0	13.2	9.9	8.7	6.9	4.8	3.1	1.3	0.8	0.5	0.3	0.2	0.1	0.1	0.7

Wind Speed (m/s)

Source: Pakistan Meteorological Deptt

3.4.5 *Seasonal Wind Frequency Distribution:*

Figures 11–14 gives seasonal wind frequency distribution and figures 15–18 give this distribution in percentage.
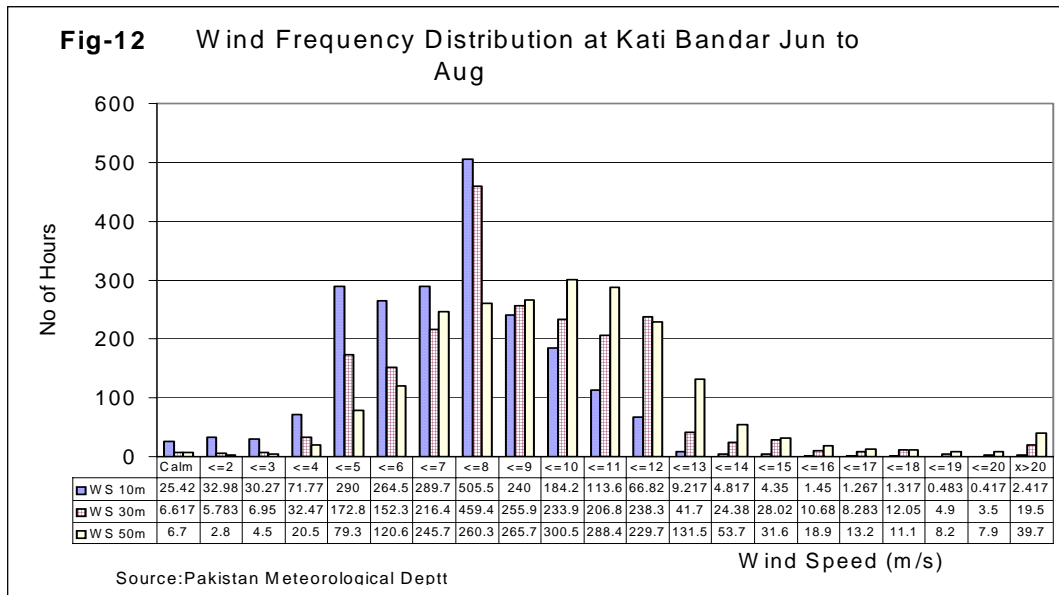
March – May

Fig-11 shows this distribution during the months of March to May. We can see that in this period at 30 meters height during 305 hours we get 5m/s, 228 hours 6m/s, 236 hours 7m/s, 404 hours 8m/s 200hrs 9m/s and even during 173 hours wind speed reaches to a maximum of 12m/s. Similarly at 50 meters we get 294 hours 7m/s, 301 hours 8m/s, 250 hours 9m/s 208 hours 11m/s and during 148 hours wind speed touches to 12m/s.
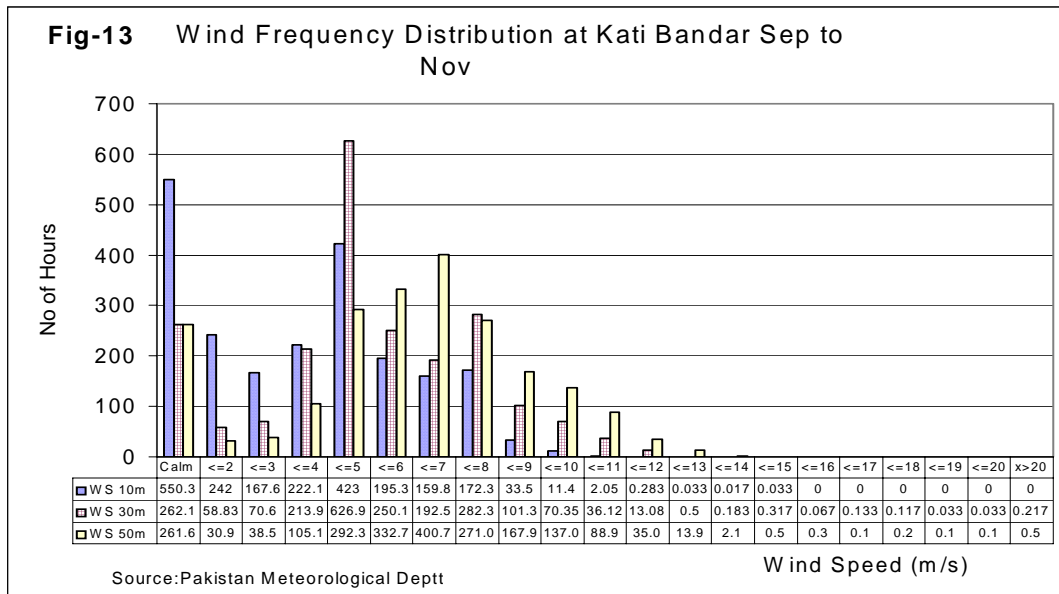

Fig-11 Wind Frequency Distribution at Kati Bandar Mar to May

	Calm	<=2	<=3	<=4	<=5	<=6	<=7	<=8	<=9	<=10	<=11	<=12	<=13	<=14	<=15	<=16	<=17	<=18	<=19	<=20	x>20
WS 10m	244.0	91.2	80.6	152.2	445.5	252.8	222.0	367.8	141.9	90.5	48.4	35.0	8.3	6.0	7.1	2.1	1.7	2.7	0.9	0.7	1.4
WS 30m	79.8	21.8	35.9	99.8	305.0	228.9	236.9	404.8	200.0	158.1	137.2	173.7	42.7	30.1	23.6	8.4	5.3	3.7	2.3	1.6	3.2
WS 50m	79.4	10.2	16.1	51.9	137.3	179.4	293.6	301.4	250.0	240.7	208.0	148.6	127.4	57.6	38.4	23.0	16.9	9.0	4.3	3.5	5.9

Wind Speed (m/s)

Source:Pakistan Meteorological Deptt

June - August

Fig-12 shows wind frequency distribution during the months of June to August. We can see that in this period at 30 meters height during 173 hours we get 5m/s, 152 hours 6m/s, 216 hours 7m/s, 459 hours 8m/s, 256 hours 9m/s, 234 hours 10m/s, and during 238 hours, wind reaches up to 12m/s. Similarly at 50 meters height during 245 hours we get wind speed of 7m/s, during 260 hours 8m/s, 266 hours 9m/s, 300 hours 10m/s, 288 hours 11m/s and during 230 hours the wind speed reaches up to 12m/s.

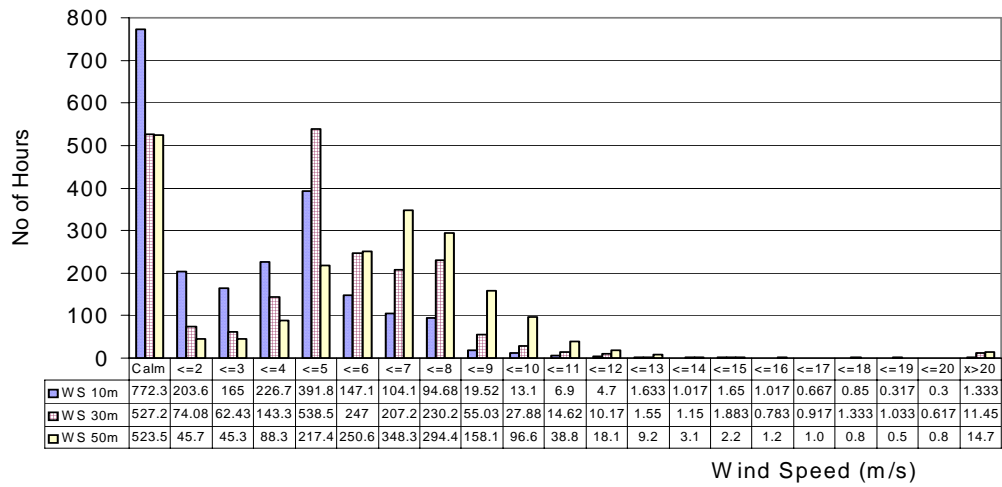Fig-12 Wind Frequency Distribution at Kati Bandar Jun to Aug

	Calm	<=2	<=3	<=4	<=5	<=6	<=7	<=8	<=9	<=10	<=11	<=12	<=13	<=14	<=15	<=16	<=17	<=18	<=19	<=20	x>20
WS 10m	25.42	32.98	30.27	71.77	290	264.5	289.7	505.5	240	184.2	113.6	66.82	9.217	4.817	4.35	1.45	1.267	1.317	0.483	0.417	2.417
WS 30m	6.617	5.783	6.95	32.47	172.8	152.3	216.4	459.4	255.9	233.9	206.8	238.3	41.7	24.38	28.02	10.68	8.283	12.05	4.9	3.5	19.5
WS 50m	6.7	2.8	4.5	20.5	79.3	120.6	245.7	260.3	265.7	300.5	288.4	229.7	131.5	53.7	31.6	18.9	13.2	11.1	8.2	7.9	39.7

Wind Speed (m/s)

Source:Pakistan Meteorological Deptt

September – November

Fig-13 shows wind frequency distribution during the period from September to November. We can see that at 30 meters height during 627 hours we get 5m/s, 250 hours 6m/s, 193 hours 7m/s, 282 hours 8m/s and during 101 hours 9m/s. Similarly at 50 meters height during 292 hours we get wind speed of 5m/s, 333 hours 6m/s, 400 hours 7m/s, 271 hours 8m/s, 168 hours 9m/s and for 137 hours we get 10m/s.

Fig-13 Wind Frequency Distribution at Kati Bandar Sep to Nov

	Calm	<=2	<=3	<=4	<=5	<=6	<=7	<=8	<=9	<=10	<=11	<=12	<=13	<=14	<=15	<=16	<=17	<=18	<=19	<=20	x>20
WS 10m	550.3	242	167.6	222.1	423	195.3	159.8	172.3	33.5	11.4	2.05	0.283	0.033	0.017	0.033	0	0	0	0	0	0
WS 30m	262.1	58.83	70.6	213.9	626.9	250.1	192.5	282.3	101.3	70.35	36.12	13.08	0.5	0.183	0.317	0.067	0.133	0.117	0.033	0.033	0.217
WS 50m	261.6	30.9	38.5	105.1	292.3	332.7	400.7	271.0	167.9	137.0	88.9	35.0	13.9	2.1	0.5	0.3	0.1	0.2	0.1	0.1	0.5

Wind Speed (m/s)

Source:Pakistan Meteorological Deptt

December – February

Fig-14 shows wind frequency distribution during the period from December to February. We can see that at 30 meters height during 539 hours we get wind speed of 5m/s, 247 hours 6m/s, 207 hours 7m/s and during 230 hours 8m/s. Similarly at 50 meters during 217 hours we get 5m/s, 250 hours 6m/s, 348 hours 7m/s, 294 hours 8m/s and during 158 hours we get 9m/s. Actually this is the period when we get generally slower wind potential as compared to other seasons.

Fig-14 Wind Frequency Distribution at Kati Bandar Dec to Feb

	Calm	<=2	<=3	<=4	<=5	<=6	<=7	<=8	<=9	<=10	<=11	<=12	<=13	<=14	<=15	<=16	<=17	<=18	<=19	<=20	x>20
WS 10m	772.3	203.6	165	226.7	391.8	147.1	104.1	94.68	19.52	13.1	6.9	4.7	1.633	1.017	1.65	1.017	0.667	0.85	0.317	0.3	1.333
WS 30m	527.2	74.08	62.43	143.3	538.5	247	207.2	230.2	55.03	27.88	14.62	10.17	1.55	1.15	1.883	0.783	0.917	1.333	1.033	0.617	11.45
WS 50m	523.5	45.7	45.3	88.3	217.4	250.6	348.3	294.4	158.1	96.6	38.8	18.1	9.2	3.1	2.2	1.2	1.0	0.8	0.5	0.8	14.7

Wind Speed (m/s)

Similarly the above mentioned seasonal frequency distribution percentage terms have been presented in figures 15–18.

Fig-15 Percentage Wind Frequency Distribution at Kati Bander Mar to May

	Calm	<=2	<=3	<=4	<=5	<=6	<=7	<=8	<=9	<=10	<=11	<=12	<=13	<=14	<=15	<=16	<=17	<=18	<=19	<=20	x>20
WS 10m	9.5	4.2	3.6	6.8	20.9	11.6	10.1	17.3	6.6	4.2	2.2	1.6	0.4	0.3	0.3	0.1	0.1	0.1	0.0	0.0	0.1
WS 30m	3.3	1.0	1.5	4.3	13.9	9.9	10.4	18.9	9.3	7.5	6.5	8.1	1.9	1.4	1.1	0.4	0.2	0.2	0.1	0.1	0.1
WS 50m	4.6	0.5	0.8	2.6	6.4	8.1	13.9	14.5	11.9	10.1	8.4	6.1	5.3	2.5	1.6	1.0	0.7	0.4	0.2	0.1	0.3

Source: Pakistan Meteorological Deptt

Wind Speed (m/s)
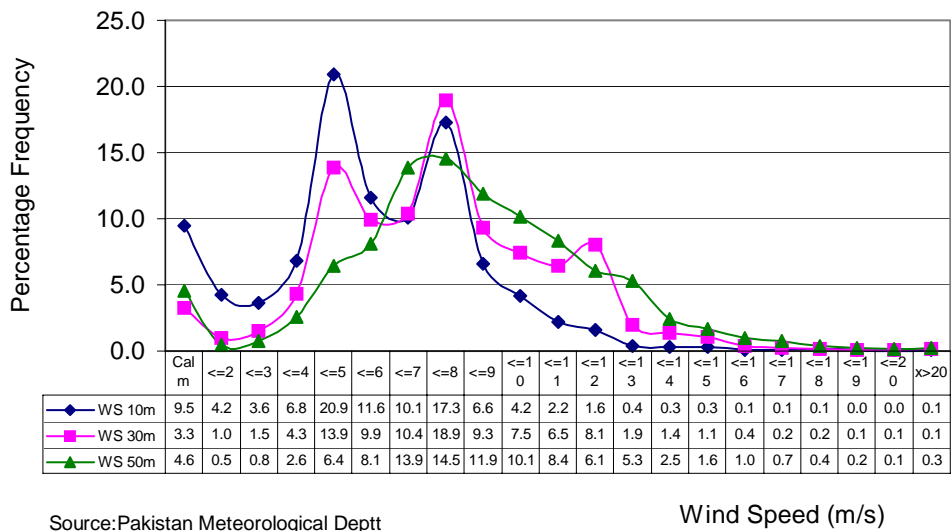
Fig-16 Percentage Wind Frequency Distribution at Kati Bander Jun to Aug

	Calm	<=2	<=3	<=4	<=5	<=6	<=7	<=8	<=9	<=10	<=11	<=12	<=13	<=14	<=15	<=16	<=17	<=18	<=19	<=20	x>20
WS 10m	1.2	1.6	1.4	3.4	13.9	12.6	13.7	23.5	11.0	8.4	5.1	3.0	0.4	0.2	0.2	0.1	0.1	0.1	0.0	0.0	0.1
WS 30m	0.3	0.3	0.3	1.6	8.3	7.3	10.3	21.7	11.9	10.8	9.5	10.9	1.9	1.1	1.3	0.5	0.4	0.5	0.2	0.2	0.9
WS 50m	0.3	0.1	0.2	1.0	3.8	5.8	11.8	12.4	12.5	14.0	13.3	10.5	6.0	2.4	1.4	0.9	0.6	0.5	0.4	0.4	1.8

Source:Pakistan Meteorological Deptt

Fig-17 Percentage Wind Frequency Distribution at Kati Bandar Sep to Nov

	Calm	<=2	<=3	<=4	<=5	<=6	<=7	<=8	<=9	<=10	<=11	<=12	<=13	<=14	<=15	<=16	<=17	<=18	<=19	<=20	x>20
WS 10m	25.2	11.0	7.7	10.2	19.4	9.0	7.4	8.0	1.5	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WS 30m	12.0	2.7	3.2	9.8	28.7	11.5	8.8	13.0	4.7	3.3	1.7	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WS 50m	12.0	1.4	1.8	4.8	13.4	15.2	18.4	12.5	7.7	6.3	4.1	1.6	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source:Pakistan Meteorological Deptt

Fig-18 Percentage Wind Frequency Distribution at Kati Bandar Dec to Feb

	Calm	<=2	<=3	<=4	<=5	<=6	<=7	<=8	<=9	<=10	<=11	<=12	<=13	<=14	<=15	<=16	<=17	<=18	<=19	<=20	x>20
WS 10m	35.7	9.5	7.7	10.5	18.1	6.8	4.8	4.4	0.9	0.6	0.3	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.1
WS 30m	24.1	3.4	3.0	6.8	25.0	11.4	9.6	10.7	2.6	1.3	0.7	0.5	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.0	0.6
WS 50m	23.9	2.1	2.1	4.2	10.2	11.7	16.1	13.6	7.3	4.5	1.8	0.8	0.4	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.7

Wind Speed (m/s)

Source:Pakistan Meteorological Deptt

3.5   Wind Rose:

Fig-17 shows the Wind Rose based on 12 months data from March 2002 – February 2003 collected at 30 meters height. Wind Rose indicates that most of the time the wind speed was west North West. The annual average wind speed is 6.75m/s and the percentage when wind speed less than 3m/s are 137% only.

Wind Rose at Kati Bandar (30m height during 12 months)

Fig 19
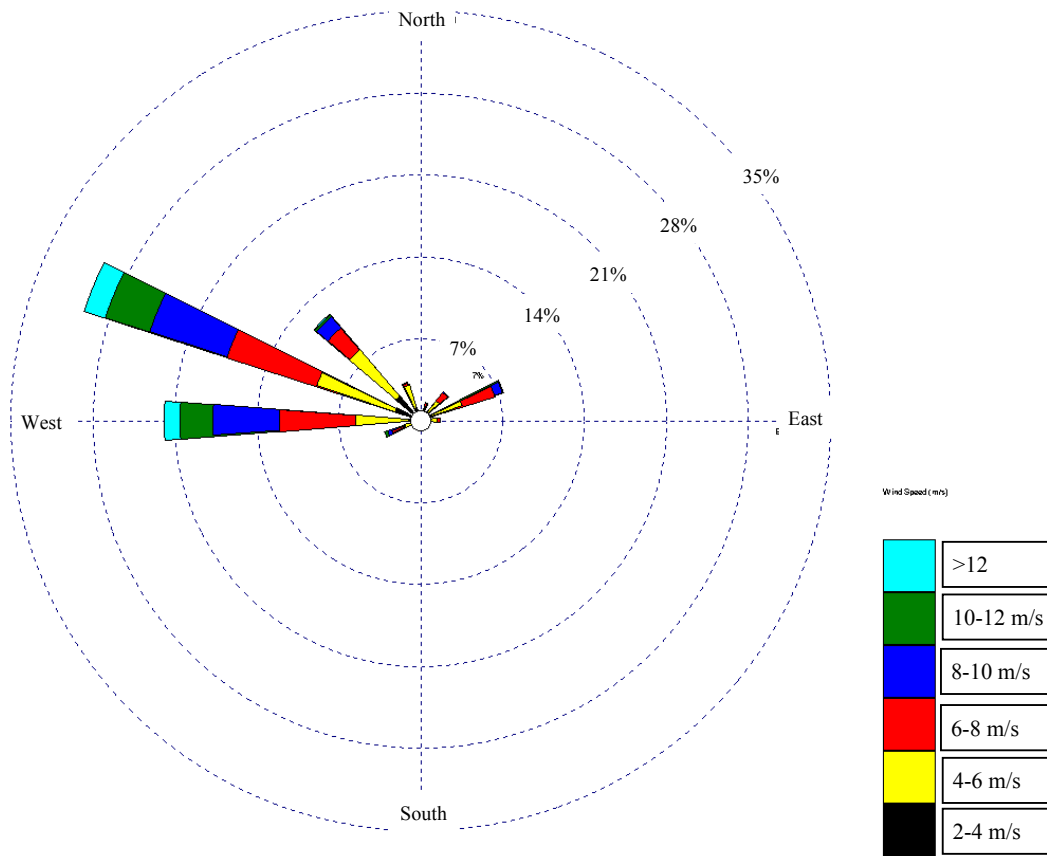
Average Wind Speed	Wind less than 3m/s	Comments
6.75 m/s	13.7 %	

Source: - Pakistan Meteorological Department

3.6   Wind speed statistic:

3.6.1   *The statistical Mean:*

It is the average of a set of n numbers. Mathematically, we can write

$$M\ e\ a\ n\ =\ \frac{\left[\sum_{i=1}^{n} x_i\right]}{N}$$

The Mean Wind Speed V can be calculated by the formula.

$$V = \sum_{i=1}^{n} V_i P(V_i)$$

Where V_i is the central wind speed of bin 1 and $P(V_i)$ is the probability/relative frequency that the wind speed has in bin i.

3.6.2   *Variance:*

It is one of the several indices of variability that statistician, use to characterize the dispersion among the measures in a given set of data. Mathematically, variance is written as

$$\text{Variance} = \sigma^2 = \sum (X_i - V)^2$$

Where V is mean of data set

In case of wind speed data, we can write it, as

$$\sigma^2 = \sum V_i^2 P(Vi) - (V)^2$$

3.6.3   *Standard Deviation*

It is the square root of the variance, denoted by σ

$$\sigma^2 = (\sigma)^{1/2} = \sum \left(V_i^2 P(V_i) - (V)^2 \right)^{1/2}$$

3.7   Wind power density:

While investigating a wind power potential of an area, the average values of wind speed does not truly represent this potential because lot of information regarding frequency distribution of wind speed is suppressed in the process of averaging wind speed. As such the most important values for estimating the wind power potential of a given site is the value of the wind power density or the available theoretical instantaneous power from the wind. This available wind power in the wind is the flux of Kinetic Energy crossing the wind energy conversion system and its cross – sectional area.

Like water flowing in the river, wind contains energy that can be converted to electricity using wind turbines. The amount of electricity that wind turbines produce depends upon the amount of energy in the wind passing through the area swept by the wind turbines blades in a unit of time. This energy flow is referred to as the wind power density.

A key aspect of wind power density is its dependence on wind speed cubed. This means that the power contained in the wind increases very rapidly with wind speed; if the speed doubles, the power increases by a factor of eight. In practice, the relationship between the power output of a wind turbine and wind speed does not follow a cubic relationship. Below a certain minimum speed, the turbine does not have enough wind to operate, whereas above a certain speed its output levels off or begins to decline. In very high winds the turbine may even be shut down to prevent damage to it.

Wind power density also depends on air density. At higher attitudes, air density decreases and, as a result, so does the available power. This effect can reduce the power output of wind turbines on high mountains by as much as 40 percent compared to the power that could be produced at the same wind speeds at sea level. Air density depends inversely on temperature: colder temperatures are favorable for higher air densities and greater wind power production.

3.7.1 *Wind power classes:*

To simplify the characterization of the wind power potential, it is common to assign areas to one of seven wind classes, each representing arrange of wind power density at the special height above the ground. The standard International wind power classifications are shown in Table 2.

Table-2:   International Wind Power Classification

Class	Resource Potential	30m Height		50m Height	
		Wind Speed m/s	Wind Power W/m²	Wind Speed m/s	Wind Power W/m²
1	---	0 – 5.1	0 – 160	0 – 5.6	0 – 200
2	Marginal	5.1 – 5.9	160 – 240	5.6 – 6.4	200 – 300
3	Moderate	5.9 – 6.5	240 – 320	6.4 – 7.0	300 – 400
4	Good	6.5 – 7.0	320 – 400	7.0 – 7.5	400 – 500
5	Excellent	7.0 – 7.4	400 – 480	7.5 – 8.0	500 – 600
6	---	7.4 – 8.2	480 – 640	8.0 – 8.8	600 – 800
7	---	8.2 – 11.0	640 – 1600	8.8 – 11.9	800 – 2000

By and large, the areas being developed today using large wind turbine are ranked as class 5 and above. Class 4 areas are also being considered for further development as wind turbines are adopted to run more efficiently a lower wind speeds. Class1 and class2 areas are not being deemed suitable for large machines, although a smaller wind turbine may be economical in areas where the value of the energy produced is higher

3.7.2 *Power of wind Energy:*

$$E = \tfrac{1}{2}mv^2$$

A parcel of Wind possesses kinetic energy ,Where v is velocity
From this, power density is calculated as

$$P = \tfrac{E}{t} = \tfrac{1}{2}\tfrac{dm}{dt}v^2$$

Where $\tfrac{dm}{dt}$ is the mass of air following time.

From fluid dynamics, it can be proved that

Where V is volume $\quad \tfrac{dm}{dt} = \varphi A V$

Volume of cylindrical cross section can be written as

$$V = \pi r^2 L \qquad \text{-------------- } (1)$$

Where r is radius of cylinder and L is length of it.
The wind moving with velocity V travels this distance L in time t so

$$S = L = vt$$

So equation L takes the form

$$V = \pi r^2 vt$$

Now mass of wind can be written as

$$m = \varphi A vt \qquad \text{Where } A = \pi r^2$$

Differentiating $\quad \tfrac{dm}{dt} = \varphi A v \ \tfrac{dt}{dt} = \varphi A v$

where φ is density of wind and others parameters have been defined in diagram?

Surface area A

Airflow, with
velocity V

Volume of cylinder
needed and density of
air determine mass of

Length, l
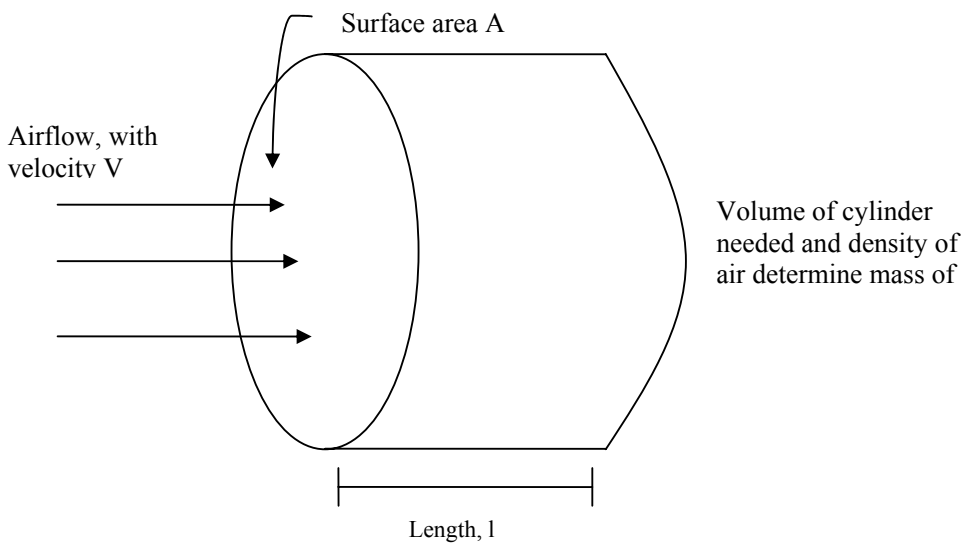
So the power is then,

$$P = \tfrac{1}{2}\,{}^{dm}\!/_{dt}\,v^2 = \tfrac{1}{2}\,\varphi A v v^2$$

$$= \tfrac{1}{2}\,\varphi A v^3$$

And power density

$$P\!/_{A} = \tfrac{1}{2}\,\varphi v^3$$

Density of air at standard condition is 1.225 kg/m^3

The area depends upon the size of the rotor. Therefore, it is clear that power density chiefly depends on wind velocity and goes up as a cube of it.

__Note:__ Fig. 20 is not included in this report

3.7.3 *Wind power calculation using Mean wind Speed:*

Wind power calculated from Mean wind speed is not true representative of wind power. In real world, the wind varies constantly. Actual wind power density at most sites can rang from 1.0 to 3 times greater then that calculated. For example, we take wind speed of 5, 7 and 8 m/sec respectively the respective power densities are 76 watt/m^2, 210 watt/m^2 and 313 watt/m^2. The average of which is 200 watt/m^2. On the other hand, the average wind speed is 6.7 m/sec and power density of average wind is 181 watt/m^2. So the power of wind calculated by mean wind speed is less than the actual power present in wind i.e. Mean wind speed is not true representative for the wind power calculations.

To overcome this drawback we find some alternative arrangement, which reduces the deficit. The Weibull distribution is the best fit of wind data to calculate wind power based on mean wind speed and variance/standard deviation.

3.7.4 *Weibull distribution:*

The Weibull distribution (named after the Swedish physicist W. Weibull, who applied it when studying material strength in tension and fatigue in the 1930s) provides a close approximation to the probability laws of many natural phenomenons. It has been used to represent wind speed distribution for application in wind loads studies for sometime. In recent years most attention has been forced on this method for wind frequency applications not only due to its greater flexible and simplicity but also because it can give a good fit to experimental data.

The Weibull distribution function, which is a two-parameter function, has been found to fit much wind data with acceptable accuracy is expressed mathematically as

$$\phi(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left(-\left(\frac{u}{c}\right)^{k}\right)$$

Where:

u is the wind speed

c is the scale parameter with units of speed

k is the shape parameter and is dimensionless

When k = 2 the distribution reduces to Rayleigh distribution and if k=1 an exponential distribution is found. These are special cased of Weibull distribution.

Solving the equation, we find that the scale factor c is closely related to the mean wind speed for the site.

$$\overline{u} = c\tau\left(1 + \frac{1}{K}\right)$$

Where τ **is the complete gamma function**
Similarly

$$\overline{u^{n}} = c^{n}\tau\left(1 + \frac{n}{k}\right)$$

And so

$$\overline{u^{3}} = c^{3}\tau\left(1 + \frac{3}{k}\right)$$

The available power density is obtained:

$$E = \frac{1}{2}\varphi c^{3}\tau\left(1 + \frac{3}{k}\right)$$

Where

E is the power density in watts / m^2

The shape factor k is related to the variance of the wind

$$\sigma^2 = c2\left[\left(1+\frac{2}{k}\right)-\left(\tau\left(1+\frac{1}{k}\right)\right)^2\right]$$

The two Weibull parameters k and c may be derived from site data.

A measure of the confidence of the fit of the Weibull curve to the real data is also returned. Often the Weibull curve is a good fit to the most of the data, but a poor fit to some. If the poor fit is in the low wind speed range, i.e. below cut in it may be possible to ignore the poor fit as this portion of wind does not contribute greatly to the overall power production.

The mathematical description of the wind frequency allows us to match with the turbine power curve. Thus a measure of the average total power capture in a year is achieved. Additionally the choice of turbine cut in and furling speed may be chosen to maximum the total energy capture.

3.7.5 *Weibull Parameters:*

Fig-20 shows the Weibull fit to the wind speed distribution. The Weibull parameters for three different heights 10 meters, 30 meters and 50 meters are given in Table-3 along with other Key results of analysis. If we look at the shape parameters, K and scale parameter, C for 50 meters height we can find that the shape parameter K varies over a wind range from the lowest of 1.51 during January to the highest of 4.14 during the month of September with an annual value of K being 2.08. The lowest values of the scale parameter C 4.93 is observed in November whilst the highest value of 12.46 is obtained in July and with an annual value of 8.09.

3.7.6 *Average Wind Speed & Standard Deviation:*

In Table-3 monthly average wind speed and standard deviation at three different heights are also given. The average wind speed values for 10 meters and 30 meters height have been obtained from the recorded data, whereas the values for the 50 meters height have been computed by using the power law as explained in the earlier section. At 10 meters height the annual average wind speed is 4.71 m/s with Standard deviation of 2.20, at 30 meters this average speed is 6.26 m/s with Standard deviation of 2.50. At 10 meters monthly average temperature from recorded data and assessed surface roughness Z_O is also given. Roughness varies accordingly to the prevailing wind direction during different months. At 50 meters the monthly average wind speed varies from the lowest of 4.41 m/s in November to highest of 11.30 m/s during July. Whereas the annual average wind speed is 7.16 m/s with Standard deviation of 3.65.

3.7.7 *Power Density:*

The monthly power densities for three different heights 10meters, 30meters and 50meters have also been given in Table-3. At 10meters this power density varies between $29m/s^2$ to $458W/m^2$ with annual of $151W/m^2$. At 30 meters height the power density varies from $65W/m^2$ in November to the highest of 847W/m2 in July and the annual values is about $300W/m^2$, which means that at 30meters wind Power potential of this areas falls in Class3 which is categorized as moderate potential. At 50meters height the power density of Kati – Bandar varies from $125W/m^2$ in November to $1086W/m^2$ in July. We can further note that the power potential, as indicated from the values of the monthly power densities at 50meters, during the period from October to January is below $200W/m^2$, which is very low. But the annual power density of the area is $414W/m^2$ which brings the area into the excellent Class 5 category of power potential, which means that in spite of low wind potential during above mentioned four months the area is suitable for large wind farms.

Table 3: Monthly Average wind, Standard Deviation and Wind power density at KATI BANDAR

	10m						
	AvgV (m/s)	St Dev	C (m/s)	K	Temp	Zo	P/A(w/m^2)
January	2.88	2.23	3.13	1.32	18.83	0.792	48.98
February	3.26	2.92	3.40	1.13	20.84	1.551	96.78
March	3.48	2.31	3.87	1.56	23.48	1.066	66.26
April	5.30	2.27	5.97	2.51	25.96	0.43	143.41
May	7.59	2.60	8.48	3.20	28.08	0.111	363.79
June	6.45	2.33	7.22	3.02	28.58	0.133	229.46
July	8.62	2.05	9.41	4.77	27.02	0.05	458.41
August	5.76	1.74	6.39	3.67	26.07	0.038	149.58
September	5.66	1.73	6.28	3.62	25.6	0.114	142.24
October	2.70	1.86	2.99	1.50	26.93	1.791	32.94
November	2.07	1.99	2.11	1.05	23.98	2.861	29.24
December	2.80	2.38	2.97	1.19	20.08	1.106	54.45
Annual	4.71	2.20	5.18	2.38	24.62	0.84	151.30

	30m						
	AvgV (m/s)	St Dev	C (m/s)	K	Temp		P/A(w/m^2)
January	4.02	2.74	4.45	1.51	18.69		106.53
February	4.90	3.43	5.41	1.47	20.7		201.04
March	5.05	2.41	5.70	2.23	23.34		136.17
April	7.31	2.29	8.13	3.53	25.82		310.61
May	9.52	2.86	10.55	3.69	27.94		671.36
June	8.09	2.73	9.02	3.26	28.44		435.57
July	10.41	2.86	11.47	4.07	26.88		847.26
August	6.93	1.94	7.64	3.98	25.93		251.52
September	7.05	1.93	7.76	4.08	25.46		262.59
October	4.27	1.90	4.82	2.41	26.79		77.45
November	3.56	2.23	3.98	1.66	23.84		65.19
December	4.03	2.70	4.48	1.54	19.94		104.31
Annual	6.26	2.50	6.95	2.79	24.48		289.13

	50m						
	AvgV (m/s)	St Dev	C (m/s)	K	Temp		P/A(w/m^2)
January	4.80	3.29	5.32	1.51	18.55		182.82
February	5.77	3.71	6.44	1.62	20.56		287.81
March	5.96	2.71	6.72	2.35	23.20		214.30
April	8.46	2.45	9.35	3.84	25.68		464.78
May	10.58	3.04	11.69	3.88	27.80		9.5.39
June	9.03	2.95	10.05	3.37	28.30		596.80
July	11.30	3.12	12.46	4.06	26.74		1086.09
August	7.68	2.15	8.47	3.99	25.79		342.32
September	7.91	2.14	8.71	4.14	25.32		369.95
October	5.21	2.29	5.87	2.44	26.65		139.31
November	4.41	2.77	4.93	1.66	23.70		124.96
December	4.82	3.19	5.36	1.56	19.80		175.73
Annual	7.16	3.65	8.09	2.08	24.34		413.56

ESTIMATING WIND GENERATED ELCECTRIC POWER OUTPUT

Appendix – I

Monthly Average Diurnal Variation of Wind Generated Electric Power Output.

Appendix – II

Hourly Wind Generated Electric Power output

4.0 **Estimating Wind Generated Electric Power Output**

The average power output of wind energy conversion technologies (WECT) is a very important parameter since it determines the energy output over time thereby influencing the economic feasibility of a wind project. It is by far more useful than the rated power, which does not account for the variability of wind velocity thereby easily overestimating energy revenues. The average power of wind turbine, $\overline{P_{WT}}$, is the power produced at each wind speed multiplied by the fraction that wind speed is experienced, integrated over all possible wind speeds. In integral form this can be expressed as (Manwell et al., 2002; Borowy and Salameh, 1996):

$$\overline{P_{WT}} = \int_{0}^{\infty} P_{WT}(v)df(v)$$

This integral can be replaced with a summation over bins, N_B, to calculate the average wind turbine power (Manwell et al., 2002).

$$\overline{P_{WT}} = \sum_{j=1}^{N_B} \left\{ \exp\left[-\left(\frac{v_{j-1}}{c}\right)^k\right] - \exp\left[-\left(\frac{v_j}{c}\right)^k\right] \right\} P_{WT}\left(\frac{v_{j-1}+v_j}{2}\right)$$

Please note that the relative frequency, f_j/N, corresponds to the term in brackets and the power output is calculated at the midpoint between v_{j-1} and v_j.

The available power at any given wind speed v that is convertible by a turbine is defined by (Manwell et al., 2002 Johnson, 1985)

$$P_{WT}(v) = \frac{1}{2}\rho A C_p \eta v^3$$

where η is the drive train efficiency (i.e generator power/rotor power), C_p, is the machine power coefficient. In an idealized wind turbine no losses are experienced and the power coefficient, C_p, is equal to Betz' limit (i.e. $C_{p,Betz} = 16/27$) and $\eta = 1$. Of course, in reality both the drive train efficiency and the power coefficient cannot be maximized. The extent to which the power output is limited by physical laws as well as engineering inefficiency is dependent on the specific characteristics of individual wind turbine types. This aspect will be discussed further in the analysis of the case study.

WECTs have a range of different power output performance curves, which need to be recognized when estimating the potential power output. The power output performance curves are not only defined by parameters such as the power coefficient and the drive train efficiency but also constrained by cut-in speed, furl-out speed and rated wind speed. Where the cut-in wind seed, v_c, is the minimum wind velocity to generate power from a turbine, the rated wind speed, v_R, is the wind speed at which the 'rated power' of a WETC is achieved and generally corresponds to the point at which the conversion efficiency is near its maximum and furl-out wind speed, v_F, is the wind speed at which the turbine shuts down to prevent structural damage.

To account for the above-mentioned constraints we can formulate a novel formula for the average electrical power output of a turbine, $\overline{P_{WTA}}$:

$$\overline{P_{WTA}} = \begin{cases} \left(\sum_{j=1}^{N_B} \left\{ \exp\left[-\left(\dfrac{v_{j-1}}{c} \right)^k \right] - \exp\left[-\left(\dfrac{v_j}{c} \right)^k \right] \right\} P_{WT}\left(\dfrac{v_{j-1} + v_j}{2} \right) \right) & (v_c \leq v \leq v_R) \\[4ex] \left\{ \sum_{j=1}^{N_B} \left\{ \exp\left[-\left(\dfrac{v_{j-1}}{c} \right)^k \right] - \exp\left[-\left(\dfrac{v_j}{c} \right)^k \right] \right\} P_{WT}(v_r) \right\} & (v_R \leq v \leq v_F) \\[4ex] 0 & (v < v_c \ and \ v > v_F) \end{cases}$$

The energy production of the wind turbine WE(t) over time t can thus be calculated as

$$WE(t) = \overline{P_{WTA}}t$$

Another way of stating the energy output from a wind turbine is to look at the capacity factor for the turbine in its particular location. The capacity factor CF, is the actual energy output over a given period of time, WE(t), divided by the theoretical maximum energy output (i.e. this means that the machine is constantly running at its rated output) during the selected time-span, RO(t). This can be formulated as

$$CF = \frac{WE(t)}{RO(t)}$$

Theoretically capacity factor vary from 0 to 100%. In practice they usually range from 20 to 70% and mostly be around 20-30 percent. However, the economic feasibility of a wind turbine does not of course depend on the capacity factor of a wind turbine alone but also depends on the costs of alternative power systems. Therefore, a low capacity factor does not automatically render a wind turbine project unfeasible.

In order to maximize the energy output of a given wind regime the optimum wind speed, v_{opt}, needs to be determined. The optimum wind speed indicates at what wind velocity most energy is available in a given wind regime. It is at this particular wind speed that engineers should ensure that the power coefficient is most efficient to allow for the highest energy conversion of a turbine. The optimum wind speed can be calculated as follows (Lu et al., 2002):

$$v_{opt} = c\left(\frac{k+2}{k} \right)^{\frac{1}{2}}$$

In this regard, the power density of a turbine is a good comparative indicator to show the average power output per m^2 of wind swept area, A, at a given site. This can be defined as

$$\text{Power Density} = \frac{\overline{P_{WTA}}}{A}$$

Another important aspect of that critically determines the energy output of a turbine is elevation. In many cases the available recorded wind speed data has been measured at a lower level than the planned hub height of the wind turbine. As wind velocity increases vertically the recorded wind speed data can be adjusted using the following standard formula (Borowy

and Salameh, 1996.) where v is the projected wind speed, v_i the wind speed at reference height, H the hub height of a turbine, Hi the reference height and α the power-law exponent.

$$v = v_i \left(\frac{H}{H_i} \right)^{\alpha}$$

α is often quoted to have a value of 1/7 and is seen as a reasonable power law exponent for even and unobstructed landscapes. However, where WECT development is planned either offshore or near woodlands or close to any other non flat terrains this value can differ subsequently and a more through analysis of α is necessary. Justus as well as Counnihan offer mathematical solution for 'fitting' α to these environments (Manwell et al., 2002).

4.1 **Hypothetical Wind Generated Electric Power**:

Hypothetical wind generated electric power output at Kati Bandar has been estimated by using the 600KW wind turbine bonus 600/44 MK IV type. The cut in wind speed of this turbine is 3m/s and cutout wind speed is 25m/s. Rotor diameter of this turbine is 44 meters and hub height has been taken as 50 meters. The monthly and annual wind generated electric power outputs at Kati Bandar along with the capacity factor are given in table 4

Table-4: Hypothetical wind generated electric energy output & capacity factor for a Bonus 600/44MK IV Turbine at Kati Bandar

PMD Calculator (using 50M)				
Month	Input W/m^2	Output W/m^2	C.F.	KWh / Month
January			15%	65961
February			21%	85168
March			20%	88211
April			41%	175467
May			60%	268654
June			46%	198266
July			66%	296318
August			32%	144365
September			35%	149898
October			13%	59613
November			11%	47860
December			15%	65038
Annual			**31%**	**1607601**

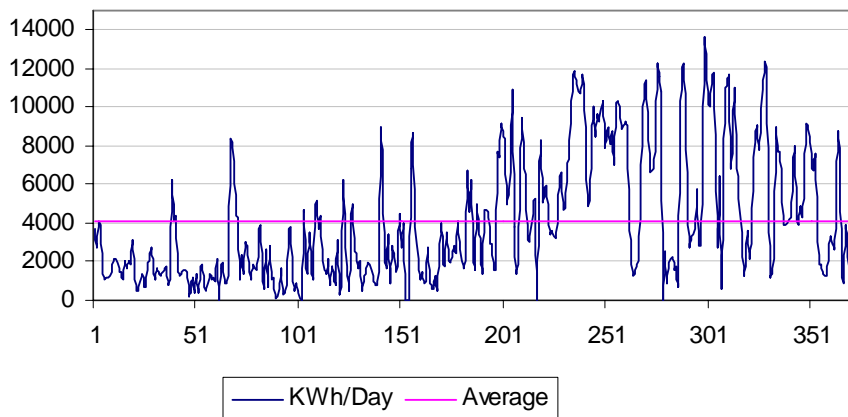| Wind Turbine Specification	
Turbine	Bonus 600/44 MKIV
Power	600 KW
Cut in Wind	3m/s
Cut out Wind	25 m/s
Rotor Diameter	44m
Hub Height	50m

Fig 21 **Kati Bandar from Oct 2002 to September 2003 Annual Average Diurnal variation of Wind Generated Electic Energy Output**
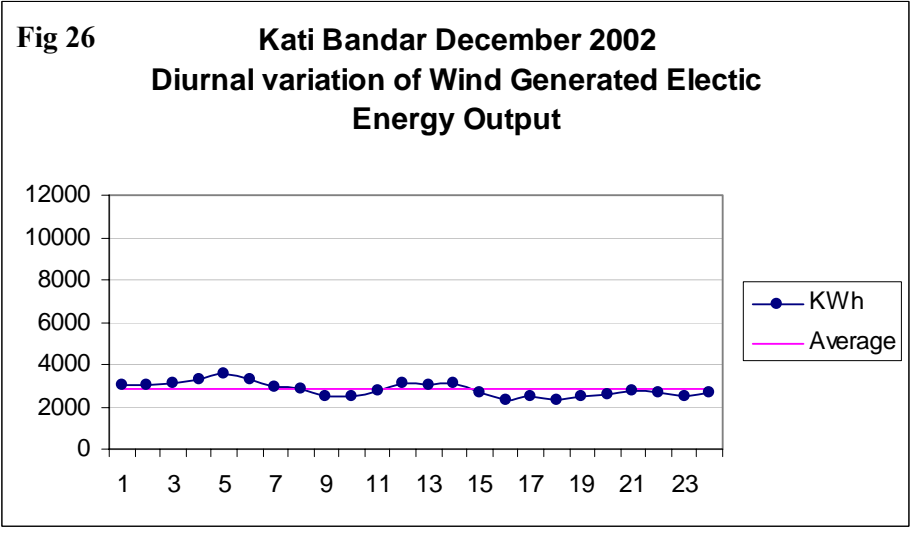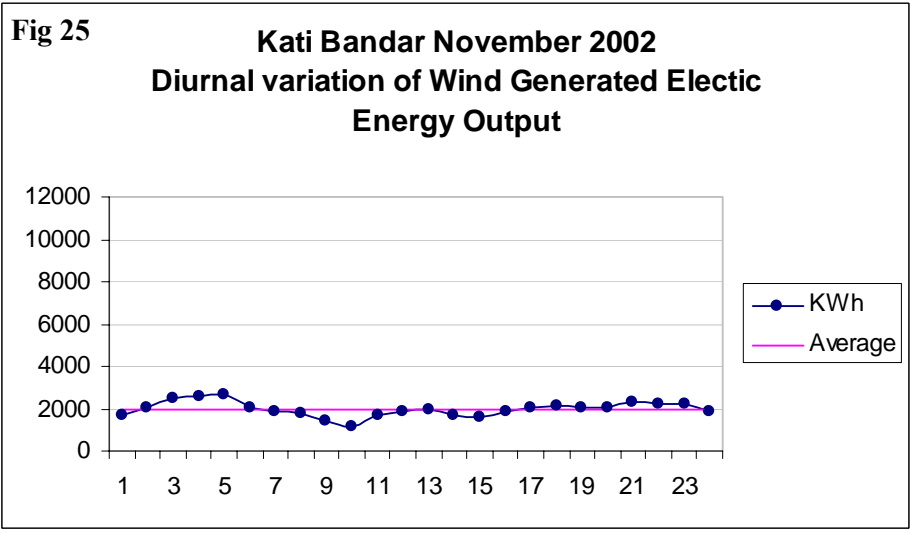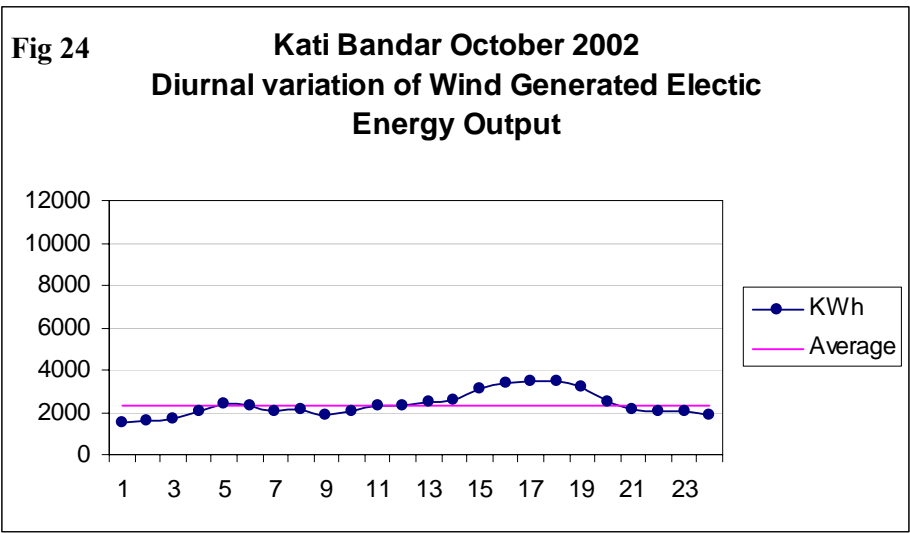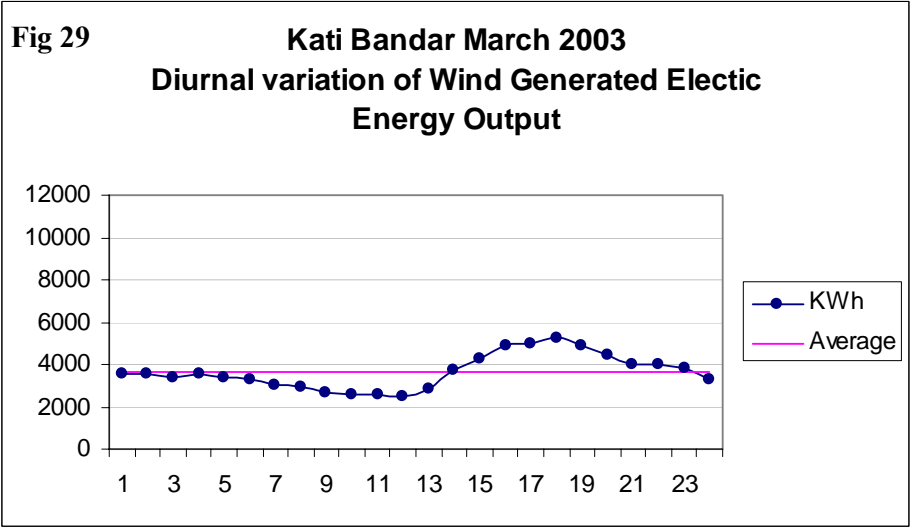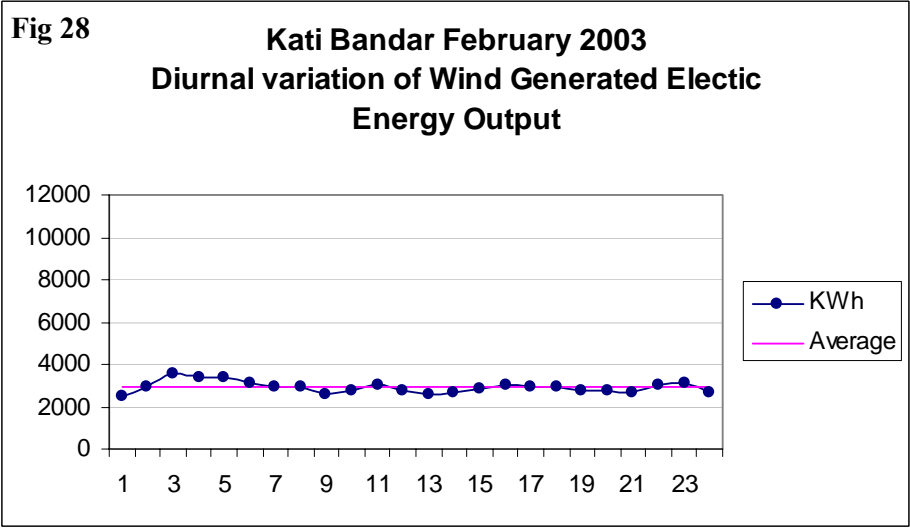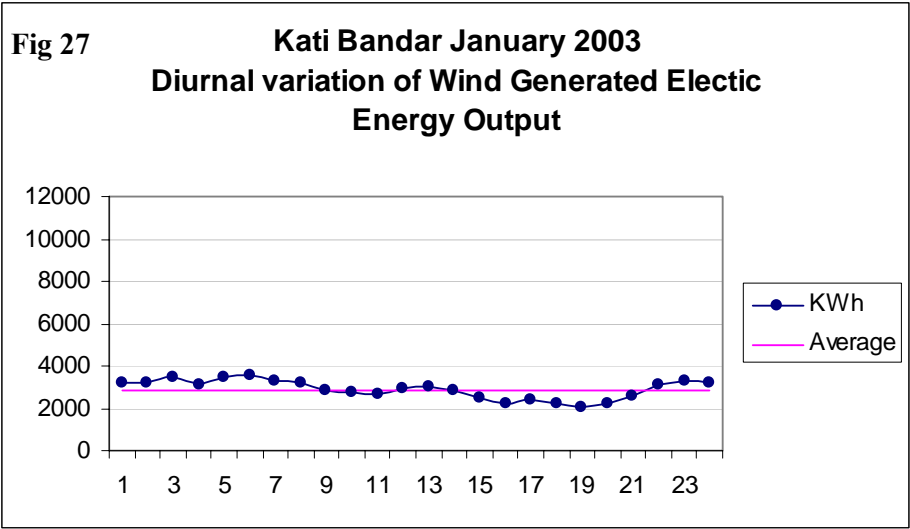

Fig 22 **Kati Bandar from Oct 2002 to September 2003 Monthly Wind Generated Electic Energy Output in KWh**

Fig 23 **Kati Bandar From October 2002 to September 2003 Daily Wind Generated Electic Energy Output in KWh**

Fig 24

Kati Bandar October 2002
Diurnal variation of Wind Generated Electic
Energy Output

Fig 25

Kati Bandar November 2002
Diurnal variation of Wind Generated Electic
Energy Output

Fig 26

Kati Bandar December 2002
Diurnal variation of Wind Generated Electic
Energy Output

Fig 27 Kati Bandar January 2003 Diurnal variation of Wind Generated Electic Energy Output

Fig 28 Kati Bandar February 2003 Diurnal variation of Wind Generated Electic Energy Output

Fig 29 Kati Bandar March 2003 Diurnal variation of Wind Generated Electic Energy Output

Fig 30

**Kati Bandar April 2003
Diurnal variation of Wind Generated Electic
Energy Output**

Fig 31

**Kati Bandar May 2003
Diurnal variation of Wind Generated Electic
Energy Output**

Fig 32

**Kati Bandar June 2003
Diurnal variation of Wind Generated Electic
Energy Output**

Fig 33

**Kati Bandar July 2003
Diurnal variation of Wind Generated Electic
Energy Output**

Fig 34

**Kati Bandar August 2003
Diurnal variation of Wind Generated Electic
Energy Output**

Fig 35

**Kati Bandar September 2003
Diurnal variation of Wind Generated Electic
Energy Output**

Mon/Hrs	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24 Hrs
Oct 2002	1553	1617	1695	2030	2401	2270	2006	2109	1827	2063	2336	2292	2518	2593	3099	3337	3504	3506	3198	2485	2121	2040	2026	1825	56,451
Nov 2002	1683	2054	2480	2605	2679	2085	1904	1811	1448	1190	1681	1904	1943	1661	1565	1851	2017	2145	2054	2029	2268	2253	2181	1885	47,375
Dec 2002	3054	3054	3094	3319	3584	3249	2919	2817	2479	2481	2730	3084	3056	3134	2642	2302	2508	2322	2528	2541	2769	2659	2467	2706	67,499
Jan 2003	3173	3202	3426	3142	3491	3547	3253	3234	2859	2728	2688	2912	3015	2807	2498	2260	2420	2234	2014	2266	2588	3067	3255	3163	69,241
Feb 2003	2485	2909	3520	3347	3412	3110	2918	2948	2616	2741	3065	2793	2568	2692	2809	2999	2898	2914	2730	2754	2707	3000	3119	2642	69,696
Mar 2003	3531	3550	3378	3537	3415	3248	3021	2953	2680	2617	2604	2527	2845	3718	4274	4872	4941	5289	4887	4412	3994	3958	3805	3315	87,371
Apr 2003	5671	5752	5897	5835	5651	5664	5753	5635	5680	5541	4819	5397	6210	6855	7895	8272	8463	8019	7121	6528	6267	5810	5637	5393	149,768
May 2003	8130	8057	8000	8025	8153	8272	8110	8771	9057	8967	9403	9698	10364	10927	11306	11643	11589	11217	10474	10170	9311	8866	8631	8372	225,514
Jun 2003	9072	9082	9141	9038	8796	8684	8117	8967	9633	9627	9861	10388	10561	10794	10741	10769	11174	10899	10404	9807	9001	8463	8357	8494	229,869
Jul 2003	7892	7601	7692	7502	7390	7292	7141	7689	7988	8226	7895	8735	7921	8391	8646	8647	9440	9181	9124	8345	7541	7727	7942	7778	193,729
Aug 2003	7389	7338	7297	7759	7579	6935	6908	6901	7383	8142	8466	8391	8636	9161	9235	9276	9318	8650	8334	7484	7461	6901	6778	6838	188,559
Sep 2003	5403	5851	5985	5969	5659	5353	5461	5218	5661	6320	6422	6752	7020	6975	6987	7061	7316	6493	5599	4999	4548	4524	4638	5073	141,288
KWh	59,035	60,068	61,605	62,108	62,211	59,709	57,513	59,053	59,312	60,643	61,969	64,873	66,656	69,707	71,699	73,289	75,589	72,868	68,466	63,822	60,575	59,268	58,837	57,483	1,526,360

Fig 36   **Kati Bandar from Oct 2002 to September 2003 Diurnal variation of Hypothetical Energy output for a Bonus 600/44MKIV Turbine**