Pakistan Meteorological Department

A STUDY OF WIND POWER POTENTIAL

AT

Kallar Kahar - CHAKWAL (PUNJAB)

By using SODAR

Technical Report No. Sodar-01/2009

(Preliminary report based on 01 month data)

JULY-2009

EXECUTIVE SUMMARY

Pakistan Meteorological Department (PMD) conducted a wind power potential survey of Kallar Kahar, District Chakwal. In this report the analysis based on data collected through SODAR wind profiler installed near Sardhi some 15 km towards South from Kallar Kahar for the month of June-2009. Wind data with ten minute average speed and direction were collected from 20 to 200 meters. Analysis in this report is based on the data of four heights 20m, 30m, 50m and 80m.

At 20 meter we have the Average wind speed reached at 6.41 m/s during the period, at 80 meter the average wind speed is 6.89 m/s. According to Wind data, the maximum wind speed is available in the day and night time thought-out the whole month. The wind frequency distribution of 20m, 30m, 50m and 80m shows that during 65%, 67%, 70% and 74% of the time wind speed is above 5 m/s respectively.

Sometimes simply wind speed averages do not give the true picture of the actual wind power potential of an area. For this purpose it is common to assign areas to one of the seven wind classes based on “Wind Power Density” of the area. Monthly wind power density has been computed and added in the report. The total power density of Kallar Kahar at 50m height is **293 W/m^2.** According to international wind classification, this power density categorizes Kallar Kahar as a marginal site for wind power generation.

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 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 resources. Where are the best potential wind sites located? How much energy could be extracted from the wind at those sites?

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 Coriolis 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 resources characteristics?

To answer these questions and to provide wind resources 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. After completion of Phase-I, Phase-II is started which covers the Northern parts of Pakistan. Besides these studies, PMD has the honour of conducting studies of other potential sites e.g. Kot-Sabzal (Rajanpur), Hari-chand (Charsada), Chitral and Kallar Kahar (Chakwal).

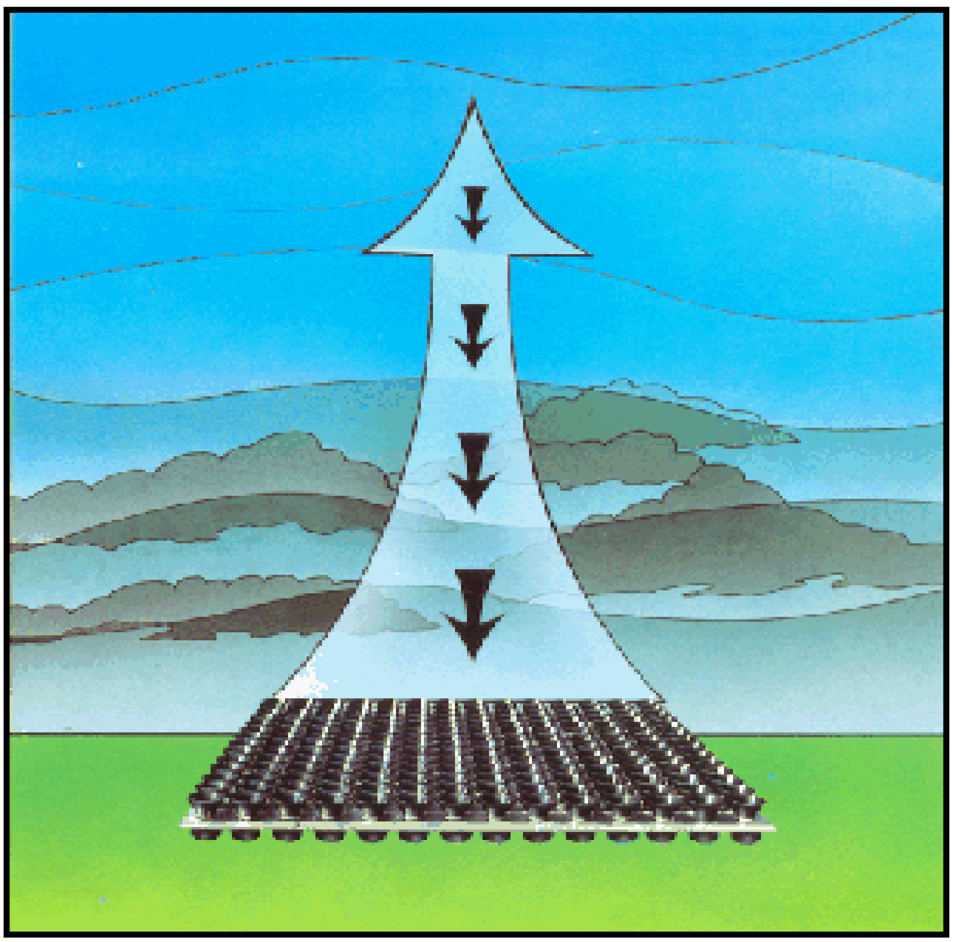
2.1 STUDY AREA:

SODAR (Sonic Detection and Ranging) installed at village Sardhi, some 15 km towards south from Kallar Kahar (Motorway-2) in District Chakwal.

Latitude and Longitude of the site is: **Latitude: 32.70º, Longitude: 72.73º**.

2.2 DATA SOURCE:

To undertake this study SODAR (PA0) system is used. This SODAR System records average wind speed from 20 to 200 meters. It consists of two main parts data receiver and antenna. The SODAR processes the echo of an acoustic pulse, which is directed into the atmosphere. The frequency shift of the echo varies according to the wind speed (this is the Doppler Effect) while the echo intensity varies according to thermal turbulence and structure. SODAR uses a single, multicellular antenna whose beam is steered electronically. The basic antenna is composed of 52 elements. It is capable of measuring up to 200 m.

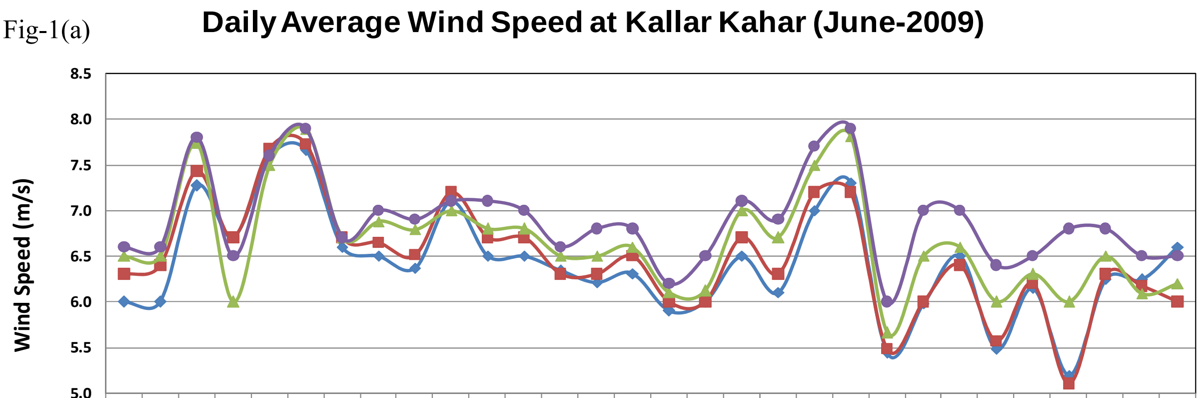


DOPLLER EFFECT OF SODAR

3.1 Average Wind Speed:

Fig-1 (a) and Fig-1(b) shows the daily Average wind speeds for the month of June-2009 at the heights of 20m, 30m, 50m and 80m in line and column graphs respectively. Average wind speed at Kallar Kahar for one month calculated at the heights of 20 meter, 30 meter, 50 meter and 80 meter are 6.41 m/s, 6.48 m/s, 6.66 m/s and 6.89 m/s respectively.

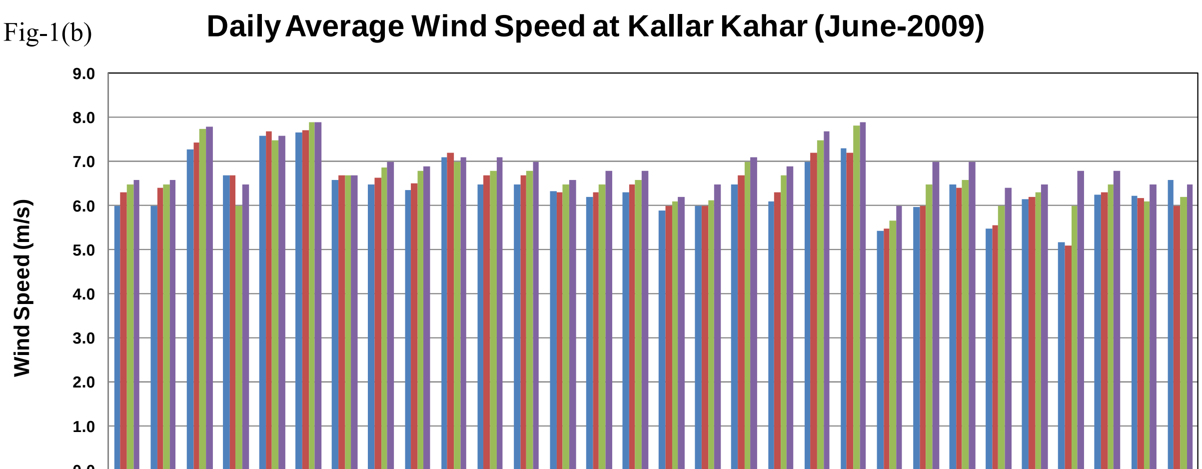
Fig-1(a)



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
20m WS	6.0	6.0	7.3	6.7	7.6	7.7	6.6	6.5	6.4	7.1	6.5	6.5	6.3	6.2	6.3	5.9	6.0	6.5	6.1	7.0	7.3	5.4	6.0	6.5	5.5	6.2	5.2	6.3	6.2	6.6
30m WS	6.3	6.4	7.4	6.7	7.7	7.7	6.7	6.7	6.5	7.2	6.7	6.7	6.3	6.3	6.5	6.0	6.0	6.7	6.3	7.2	7.2	5.5	6.0	6.4	5.6	6.2	5.1	6.3	6.2	6.0
50m WS	6.5	6.5	7.7	6.0	7.5	7.9	6.7	6.9	6.8	7.0	6.8	6.8	6.5	6.5	6.6	6.1	6.1	7.0	6.7	7.5	7.8	5.7	6.5	6.6	6.0	6.3	6.0	6.5	6.1	6.2
80m WS	6.6	6.6	7.8	6.5	7.6	7.9	6.7	7.0	6.9	7.1	7.1	7.0	6.6	6.8	6.8	6.2	6.5	7.1	6.9	7.7	7.9	6.0	7.0	7.0	6.4	6.5	6.8	6.8	6.5	6.5

Days

Fig-1(b)



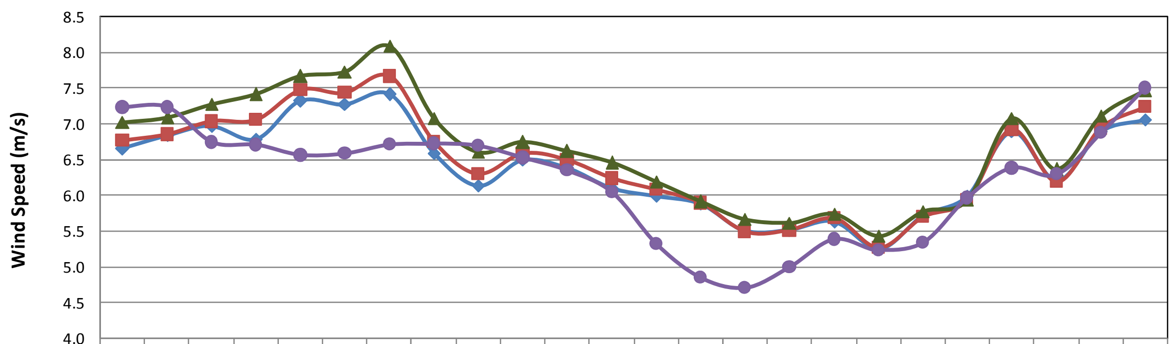
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
20m WS	6.0	6.0	7.3	6.7	7.6	7.7	6.6	6.5	6.4	7.1	6.5	6.5	6.3	6.2	6.3	5.9	6.0	6.5	6.1	7.0	7.3	5.4	6.0	6.5	5.5	6.2	5.2	6.3	6.2	6.6
30m WS	6.3	6.4	7.4	6.7	7.7	7.7	6.7	6.7	6.5	7.2	6.7	6.7	6.3	6.3	6.5	6.0	6.0	6.7	6.3	7.2	7.2	5.5	6.0	6.4	5.6	6.2	5.1	6.3	6.2	6.0
50m WS	6.5	6.5	7.7	6.0	7.5	7.9	6.7	6.9	6.8	7.0	6.8	6.8	6.5	6.5	6.6	6.1	6.1	7.0	6.7	7.5	7.8	5.7	6.5	6.6	6.0	6.3	6.0	6.5	6.1	6.2
80m WS	6.6	6.6	7.8	6.5	7.6	7.9	6.7	7.0	6.9	7.1	7.1	7.0	6.6	6.8	6.8	6.2	6.5	7.1	6.9	7.7	7.9	6.0	7.0	7.0	6.4	6.5	6.8	6.8	6.5	6.5

Days

3.2 Diurnal Wind speed Variation:

Fig-2 shows the diurnal wind speed variations at Kallar Kahar for June-2009. The wind speed is generally the same during day and night. In early morning it reaches maximum, wind speeds are around 7.4 m/s, 7.7 m/s, and 8.1 m/s at 20 meter, 30 meter and 50 meter height respectively.

Fig-2 **Diurnal Variation Wind Speed at Kallar Kahar (June-2009)**



	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
WS10m	6.7	6.8	7.0	6.8	7.3	7.3	7.4	6.6	6.1	6.5	6.4	6.1	6.0	5.9	5.5	5.5	5.6	5.3	5.7	6.0	6.9	6.2	6.9	7.1
WS30m	6.8	6.9	7.0	7.1	7.5	7.4	7.7	6.8	6.3	6.6	6.5	6.2	6.1	5.9	5.5	5.5	5.7	5.3	5.7	5.9	6.9	6.2	6.9	7.2
WS50m	7.0	7.1	7.3	7.4	7.7	7.7	8.1	7.1	6.6	6.7	6.6	6.5	6.2	5.9	5.7	5.6	5.7	5.4	5.8	5.9	7.1	6.4	7.1	7.5
WS80m	7.2	7.2	6.7	6.7	6.6	6.6	6.7	6.7	6.7	6.5	6.4	6.0	5.3	4.9	4.7	5.0	5.4	5.2	5.3	6.0	6.4	6.3	6.9	7.5

PST (Hours)

3.3 Wind speed Frequency Distribution:

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

3.3.1 *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.

3.3.2 *Relative Frequency:*

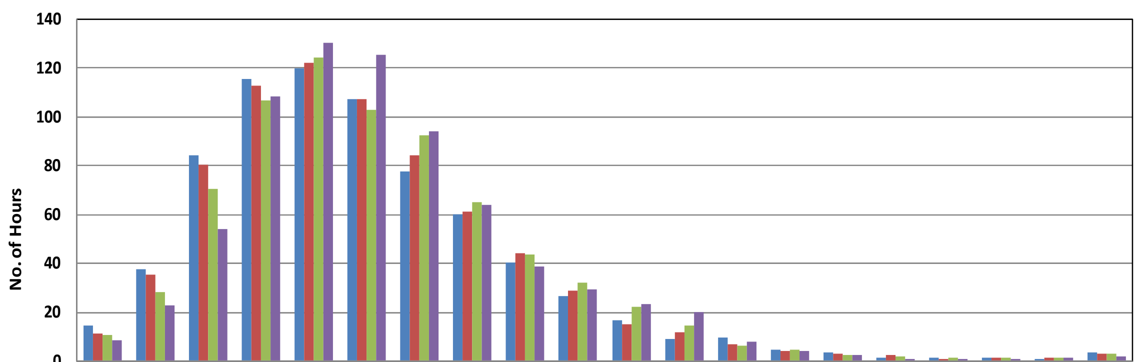
It is proportional wind speed in each bin. It can be viewed as the estimate of probability of given wind speed in the bin. Relative frequency is defined as:

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

3.3.4 *Wind Frequency Distribution:*

Fig-3 shows the wind frequency distribution at Kallar Kahar. We can see that at 20 meter during 120 hours wind speed is 5 m/s, at 30 meter during 122 hours wind speed is 5 m/s, at 50 and 80 meters during 124 and 130 hours wind speed is 5 m/s and so on.

Fig-3 **Wind Frequency Distribution at Kallar Kahar (June-2009)**



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
20m	15	38	84	115	120	107	77	60	40	26	17	9	9	4	4	1	1	1	1	3
30m	11	35	80	112	122	107	84	61	44	29	15	12	7	4	3	2	1	1	1	3
50m	11	28	70	107	124	103	92	65	44	32	22	14	6	5	2	2	1	1	1	3
80m	8	23	54	108	130	125	94	64	39	29	23	20	8	4	2	1	1	1	1	2

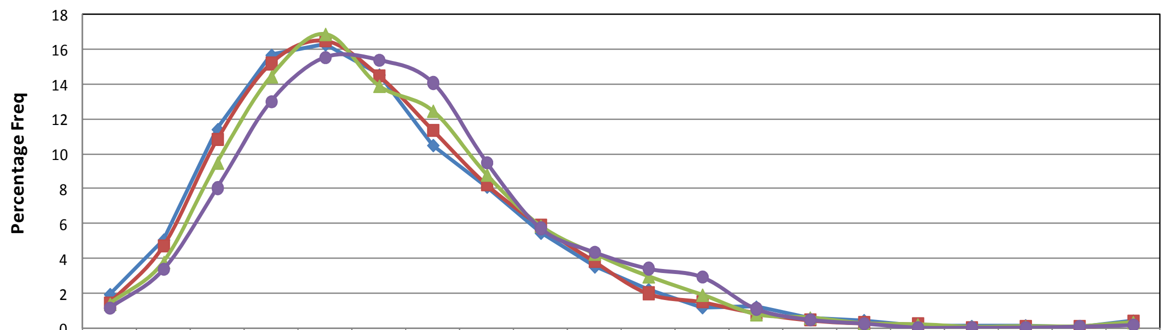
Wind Speed (m/s)

3.3.5 *Percentage Wind Frequency Distribution:*

Fig-4 shows the percentage wind frequency distribution at Kallar Kahar. At 80 meters we find that during 15.5% of time wind is 5m/s, at 50 meters 16.9% of the time wind is 5m/s and at 30 meters 16.5% of the time it is 5 m/s.

Fig-4

Percentage Wind Frequency Distribution at Kallar Kahar (June-2009)



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
20m	2.0	5.1	11.4	15.7	16.3	14.6	10.5	8.1	5.5	3.6	2.3	1.2	1.3	0.6	0.5	0.2	0.1	0.2	0.1	0.5
30m	1.5	4.8	10.9	15.2	16.5	14.5	11.4	8.3	5.9	3.9	2.0	1.6	0.9	0.5	0.3	0.3	0.1	0.1	0.1	0.4
50m	1.4	3.8	9.5	14.4	16.9	13.9	12.5	8.8	5.9	4.3	3.0	2.0	0.8	0.6	0.3	0.3	0.1	0.1	0.1	0.4
80m	1.2	3.4	8.1	13.0	15.5	15.4	14.1	9.5	5.8	4.4	3.5	3.0	1.2	0.5	0.3	0.1	0.1	0.1	0.2	0.3

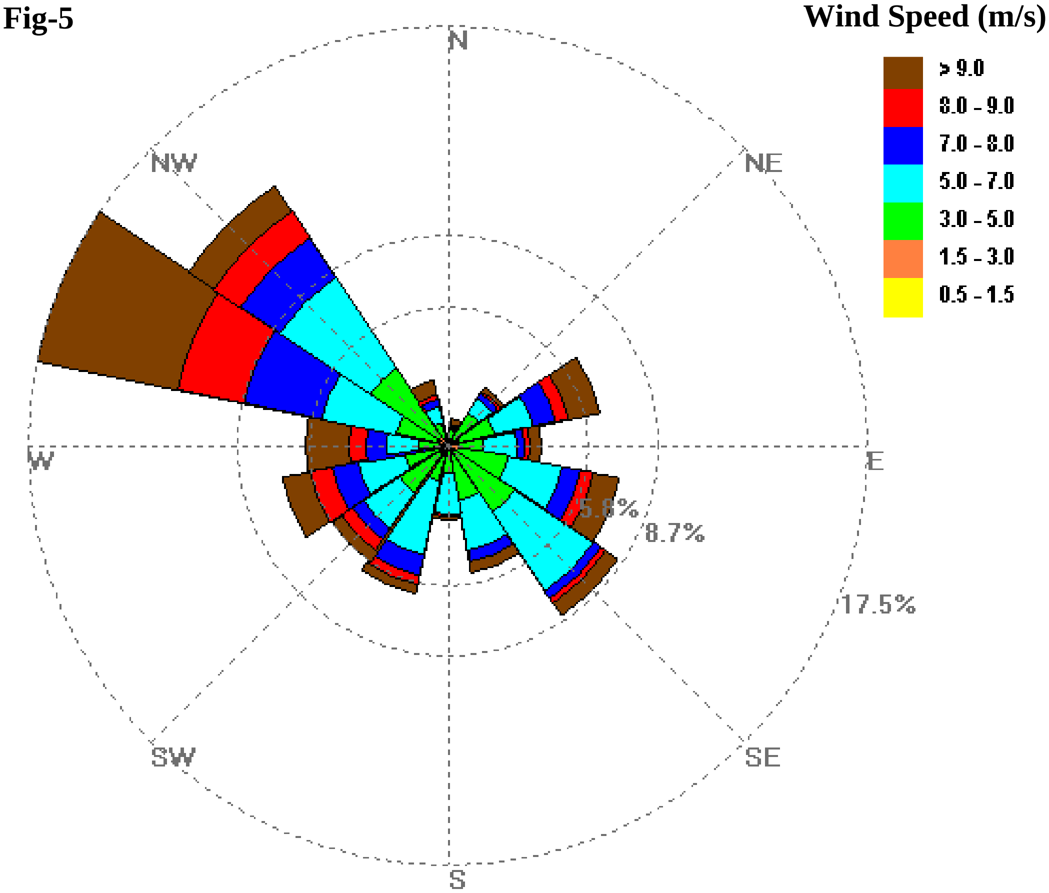
Wind Speed (m/s)

3.4 Wind Rose:

Fig-5 shows the Wind Rose based on 01 month data of June 2009 collected at 50 meters height. Wind Rose indicates that the wind direction is mostly between West and North West. The average wind speed is 6.66 m/s and the percentage of wind speed greater than 5 m/s is 70%.

Wind Rose at Kallar Kahar (50m height during 01 month)

Fig-5



Average Wind Speed at 50m	Average Wind Direction at 50m	Wind speed greater than 5 m/s
6.66 m/s	216°	70%

3.5 Wind speed statistic:

3.5.1 *The statistical Mean:*

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

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

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

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

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

3.5.2 *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

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

3.5.3 *Standard Deviation*

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

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

3.6 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.

3.6.1 *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	Poor	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/Fair	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	Outstanding	7.4 – 8.2	480 – 640	8.0 – 8.8	600 – 800
7	Superb	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

3.6.2 ***Power of wind Energy:***

A parcel of Wind possesses kinetic energy

$$E = \frac{1}{2} m V^2$$

From this, power density is calculated as

$$P = \frac{e}{t} = \frac{1}{2} \frac{dm}{dt} V^2$$

Where $\frac{dm}{dt}$ is the mass of air following time.
From fluid dynamics, it can be proved that

$$\frac{dm}{dt} = \varphi A V$$

Volume of cylindrical cross section can be written as

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

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

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

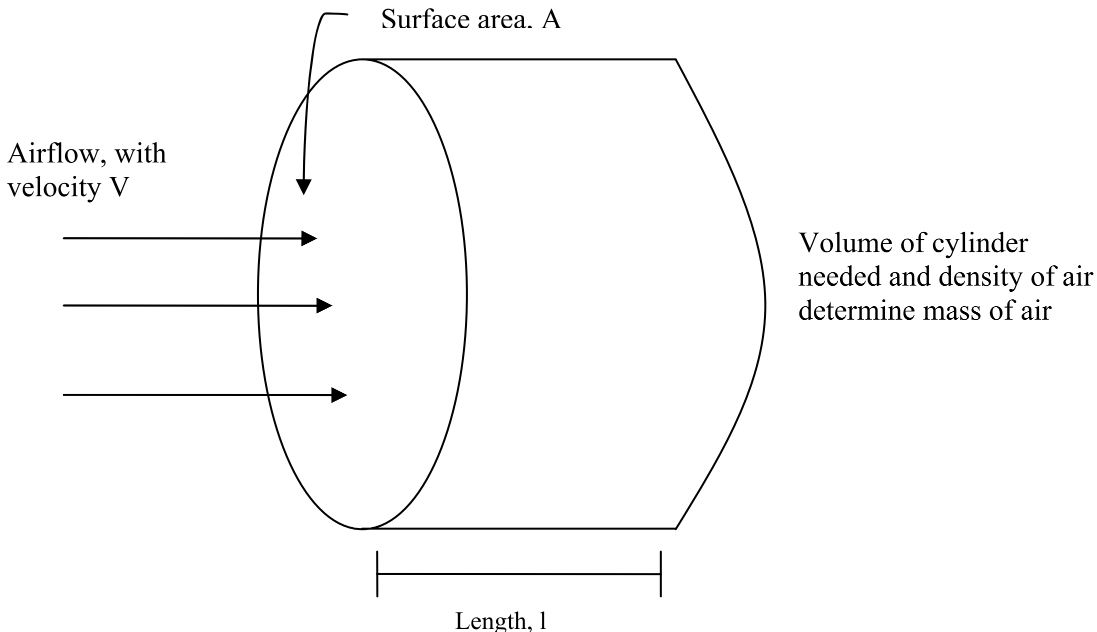
Now mass of wind can be written as

$$M = \varphi A v t$$

Differentiating

$$\frac{dm}{dt} = \varphi A V \frac{d}{dt(t)} = \varphi A V$$

Where φ is density of wind and others parameters have been defined in diagram.



So the power is then,

$$P = \tfrac{1}{2}\, \tfrac{dm}{dt}\, V^2 = \tfrac{1}{2}\varphi AVT/t\ V^2$$

$$= \tfrac{1}{2}\varphi AV^3$$

And power density

$$P/A = \tfrac{1}{2}\varphi V^3$$

Density of wind at mean sea level is 1.225 kg/m^3

At 15° C, 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.

3.6.3 ***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 ring 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 wat/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.

3.6.4 ***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.

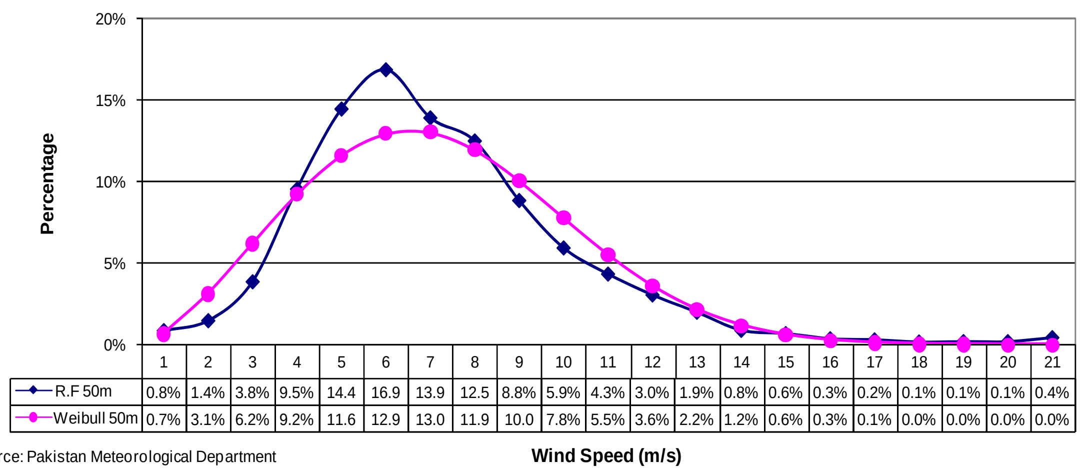
The mathematical description of the wind frequency allows us to match with the turbine power curve. Thus a measure of the average total power capture in a year is achieved. Additionally the choice of turbine cut in and furling speed may be chosen to maximum the total energy capture.

3.7.5 *Weibull Parameters:*

Fig-6 shows the Weibull fit to the relative frequency of wind speed.

Fig-6

Relative Frequency an Weibull Probability at Kallar Kahar (50 m height)



Source: Pakistan Meteorological Department

The Weibull parameters for four different heights 20 meters, 30 meters, 50 meters and 80 meters are given in **Table-2** along with other key results of analysis.

Table-2: Monthly Average Wind, St. Deviation and Wind Power Density at Kallar Kahar

Month: June-2009					
Heights	AWS (m/s)	St Dev	C (m/s)	K	**P/A (w/m^2)**
20m	6.41	2.98	7.23	2.29	**271.21**
30m	6.48	2.91	7.31	2.38	**272.52**
50m	6.66	2.94	7.53	2.44	**293.00**
80m	6.89	2.77	7.64	2.64	**291.30**

Table-3: Hypothetical wind generated electric energy output & Capacity Factor for a Bonus 600/44MK IV Turbine at Kallar Kahar.

PMD Calculator (using 50M at Kallar Kahar) June-2009				
Month	**Input W/m^2**	**Output W/m^2**	**C.F.**	**KWh / Month**
June-2009	**309**	**110**	**28%**	**120,634**