An Investigation on Wind Power Potential of Gharo-Sindh, Pakistan

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Abstract

This paper investigates the wind power potential of Gharo-Sindh, a coastal station of Pakistan. A special wind tower was installed for this purpose and data was collected for three years from April, 2002 to March, 2005 at 10 meters and 30 meters height. The wind data was extrapolated to 50 meters height by using Power Law. The wind resource at 50 meter yielded an annual mean wind speed of 6.6 m/s and mean wind power density of 360 W/m². At this height 600 KW hypothetical wind turbine can achieve an annual capacity factor of 27% and total annual power production of 1401 MWh which make the area economically viable for establishment of commercial wind farms.

Key words: Wind speed frequency; Weibull distribution; wind power density; wind power generation

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 is the best potential wind sites located? How much energy could be extracted from the wind at those sites?

Analysis

Wind data

To undertake this study 30-meters high tower was erected in Gharo, which is a small town near the coast of Sindh, Pakistan. On this tower two wind speed anemometers were installed at the height of 10 meters and 30 meters and wind vane was installed at 10 meters height. Temperature sensor was also installed at 10 meters level. Automatic data logger installed was recording one minute average wind speed at both levels, one minute average wind direction, five minute average temperature and 10 minute average minimum and maxim wind speed. During installation of this wind tower international guidelines were followed regarding local obstructions, height and spacing of sensors and towers etc. This data was collected for three years from April 2002 – March 2005.[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 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

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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 50 meters or above.

In this study Power Law is used to compute the increase in wind speed with height [6]

$$\frac{\mathbf{U}}{\mathbf{U_R}} = \left(\frac{\mathbf{Z-D}}{\mathbf{Z_R}}\right)^{\alpha} \qquad (1)$$

Where:

α	is the power law exponent
$\mathbf{U_R}$	is the wind speed at reference height $\mathbf{Z_R}$

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.

$$\alpha = \frac{\ln\left(\ln\left(Z/Zo\right) / \ln\left(Z_R/Z_O\right)\right)}{\ln\left(Z/Z_R\right)} \approx \frac{1}{\ln\sqrt{Z.Z_R/Z_O}} \qquad (2)$$

Where:

$\mathbf{Z}$	is the measurement height
$\mathbf{Z_R}$	is the reference height
$\mathbf{Z_0}$	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. The Power Law is a simplified expression of the wind profile. This is valid in flat homogeneous terrain. So it does 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. [3]

Type of terrain	Z_o	α
Mud Flats, Ice	10-5 to 3x 10-5	
Calm Sea	2x10-4 to 3x10-4	
Sand	2x10-4 to 10-3	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	

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.

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 $3 < X \leq 4$ 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.

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**

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.

In this regard, the power density of turbine is a good comparative indicator to show the average power output per m² of wind swept area A, at a given site [4]. This can be defined as:

$$\text{Power Density} = \frac{1}{2}\rho A V^3 \qquad (3)$$

Where $\rho\left(\frac{kg}{m^3}\right)$ is the air density and V is the mean speed in (*m/s*). The area *A*, 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.

Weibull Distribution

The Weibull distribution is used to represent wind speed distribution for application in wind loads studies 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 by [5] [8] as:

$$\phi(\mathbf{u}) = \frac{\mathbf{k}}{\mathbf{c}}\left(\frac{\mathbf{u}}{\mathbf{c}}\right)^{\mathbf{k-1}} \mathbf{exp}\left(-\left(\frac{\mathbf{u}}{\mathbf{c}}\right)^{\mathbf{k}}\right) \qquad (4)$$

Where:

U is the wind speed
c is the scale parameter with units of speed
k is the shape parameter and is dimensionless

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

Estimating Wind Generated Power Output

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 [2] [6]:

$$\overline{P_{WT}} = \int_0^\infty P_{WT}(v)\,df(v) \qquad (5)$$

This integral can be replaced with a summation over bins, NB, to calculate the average wind turbine power [6].

$$\overline{P_{WT}} = \sum_{j=1}^{N_B}\left\{\exp\left[-\left(\frac{v_{j-1}}{c}\right)^k\right] - \exp\left[-\left(\frac{v_j}{c}\right)^k\right]\right\} P_{WT}\left(\frac{v_{j-1}+v_j}{2}\right) \qquad (6)$$

The average power of a wind turbine, P_{WT}, at any given wind speed v that is convertible by a turbine is defined by [6] [7] as:

$$P_{WT}(v) = \frac{1}{2}\rho A C_p \eta \upsilon^3 \qquad (7)$$

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 power output performance curves of turbines 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 speed, 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 turbine 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 formula for the average electrical power output of a turbine, $\overline{P_{WTA}}$ [6]:

$$\overline{P_{WTA}} = \begin{Bmatrix} \sum_{j=1}^{N_B} \left\{ \exp\left[-\left(\frac{v_{j-1}}{c} \right)^k \right] - \exp\left[-\left(\frac{v_j}{c} \right)^k \right] \right\} P_{WT}\left(\frac{v_{j-1}+v_j}{2} \right) \\ \sum_{j=1}^{N_B} \left\{ \exp\left[-\left(\frac{v_{j-1}}{c} \right)^k \right] - \exp\left[-\left(\frac{v_j}{c} \right)^k \right] \right\} P_{WT}\left(v_r \right) \end{Bmatrix} \quad \begin{pmatrix} v_c \le v \le v_R \\ v_R \le v \le v_F \\ v < v_c and v > v_F \end{pmatrix} \quad (8)$$

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

$$WE(t) = \overline{P_{WTA}}t \qquad (9)$$

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 [U1] [U4] as

$$CF = \frac{WE(t)}{RO(t)} \qquad (10)$$

Results and Discussion

Wind Rose

Gharo's wind climate is characterised by low wind speed during winter and strong winds during summer and mostly sea breeze from Southwest. Figure-1 shows the Wind Rose based on 36 months data from April, 2002 – March, 2005 collected at 30 meters height and direction at 10 meters. This Wind Rose indicates that most of the time the wind direction was West-Southwest. The annual average wind speed is 6.18 m/s and the percentage of time when wind speed was less than 3 meters is only 22%.

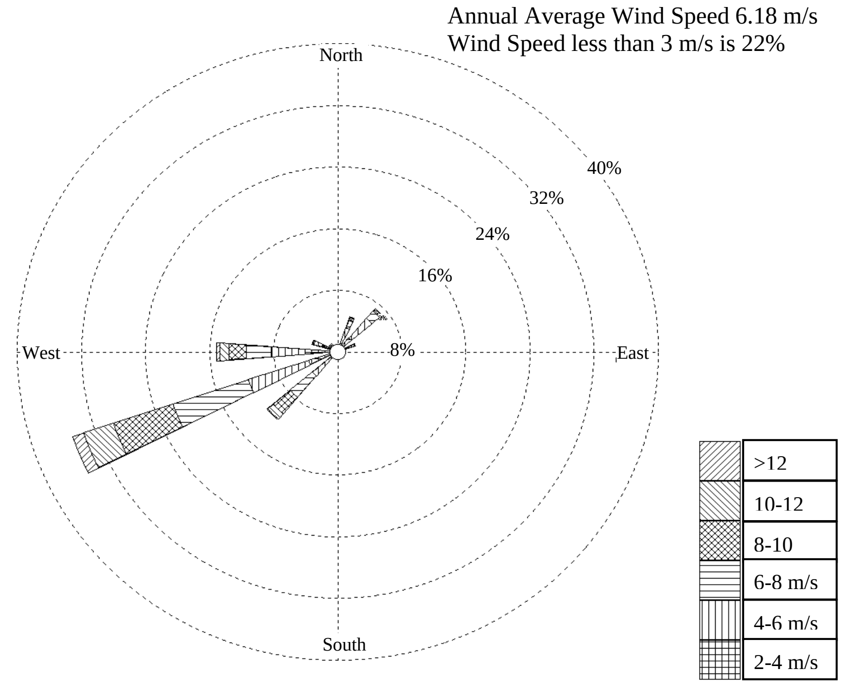

Fig 1: Wind Rose at Gharo (30 meter height)

Average wind speed:

By using the method explained in part 2.2 above, the wind speed at 50 meters has been computed. Figure-2 shows monthly average wind speed at Gharo.

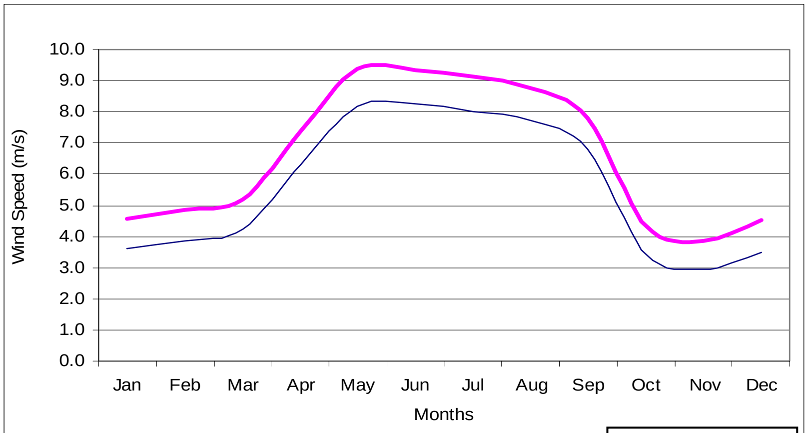

Fig 2: Monthly Average Wind Speed.

At 30 meters height, we have averaged wind speed of greater than 5 m/s during 6-months of the year from April to September. Whereas, the maximum average wind speed of 8.3 m/s is during June. At 50 meters, we have the average wind speed of >5 m/s during 8-months from February to September and annual average is 6.6 m/s at this height. Wind data at 50 meters indicate that there is good wind power potential during at least eleven months of year when the wind speed is >4.5 m/s.

Diurnal Wind Speed Variation:

Figure-3 shows the annual diurnal wind speed variation at Gharo. The wind speed is generally lower during night and after sunrise it starts picking and reaches maximum around 4-5 p.m. which is around 6.9 m/s at 30 meters and 7.9 m/s at 50 meters. Then after sunset it starts generally decreasing and minimum around 6-7 a.m.

Wind Speed Frequency Distribution:

Figure-4 shows the annual cumulative wind frequency distribution at 30 and 50 meters height. The analysis indicate that in a year at a height of 30-meters during 5989 hours the wind speed is greater than 5 m/s which indicate that a wind turbine of 30m hub height having 5m/s cut-in wind speed will produce Electricity for at least 5989 out of 8760 hours in a year and seems enough to generate the electric power. Whereas, at 50-meters, in a year during 6656 hours the wind speed is equal and greater than 5 m/s.

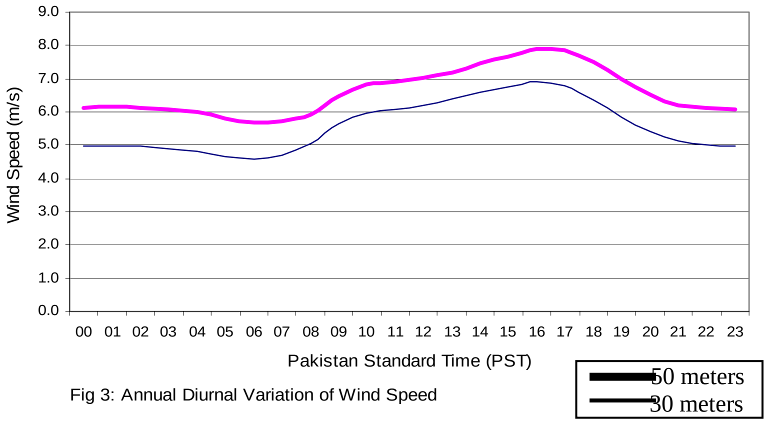

Fig 3: Annual Diurnal Variation of Wind Speed

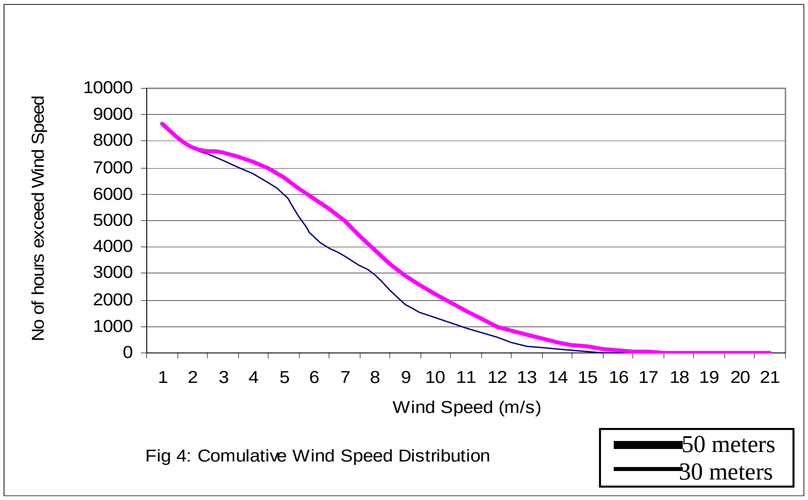

Fig 4: Comulative Wind Speed Distribution

Figure-5 shows the annual frequency distribution. At 50-meters during 852 hours wind speed is 6 m/s, 1088 hours speed is 7 m/s, 980 hours speed is 8 m/s, 711 hours speed is 9 m/s and during 633 hours the wind speed is 10 m/s and so on.

Figure-6 gives this frequency distribution in percentage. At 50-meters we find that during 12.6% of time wind is 7 m/s, 11.3% of the time 8 m/s and 8.2% time it is 9 m/s. This appears to be reasonably enough to generate power from the wind.

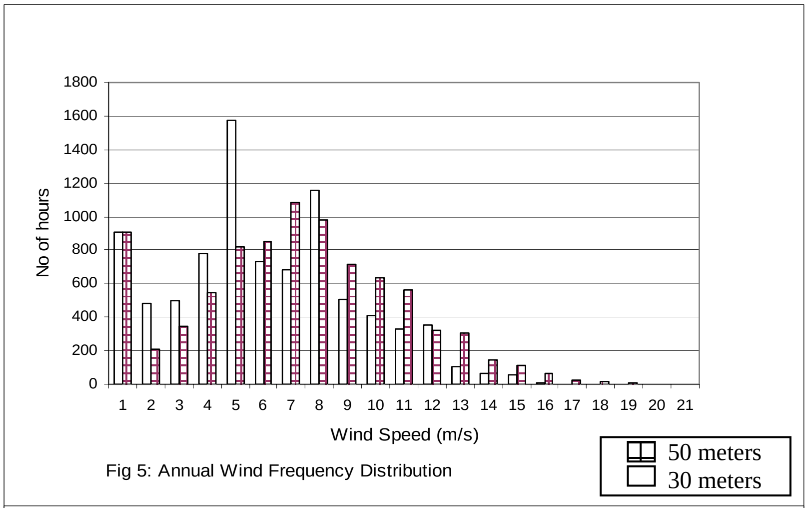

Fig 5: Annual Wind Frequency Distribution

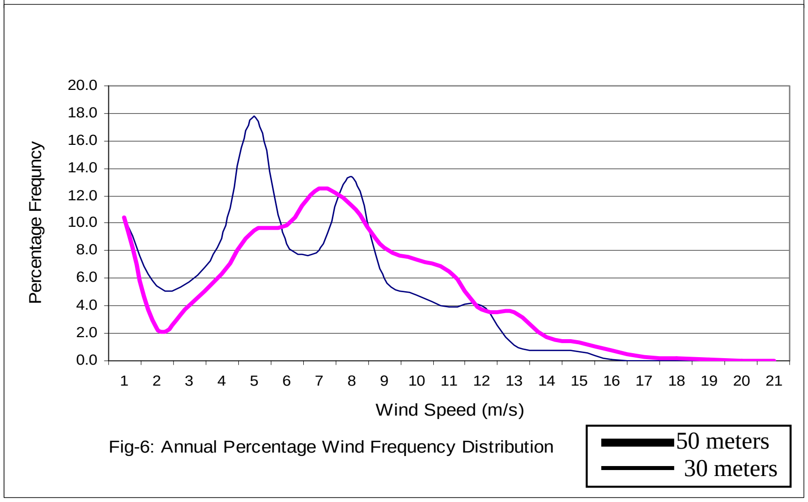

Fig-6: Annual Percentage Wind Frequency Distribution

Power Density:

The monthly power densities at 50-meters height are given in Table-2. This indicates that power density varies from 110 W/m² in Novembers to 730 W/m² in June. We can further note that the power potential, as indicated from the values of the monthly power densities, during the period from October to March is below 200 W/m², which is very low. But the annual power density of the area is 360 W/m², which brings the area into the moderate class-3 category of power potential. Which means that inspite of low wind potential during six months of the year, the area is suitable for large wind farms.

Table 2: Average Monthly Wind Power Density at Gharo (50m)

Month	AvgV (m/s)	St Dev	C (m/s)	K	Temp	Zo	P/A(w/m2)
January	4.6	2.8	5.2	1.7	17.8	3.213	139.3
February	4.9	2.9	5.5	1.8	20.5	3.177	162.0
March	5.2	2.8	5.9	2.0	24.7	2.732	167.4
April	7.4	2.8	8.4	2.9	27.2	1.009	363.7
May	9.4	3.2	10.6	3.2	28.7	0.531	712.0
June	9.3	3.5	10.6	3.0	29.4	0.380	730.4
July	9.1	3.4	10.3	2.9	28.1	0.523	685.4
August	8.8	2.9	9.9	3.3	27.2	0.453	575.6
September	7.8	2.8	8.8	3.0	26.6	0.515	420.6
October	4.4	2.7	5.0	1.7	26.6	3.594	125.9
November	3.8	2.7	4.4	1.5	23.3	4.526	110.0
December	4.5	2.9	5.2	1.6	19.4	4.839	146.4
Annual	6.6	3.7	7.5	1.9	25.0	2.124	359.5

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 3.

Table-3: 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 [U2] [U3]

Weibull Probability Density Function Distribution

In order to observe the Weibull distribution graphically, the Weibull probability density function distribution are shown in Fig-7. The advantage of doing this is that data sets with few or no failures can be analyzed. The Weibull PDF is positively skewed (has a right tail). The graph indicates about 99.5% area under the curve is within the available binning range. If we look at the monthly values of shape parameter k and scale parameter c given in Table-2 we find that the k varies over a wide range from 1.5 during November to the highest value of 3.3 during August with an annual value of k being 1.9. The lowest value of scale parameter c = 4.4 m/s is also observed in November, while the highest value of 10.60 m/s is obtained in May and June.

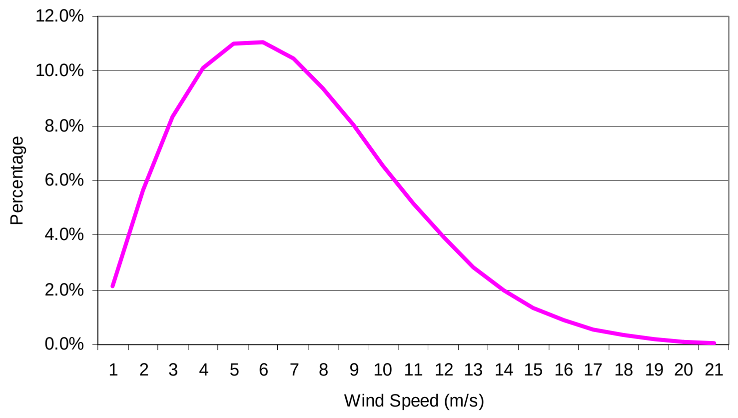

Fig 7: Weibul Probability density function distribution (50m height)

Hypothetical Wind Generated Electric Power

Hypothetical wind generated electric power output at Gharo 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 cut-out 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 Gharo 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 Gharo.

Month	Input W/m2	Output W/m2	C.F.	KWh / Month
January	138	50	13%	56,504
February	159	57	14%	60,056
March	162	60	15%	68,116
April	349	124	32%	136,134
May	679	197	50%	222,477
June	695	193	49%	211,728
July	655	187	47%	210,937
August	552	178	45%	201,031
September	404	140	36%	153,442
October	121	44	11%	49,922
November	107	38	10%	41,243
December	144	51	13%	57,465
Annual	348	105	27%	1,401,010

The data in Table-4 indicate that during the six months period capacity factor achieved could range between 32% to 50% which is relatively high as compare to a common minimum limit of 25% [U4]. Whereas, during remaining six months the capacity factor range between 10-15% which is very low. However, annual capacity factor is still 27% which indicate that this still enough to establish commercially viable wind farms in the area. Further, the total annual output of electric power from a single 600 KW turbine could be 1401 MWh.

Concluding Remarks

Renewable energy resources assessment and power output estimation from a hypothetical wind turbine at Gharo have shown that normally during summer six months April-September, there are strong sustainable winds mostly from Southwest and during this high capacity factor of 32-50% could be achieved. Normally during summer hot months local power demand is also expected to be high. However, during remaining six months the generally moderate winds are experienced and normally during this period local power demands is also low. Annual capacity factor of 27% indicate that summer six months energy production is still compensating the low power output during remaining six months and the area is suitable for establishing commercially viable wind farms.

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References

1. **Chaudhry Qamar Z, Hussain A**. Preliminary Investigation of Wind Power Potential of Gharo-Sindh. PMD Tech. Report No.6/2003
2. **Borowy BS, Salameh ZM. 1996.** Methodology for optimally sizing the Combination of a battery bank and PV array in a wind/PV hybrid system. IEEE Transactions on Energy Conversion EC 11(2): Pages 367-375
3. **Tony Burton, David Sharpe, Nick Jenkins, Ervin Bossanyi**. Wind Energy Handbook. Published by John Wiley and Sons Ltd.; **2001**
4. **Weisser D, Foxon TJ.** Implications of seasonal and diurnal variations of wind velocity for power output estimation of a turbine: a case study of Grenada. Int. J. Energy Res. **2003**; 27:1165-1179
5. **Lam J.C, Lun I.Y.F.** A Study of Weibull parameters using Long-term Wind Observations. Renewable Energy 20 (**2000**), Pages 145-153.
6. **Manwell JF, McGowan JG, Rogers AL. 2002**. Wind Energy Explained: Theory, Design and Application. Wiley: Chichester.
7. **Johnson GL. 1885.** Wind Energy Systems. Prentice-Hall: Englewood Cliffs, NJ.
8. **The Nature of Atmospheric Wind**, Postgraduate Distance Learning Series in Renewable Energy Systems Technology CREST2000.

URL

U1. http://www.ceere.org/rerl/about_wind/RERL_Fact_Sheet_2a_Capacity_Factor.pdf

U2. http://www.awea.org/faq/basicwr.html "American Wind Energy Association"

U3. http://rredc.nrel.gov/wind/pubs/atlas/tables/1-1T.html US Wind Energy Resource Atlas

U4. http://www.awea.org/faq/wwt_basics.html "American Wind Energy Association"