Analysis of Wind Regimes and Performance of Wind Turbines

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With the present day's energy crisis and growing environmental consciousness, the global perspective in energy conversion and consumption is shifting towards sustainable resources and technologies. This resulted in an appreciable increase in the renewable energy installations in different part of the world. For example, Wind power could register an annual growth rate over 25% for the past 7 years, making it the fastest growing energy source in the world. The global wind power capacity has crossed well above 160 GW today [1] and several Multi-Megawatt projects-both on shore and offshore-are in the pipeline. Hence, wind energy is going to be the major player in realizing our dream of meeting at least 20% of the global energy demand by new-renewables by 2020.

Assessing the wind energy potential at a candidate site and understanding how a wind turbine would respond to the resource fluctuations are the initial steps in the planning and development of a wind farm project. Energy yield from the Wind Energy Conversion System (WECS) at a given site depends on (1) strength and distribution of wind spectra available at the site (2) performance characteristics of the wind turbine to be installed at the site and more importantly (3) the interaction between the wind spectra and the turbine under fluctuating conditions of the wind regime.

Thus, models which integrate the wind resource as well as the turbine performance parameters are to be used in estimating the system performance. Based on the above parameters, methods for assessing the available wind energy resource at

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a candidate site and the performance expected from a wind turbine installed at this site are presented in this chapter.

1 Wind Regime Characteristics

In this section we will discuss how the characteristics of the wind regimes can be incorporated in assessing the wind energy potential as well as estimating the output from a wind energy conversion system.

1.1 Boundary Layer Effects

The first factor to be considered while estimating the wind resource and wind turbine performance at a given site is the variations in wind velocity due to the boundary layer effect. Due to the frictional resistance offered by the earth surface (caused by roughness of the ground, vegetations etc.) to the wind flow, the wind velocity may vary significantly with the height above the ground. For example, wind profile at a site is shown in Fig. 1. Variations in the wind velocity with height are quite evident in the figure. Thus, if the wind data available are not collected from the hub height of the turbine, the data are to be corrected for the boundary layer effect.

Ground resistance against the wind flow is represented by the roughness class or the roughness height (Z_0). The roughness height of a surface may be close to zero (surface of the sea) or even as high as 2 (town centers).

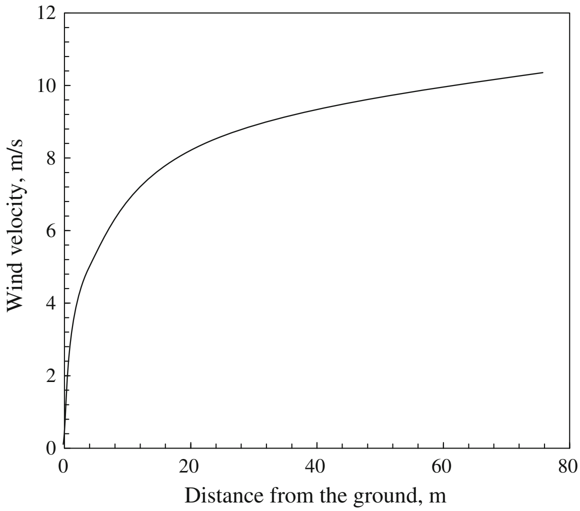


Fig. 1 Variation of wind velocity with height [2]

Some typical values for the roughness heights are 0.005 for flat and smooth terrains, 0.025–0.1 for open grass lands, 0.2–0.3 for row crops, 0.5–1 for orchards and shrubs and 1–2 for forests, town centers etc. On the basis of the roughness height of the terrain, wind data collected at different heights are to be extrapolated to the hub height of the turbine. If the wind data are available at a height Z and the roughness height is Z_0, then the velocity at a height Z_R is given by [3, 4].

$$V(Z_R) = V(Z)\frac{\ln\left(Z_R/Z_0\right)}{\ln\left({}^{Z}/_{Z_0}\right)} \tag{1}$$

where $V(Z_R)$ and $V(Z)$ are the velocities at heights Z_R and Z respectively. Thus, if the velocity of wind measured at a height of 10 m is 7 m/s and the roughness height is 0.1, the velocity at the hub height—say 100 m—is 10.5 m/s. It should be noted that the power available at 100 m would be 3.4 times higher than at 10 m.

In some cases, we may have data from a reference location (meteorological station for example) at a certain height. This data is to be transformed to a different height at another location with similar wind profile but different roughness height (for example, the wind turbine site). Under such situations, it is logical to assume that the wind velocity is not significantly affected by the surface characteristics beyond a certain height. This height may be taken as 60 m from the ground level [5]. With this assumption and equating the velocities at 60 m height at both the sites as per Eq. 1, we get

$$V(Z) = V(Z_R)\left(\frac{\ln\left(60/Z_{OR}\right)\,\ln\left(Z/Z_O\right)}{\ln\left({}^{60}/_{Z_O}\right)\,\ln\left({}^{Z_R}/_{Z_{OR}}\right)}\right) \tag{2}$$

where Z_{OR} is the roughness height at the reference location.

1.2 Wind Velocity Distribution

Being a stochastic phenomena, speed and direction of wind varies widely with time. Apart from the seasonal variations, the differences can be considerable even within a short span of time. These variations can significantly affect the energy yield from the turbine at a given site. For example, a turbine may deliver entirely different amount of energy when it is installed in two sites with the same average wind velocity but different velocity distributions. Similarly, two wind turbines with the same output rating but different in the cut-in, rated and cut-out velocities may behave differently at the same site. Statistical distributions are used to take care of these variations in wind energy calculations.

Several attempts were made to identify the statistical distribution most suitable for defining the characteristics of wind regime. A wide range of distributions are being tried by the researchers. The Weibull distribution, which is a special case of Pierson class III distribution, is well accepted and commonly used for the wind energy analysis as it can represent the wind variations with an acceptable level of accuracy [6–9]. In some situations, Rayleigh distribution—which is a simplified form of Weibull distribution—is also being used. It is worth mentioning that some innovative attempts are also been made by applying the Minimum Cross Entropy (MinxEnt) [10] and Maximum Entropy (ME) [11] principles in wind energy analysis. However, a recent study comparing various statistical distributions in wind energy analysis has established the acceptability of Weibull distribution [9]. Hence we will follow the Weibull distribution in our analysis.

The Weibull distribution can be defined by its probability density function *f(V)* and cumulative distribution function *F(V)* where:

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-(V/c)^k} \tag{3}$$

and

$$F(V) = \int f(V)\, dV = 1 - e^{-(V/c)^k} \tag{4}$$

where k is the Weibull shape factor, c the scale factor and V is the velocity of interest. Here, *f(V)* represents the fraction of time (or probability) for which the wind blows with a velocity V and *F(V)* indicates the fraction of time (or probability) that the wind velocity is equal or lower than V.

From Eqs. 3 and 4, it is evident that k and c are the factors determining the nature of the wind spectra within a given regime. Effects k and c on the probability density and cumulative distribution of wind velocity are demonstrated using the wind data from three potential wind farm sites in Figs. 2 and 3. The site wind velocities are represented in Table 1.

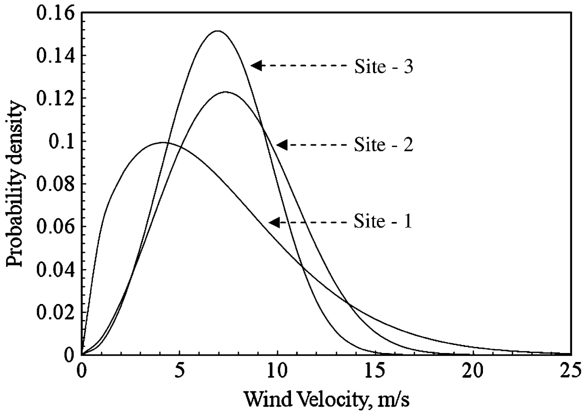


Fig. 2 Effect of Weibull shape factor on the probability density of wind velocity of some potential sites

Fig. 3 Effect Weibull shape factor on the cumulative distribution of wind velocity at some potential sites

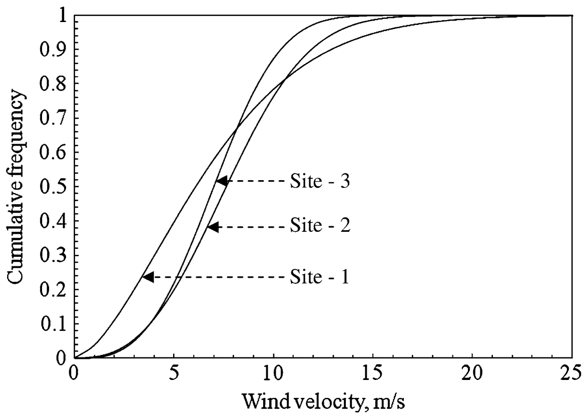


Table 1 Weibull shape and scale factors of some wind farm sites

Site no.	Mean wind velocity, m/s	Standard deviation, m/s	*k*	*c*, m/s
1	6.79	4.11	1.6	7.66
2	7.75	3.11	2.7	8.74
3	6.99	2.50	3.06	7.89

There are several methods for determining k and c from the site wind data. Some of the common methods are the graphical method, moment method, maximum likelihood method, energy pattern factor method and the standard deviation method [2]. For example, in the standard deviation approach, the relationship between the mean (V_m) and standard deviation (σ_V) of the wind velocities and k are correlated as

$$\left(\frac{\sigma_V}{V_m}\right)^2 = \frac{\Gamma\left(1+\frac{2}{k}\right)}{\Gamma^2\left(1+\frac{1}{k}\right)} - 1 \tag{5}$$

Once Vm and σ_V are calculated for a given data set, then k can be determined by solving the above expression numerically. Once k is determined, c is given by

$$c = \frac{V_m}{\Gamma\left(1+\frac{1}{k}\right)} \tag{6}$$

In a simpler approach, an acceptable approximation for k can be made as [7, 12]

$$k = \left(\frac{\sigma_V}{V_m}\right)^{-1.090} \tag{7}$$

and c can be approximated as

$$c = \frac{2\,V_m}{\sqrt{\pi}} \tag{8}$$

1.3 Energy Density

The power available in a wind stream of velocity V, per unit rotor area, is given by

$$P_V = \frac{1}{2}\,\rho_a\,V^3 \tag{9}$$

where P_V is the power and ρ_a is the density of air. The fraction of time for which this velocity V prevails in the regime is given by the probability density function *f(V)*. Thus, the energy contributed by V, per unit time and unit rotor area, is $P_V\,f(V)$. Hence, the total energy contributed by all possible velocities in the wind regime, available for unit rotor area in unit time (that is energy density, E_D) may be expressed as

$$E_D \;=\; \int_0^\infty P_V f(V)\,dV \tag{10}$$

Substituting for *P(V)* and *f(V)* in the above expression and simplifying, we get

$$E_D = \frac{1}{2}\rho_a\frac{k}{c^k}\int_0^\infty V^{(k+2)}e^{-\,(V/c)^k}\,dV \tag{11}$$

This can further be simplified as [2]

$$E_D = \frac{3}{2}\,\rho_a\frac{c^3}{k}\,\Gamma\!\left(\frac{3}{k}\right) \tag{12}$$

2 Velocity–Power Response of the Turbine

Power curve of a 2 MW pitch controlled wind turbine is shown in Fig. 4. The turbine has cut-in, rated and cut-out velocities 3.5, 13.5 and 25 m/s respectively. The given curve is a theoretical one and in practice we may observe the velocity power variation in a rather scattered pattern.

In this curve, we can observe that the turbine has four distinct performance regions.

1. For velocities from 0 to the cut-in (V_I), the turbine does not yield any power.
2. Between the cut-in and rated velocities (V_I to V_R), the power increases with the wind velocity. Though, theoretically, this increase should be cubic in nature, in practice it can be linear, quadratic, cubic and even higher powers and its combinations, depending upon the design of the turbine.
3. From the rated to cut-out wind speed (V_R to V_O), the power is constant at the rated power P_R, irrespective of the change in wind velocity.
4. Beyond the cut-out velocity, the turbine is shut down due to safety reasons.

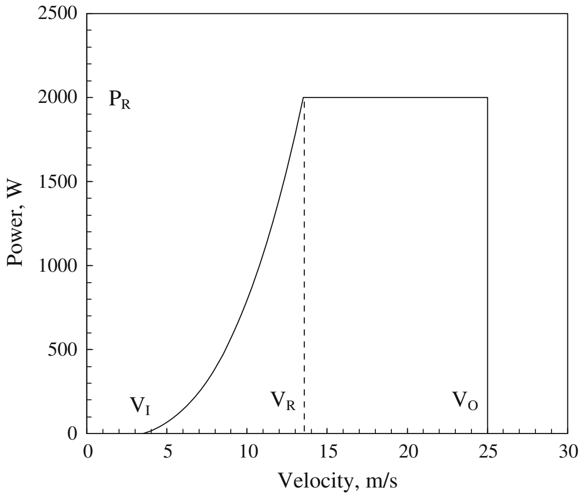


Fig. 4 Theoretical power curve of a 2 MW wind turbine

So, the wind turbine is 'productive' only between the velocities V_I and V_O. For any wind velocity between V_I and V_R, the power P_V can generally be expressed as

$$P_V = aV^n + b \tag{13}$$

where a and b are constants and n is the velocity–power proportionality. Now consider the performance of the system at V_I and V_R. At $V_{I,}$ the power developed by the turbine is zero. Thus

$$aV_I^n + b = 0 \tag{14}$$

At V_R power generated is P_R. That is:

$$aV_R^n + b = P_R \tag{15}$$

Solving Eqs. 14 and 15 for a and b and substituting in Eq. 13 yields

$$P_V = P_R\left(\frac{V^n - V_I^n}{V_R^n - V_I^n}\right) \tag{16}$$

Above equation gives us the power response of the turbine between the cut-in and rated wind speeds. Obviously, the power between V_R and V_O is P_R.

In the above expression, the major factor deciding the variations in power with velocity in the cut-into rated wind speed region is n. Value of n differs from turbine to turbine, depending on the design features. For example, Fig. 5 compares the power responses of two commercial wind turbines in this performance region. The curves are derived from data available from the manufactures. It should be noted that, although both the turbines are of the same 2 MW rated capacity, their power responses in the 'cut-into rated' velocity region differ significantly.

For a specific turbine, n can be calculated from its power curve data, available from the manufacturer. For example, the cut-in, rated and cut-out wind velocities

Fig. 5 Variations in output power from cut-into cut-out velocities for two wind turbines of 2 MW rated capacity

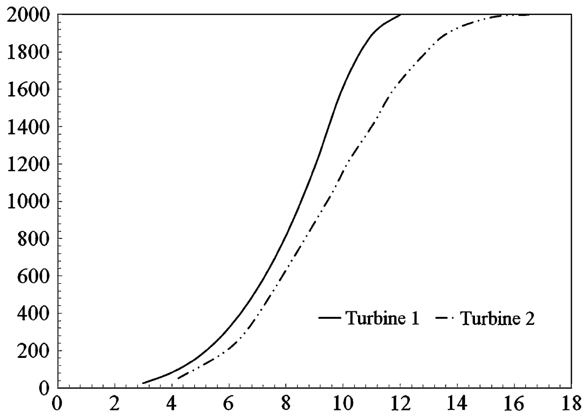


Table 2 Cut-in, rated and cut-out wind velocities of the turbines

Turbine no.	Cut-in velocity, m/s	Rated velocity, m/s	Cut-out velocity, m/s
1	3	12	28
2	4	16	25

of the two turbines compared above are shown in Table 2. Putting these values in Eq. 16 we get

$$P_V[T1] = 2000 \times \left(\frac{V^n - 3^n}{12^n - 3^n}\right) \text{ and } P_V[T2] = 2000 \times \left(\frac{V^n - 4^n}{16^n - 4^n}\right)$$

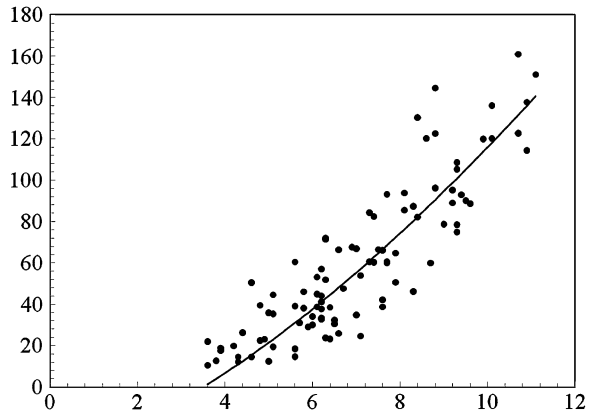
where T1 and T2 represents the turbines 1 and 2 respectively. Solving the above relationship with the velocity power data for the turbines (available from the manufacturer or obtained by digitizing the power curve) we can find out the value of n. Any standard curve fitting package can be used for the solution. Following this method, n for the turbines T1 and T2 are 1.8 ($R^2 = 0.97$) and 0.6 ($R^2 = 0.95$) respectively.

Instantaneous values of wind velocity and corresponding power were recorded from a 225 kW wind turbine installed at a wind farm and are plotted in Fig. 6. Cut-in and rated wind velocities of this turbine are 3.5 and 14.5 m/s respectively. Scattered points represent the measured power where as the continuous line represents the power computed using Eq. 16. Reasonable agreement could be observed between measured and computed values.

3 The Energy Model

To estimate the energy generated by the turbine at a given site over a period, the power characteristics of the turbine is to be integrated with the probabilities of different wind velocities expected at the site. For example, power curve of a wind

Fig. 6 Field performance of a 225 kW wind turbine



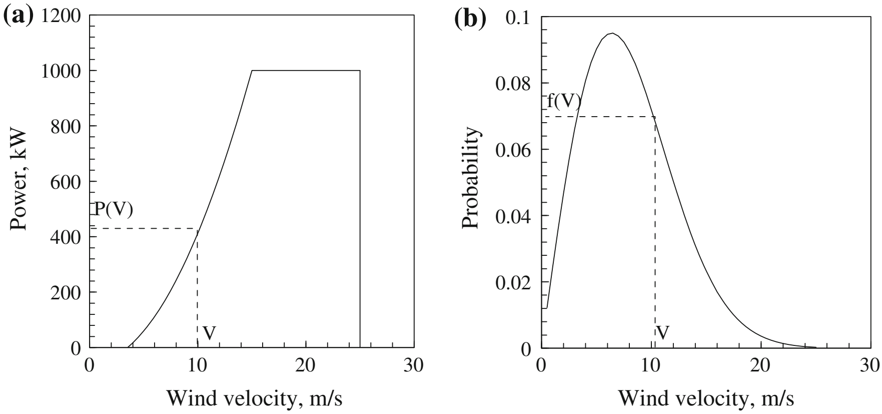


Fig. 7 Integrating the power (**a**) and probability (**b**) curves to derive the energy yield

turbine is shown in Fig. 7a whereas Fig. 7b presents the Weibull probability density function of a candidate site. In the wind regime, the fraction of energy contributed by any wind velocity V is the product of power corresponding to V in the power curve, that is $P(V)$ and the probability of V in the probability density curve, which is $f(V)$. Thus, at this site, the total energy generated by the turbine E, over a period T, can be estimated by

$$E = T \int_{V_i}^{V_o} P_V f(V)\, dV \tag{17}$$

As we have discussed, the power curve has two distinct productive regions—from V_I to V_R and V_R to V_O. Thus, let us take

$$E = E_{IR} + E_{RO} \tag{18}$$

where E_{IR} and E_{RO} are the energy yield corresponding to V_I to V_R and V_R to V_O respectively. From the foregoing discussions, we have

$$E_{IR} = T \int_{V_i}^{V_R} P_V f(V)\, dV \tag{19}$$

and

$$E_{RO} = T\, P_R \int_{V_R}^{V_O} f(V) dV \tag{20}$$

Substituting for *f(V)* and *P(V)* from Eqs. 3 and 16 in Eq. 19, we get

$$\begin{aligned} E_{IR} &= P_R T \int_{V_I}^{V_R} \left[\frac{V^n - V_I^n}{V_R^n - V_I^n}\right] \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} e^{-(V/c)^k}\, dV \\ &= \left(\frac{P_R T}{V_R^n - V_I^n}\right) \int_{V_I}^{V_R} \left(V^n - V_I^n\right) \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} e^{-(V/c)^k} dV \end{aligned} \tag{21}$$

For simplifying the above expression and bringing it to a resolvable form, let us introduce the variable X such that

$$X = \left(\frac{V}{c}\right)^k \tag{22}$$

Then,

$$dX = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \text{ and } V = cX^{\frac{1}{k}} \tag{23}$$

With Eq. 22, we have

$$X_I = \left(\frac{V_I}{c}\right)^k, X_R = \left(\frac{V_R}{c}\right)^k \text{ and } X_O = \left(\frac{V_O}{c}\right)^k \tag{24}$$

With this substitution, and simplification thereafter, E_{IR} can be expressed as

$$\begin{aligned} E_{IR} = \frac{P_R T c^n}{(V_R^n - V_I^n)} \int_{X_I}^{X_R} X^{n/k} e^{-X} dX \\ - \frac{P_R T V_I^n}{(V_R^n - V_I^n)} \left[e^{-X_I} - e^{-X_R}\right] \end{aligned} \tag{25}$$

Now consider the second performance region. From Eq. 20, E_{RO} may be represented as

$$E_{RO} = P_R\,T \int_{V_R}^{V_O} \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} e^{-(V/c)^k}\, dV \tag{26}$$

As $\int f(V)\, dV = F(V)$, from Eqs. 4 and 16, the above equation can be simplified as

$$E_{RO} = T\,P_R \left(e^{-X_R} - e^{-X_O}\right) \tag{27}$$

The above expressions can be evaluated numerically.

The capacity factor C_F —which is the ratio of the energy actually produced by the turbine to the energy that could have been produced by it, if the machine would have operated at its rated power throughout the time period—is given by

$$C_F = \frac{E}{P_R\,T} = \frac{E_{IR} + E_{RO}}{P_R T} \tag{28}$$

Thus,

$$\begin{aligned} CF = {} & \frac{c^n}{V_R^n - V_I^n} \int_{X_I}^{X_R} X^{n/k}\, e^{-X}\, dX \\ & - \frac{V_I^n}{V_R^n - V_I^n}\left[e^{-X_I} - e^{-X_R}\right] + \left(e^{-X_R} - e^{-X_O}\right) \end{aligned} \tag{29}$$

The energy model discussed above is validated with the field performance of a 10 kW wind turbine [13] in Fig. 8. The turbine considered here has cut-in, rated and cut-out wind speeds of 3.0, 13.5 and 25 m/s respectively. From the manufacturer's power curve, the velocity–power proportionality for the design was

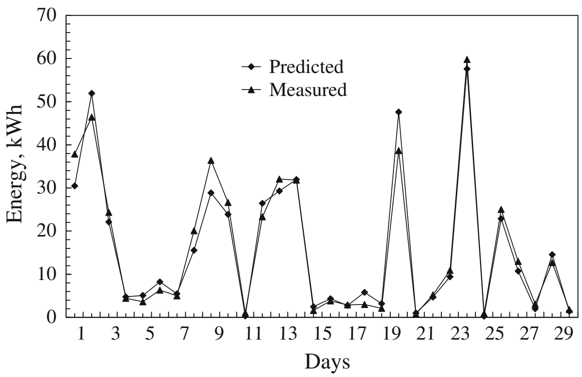


Fig. 8 Comparison between estimated and measured daily energy yield from a 10 KW wind turbine

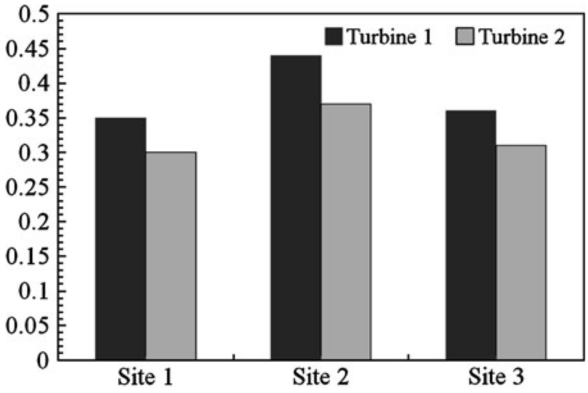


Fig. 9 Comparative performance of two 2 MW wind turbines in different wind regimes

found to be 2.16. It can be observed that the predicted performance closely follows the measured values throughout the period.

4 Conclusion

A method for assessing the wind energy resource available at a potential wind farm site has been presented in the above sections. Model for simulating the performance of wind turbines at a given site has also been discussed.

For example, the performances expected from the turbines given in Table 2, when installed at the sites described in Table 1 are compared in Fig. 9. Though both the turbines have the same rated power of 2 MW, the first turbine is expected to generate more energy from all the three sites. This is obvious as (1) the first turbine has lower cut-in and higher cut-out velocities, making it capable of exploiting a broader range of wind spectra available at the site (2) The first turbine shows better power response between the cut-into rated wind speeds as seen from Fig. 5.

The methods described above can be useful in the preliminary planning of wind power project. However, for a final investment decision, apart from a more rigorous technical analysis, economical and environmental dimensions of the project should be investigated.

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