The Impact On Tower Height Of Wind Turbine

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Abstract

Wind is the fastest growing energy source in the world today. The most critical factor influencing the power developed by a wind energy conversion system is the wind velocity. Wind velocity increases with height due to wind shear. Hence, the taller the tower, the higher will be the power available to the rotor. However, taller towers cost more. Thus, the optimum tower height should be taken into account by working out the economics of the options in terms of cost per kWh of electricity generated. Other factors must also be considered in the design of tower height such as the limitation of regulatory law and the difficulty of service and maintenance. So, final decision on the tower height should be made after considering all these factors.

Keywords : wind velocity, tower height, wind turbine, wind energy conversion system

I. Introduction

Wind energy has been used for thousands of years for milling grain, pumping water, and other mechanical power applications. Today, there are several hundred thousand windmills in operation around the world, many of which are used for water pumping. But it is the use of wind energy as a pollution-free means of generating electricity on a significant scale that is attracting most current interest in the subject. Strickly speaking, a windmill is used for milling grain, so modern ‘windmills’ tend to be called wind turbine, partly because of their functional similarity to the steam and gas turbines that are used to generate electricity, and partly to distinguish them from their traditional forbears. They are also sometimes referred to as Wind Energy Conversion Systems (WECS) and those used to generate electricity are sometimes described as wind generators or aerogenerators [Boyle, 2004].

Growing energy demand and environmental consciousness have re-evoked human interest in wind energy. As a result, wind is the fastest growing energy source in the world today. Policy frame works and action plans have already been formulated at various corners for meeting at least 20 % of the global energy demand with renewable energy by 2010, among which wind is going to be the major player.

II. Power

Power in the wind can be expressed as :

$$P_w = \frac{1}{2}\rho A v^3 \qquad \text{.......} \quad (1)$$

In S.I. Units ; P_w is the power in the wind (watts); ρ is the air density (kg/m^3) (at 15 ℃ and 1 atm, ρ = 1.225 kg/m^3); *A* is the cross-sectional area through which the wind passes (m^2); and *v* = wind speed normal to *A* (m/s) (a useful conversion : 1 m/s = 2.237 mph).

Notice that the power in the wind increases as the *cube* of wind speed. This means, for example, that doubling the wind speed increases the power by eightfold.

The power extracted by the rotor blades is customarily expressed as a fraction of the upstream wind power as follows :

$$P_t = \frac{1}{2} C_p \rho A v^3 \qquad \text{.......} \quad (2)$$

where C_p is the fraction of the upstream wind power, which is captured by the rotor blades. The remaining power is discharged or wasted in the downstream wind. The factor C_p is called the power coefficient of the rotor or the rotor efficiency. The theoretical maximum value of C_p is 0.59. In practical designs, the maximum achievable C_p is below 0.5 for high speed, two-blades turbines, and between 0.2 and 0.4 for slow speed turbines with more blades.

The power produced by the wind generator can be expressed by the following equation :

$$P_g = \frac{1}{2}\, C_p\, \eta_{tr}\, \eta_g\, \rho\, A\, v^3 \qquad (3)$$

If the system equipped with the battery, so :

$$P_g = \frac{1}{2}\, C_p\, \eta_{tr}\, \eta_g\, \eta_b\, \rho\, A\, v^3 \qquad (4)$$

where η_{tr} = gear box or transmission efficiency ; η_g = generator efficiency ; and η_b = battery efficiency.

III. Wind Shear

The flow of air above the ground is retarded by frictional resistance offered by the earth surface (boundary layer effect). This resistance may be caused by the roughness of the ground itself or due to vegetations, buildings and other structures present over the ground. For example, a typical vertical wind profile at a site is shown in Fig. 1.

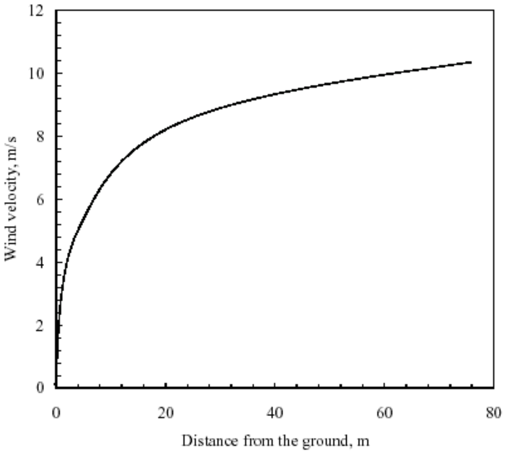

Fig. 1. Variation of wind velocity with height

Theoretically, the velocity of wind right over the ground surface should be zero. Velocity increases with height up to a certain elevation. The rate at which the velocity increases with height depends on the roughness of the terrain. Presence of dense vegetations like plantations, forests, and bushes slows down the wind considerably. Level and smooth terrains do not have much effect on the wind speed. The surface roughness of a terrain is usually represented by the roughness class or roughness height. The roughness height of a surface may be close to zero (surface of the sea) or even as high as 2 (town centers). Some typical values are 0.005 for flat and smooth terrains, 0.025 to 0.1 for open grass lands, 0.2 to 0.3 for row crops, 0.5 to 1 for orchards and shrubs and 1 to 2 for forests, town centers etc.

Roughness height is an important factor to be considered in the design of wind power plants. Suppose we have a wind turbine of 30 m diameter and 40 m tower height, installed over the terrain described in Fig. 1. The tip of the blade, in its lower position, would be 25 m above the ground. Similarly, at the extreme upper position, the blade tip is 55 m above the ground. As we see, the wind velocities at these heights are different. Thus, the forces acting on the blades as well as the power available would significantly vary during the rotation of the blades. This effect can be minimized by increasing the tower height.

The wind data available at meteorological stations might have been collected from different sensor heights. In most of the cases, the data are logged at 10 m as per recommendations of the World Meteorological Organization (WMO). In wind energy calculations, we are concerned with the velocity available at the rotor height. The data collected at any heights can be extrapolated to other heights on the basis of the roughness height of the terrain.

Due to the boundary layer effect, wind speed increases with the height in a logarithmic pattern. If the wind data is available at a height Z and the roughness height is Z_O, then the velocity at a height Z_R is given by

$$V(Z_R) = V(Z)\frac{\ln\left(Z_R/Z_O\right)}{\ln\left(Z/Z_O\right)} \qquad \text{.......... (5)}$$

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 4 m/s and the roughness height is 0.1, the velocity at 40 m above the ground is 5.2 m/s. It should be noted that the power available at 40 m is 2.2 times higher than at 10 m. The wind velocities at different heights relative to that at 10 m, as affected by the roughness heights, are shown in Fig. 2.

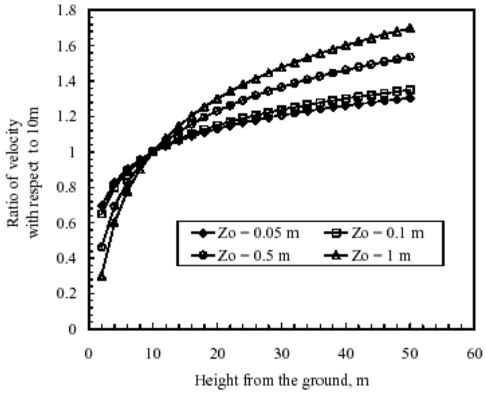

Fig. 2. Velocity ratio with respect to 10 m for different roughness heights

Eq. (5) is commonly used in Europe. There is another approach that is often used in the United States, namely :

$$V(Z_R) = V(Z)\left(\frac{Z_R}{Z}\right)^{\alpha} \qquad \text{.......... (6)}$$

where α the friction coefficient. The friction coefficient α is a function of the terrain over which the wind blows. Table 1 gives some representative values for rather loosely defined terrain types.

Table 1. Friction coefficient for various terrain characteristics

Terrain characteristics	Friction coefficient α
Smooth hard ground, calm water	0.10
Tall grass on level ground	0.15
High crops, hedges and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40

Oftentimes, for rough approximations in somewhat open terrain a value of 1/7 (the “one-seventh” rule-of-thumb) is used for α .

IV. Capacity Factor

Capacity factor is one of the important indices for assessing the field performance of a wind turbine. The capacity factor (C_F) of a WECS (Wind Energy Conversion System) at a given site is defined as the ratio of the energy actually produced by the system to the energy that could have been produced by it, if the machine would have operated at its rated power throughout the time period. Thus

$$C_F = \frac{E_T}{T\,P_R} \quad \text{.......} (7)$$

The capacity factor reflects how effectively the turbine could harness the energy available in the wind spectra. Hence, C_F is a function of the turbine as well as the wind regime characteristics. Usually the capacity factor is expressed on an annual basis. Capacity factor for a reasonably efficient turbine at a potential site may range from 0.25 to 0.4. A capacity factor of 0.4 or higher indicates that the system is interacting with the regime very efficiently.

Information on the capacity factor of the turbine at a given site may not readily available during the initial phases of project identification. Under such situations, it is advisable to calculate the rough capacity factor (RC_F). This is basically deduced from the power curve of the machine, based on the average wind velocity at the site. From the power curve, we can locate the power corresponding to the average wind velocity. Dividing this power (P_{VM}) by the rated power of the turbine, the rough capacity factor can be calculated. Thus,

$$RC_F = \frac{P_{VM}}{P_R} \quad \text{.......} (8)$$

V. Tower

Tower supports the rotor and nacelle of a wind turbine at the desired height. The major types of towers used in modern turbines are lattice tower, tubular steel tower, and guyed tower. Schematic views of these towers are shown in Fig. 3.

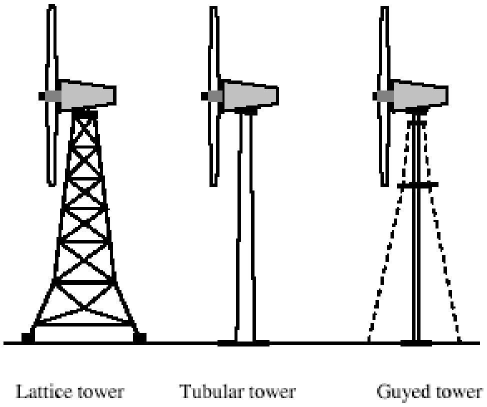

Fig. 3. Different types of towers

The lattice towers are fabricated with steel bars joined together to form the structure as shown in the figure. They are similar to the transmission towers of electric utilities. Lattice towers consume only half of the material that is required for a similar tubular tower. This makes them light and thus cheaper. For example, lattice tower for a typical turbine may cost $ 25,000 less than the tubular option of similar size. Legs of these towers are spread widely as shown in the figure. As the load is distributed over a wider area, these towers require comparatively lighter foundation, which will again contribute to the cost reduction.

Lattice towers have several demerits. The major problem is the poor aesthetics as they may be visually unacceptable to some viewers. Similarly, avian activities are more intense around the lattice towers as the birds can conveniently perch on its horizontal bars. This may increase the rate of avian mortality. Lattice towers are not maintenance friendly. At installations where the temperature drops to an extremely low level, maintenance of systems with lattice towers is difficult as workers would be exposed to the chilling weather. Moreover, as these towers do not have any lockable doors, they are less secure for maintenance.

Due to these limitations, most of the recent installations are provided with tubular steel towers. These towers are fabricated by joining tubular sections of 10 to 20 m length. The complete tower can be assembled at the site within 2 or 3 days. The tubular tower, with its circular cross-section, can offer optimum bending resistance in all directions. These towers are aesthetically acceptable and pose less danger to the avian population.

For small systems, towers with guyed steel poles are being used. By partially supporting the turbine on guy wires, weight and thus the cost of the tower can be considerably reduced. Usually, four cables equally spaced and inclined at 45°, support the tower. As accesses to these towers are difficult, they are not popular with large scale installations. However, guyed towers are in use even with MW sized installations in Germany.

Load acting on the tower increases with size of the turbine. Hence, the recent trend for MW sized systems would in turn demand for higher tower dimensions in terms of diameter and wall thickness. This impose limitations while transportation of these towers. Usually, inland transportation of structures with size higher than 4.3 m and weight more than 50 to 60 tons is difficult. Further, fabricating these huge structures is not an easy task, as rolling and welding plates with wall thickness more than 50 mm is difficult. Due to these problems, hybrid towers are proposed for high capacity systems.

In concrete-tubular hybrid tower, the lower part is made of concrete where as the upper part is with conventional tubular steel structure. One of such design uses prefabricated long and narrow concrete elements for the lower portion. These elements are 10-15 m long, 3-4 m wide and 250-350 mm thick. With these dimensions, they can be transported in a truck. Steel cables, protected against corrosion, are used to pre-stress the concrete in this design. The whole structure can be assembled at the field within a week.

Another design of the hybrid towers is proposed by NREL. This is a combination of truss, tubular and guyed towers, as shown in Fig. 4.

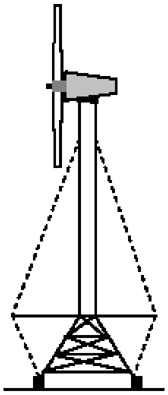

Fig. 4. The hybrid tower concept

The lower truss portion allows the design to utilize the advantage of larger foot prints, whereas with the guyed wires, size of tubular steel can be reduced. Cost of this tower is slightly higher than other tower options. However, this concept could reduce the maximum tube diameter required, resolving the transport problem. Similarly, the total mass of the structure could be reduced by 25 %.

By using Eq.(5), let us examine the effect of tower height on the performance of a typical wind turbine. Suppose the average wind velocity at the site, at 30 m tower height, is 8.2 m/s. Let the roughness height be 0.04 m, which is logical for smooth open grass lands. Change in velocity with height under these conditions is shown in Fig. 5.

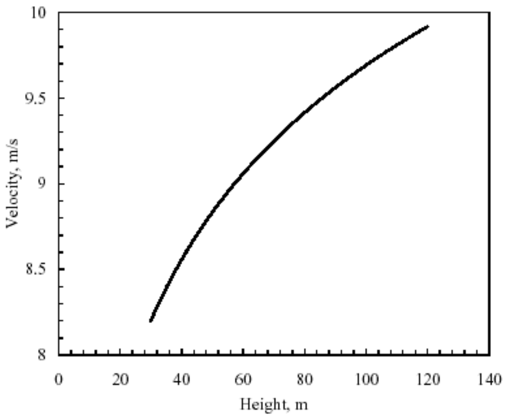

Fig. 5. Effect of tower height on the velocity at hub height

The velocity at 120 m hub height is 9.9 m/s, which means that, the available power is 1.76 times higher than that at 30 m height. In tune with the increase in velocity, capacity factor of the turbine also improves as shown in Fig. 6. For example, the capacity factor at 30 m is 0.26 whereas, at 120 m height, the system could attain a capacity factor of 0.37.

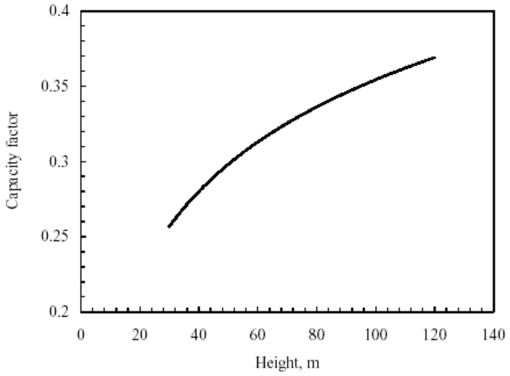

Fig. 6. Effect of tower height on the capacity factor

Apart from the increase in wind velocity, better matching between the wind spectra and the turbine also improves the capacity factor. Thus, performance of a wind turbine improves with its tower height. However, taller towers cost more. Towers account for around 20% of the total systems cost. At present, cost of every additional 10 m of tower is approximately $15,000. This means that, while we increase the tower height from 30 m to 120 m as in the example, the system cost would shoot up by $ 135,000. Can this additional cost be justified by the improvement in system performance? In other words, what should be the optimum tower height? The best criterion is to work out the economics of the options in terms of cost per kWh of electricity generated. The cost of wind generated electricity (*c*) is given by

$$c = \frac{C_1}{8760\, n}\left(\frac{1}{P_R\, C_F}\right)\left\{1 + m\left[\frac{(1+I)^n - 1}{I(1+I)^n}\right]\right\} \qquad \text{.....(9)}$$

where C_1 is the capital investment for the system, *n* is the expected life, P_R is the rated power, C_F is the capacity factor, *m* is the maintenance cost and *I* is the discounting rate corrected for inflation and escalation. Here, C_1 increases with the tower height. However, with increase in height, C_F also improves. Thus, the selection of the optimum tower height is ultimately a trade-in between the cost of the system and its performance.

VI. Example

Cost of a 600 kW wind turbine and attachments, with the standard 30 m tower, is \$ 650,000. Every 10 m tower cost an additional \$ 15,000. Expected life of the turbine is 20 years. Annual operational and maintenance costs accounts for 3.5 % of the initial cost. Discounting rate, corrected for inflation and escalation is 7 %. Average wind velocity at the site is 8.2 m/s and the roughness height is 0.04 m. Estimate the optimum tower height for the system.

Here, first of all, we have to compute the wind velocities at different tower heights using Eq. (5). The capacity factor of the system, corresponding to these velocities, can be computed using the 'WIND TURBINE-RAYLEIGH' module of WERA (Wind Energy Resource Analysis) programme. Once the capacity factors for different tower heights are available, corresponding unit cost of electricity can be estimated using Eq. (9). It should be noted that, for increase in every 10 m tower height, \$ 15,000 should be added to the capital cost.

The results are plotted in Fig. 7. Up to a tower height of 80 m, the cost of kWh generated is declining gradually due to the improvement in the turbine performance. However, above 80 m, the increase in initial investment due to additional tower height is not justified by the improvement in the capacity factor. As a result, the cost per kWh generated starts increasing beyond a tower height of 80 m.

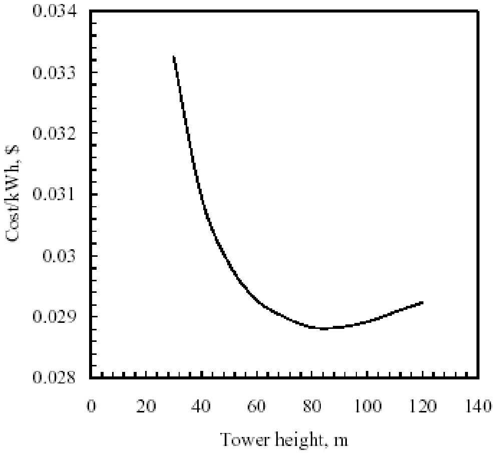

Fig. 7. Effect of tower height on generation cost

The optimum tower height for a system is a site specific issue. Wind shear varies from place to place depending on the ground conditions. Apart from the shear, presence of trees or other obstructions in the wind flow path may demand taller towers.

There are some limitations for increasing the tower height due to regulatory limits. The maximum permissible limit may vary from country to country. For example, in United States, this limit is 61.4 m. German regulations exempt a height up to 100 m from obstruction marking. If the turbines happen to be in prominent flight paths, the regulatory authorities may insist for navigation lights on taller towers. Unfortunately, any such markings may make the tower more visible to the public, thus causing visual annoyance. Further, extra heights added to the tower may cause its servicing and maintenance difficult, unless we have specialized lifts to reach the nacelle. Requirement of such devices may not be economically justifiable in many cases. Final decision on the tower height should be made after considering all these factors.

VII. Conclusion

The most critical factor influencing the power developed by a wind energy conversion system is the wind velocity. Due to the cubic relationship between velocity and power, even a small variation in the wind speed may result in significant change in power.

Wind velocity increases with height due to wind shear. Hence, the taller the tower, the higher will be the power available to the rotor. Rate at which the available power increases with height depends on the surface roughness of the ground.

As the wind velocity and thus the power vary from place to place, the first step in planning a wind energy project is to identify a suitable site, having strong and impressive wind spectra.

The performance of a wind turbine improves with its tower height (higher wind velocity and capacity factor). However, taller towers cost more. Thus, the optimum tower height should be taken into account by working out the economics of the options in terms of cost per kWh of electricity generated.

There are some limitations for increasing the tower height due to regulatory limits. The maximum permissible limit may vary from country to country. Further, extra heights added to the tower may cause its servicing and maintenance difficult, unless we have specialized lifts to reach the nacelle. Requirement of such devices may not be economically justifiable in many cases. Final decision on the tower height should be made after considering all these factors.

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