Energy Resources

Dr. Fahad Noor
Assosciate Professor
f.noor@uet.edu.pk

Engr. Adnan Qamar
Lecturer
adnan@uet.edu.pk

Introduction

Wind results from expansion and convection of air as solar radiation is absorbed on Earth. On a global scale these thermal effects combine with dynamic effects from the Earth’s rotation to produce prevailing wind patterns.

There is considerable regional and local variation caused by geographical and environmental factors. In general, wind speeds increase with height, with the horizontal components significantly greater than the vertical components.

Introduction

Wind speed varies significantly with time over periods from seconds to seasons and years, and over distances ~1 km, especially in hilly terrain.

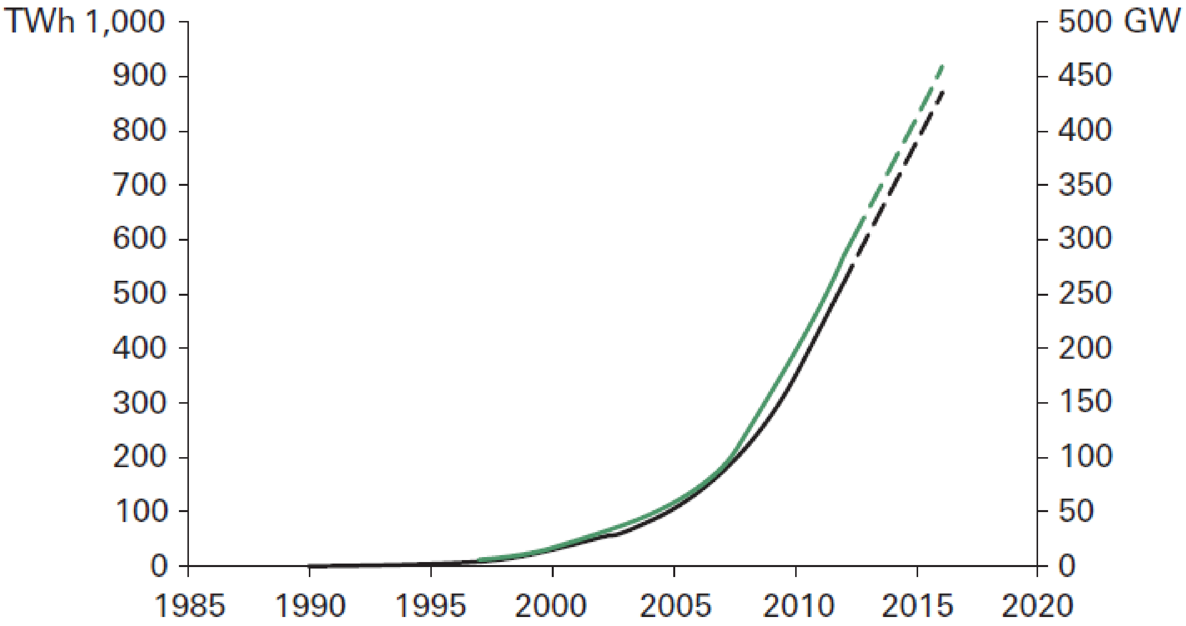
Therefore it is important to make measurements at the nominated site at several heights for at least 12 months and compare these with official meteorological data and wind atlas information

Introduction

Human efforts to harness wind for energy date back to the ancient times, when he used sails to propel ships and boats.

Later, wind energy served the mankind by energising his grain grinding mills and water pumps.

Introduction

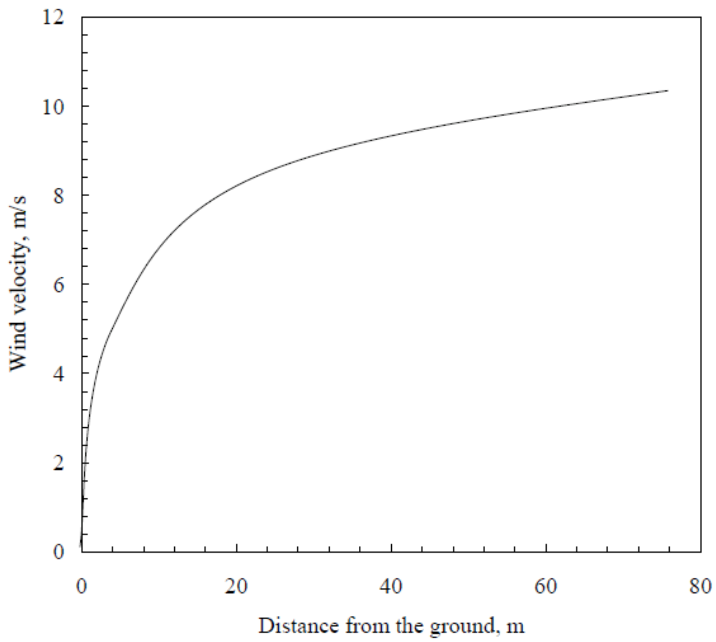


Introduction (Wind shear)

Presence of dense vegetations like plantations, forests, and bushes slows down the wind considerably.

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, 0.025-0.1 for open grass lands, 0.2 to 0.3 for row crop.



Introduction (Wind shear)

Suppose we have a wind turbine of 30 m diameter and 40 m tower height. 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

Introduction (Wind shear)

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).

The data collected at any heights can be extrapolated to other heights on the basis of the roughness height of the terrain.

$$V(Z_R) = V(Z)\,\frac{\ln\left(Z_R / Z_0\right)}{\ln\left(Z / Z_0\right)}$$

If the wind data is available at a height Z and the roughness height is Z_0, then the velocity at a height Z_R

Introduction (Wind shear)

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 40 m above the ground is 9.1 m/s.

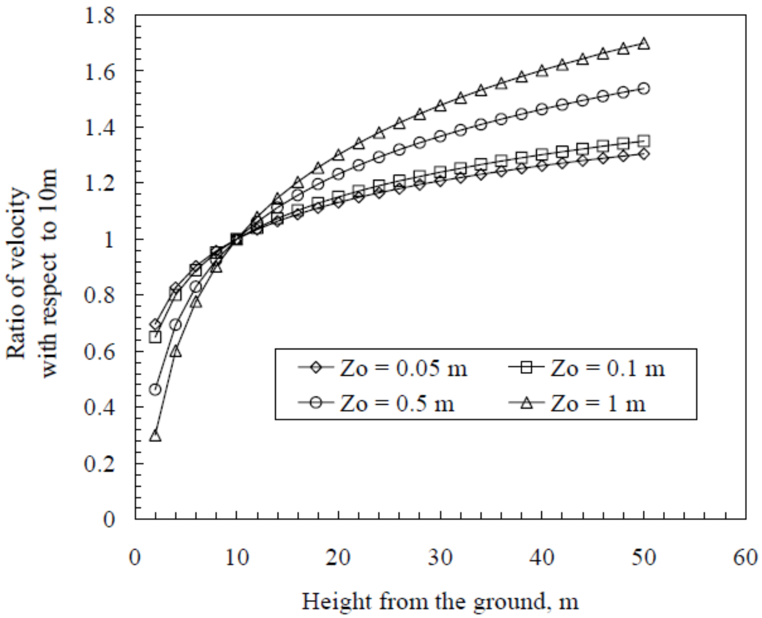
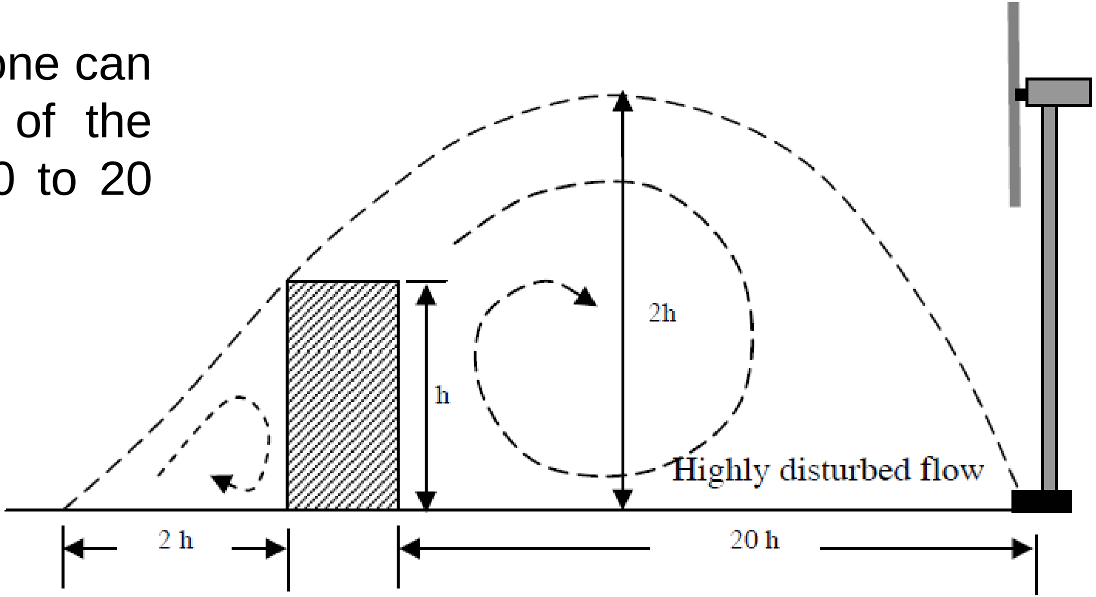


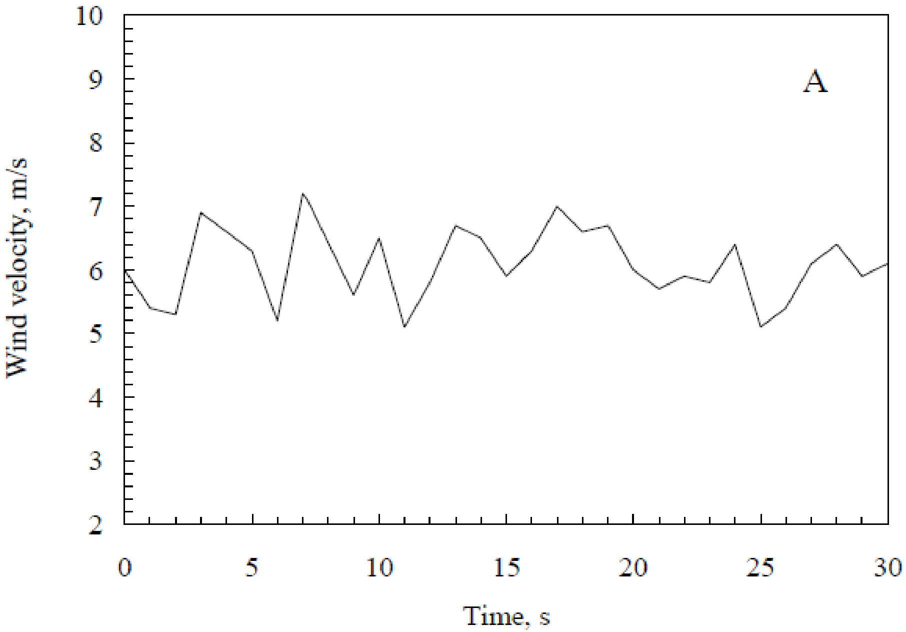
Fig. 3.3. Velocity ratio with respect to 10 m for different roughness heights

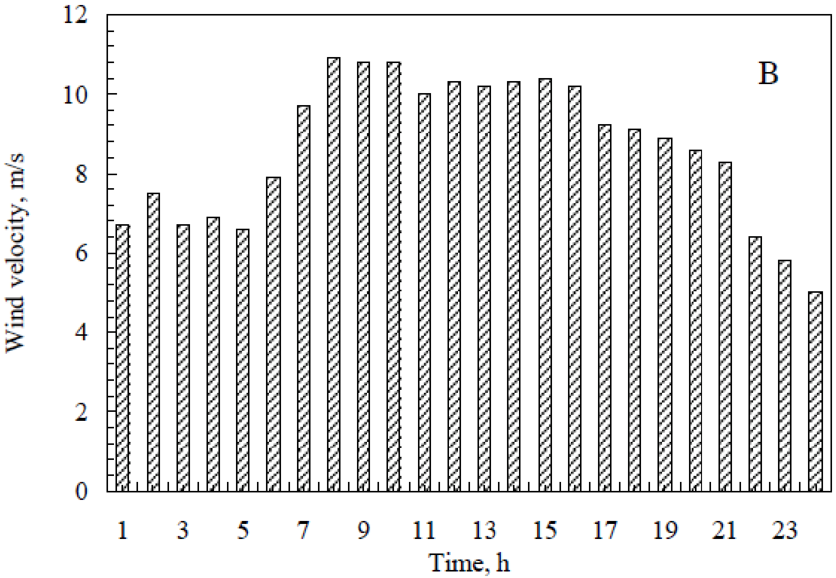
Introduction (Wind shear)

Based on its nature, the turbulent zone can extend up to 2 times the height of the obstacle in the upwind side and 10 to 20 times in the downwind side.



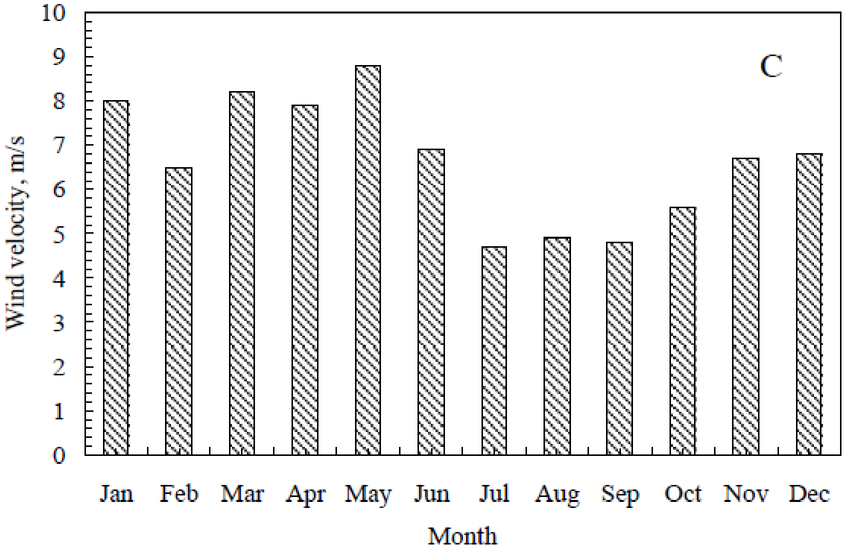
Introduction (Wind shear)





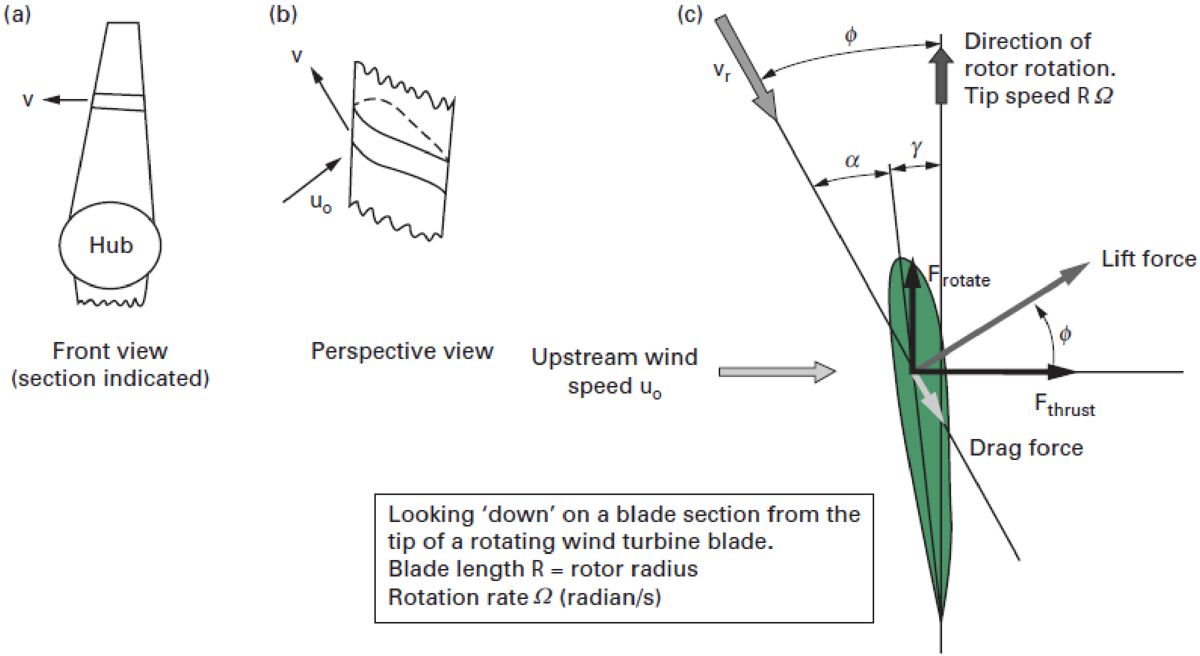
Introduction (Wind shear)

Velocity and direction of wind changes rapidly with time. In tune with these changes, the power and energy available from the wind also vary. The variations may be short time fluctuation, day-night variation or the seasonal variation.



Knowledge of these time variations of velocity at a potential wind site is essential to ensure that the availability of power matches with the demand.

Introduction



Power available in wind

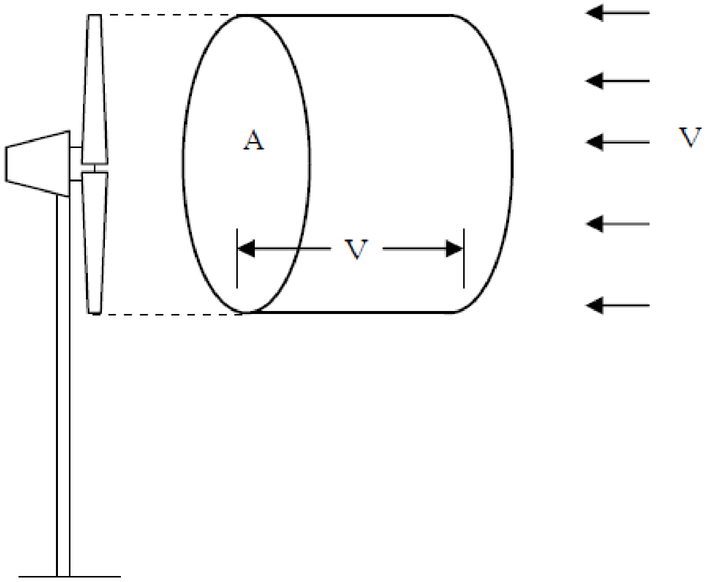


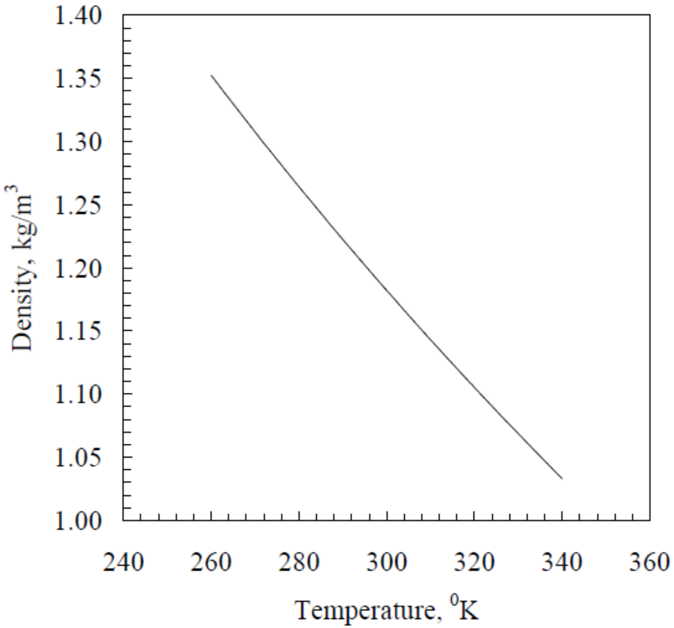
Fig. 2.1. An air parcel moving towards a wind turbine

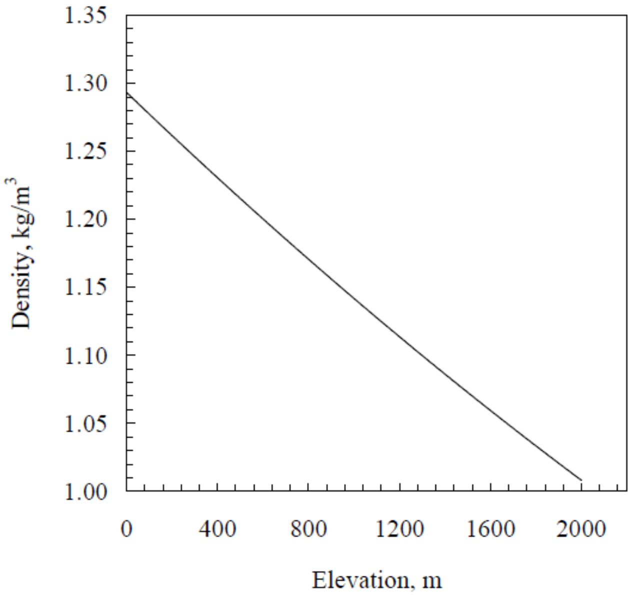
$$E = \frac{1}{2} m V^2$$

$$E = \frac{1}{2} \rho_a \, v \, V^2$$

$$P = \frac{1}{2} \rho_a \, A_T \, V^3$$

Power available in wind





The density of air decreases with the increase in site elevation and temperature. The air density may be taken as 1.225 for most of the practical cases.

Power available in wind

$$P = \frac{1}{2} \rho_a \ A_T \ V^3$$

- The most prominent factor deciding the power available in the wind spectra is its velocity. When the wind velocity is doubled, the available power increases by 8 times.
- In other words, for the same power, rotor area can be reduced by a factor of 8, if the system is placed at a site with double the wind velocity.
- Hence, selecting the right site play a major role in the success of a wind power projects.

Power available in wind

When the wind stream passes the turbine, a part of its kinetic energy is transferred to the rotor and the air leaving the turbine carries the rest away.

Actual power produced by a rotor would thus be decided by the efficiency with which this energy transfer from wind to the rotor takes place. This efficiency is usually termed as the power coefficient (Cp).

The power coefficient of the rotor can be defined as the ratio of actual power developed by the rotor to the theoretical power available in the wind.

$$C_p = \frac{2 \; P_T}{\rho_a \; A_T \; V^3}$$

Power available in wind

$$V_m = \frac{1}{n}\sum_{i=1}^{n} V_i$$

Table 3.1. Wind velocity at 10 minutes interval

No	V, m/s	V^3	P, W/m^2
1	4.3	79.51	49.29
2	4.7	103.82	64.37
3	8.3	571.79	354.51
4	6.2	238.33	147.76
5	5.9	205.38	127.33
6	9.3	804.36	498.70

Power available in wind

The hourly average wind velocity is 6.45 m/s. Taking the air density as 1.24 kg/m^3, the corresponding average power is 166.37 W/m^2.

If we calculate the power corresponding to individual velocities and then take the average, the result would be 207 W/m^2.

Table 3.1. Wind velocity at 10 minutes interval

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$$V_m = \frac{1}{n}\sum_{i=1}^{n} V_i$$

Power available in wind

$$V_m = \left(\frac{1}{n} \sum_{i=1}^{n} V_i^{\ 3} \right)^{1/3}$$

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The average velocity in the previous example is 6.94 m/s and the corresponding power is 207 W/m^2

Power available in wind

$$F = \frac{1}{2} \rho_a \; A_T \; V^2$$

$$T = \frac{1}{2} \rho_a \; A_T \; V^2 R$$

$$C_T = \frac{2 \; T_T}{\rho_a \; A_T \; V^2 R}$$

Tip speed ratio

The ratio between the velocity of the rotor tip and the wind velocity is termed as the tip speed ratio (λ).

$$\lambda = \frac{R\,\Omega}{V} = \frac{2\pi N R}{V}$$

Consider a situation in which the rotor is rotating at a very low speed and the wind is approaching the rotor with a very high velocity. Under this condition, as the blades are moving slow, a portion of the air stream approaching the rotor may pass through it without interacting with the blades and thus without energy transfer. Similarly if the rotor is rotating fast and the wind velocity is low, the wind stream may be deflected from the turbine and the energy may be lost due to turbulence and vortex shedding.

Tip speed ratio

$$C_p = \frac{2\ P_T}{\rho_a\ A_T\ V^3} = \frac{2\ T_T\ \Omega}{\rho_a\ A_T\ V^3}$$

$$\frac{C_p}{C_T} = \frac{R\ \Omega}{V} = \lambda$$

Thus, the tip speed ratio is given by the ratio between the power coefficient and torque coefficient of the rotor.

Tip speed ratio

Consider a wind turbine with 5 m diameter rotor. Speed of the rotor at 10 m/s wind velocity is 130 r/min and its power coefficient at this point is 0.35. Calculate the tip speed ratio and torque coefficient of the turbine. What will be the torque available at the rotor shaft? Assume the density of air to be 1.24 kg/m^3.

Classification of wind turbine

- Axis of rotation
- No of blades
- Direction of receiving wind
- Size of turbine

Classification of wind turbines

Horizontal axis machines have some distinct advantages such as low cut-in wind speed and easy furling. In general, they show relatively high power coefficient. However, the generator and gearbox of these turbines are to be placed over the tower which makes its design more complex and expensive. Another disadvantage is the need for the tail or yaw drive to orient the turbine towards wind.

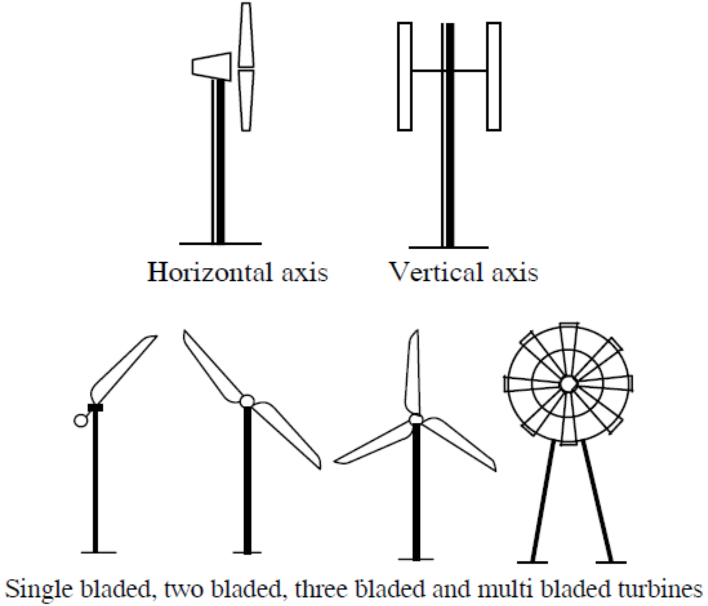
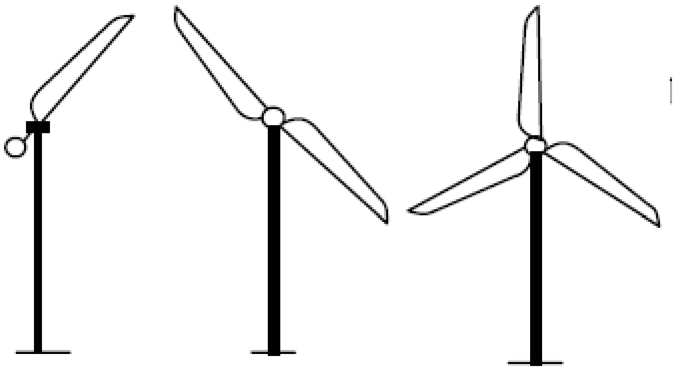


Fig. 2.4. Classification of wind turbines

Classification of wind turbines



Single bladed, two bladed, three bladed and mu

Single bladed turbines are cheaper due to savings on blade materials. The drag losses are also minimum for these turbines. However, to balance the blade, a counter weight has to be placed opposite to the hub. Single bladed designs are not very popular due to problems in balancing and visual acceptability. Two bladed rotors also have these drawbacks, but to a lesser extent. Most of the present commercial turbines used for electricity generation have three blades.

Classification of wind turbines

Machines with more number of blades (6, 8, 12, 18 or even more) are also available.

The ratio between the actual blade area to the swept area of a rotor is termed as the **solidity**.

Multi-bladed rotors are also called high solidity rotors. These rotors can start easily as more rotor area interacts with the wind initially. Some low solidity designs may require external starting

Classification of wind turbines

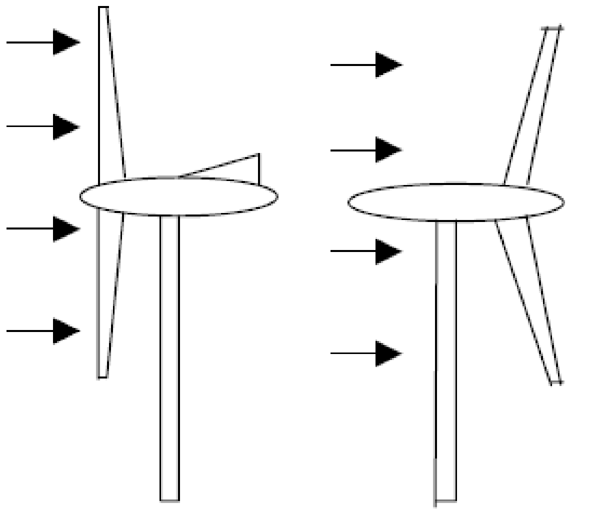


Fig. 2.5. Upwind and downwind turbines

Classification of wind turbines

Upwind turbines have their rotors facing the wind directly. As the wind stream passes the rotor first, they do not have the problem of tower shadow. However, yaw mechanism is essential for such designs to keep the rotor always facing the wind. On the other hand, downwind machines are more flexible and may not require a yaw mechanism. But, as the rotors are placed at the lee side of the tower, there may be uneven loading on the blades as it passes through the shadow of the tower.

Classification of wind turbines

VAWT can receive wind from any direction. Hence complicated yaw devices can be eliminated. The generator and the gearbox of such systems can be housed at the ground level, which makes the tower design simple and more economical. Moreover the maintenance of these turbines can be done at the ground level. For these systems, pitch control is not required when used for synchronous applications.

Classification of wind turbines

The major disadvantage of some VAWT is that they are usually not self starting.

Additional mechanisms may be required to ‘push’ and start the turbine, once it is stopped.

Classification of wind turbines

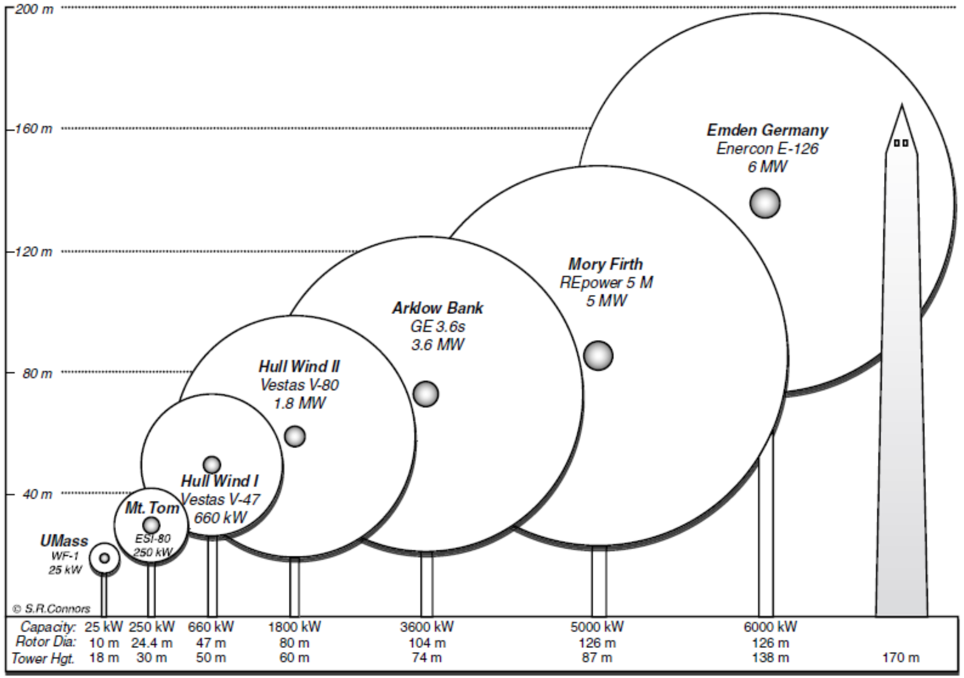
Wind turbines are available in various sizes ranging from a fraction of kW to several MW. Based on the size, the turbines may be classified as small (< 25 kW) medium (25-100 kW), large (100-1000 kW) and very large (>1000 kW) machines.

Classification of wind turbines

Table 8.1 Typical wind turbine-generating characteristics at rated power P_T in 12 m/s wind speed. Data calculated assuming power coefficient $C_p = 30\%$, air density $\rho = 1.2$ kg/m, tip-speed ratio $\lambda = 6$. Rated power $P_T = \frac{1}{2}\rho(\pi D^2/4)(\bar{u}_0)^3 C_p$. Hence $D = (2.02\text{ m})\sqrt{(P/1\text{ kW})}$, $T = (0.0436\text{ s m}^{-1})D$.

Class	*Small*		*Intermediate*			*large*		
Rated power P_T/kW	10	50	100	250	500	1000	3000	6000
Diameter D/m	6.4	14	20	32	49	64	110	160
Period T/s	0.3	0.6	0.9	1.4	2.1	3.1	4.8	6.8

Classification of wind turbines



Classification of wind turbines

In general, initially the power coefficient of the turbine increases with the tip speed ratio, reaches a maximum at a typical □ , and then decreases with further increase in the tip speed ratio

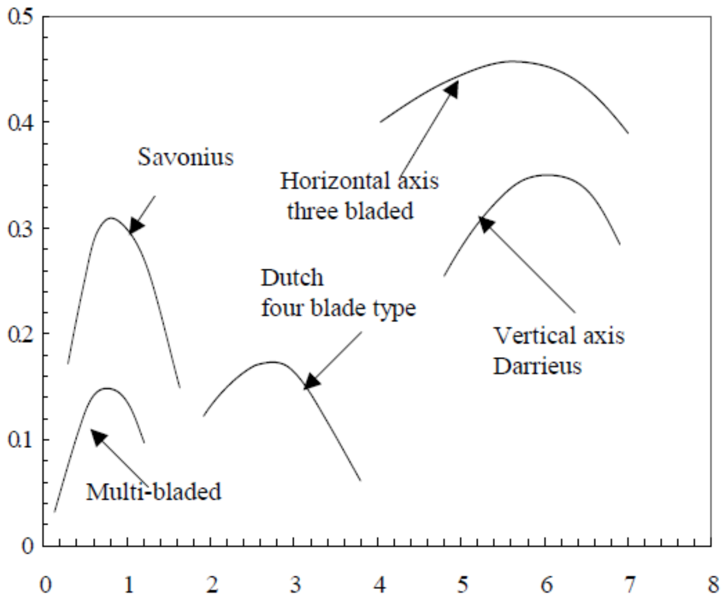
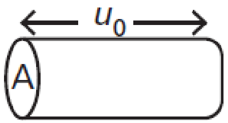
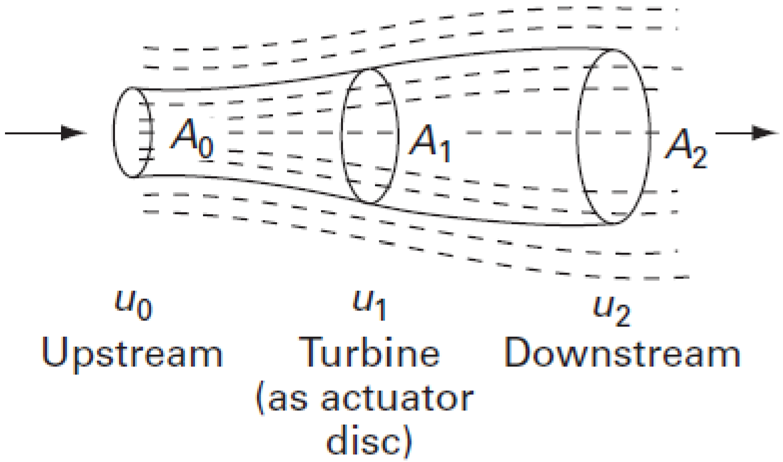


Fig. 2.10. Performance characteristics of wind rotors

Betz criterion



Mass of column $\rho A u_0$, kinetic energy $\frac{1}{2}(\rho A u_0)u_0^2$



Betz criterion

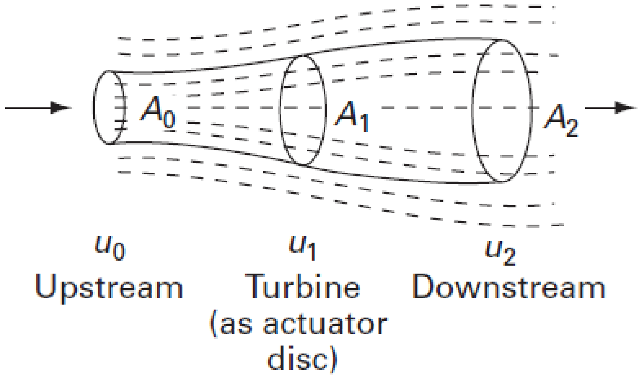
$$F = \dot{m}u_0 - \dot{m}u_2$$

$$P_T = Fu_1 = \dot{m}(u_0 - u_2)u_1$$

$$P_W = \tfrac{1}{2}\dot{m}(u_0^2 - u_2^2)$$

$$\dot{m}(u_0 - u_2)u_1 = \tfrac{1}{2}\dot{m}(u_0^2 - u_2^2) = \tfrac{1}{2}\dot{m}(u_0 + u_2)(u_0 - u_2)$$

$$u_1 = \tfrac{1}{2}(u_0 + u_2)$$



Betz criterion

$$\dot{m} = \rho A_1 u_1 \qquad P_T = F u_1 = \dot{m}(u_0 - u_2)u_1$$

$$P_T = \rho A_1 u_1^2 (u_0 - u_2)$$

$$P_T = \rho A_1 u_1^2 [u_0 - (2u_1 - u_0)] = 2\rho A_1 u_1^2 (u_0 - u_1)$$

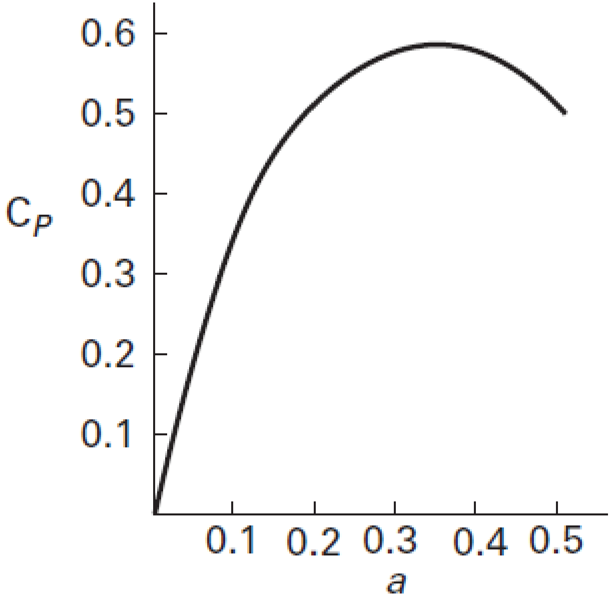
$$a = (u_0 - u_1) / u_0$$

$$u_1 = (1 - a)u_0 = \tfrac{1}{2}(u_0 - u_2)$$

$$a = (u_0 - u_2) / (2u_0)$$

$$\begin{aligned} P_T &= 2\rho A_1 u_1^2 (u_0 - u_1) = 2\rho A_1 (1-a)^2\, u_0^2 [u_0 - (1-a)u_0] \\ &= [4a(1-a)^2]\, (\tfrac{1}{2}\rho A_1 u_0^3) \\ &= 2\rho A_1 u_0^3 a (1-a)^2 \end{aligned}$$

Betz criterion



$$P_T = C_P P_0$$

$$C_P = 4a(1 - a)^2$$

$$C_P^{max} = 16/27 = 0.59$$

1 when $a = 1/3$, then $u_1 = 2\ u_0/3$ and $u_2 = u_0/3$
2 when $a = 0.5$, $u_1 = u_0/2$ and $u_2 = 0$ (which would imply zero flow out of the turbine, but in fact indicates a change in mode of flow, as dis-

Betz criterion

Design tip speed ratio depends on the application for which the turbine is being developed. For example, when we design the rotor for a wind pump which require high starting torque, low tip speed ratio is chosen.

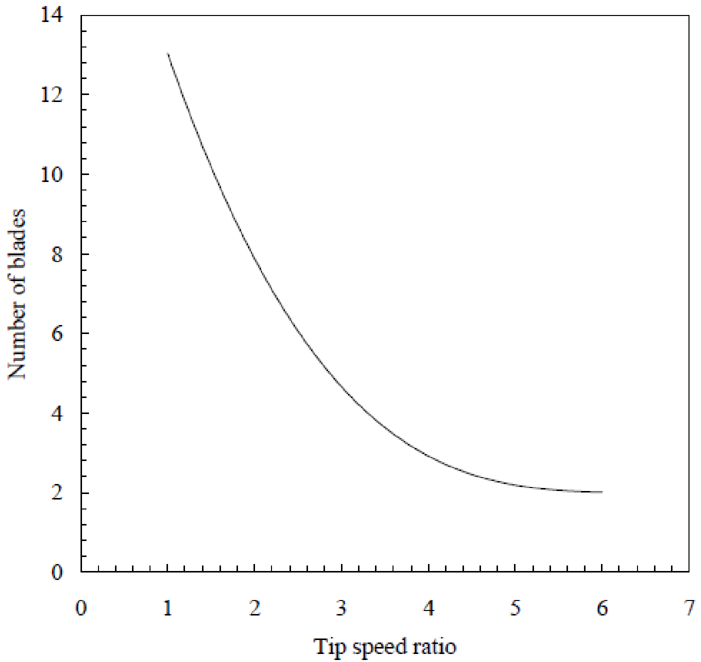


Fig. 2.18. Number of blades and design tip speed ratio

Betz criterion

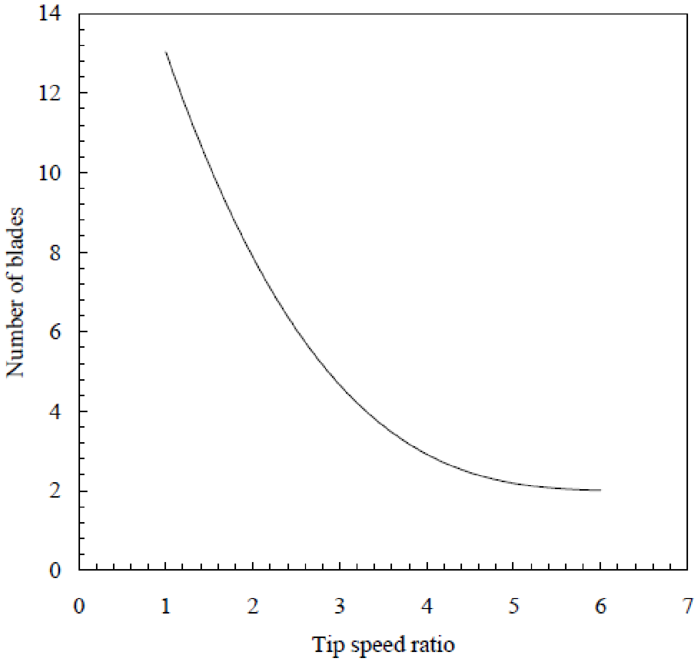
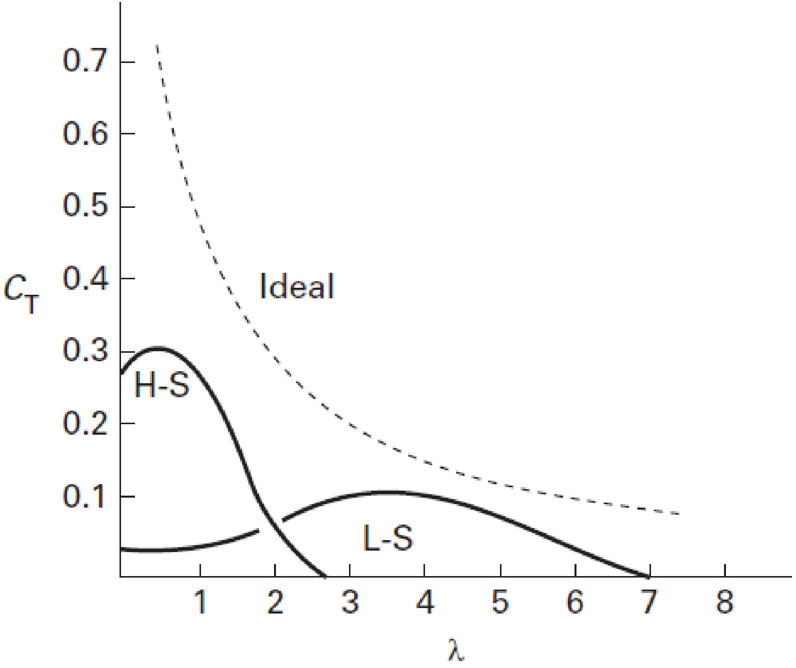
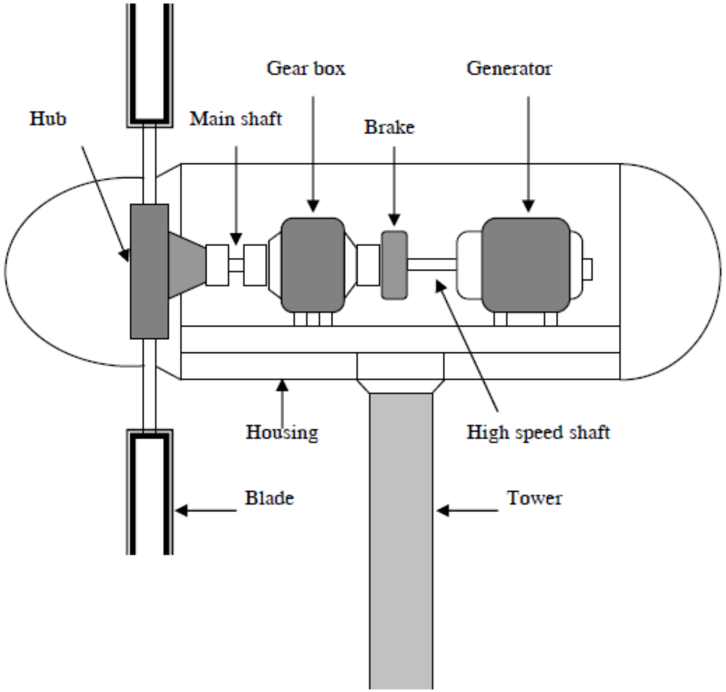


Fig. 2.18. Number of blades and design tip speed ratio



Wind turbine (Construction)

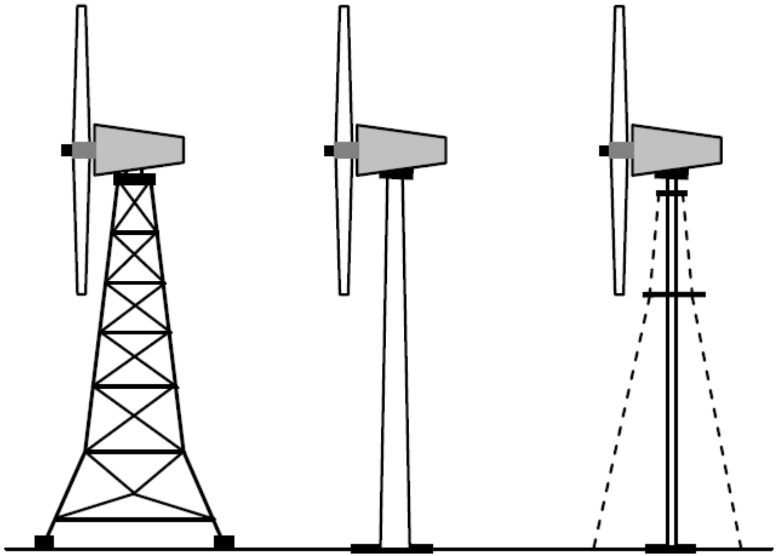


Wind turbine (Tower)

Lattice towers consume only half of the material that is required for a similar tubular tower.

The major problem is the poor aesthetics as they may be visually unacceptable to some viewers.

Maintenance of systems with lattice towers is difficult



Wind turbine (Tower)

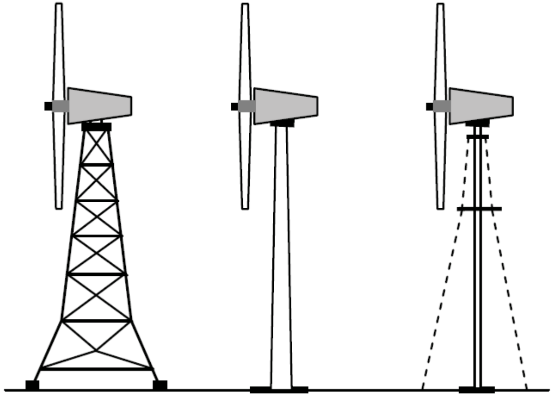
<u>Tubular Tower</u>

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.

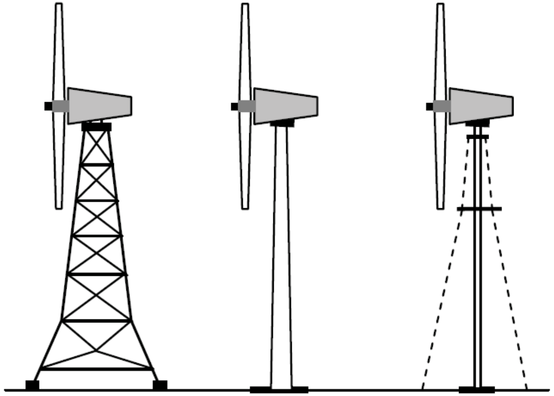


Wind turbine (Tower)

Guyed Tower

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.



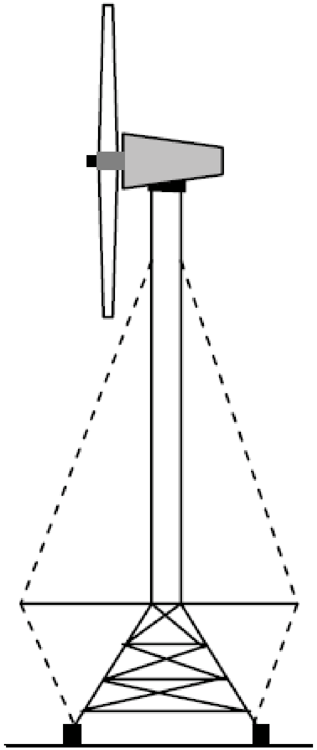
Wind turbine (Tower)

The recent trend for MW sized systems would in turn demand for higher tower dimensions in terms of diameter and wall thickness.

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



Wind turbine (Rotor)

It is possible to design the rotor with a single blade, balancing of such rotors would be a real engineering challenge.

Rotors with single blade run faster and thus create undue vibration and noise. Further, such rotors are not visually acceptable.

Two bladed rotors also suffer from these problems of balancing and visual acceptability. Hence, almost all commercial designs have three bladed rotors.

Some of the small wind turbines, used for battery charging, have more number of blades- four, five or even six-as they are designed to be self starting even at low wind speeds.

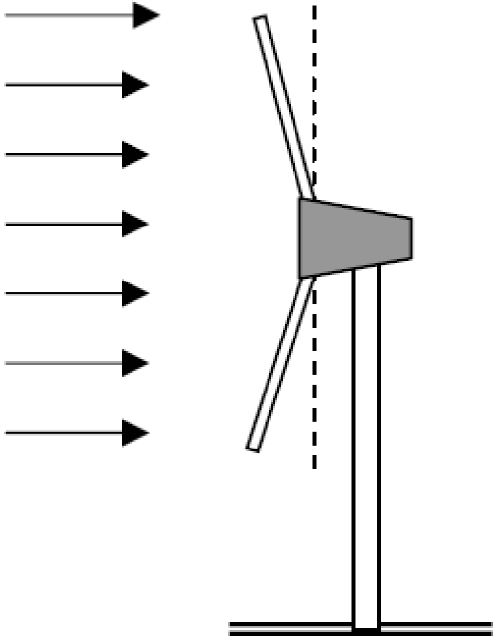
Wind turbine (Rotor)

Blades are fabricated with a variety of materials ranging from wood to carbon composites.

Use of wood and metal are limited to small scale units. Most of the large scale commercial systems are made with multi layered fiberglass blades.

Attempts are being made to improve the blade behavior by varying the matrix of materials, reinforcement structures, ply terminations and manufacturing methods.

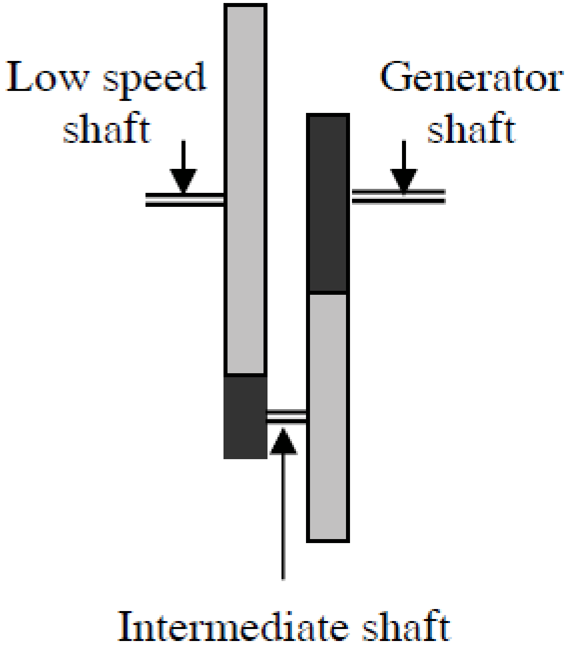
Wind turbine (Rotor)



Wind Turbine (Gear Box)

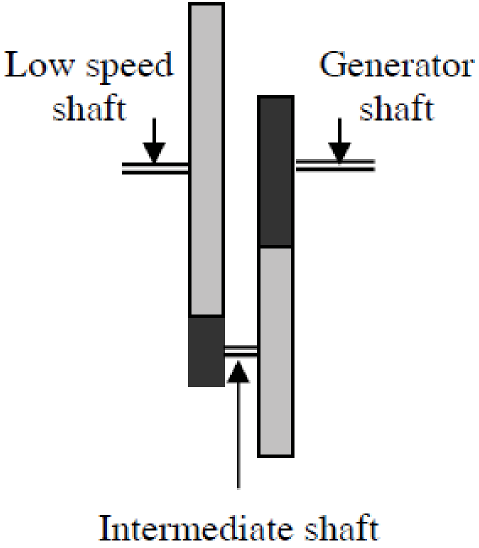
Speed of a typical wind turbine rotor may be 30 to 50 r/min whereas, the optimum speed of generator may be around 1000 to1500 r/min.

Hence, gear trains are to be introduced in the transmission line to manipulate the speed according to the requirement of the generator.



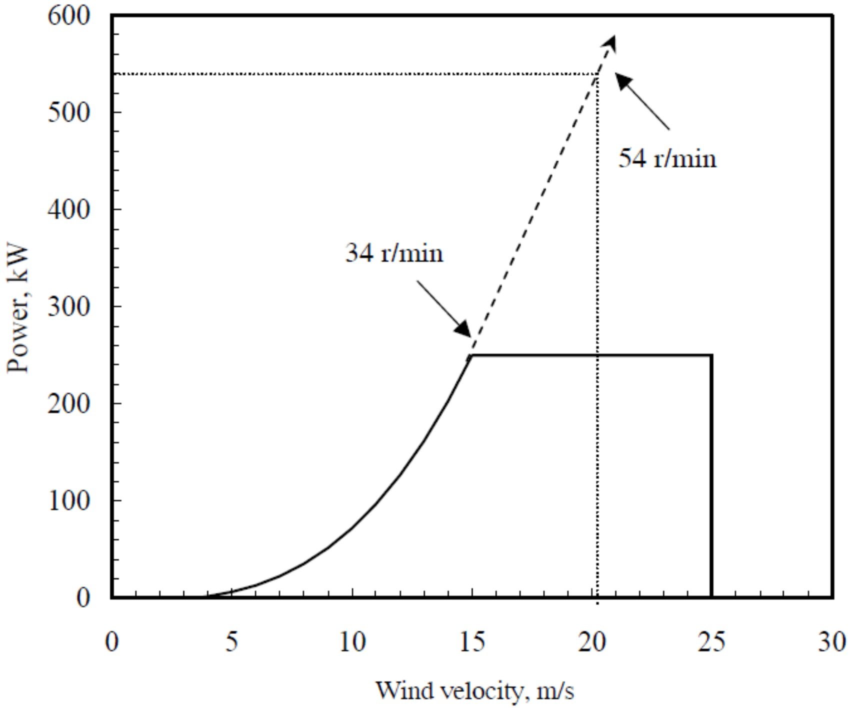
Wind Turbine (Gear Box)

An ideal gear system should be designed to work smoothly and quietly-even under adverse climatic and loading conditions-throughout the life span of the turbine.



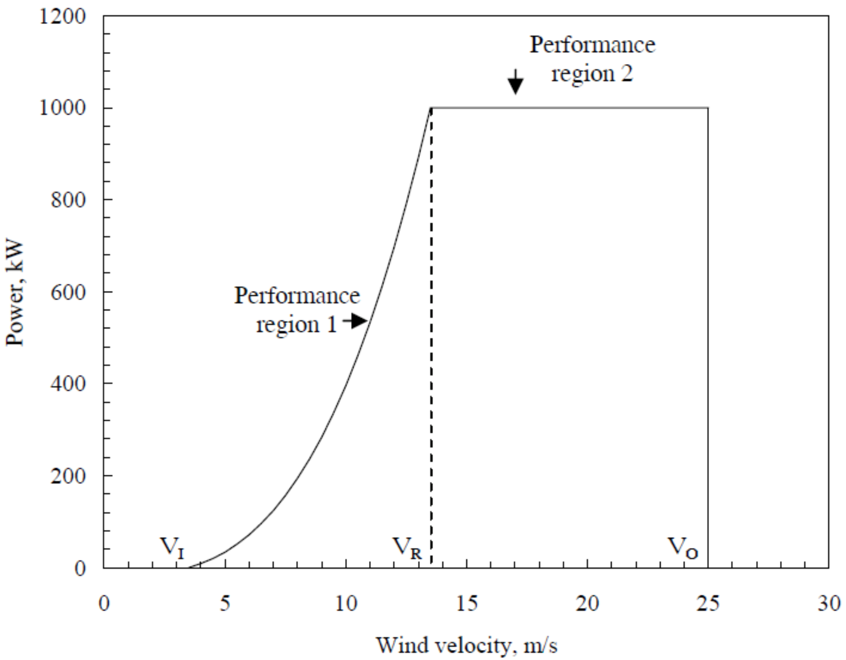
Wind turbine (power regulation)

Between the rated velocity and cut-out velocity (25 m/s), the system generates the same rated power of 250 kW, irrespective of the increase in wind velocity.



Wind turbine (power regulation)

Velocity range	Power
0 to V_I	No power as the system is idle
V_I to V_R	Power increases with V
V_R to V_O	Constant power P_R
Greater than V_O	No power as the system is shut down



Pitch control/regulation

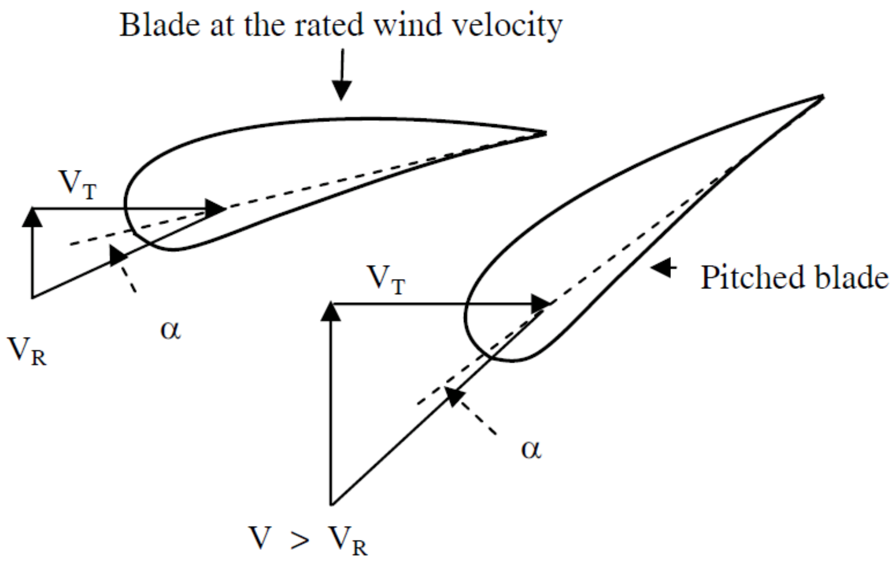


Fig. 4.10. Principle of pitch control

Pitch control/regulation

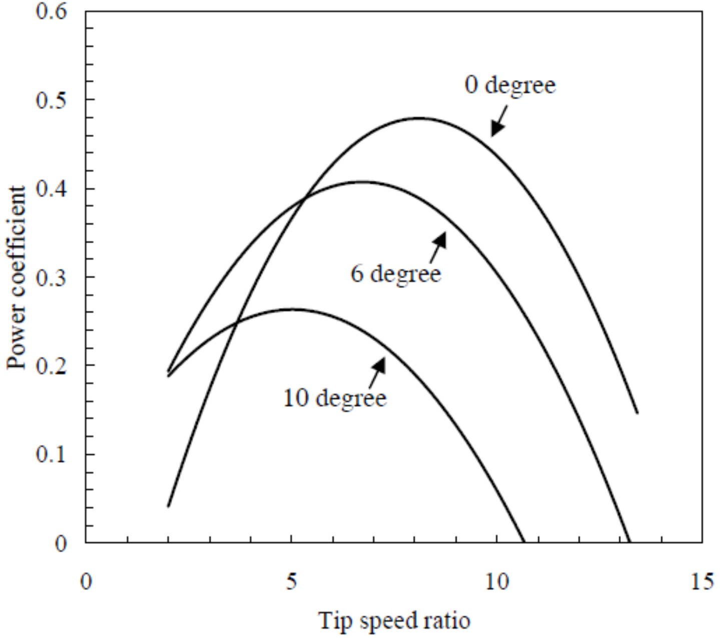


Fig. 4.11. Effect of blade pitch on the rotor performance

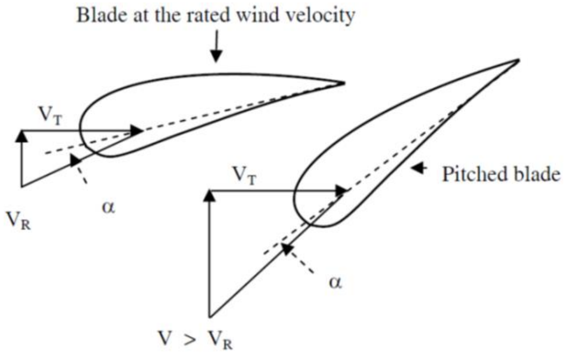


Fig. 4.10. Principle of pitch control

Pitch Regulation

In a pitch controlled turbine, the blades are to be turned about their longitudinal axis by the pitch control mechanism in tune with the variations in wind speed.

The pitch control mechanisms are driven by a combination of hydraulic and mechanical devices.

In order to avoid sudden acceleration or deceleration of the rotor, the pitch control system should respond fast to the variations in wind velocity.

Similarly, for maximum performance, the pitching should exactly be at the desired level.

Stall Regulation

In these turbines, profile of the blades is designed in such a way that when the wind velocity exceeds beyond the rated limit, the angle of attack increases.

With this increase in angle of attack, air flow on the upper side of the blade ceases to stick on the blade. Instead, the flow starts whirling in an irregular vortex, causing turbulence. This kills the lift force on the blades, finally leading to blade stall.

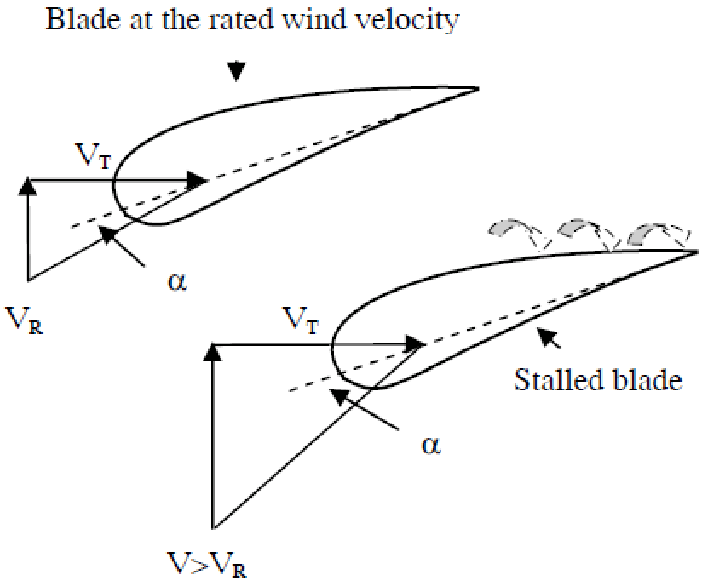


Fig. 4.12. Principle of stall control

Stall regulation

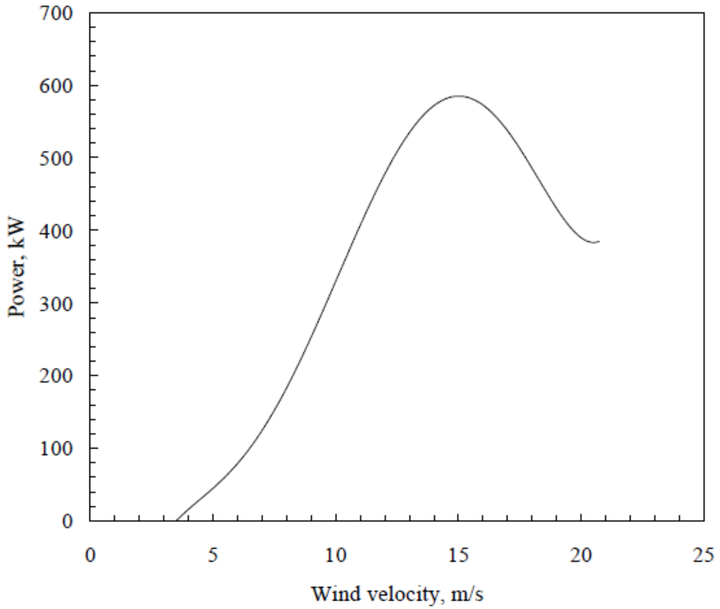


Fig. 4.13. Power curve of a typical stall controlled wind turbine

Pitch v/s stall regulation

Pitch controlled turbines can capture the power more effectively in moderate winds as the blades can be set to its optimum angle of attack by pitching. However, moving components are to be introduced in the blade itself for adjusting its angle, which is a drawback of these systems. Similarly, the control unit should have high sensitivity towards wind fluctuations which makes them costlier.

On the other hand, stall controlled blades do not require any control system or pitching mechanism. However, the blades are to be aerodynamically twisted along its longitudinal axis. Design and manufacturing of such blades demand sophistication. Structural dynamics of the system should be carefully analyzed before the design to avoid any possible problems like the stall induced vibrations.

Active stall regulation

Some modern turbines exploit the advantages of both the pitch and stall controlled options for regulating its power. This is called the active stall controlled power regulation. In this method, the blades are pitched to attain its best performance in lower winds. However, once the wind exceeds the rated velocity, the blades are turned in the opposite direction to increase the angle of attack and thus forcing the blades into a stall region. The active stall allows more effective power control and the turbine can be run nearly at its rated capacity at high winds.

Yaw control/regulation

Another method of power control is to push the rotor partly away from the wind direction at higher wind speeds. This is called the furl or yaw control.

The rotor spin axis is pushed to an angle to the incoming wind direction at high winds for regulating the power.

Safety brakes

During the periods of extremely high winds, wind turbines should be completely stopped for its safety. Similarly, if the power line fails or the generator is disconnected due to some reason or the other, the wind turbine would rapidly accelerate.

This leads the turbine to run-away condition within a few seconds.

The turbine should essentially be fitted with safety devices, which will break the system and bring it to halt under such conditions.

Safety brakes

Two types of brakes are commonly used with wind turbines. They are aerodynamic brakes and mechanical brakes. In order to ensure the safety, wind turbines usually have two braking systems, one functioning as the primary brake and the other as a backup option which comes in to action if the primary system fails.

They are also useful to lock the rotor during the turbine maintenance.

Generator

In contrast with the generators used in other conventional energy options, generator of a wind turbine has to work under fluctuating power levels, in tune with the variations in wind velocity. Different types of generators are being used with wind machines. Small wind turbines are equipped with DC generators of a few Watts to kilo Watts in capacity. Bigger systems use single or three phase AC generators.

As large-scale wind generation plants are generally integrated with the

grid, three phase AC generators are the right option for turbines installed at such plants. These generators can either be induction (asynchronous) generators or synchronous generators.

Environmental impact

Environmental impact

As in case of any human activities, wind energy generation is also not totally free from environmental consequences.

The major environmental problem with wind energy is avian mortality due to collision with turbines and related structures.

Noise emission and the visual impacts on landscapes are the other issues to be tackled.

However, it should be noted that these environmental impacts are not global (as in case of atmospheric emissions and global warming) and thus can be monitored and resolved at local level.

Environmental impact

The fuel used here is bituminous coal and the flue gases are undergone desulphurization using the lime stone/gypsum.

It should be noted that ninety per cent of the sulfur dioxide are removed under this process and still the level of emission is higher than the acceptable limit.

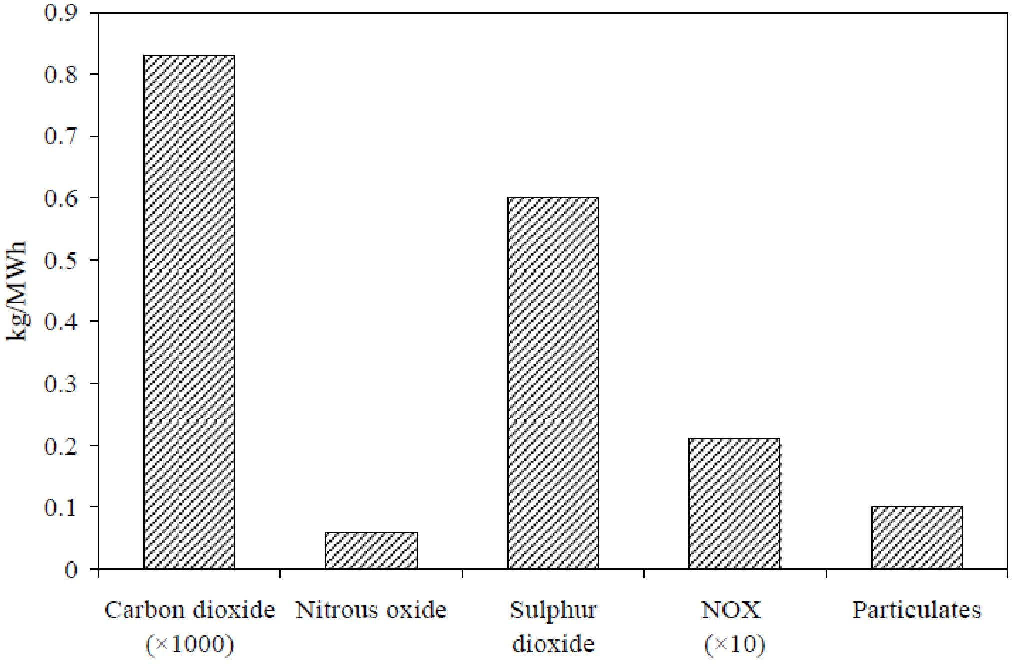


Fig. 6.1. Atmospheric emissions from a coal based power plant

Environmental impact

(1) Don’t we require energy for manufacturing the turbine and constructing the plant?

(2) Shouldn’t we account the emissions in the manufacturing and commissioning stages of the system in our analysis?

(3) Shouldn’t we consider the energy required for disposing the plant after its life period?

(4) If we consider these factors, can we say that the process of generating energy from wind is totally free from atmospheric emissions?

(5) How rapidly could the system recover all the energy consumed for its manufacturing, installation, operation and dismantling?

Environmental impact

In the life cycle based analysis, we look at a system or technology in its totality and account the energy use and related emissions involved in all the stages of its production, use and disposal.

This essentially should include the extraction of raw materials, its conversion into different components, manufacturing, commissioning and operation of the system, and finally its disposal or recycling after use.

Environmental impact

When we assess such systems, it is logical to account the energy flow and emission potential of all the phases of the project life.

Upto the phase of turbine manufacturing, energy of various forms are consumed and thus the system will have a negative impact on environment. In contrast, during the operational phase, energy is being generated without any pollution and thus the project reacts positively to the environment.

Life cycle of wind turbine

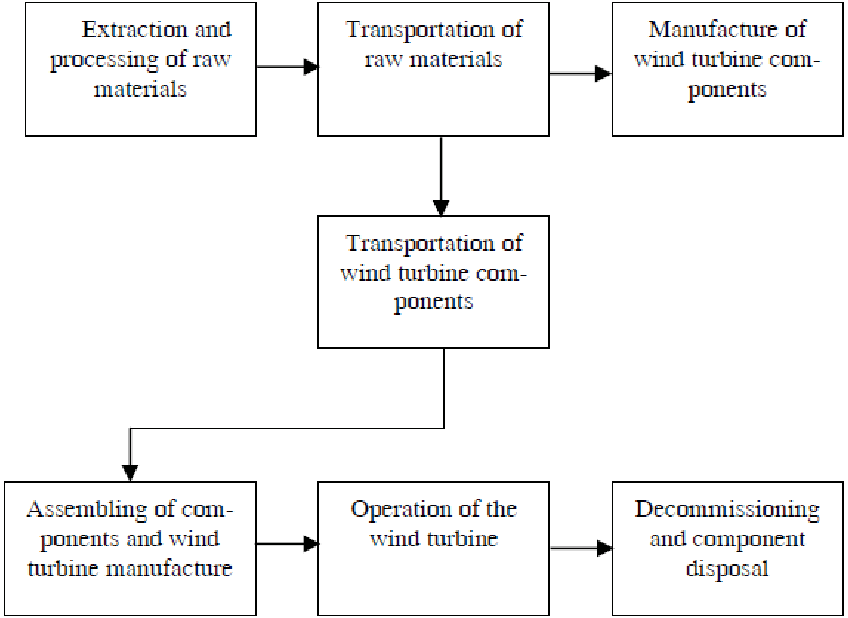


Fig. 6.2. Various stages of the life cycle of a wind turbine

Life cycle of wind turbine

Energy Payback Ratio

The useful energy produced by the system (E_P) with the energy consumed by it throughout its life cycle (E_{CL}).

$$EPR = \frac{E_p}{E_{CL}} = \frac{E_A\ L}{E_{CL}}$$

Energy Payback Period

The time required for the system to pay back all the energy consumed by it.

$$EPP = \frac{E_{CL}}{E_A}$$

Wind energy economics

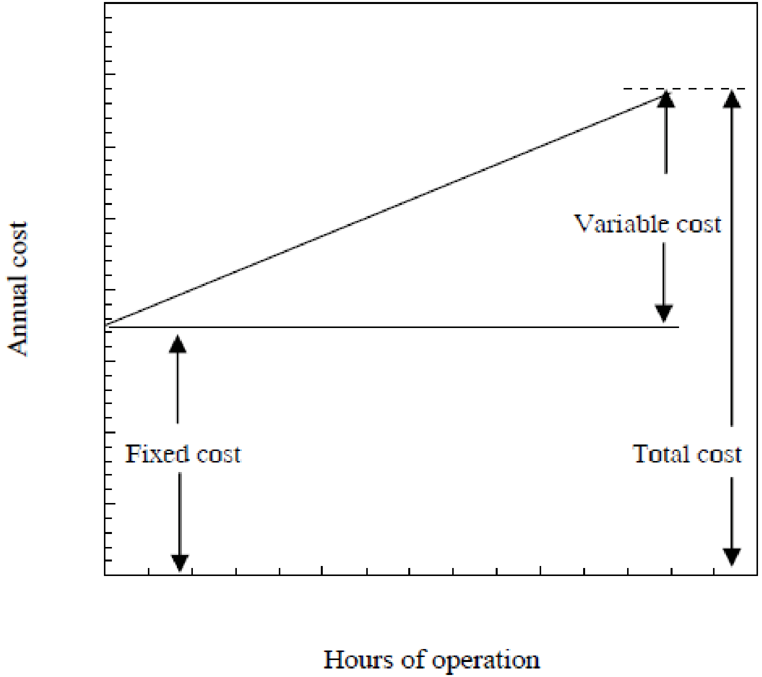
Wind energy economics

There are several factors that affect the unit cost of electricity produced by a wind turbine. These may vary from country to country and region to region. Economic merit of a wind powered generation plant heavily depends on the local conditions.

For a wind turbine, the fuel is free, but the capital investment is high. While assessing the initial investment for the project, apart from the cost of the wind turbine, investment for other essential requirements like land, transmission lines, power conditioning systems etc. should also be accounted.

Wind energy economics

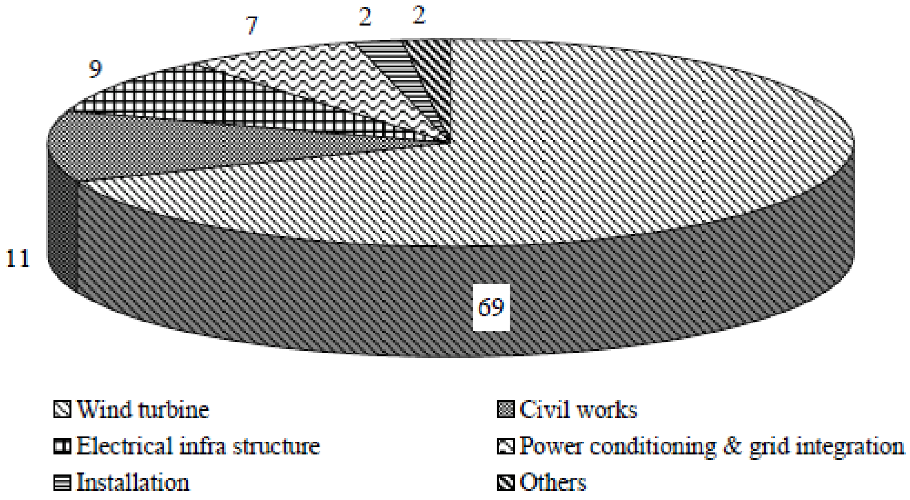
Fixed costs refer to the costs that are to be incurred by virtue of mere existence of the project. That is, fixed costs are to be met, irrespective of whether the project is functional and how much power is being generated. On the other hand, the variable costs vary in proportion to the quantity of project output.



Wind energy economics

The major part of the investment- around 69 percent- is for the turbine itself. Civil works, electrical infrastructure and power conditioning required 11, 9 and 7 per cents respectively of the total initial investment.

Installation and other miscellaneous charges account for 4 per cent.



Thank You