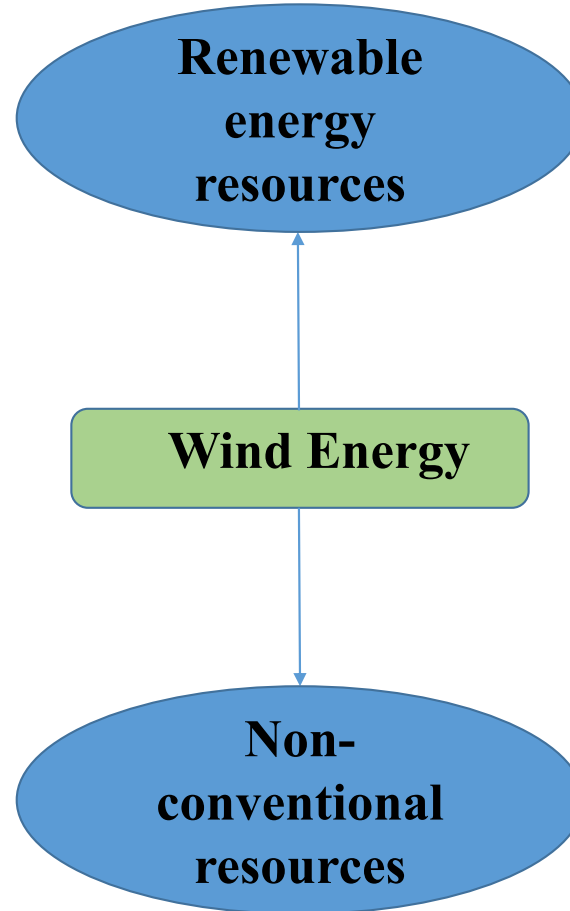


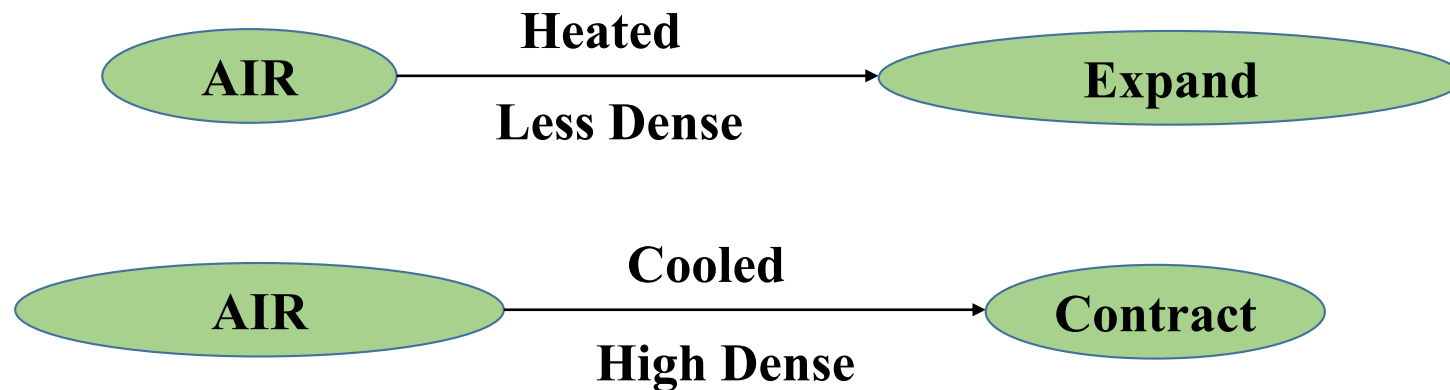
## Wind Energy



**It can be renew by nature again and again.**

## The Earth's Wind Systems

- Like all gases, air expands when heated, and contracts when cooled.
- Thus warm air is less dense than cold air and will rise to high altitudes when strongly heated by solar radiation.



## Origin of Winds

The winds can be classified as:

- Global winds
- Local winds
- **Global Winds:** The primary force for global winds is produced due to differential heating of the earth surface at equator (0 degree longitude) and polar regions (about  $\pm 90$  degree longitude).
- Cold winds move from polar to equatorial regions.
- These air currents are also called **trade winds** as sailing ships in the past used these air currents for ship movement and trading.

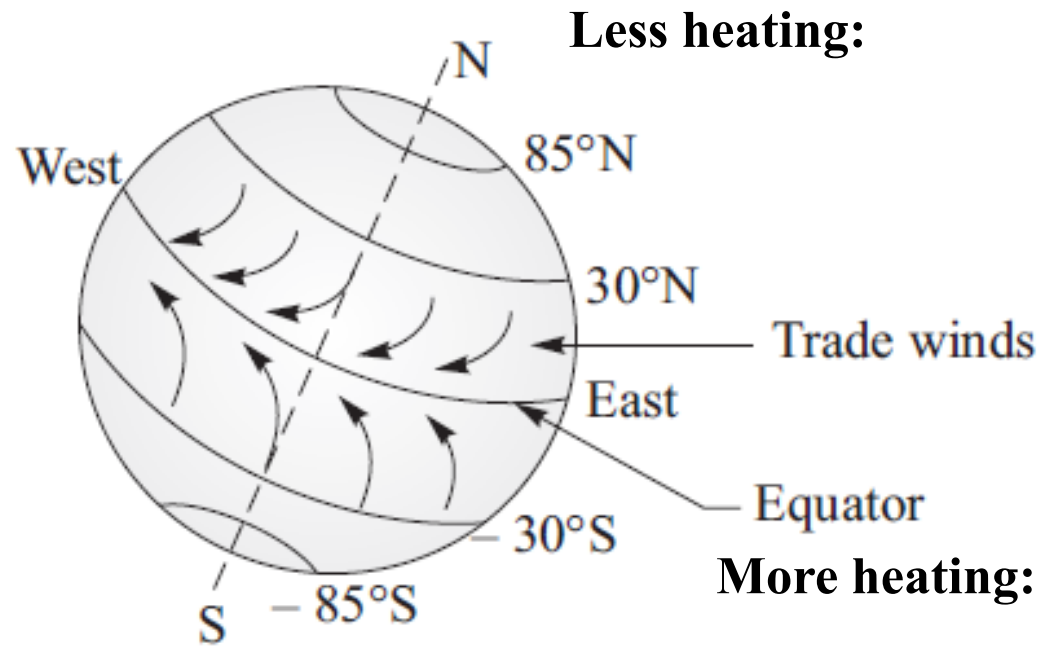


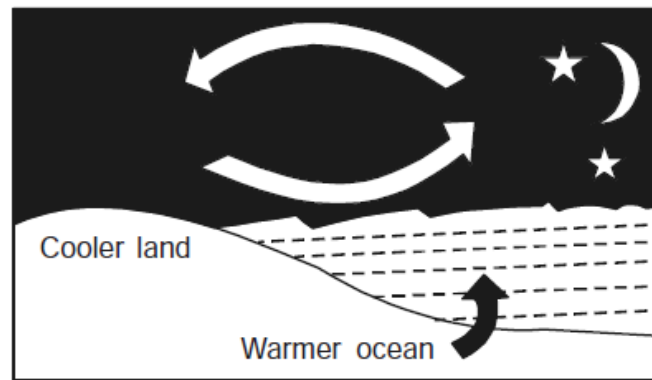
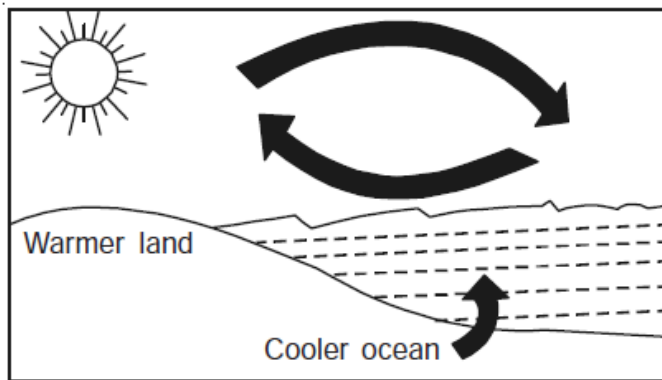
Figure: Global winds and their circulations.

## **Origin of Winds cont.. Local Winds**

- **Local winds are generated due to uneven heating.**
- **Uneven heating occurs on land surface and water bodies due to solar radiation.**

## Wind Energy

- Sun is the main source of wind, and hence, wind is considered a form of solar energy.
- Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth.
- Heating and cooling of the atmosphere which generates convection currents.
- The wind flow or motion energy is 'harvested' by modern wind turbines.



**Due to different heat capacities of land and ocean.**

**(a) Wind from ocean to land during daytime, and (b) Wind from land to ocean during night.**

## **Wind Energy cont.**

- **During daytime, the air over the land mass heats up faster than the air over the oceans.**
- **Hot air expands and rises while cool air from oceans rushes to fill the space, creating local winds.**
- **At night the process is reversed as the air cools more rapidly over land than water over off-shore land, causing breeze.**

## **Advantages of Wind Energy**

- ✓ **Freely and abundantly available in nature.**
- ✓ **It is a renewable energy source.**
- ✓ **It does not cause pollution to environment.**
- ✓ **It require minimal maintenance and operating cost.**

## **Disadvantages of Wind Energy**

- ✓ **It can not produce steady and consistent power.**
- ✓ **It can generate only low power.**

**Renewable:-Resources which can be renewed by nature again and again so that their supply is not adversely affected by the rate of their consumption. Examples are:**

- ✓ **Wind**
- ✓ **Solar**
- ✓ **Hydel**
- ✓ **Geothermal**

## Wind Energy Conversion System (WECS)

- If the mechanical energy is used directly by machinery, such as for a pump or grinding stones, the machine is usually called a windmill.
- Wind turbines are also sometimes referred to as WECS.



Wind mills



Wind turbines



### **Wind Energy Conversion System (WECS) cont.**

- **Wind turbines deliver their power through a revolving shaft, and in this respect, they are similar to other prime movers such as diesel engine and stream turbines.**
- **A generator can be coupled to this shaft and the electrical power delivered can be used to serve the multitude of different purposes for which electricity is required today.**
- **In practice, an important difference between the wind turbine and the power delivered by engines and stream turbines is that the power delivered by wind turbines to the same extent uncontrolled and unpredictable over very short periods of time.**
- **In most applications for electricity, power is normally required on demand and not whenever available. Therefore, it is important to have some storage or reserve supply. This requirement has been one of the main limitations.**
- **If the mechanical energy is then converted to electricity, the machine is called a wind generator.**

## Air Mass Density

*From the universal gas equation,*

$$\rho = \left[ \frac{P}{(R.T)} \right]$$

Where,

$\rho$  is the density of in kg/m<sup>3</sup>

P is the air pressure in Pascal i.e., N/m<sup>3</sup>

R is the specific gas constant for air i.e., 287 J/kg.K

T is the air temperature in degree Kelvin ( $K = C^{\circ} + 273$ )

An approximate value of  $\rho$  based on altitude only is given by  $\rho = 1.225 - [1.194 \times$

## Energy and Power in the Wind

- The energy contained in the wind is its kinetic energy.
- Kinetic energy =  $\frac{1}{2}mV^2$  (1)

Where, m = Mass of the air , kilograms

V = Velocity of the air, m/s

$$\begin{aligned}\text{Mass (m) of air per second} &= \text{air density} \times \text{volume of air passing per second} \\ &= \text{air density} \times \text{area} \times \text{length} \\ &= \text{air density} \times \text{area} \times \text{velocity}\end{aligned}$$

That is:  $m = \rho AV$

Substituting for m in (1) above gives:

$$\text{Kinetic energy per second} = 0.5 \rho AV^3 \text{ (joules per second)}$$

## Energy and Power in the Wind cont..

Density of air ( $\rho$ ) =  $1.2256 \text{ kgm}^{-3}$  *at sea level*

$$\text{Power} = \frac{\text{Energy}}{\text{time}} (\text{watts}) \Rightarrow 0.5\rho AV^3$$

The power in the wind is proportional to:

- The density of the air
- The area through which the wind is passing (i.e. through a wind turbine rotor),
- The cube of the wind velocity.

$$\frac{\text{Power}}{A} = 0.5\rho V^3 \Rightarrow \text{Wind power density i. e, wind power over a unit area}$$

## Energy and Power in the Wind cont..

*Energy is defined as (power x time)*

$$\text{Power} = \frac{\text{Energy}}{\text{time}} (\text{watts}) \Rightarrow 0.5\rho AV^3$$

*Wind energy density over time 0 to t,*

$$\frac{E_w}{A} = \int_0^t \left( \frac{P_w}{A} \right) . dt$$

$$\frac{E_w}{A} = 0.5\rho \int [V^3] dt$$

$$\frac{E_w}{A} = 0.5\rho \sum V^3 . \Delta T$$

*$\Delta T$  indicates time in hours*

## Wind Potential

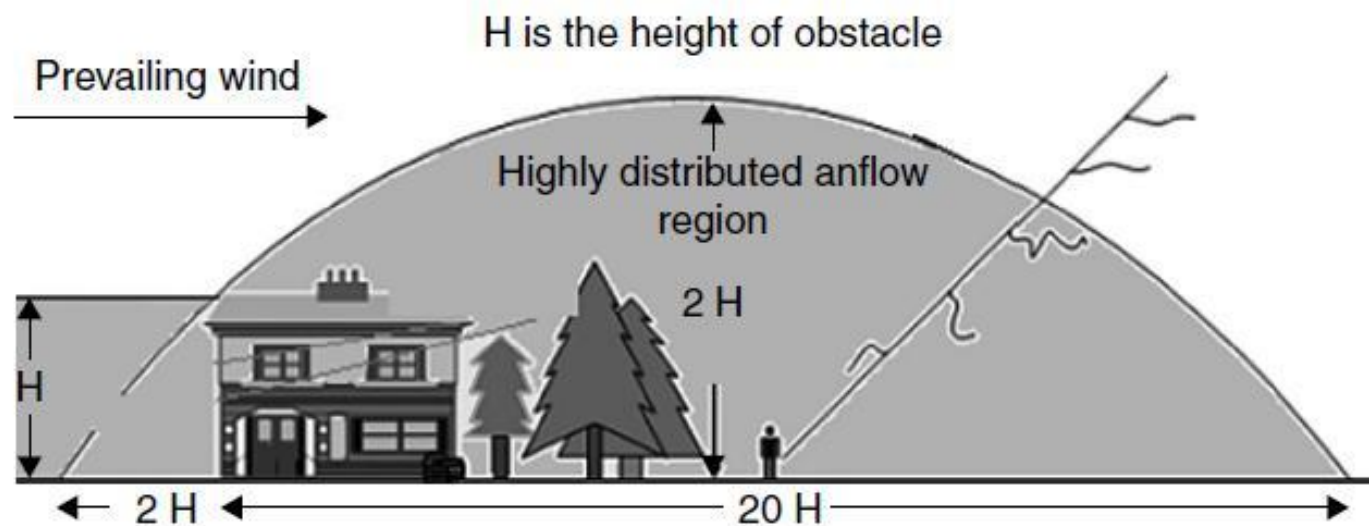
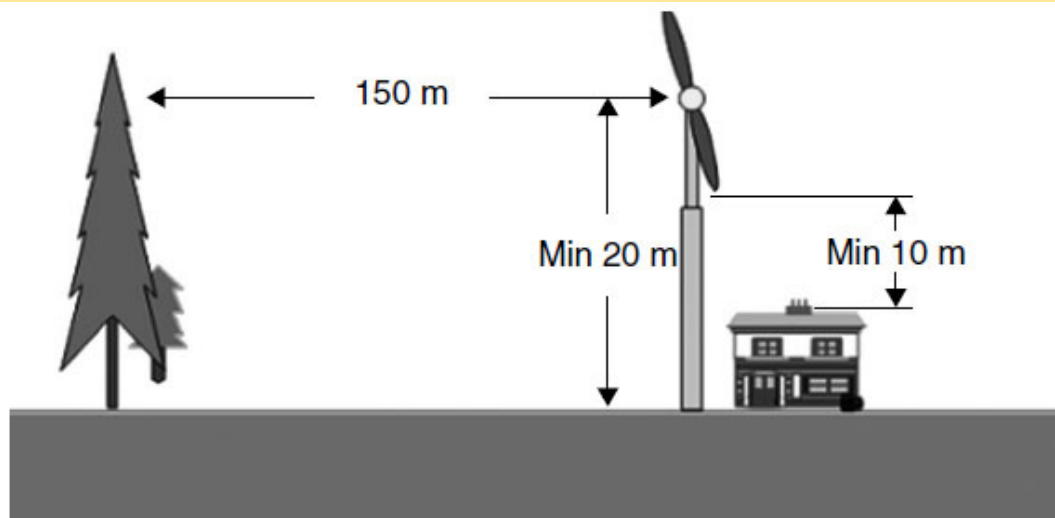
- **In order for a wind energy system to be feasible, there must be an adequate wind supply.**
- **A wind energy system usually requires an average annual wind speed of at least 15 km/h.**
- **Table represents a guideline of different wind speeds and their potential in producing electricity.**
- **A wind generator will produce lesser power in summer than in winter at the same wind speed as air has lower density in summer than in winter.**
- **Similarly, a wind generator will produce lesser power in higher altitudes—as air pressure as well as density is lower—than at lower altitudes.**

## Wind Turbine Performance with Wind Speed

Average Wind Speed Suitability (km/h)	Wind Turbine Performance
Up to 15	Extremely poor
18	Poor
22	Moderate
25	Good
29	Excellent

- **Obstructions such as trees or hills can interfere with the wind supply to the rotors. To avoid this, rotors are placed on top of towers to take advantage of the strong winds that blow high above the ground.**
- **The towers are generally placed 100 m away from the nearest obstacle. The middle of the rotor is placed 10 m above any obstacle that is within 100 m.**

## Installation of wind turbine (simple rule of thumb)





## Wind Turbine Siting

The main considerations for selecting a site for wind generator are as follows:

- (i) **High annual mean wind speed.** A basic requirement for a successful use of a windmill or farm is an adequate supply of wind and good wind speeds. The wind power is proportional to the cubic power of wind speed.
- (ii) **No obstruction.** There should not be any high structure to obstruct wind for a distance of 3 km to the windmill.
- (iii) **Open plain.** The site should be the open plain such as open sea shoreline where strong winds prevail.
- (iv) **Height.** The wind speed increases with height, which can be obtained when the windmill is located on a hill or a ridge with gentle slope.
- (v) **Near lake or ocean.** Differential heating of water and land generates wind of sufficient speeds.
- (vi) **Topography.** Topography such as mountain gap helps to channelise and speed up winds.
- (vii) **Favourable land cost.** It helps in restriction or reducing the cost of project.
- (viii) **Nearness to load centre.** It reduces the cost of transmission of the generated power.
- (ix) **Nearness to road or rail link.** It helps in installation of windmill.
- (x) **Availability of wind rose.** It helps in designing of windmill as wind data of the site can be determined.

***Numerical Problem on Wind power density i. e, wind power over a unit area***

**Q.** Wind speed is 10 m/s at the standard atmospheric pressure. Calculate (i) the total power density in wind stream, (ii) the total power produced by a turbine of 100 m diameter with an efficiency of 40%.

**Solution:** (i) Total Power density  $= \frac{\text{Total Power}}{\text{Area}} \Rightarrow \frac{\frac{1}{2}\rho AV^3}{A} = \frac{1}{2}\rho V^3$

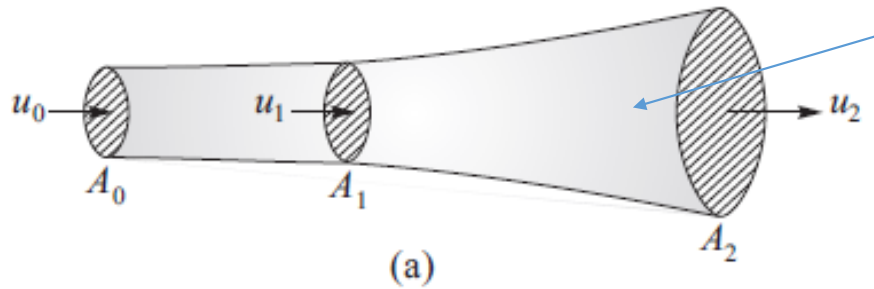
$$= 0.5 \times 1.226 \times 10^3 \Rightarrow 613 \text{ W/m}^2$$

(ii) Efficiency  $= \frac{\text{Desired output}}{\text{Required input}}$

$$0.40 = \frac{\text{Power produced}}{613 \times \frac{\pi}{4} \times 100^2}$$

$$\text{Power produced} = 1924820 \text{ W} \Rightarrow 1924.82 \text{ kW}$$

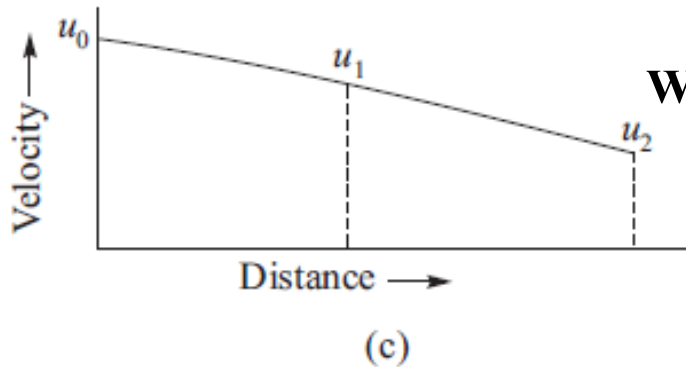
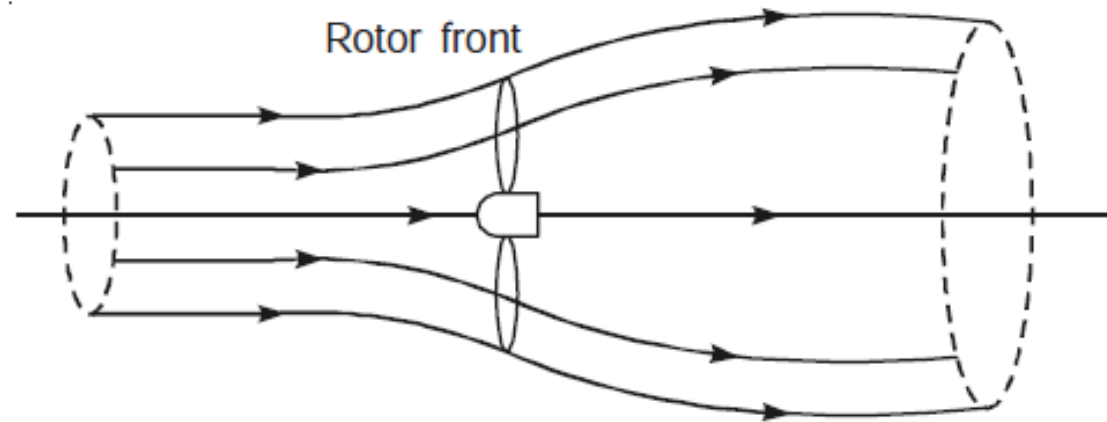
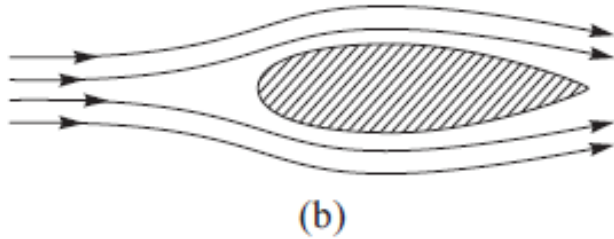
## Principle of Power Generation or Betz model of expanding airstream tube



*Airstream tube*

*Law of continuity*

$$Q \Rightarrow A_0 u_0 = A_2 u_2 = \text{constant}$$



Where,

$u_0$  = Wind velocities at upstream direction

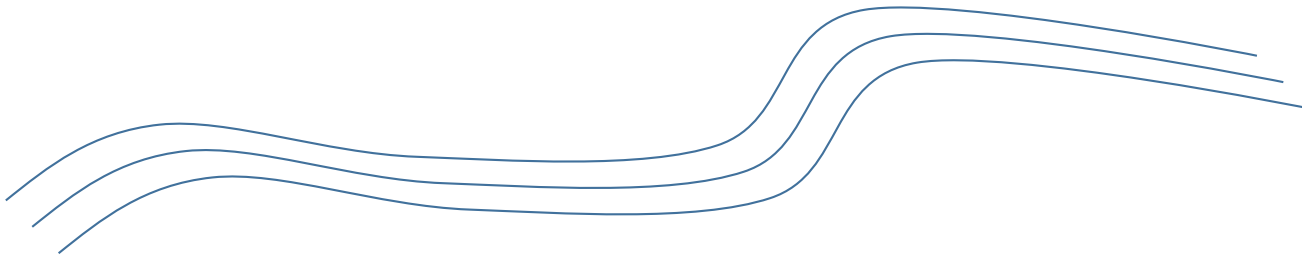
$u_1$  = Wind velocities while passing through rotor blade

$u_2$  = Wind velocities at downstream direction

- The rotor of the wind turbine collects wind from the whole area swept by the rotor.
- Air mass flow rate should be same everywhere within the stream tube.

## Bernoulli's Principle

- It is based on the principle of conservation of energy.
- In a steady flow the sum of all forms of mechanical energy in a fluid along a streamline is the same at all points on that streamline.



## DESIGN OF WIND TURBINE ROTOR

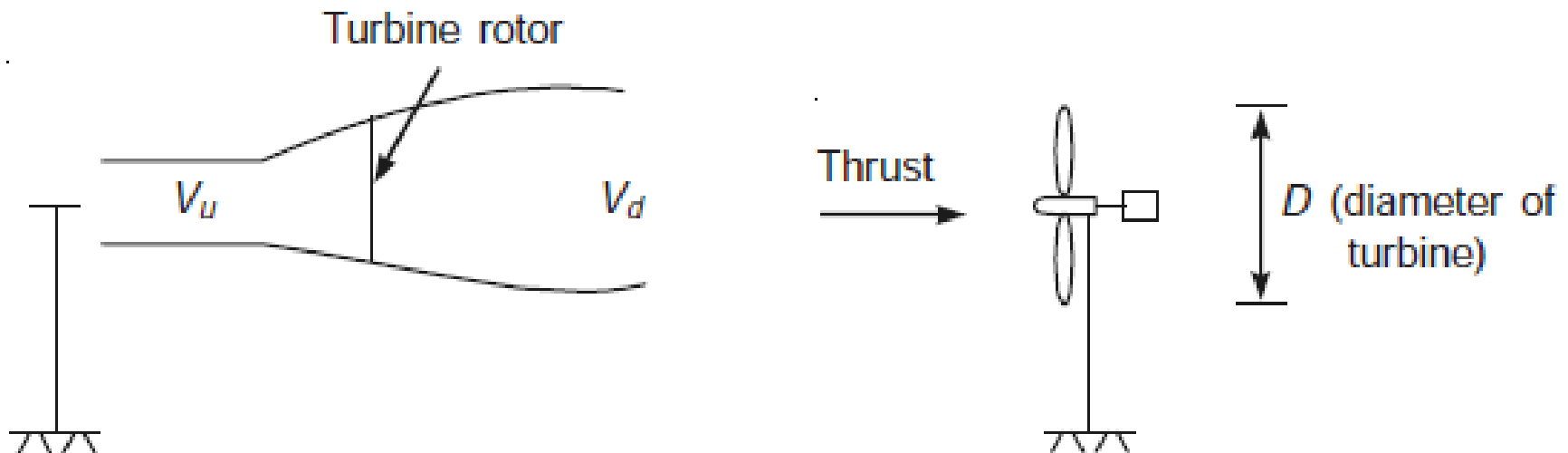
Two forces that operate on the blades of a propeller type wind turbine

Axial Thrust

Acts in the same direction as that of the flowing wind stream.

Circumferential force

Acting in the direction of wheel rotation that provides the torque.



## Mechanical Power

*Mechanical Power = Torque imparted by the wind  $\times$  Angular velocity*

$$P_T = T \times \omega$$

$$T = F \times R$$

## Numerical Problems

***Q1.*** Wind at one standard atmospheric pressure and  $15^{\circ}\text{C}$  has a speed of  $10\text{ m/s}$ . A  $10\text{-m}$  diameter wind turbine is operating at  $5\text{ rpm}$  with maximum efficiency of  $40\%$ . Calculate

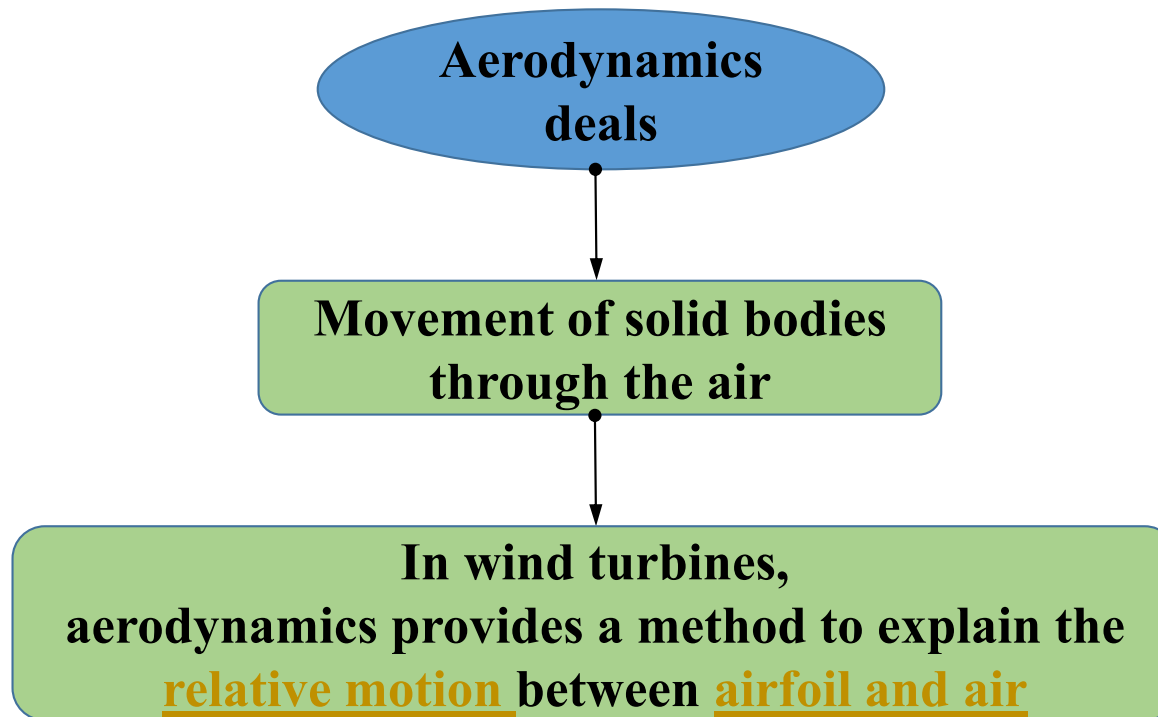
- (i) The total power density in wind stream,*
- (ii) The maximum power density,*
- (iii) The actual power density,*
- (iv) The power output of the turbine, and*
- (v) The axial thrust on the turbine structure.*

## Numerical Problems

**Q2.** *A WEG generates 1500 watts at rated speed of 24 kmph at the atmospheric pressure and temperature of 20°C. Calculate the change in output if the wind generator is operated at an altitude of 1800 m, temperature 10°C, wind speed 30 kmph, and air pressure 0.88 atmosphere.*

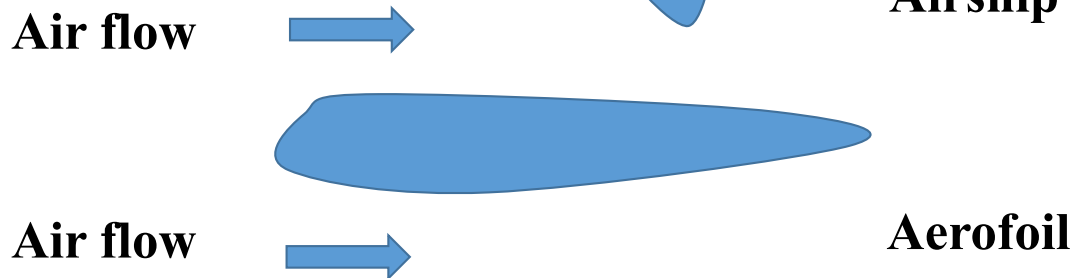
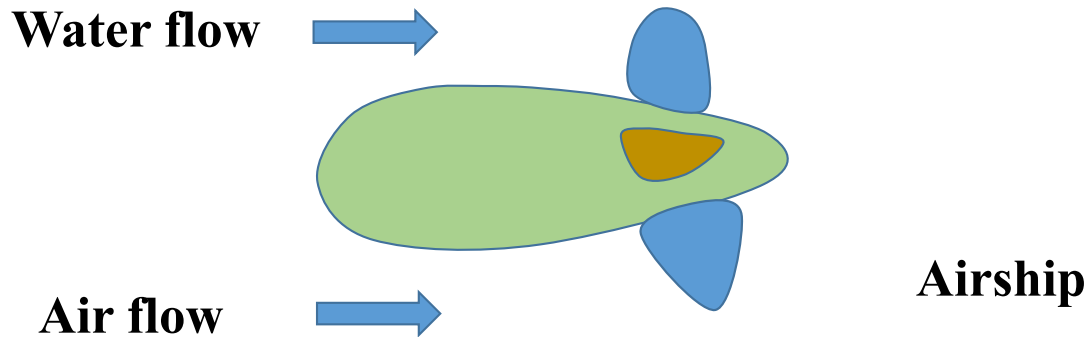
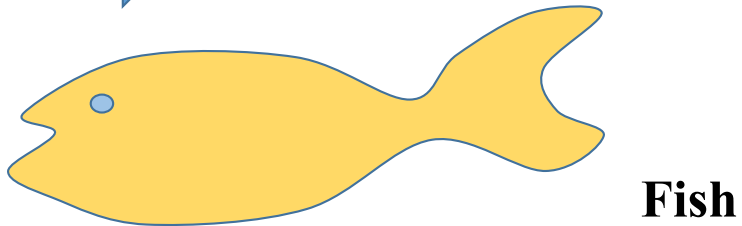
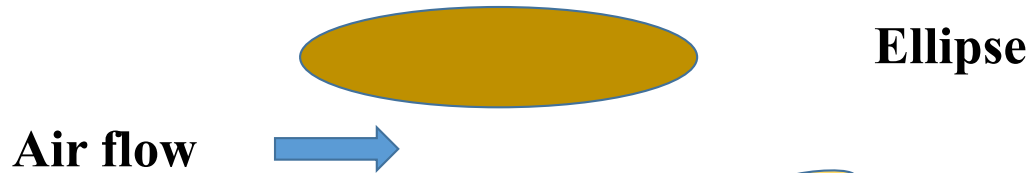


## AERODYNAMIC OPERATION OF WIND TURBINES



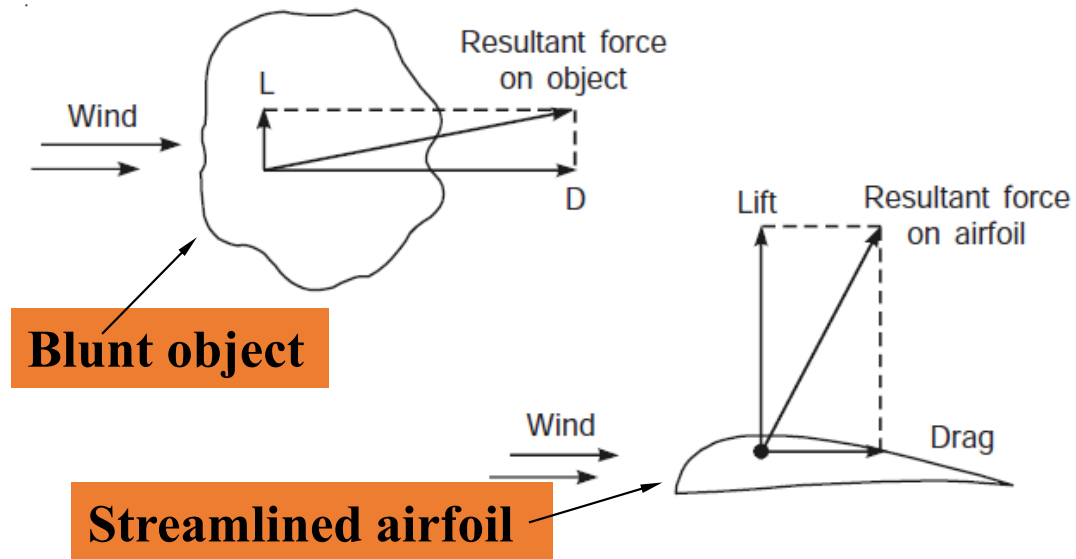
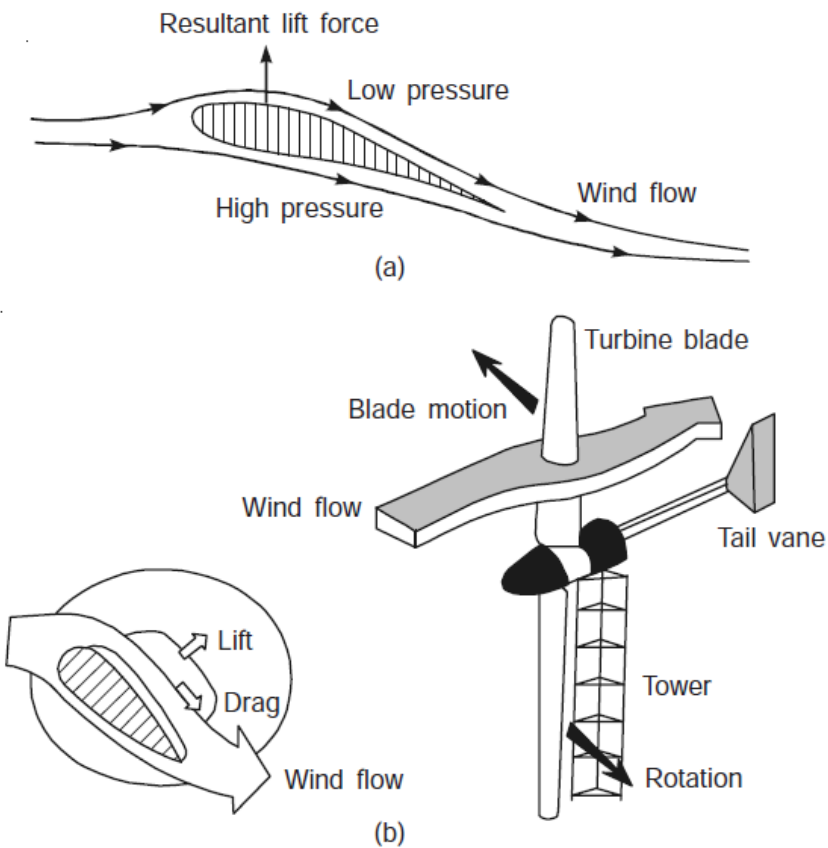
**Airfoil is the cross-section of the wind turbine blade.**

## Some Examples of Streamlined Shapes



**Streamlined objects  
experience a smaller  
drag force than that  
experienced by blunt  
objects**

## PRINCIPLES OF WIND ENERGY CONVERSION (AERODYNAMICS) cont..



**Figure:** Relative magnitudes of lift and drag forces on a blunt object and a streamlined airfoil.

**Figure:** (a) Aerodynamic lift force on blade cross-section of wind turbine, and (b) the basic operating principle of wind turbine aerodynamic lift.

## Drag force

- **Drag :** It is the resistance which a body experiences when a fluid moves over it.
- The force that a flowing fluid exerts on a body in the direction of flow is called ‘drag force’.
- Streamlined objects experience a smaller drag force than that experienced by blunt objects.
- Generation of lift always creates a certain amount of drag force.
- **Friction acts to help us as a ‘life saver’ in brakes of automobiles. Similarly, the drag force is useful in safe landing with a parachute.**
- **Reduction of drag is the basic engineering approach, associated with the reduction in fuel consumption in automobiles, aircraft and submarines.**

## Lift force

- When a body is immersed in a standstill fluid, only the normal pressure force is exerted on it.
- A flowing fluid in addition exerts tangential shear forces on the surface. Both these forces have two components, one is drag in the flow direction, the other is perpendicular to the fluid flow called 'lift'.
- It causes the body to move in the upward direction. The relative magnitudes of drag and lift forces depend completely on the shape of the object.
- Airfoils of a wind turbine are especially shaped to produce lift force on coming in contact with the moving air.
- It is achieved by fabricating the top surface of the airfoil as curved and the bottom surface nearly flat.

## PRINCIPLES OF WIND ENERGY CONVERSION (AERODYNAMICS)

- There are two primary physical principles by which energy can be extracted from the wind.
- These are through the creation of either lift or drag force (or through a combination of the two), as shown in Figure.

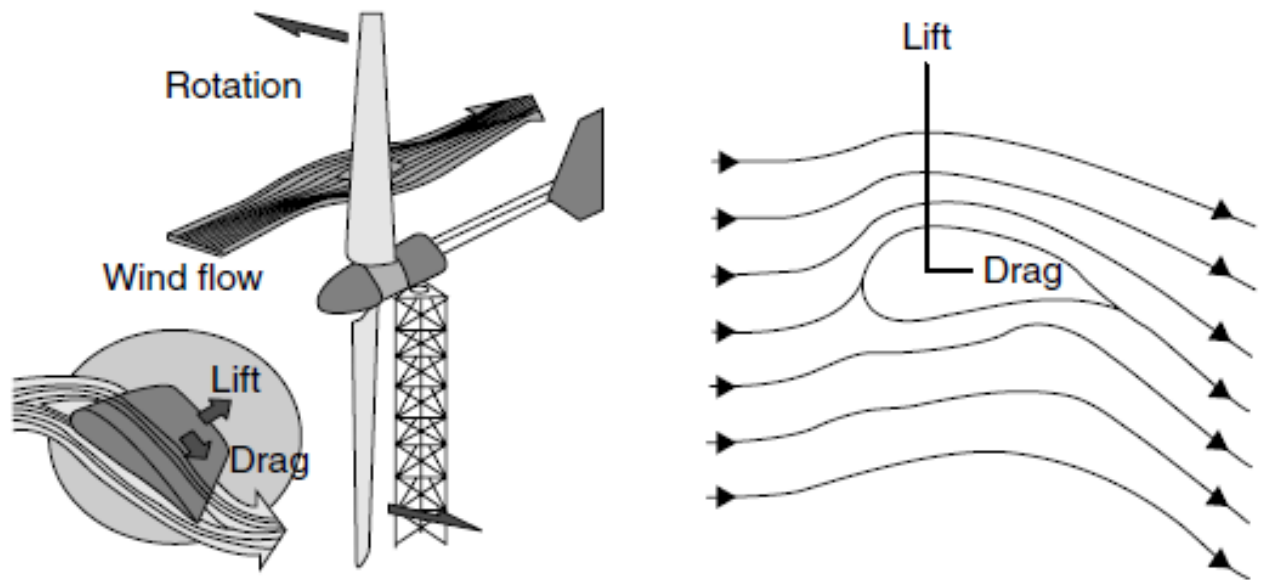
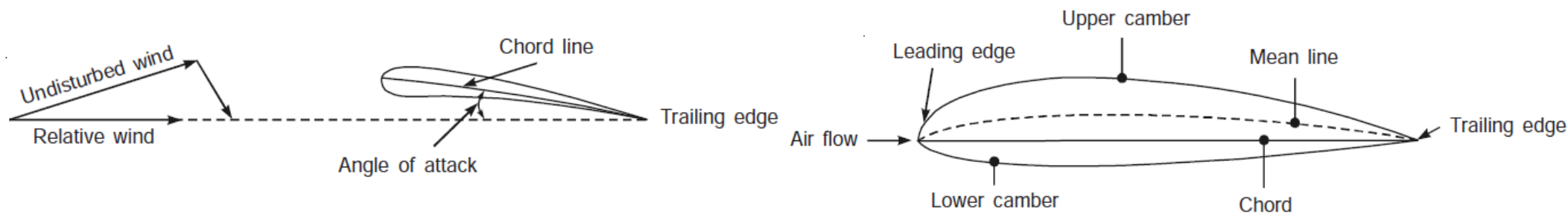


Figure: Principles of wind turbine aerodynamics

## TERMS USED IN WIND ENERGY

**Airfoil (Aerofoil):** A streamlined curved surface designed for air to flow around it in order to produce low drag and high lift forces.

**Angle of attack:** It is the angle between the relative air flow and the chord of the airfoil.

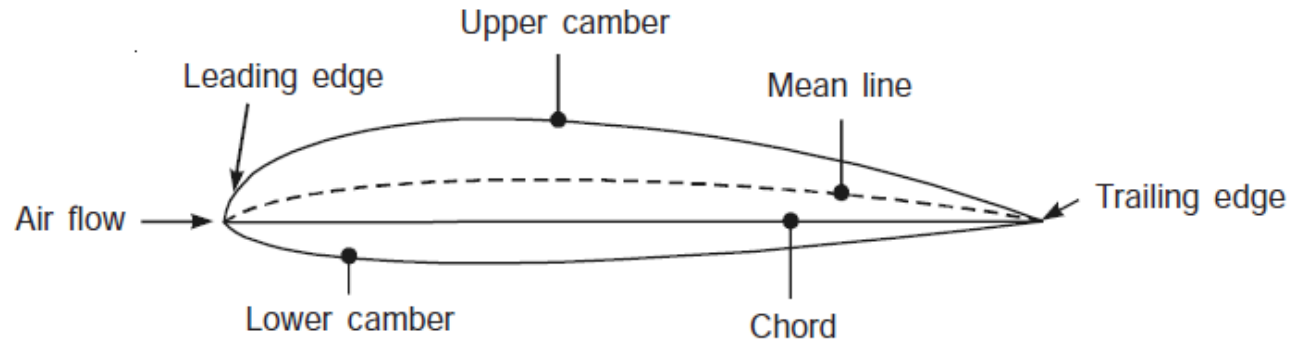


**Blade:** An important part of a wind turbine that extracts wind energy.

**Leading edge:** It is the front edge of the blade that faces towards the direction of wind flow [Figure].

**Trailing edge:** It is the rear edge of the blade that faces away from the direction of wind flow [Figure].

## TERMS USED IN WIND ENERGY cont.



**Mean line:** A line that is equidistant from the upper and lower surfaces of the airfoil.

**Camber:** It is the maximum distance between the mean line and the chord line, which measures the curvature of the airfoil.

**Rotor:** It is the prime part of the wind turbine that extracts energy from the wind. It constitutes the **blade-and-hub assembly**.

**Hub:** Blades are fixed to a hub which is a central solid part of the turbine.



## TERMS USED IN WIND ENERGY cont.

**Propeller:** It is the turbine shaft that rotates with the hub and blades and is called the propeller. Blades are twisted as per design. The outer profile of the blades conforms to aerodynamic performance while the inner profile meets the structural requirements.

**Tip speed ratio:** It is the ratio of the speed of the outer blade tip to the undisturbed natural wind speed.

**Swept area:** This is the area covered by the rotating rotor.

**Solidity:** It is the ratio of the blade area to the swept area.

- A windmill has rotor of 6 m with 30 blades. Each blade has width of 0.30 m, find the solidity. What is the implication of solidity?

$$\text{Solidity} = \frac{\text{Projected area of blades}}{\text{Swept area}}$$

$$\begin{aligned}\text{Solidity} &= \frac{30 \times 0.30}{\pi \times 6^2} \times 100\% \\ &= 7.96\%\end{aligned}$$

The fraction of the swept area that is solid.

## TERMS USED IN WIND ENERGY cont.

The greater is the solidity of a rotor, the slower it needs to turn to intercept the wind. When windmill has a lesser number of blades, it needs to rotate fast to intercept the wind so that wind should not be lost through the large gap existing between two blades without importing a part of wind power.

- Find the tip-speed ratio if a 6 m diameter rotor has rotation of 20 rpm and the wind speed is 4 m/s. What is the implication of tip speed ratio?

$$v = \omega R$$

= Linear velocity

$$\begin{aligned}\text{Tip speed ratio} &= \frac{W.R}{u_0} \\ \text{Tip speed ratio} &= \frac{\pi R N}{60} \\ &= \frac{\pi \times 6 \times 20}{60 \times 4} = 1.6\end{aligned}$$

$$\omega = \frac{2\pi \times 20}{60} \text{ Rad/sec} \Rightarrow 2.09 \text{ Rad/sec}$$

$$\text{Ratio} = \frac{2.09 \times 3}{4} = 1.57$$

The windmill rotating fast has tip speed ratio greater than 1. Two or three-bladed rotors rotate faster, thereby having tip speed ratio ranging from 3 to 10. More bladed rotors rotate move slowly, thereby having tip speed ratio between 1 and 2.

**Drag force:** It is the force component which is in line with the velocity of wind.

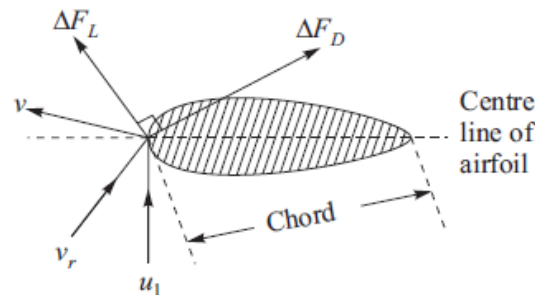
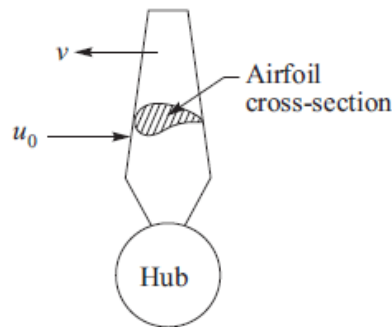
**Lift force:** It is the force component perpendicular to drag force.

## TERMS USED IN WIND ENERGY cont.

- Yaw control:** As the direction of the wind changes frequently, the yaw control is provided to steer the axis of the turbine in the direction of the wind.
- It keeps the turbine blades in the plane perpendicular to the wind, either in the upward wind direction or in the downward wind direction.

## Lift Type and Drag Type Wind Turbines

- Two important aerodynamic principles are used in wind turbine operations, i.e., lift and drag.
- Wind can rotate the rotor of a wind turbine either by lifting (lift) the blades or by simply passing against the blades (drag).
- Wind turbines can be identified based on their geometry and the manner in which the wind passes over the blades.
- Drag force: It is the force component which is in line with the velocity of wind.
- Lift force: It is the force component perpendicular to drag force.



**Chord:-** Width of the blade from one edge to the other edge.

## **Parts of a Wind Turbine**

- 1. The nacelle contains the key components of the wind turbine, including the gearbox and the electrical generator.**
- 2. The tower of the wind turbine carries the nacelle and the rotor. Generally, it is an advantage to have a high tower, since wind speeds increase farther away from the ground.**
- 3. The rotor blades capture wind energy and transfer its power to the rotor hub.**
- 4. The generator converts the mechanical energy of the rotating shaft to electrical energy.**
- 5. The gearbox increases the rotational speed of the shaft for the generator.**

## CLASSIFICATION AND DESCRIPTION OF WIND MACHINES

- The basic wind energy conversion device is the wind turbine.
- Although various designs and configurations exist, these turbines are generally grouped into two types depending on the *position of the rotor axis*.
- Figure illustrates the two types of turbines and typical subsystems for an electricity generation application.

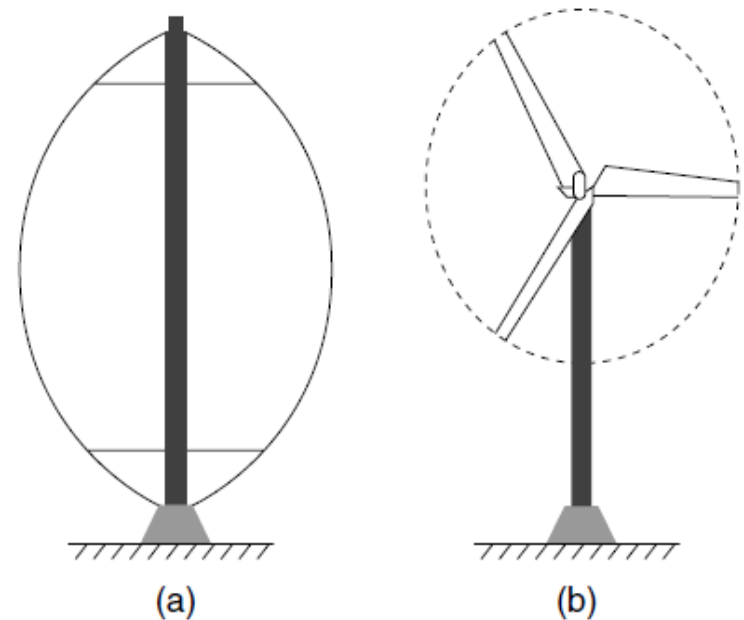
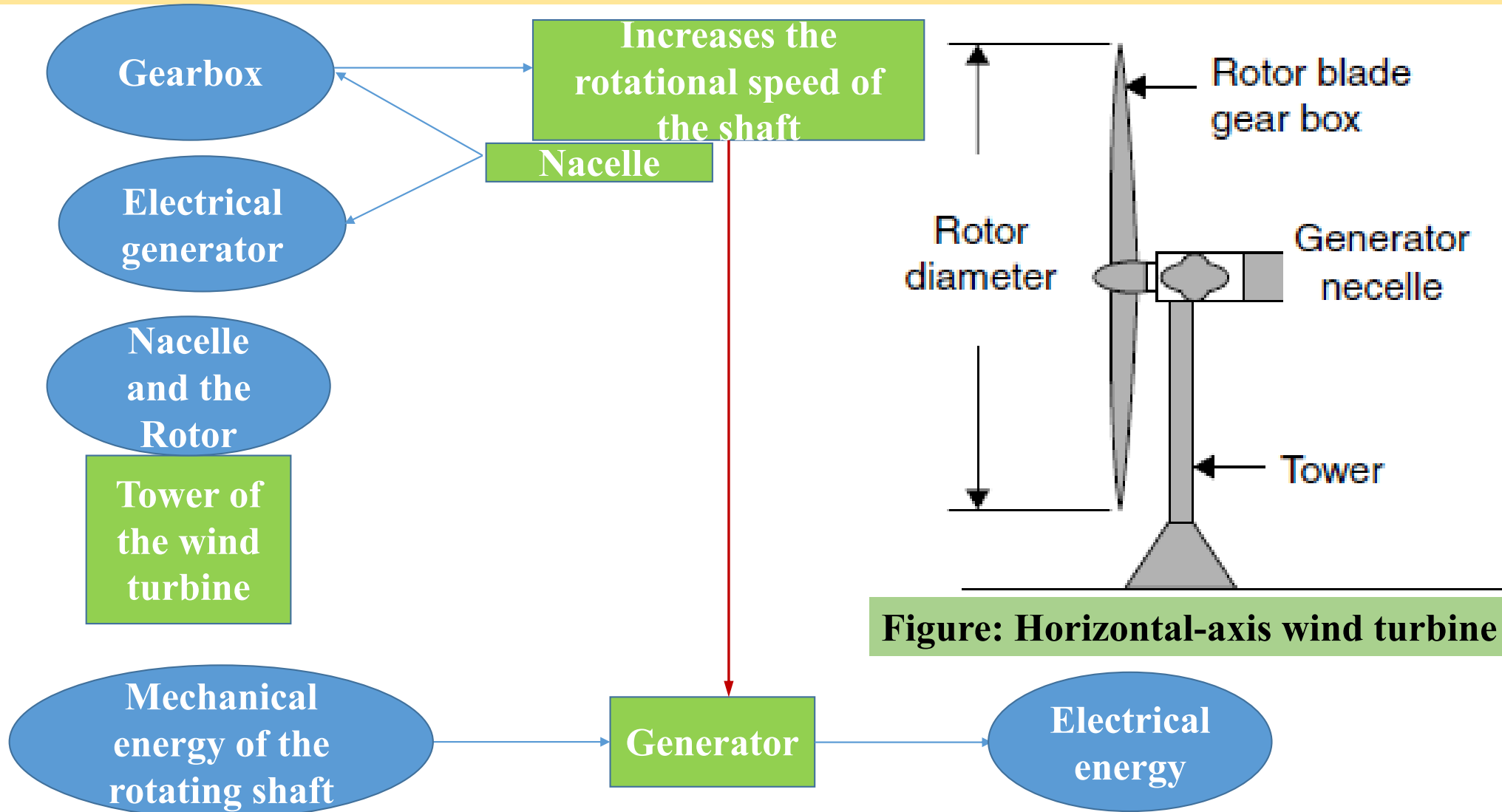


Figure : Wind rotor configurations (a) Vertical axis  
(b) Horizontal axis

## CLASSIFICATION AND DESCRIPTION OF WIND MACHINES cont..

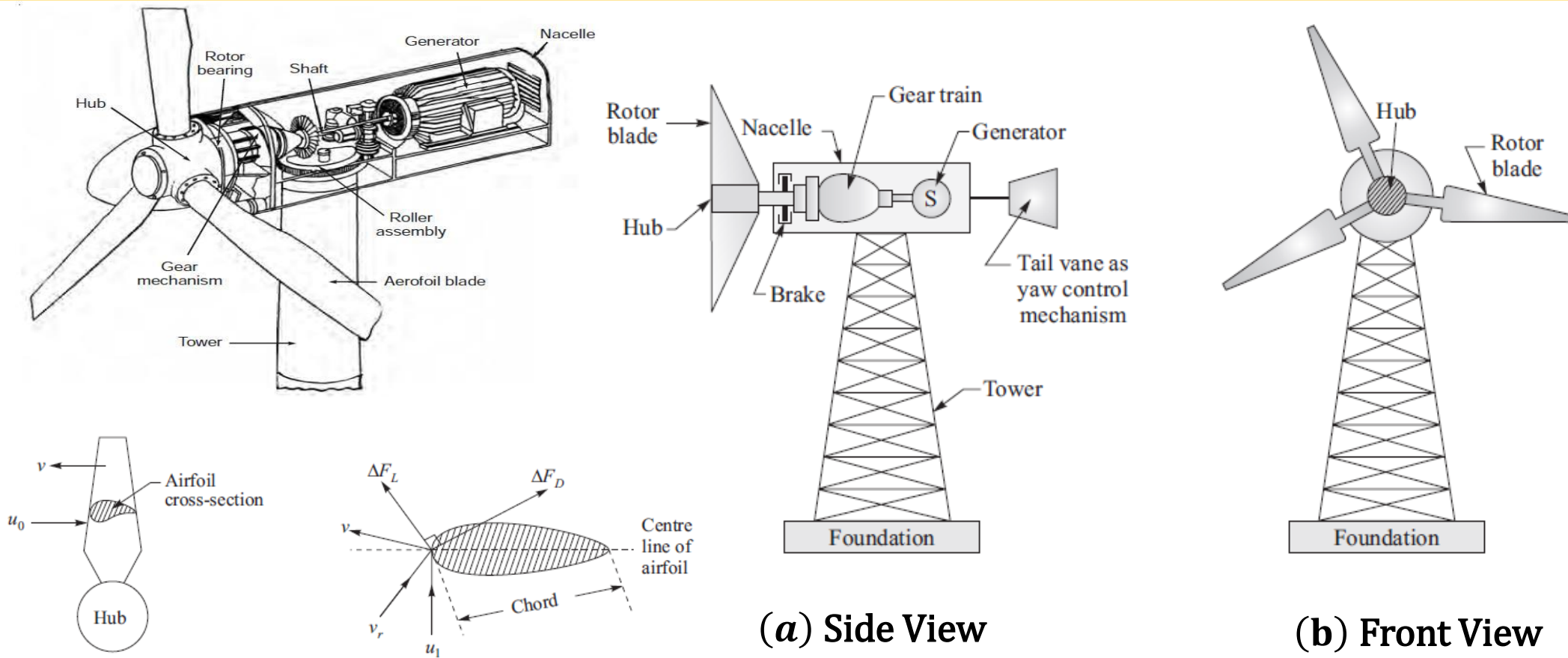
- For a horizontal-axis turbine, *the rotor axis is kept horizontal* and aligned parallel in the direction of the wind stream.
- In a vertical-axis turbine, *the rotor axis is vertical* and fixed, and remains perpendicular to the wind stream.

## Parts of a Wind Turbine cont.





## Parts of a Horizontal Axis Type Wind Turbine cont.



- **Blades have aerofoil type cross section to extract energy from wind.**
- **Hub, helps in the attachment of all blades.**

## **Reference books**

- **Non-Conventional Energy Resources - G.S. Sawhney**
- **Renewable Energy Resources and Emerging Technologies – D. P. Kothari, K. C. Singal, and Rakesh Ranjan**
- **Non-Conventional Energy Resources – Shobh Nath Singh**
- **Renewable Energy – M. K. Ghosh Roy**