MET445- RENEWABLE ENERGY ENGINEERING

Module-3

Department of Mechanical Engineering

MEAEC

Module 3

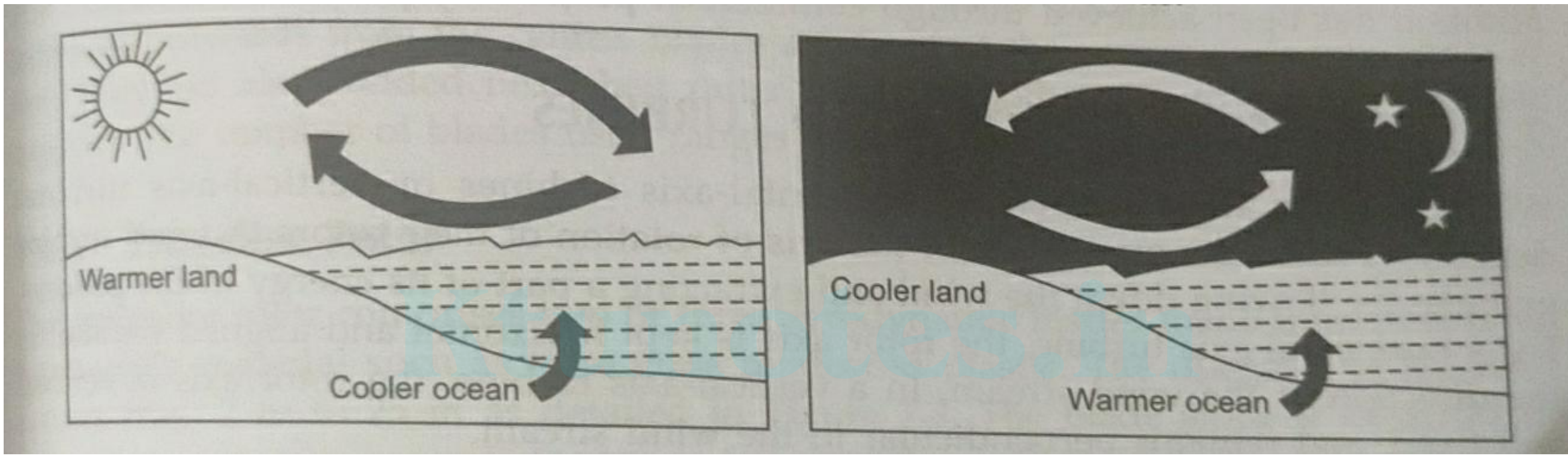
Wind Energy- classification of wind turbines and power performance curve, Energy in wind, calculation of energy content, Power coefficients, Betz limit theory, tip speed ratio, solidity of turbine' power control strategies, Basic principles of Wind Energy Conversion Systems (WECS), Classification of WECS, Parts of WECS

List of 10 Largest Wind Power Plants in India

Wind Power Plant	Megawatt (MW)	Location
Muppandal wind farm	1500	Tamil Nadu, Kanyakumari
Jaisalmer Wind Park	1064	Rajasthan, Jaisalmer
Brahmanvel wind farm	528	Maharashtra, Dhule
Dhalgaon wind farm	278	Maharashtra, Sangli
Vankusawade Wind Park	259	Maharashtra, Satara District.
Vaspet	144	Maharashtra, Vaspet
Tuljapur	126	Maharashtra, Osmanabad
Beluguppa Wind Park	100.8	Beluguppa, Andhra Pradesh
Mamatkheda Wind Park	100.5	Madhya Pradesh, Mamatkheda
Anantapur Wind Park	100	Andhra Pradesh, Nimbagallu

Wind energy

- Wind is air in motion and it derives energy from solar radiation.
- About 2% of the total solar flux that reaches the earth's surface is transformed into wind energy due to uneven heating of the atmosphere.
- During daytime, the air over the land mass heats up faster than the air oven the oceans.
- Hot air expands and rises while cool air from oceans rushes to fill the space, creating local winds.



(a) Wind from ocean to land during daytime, (b) wind from land to ocean during night

- At night the process is reversed as the air cools more rapidly over land than water over off shore land, causing breeze.
- On a global scale low pressure exists near the equator due to greater heating, causing winds to blow from subtropical belts towards the equator.
- Axial rotation of earth induces a centrifugal force which throws equatorial air masses to the upper atmosphere, causing deflection of winds.

Classification of Wind turbines

Depending upon the orientation of the axis of rotation of their rotors, wind turbines are of two types:

1. Horizontal axis wind turbines
2. Vertical axis wind turbines

A wind turbine operates by slowing down the wind and extracting a part of its energy in the process.

Horizontal axis wind turbine

Figure 5-2 Various wind turbine designs and their categorization. (*Adapted from Manwell et al., 2010*).

Vertical axis wind turbine

Figure 5-2 (Continued)

- 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.
- Wind turbines have blades, sails or buckets fixed to a central shaft.

- The extracted energy causes the shaft to rotate. This rotating shaft is used to drive a pump, to grind seeds or to generate electric power.
- Wind turbines are further classified as (i) Lift (ii) Drag type.

(i) Lift type and Drag type wind turbines

Wind can rotate the rotor of a wind turbine by lifting (lift) the blades.

Wind can rotate the rotor of a wind 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.

- Slow speed turbines are mainly driven by the drag forces acting on the rotor.
- The torque at the shaft is comparatively high which is of prime importance for mechanical applications such as water pumps.
- For slower turbines, a greater blades area is required, so the fabrication of blades is undertaken using curved plates.

- High speed turbines utilise lift forces to move the blades, which is similar to the what acts on the wings of an aeroplane.
- Faster turbines requires aerofoil type blades to minimize the adverse effect of the drag forces.
- The blades are fabricated from aerofoil sections with a high thickness to chord ratio in order to produce a high lift relative to drag.

Types of rotors

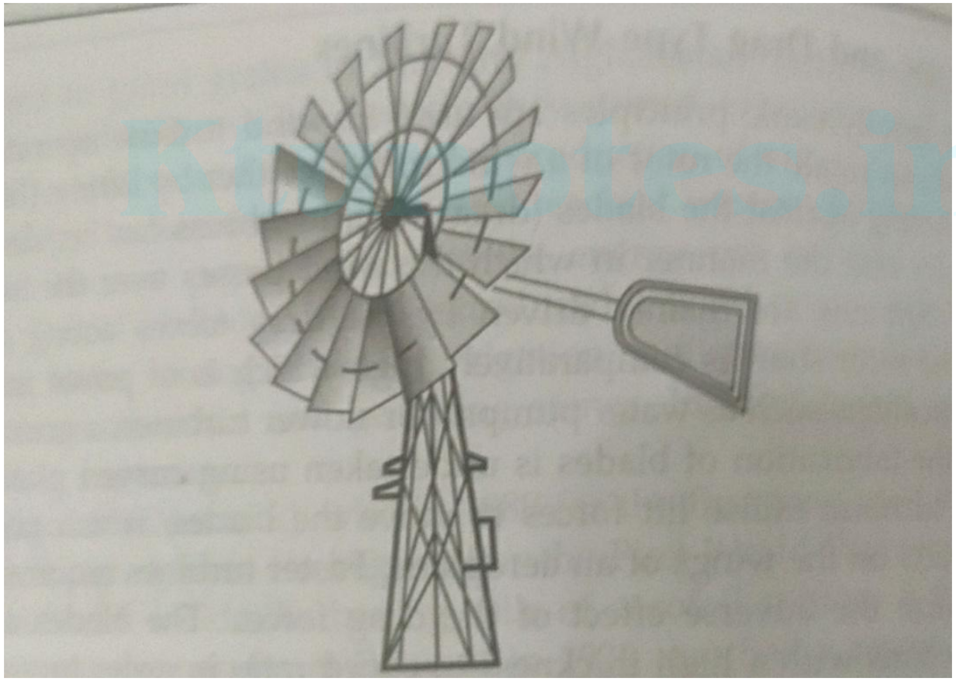
- Different types of rotors used in wind turbines are (i) multiblade type, (ii) Propeller type, (iii) Savonious type, and (iv) Darrieus type.

(i) Multiblade type

- The multiblade rotor is fabricated from curved sheet metal blades.
- The width of the blades increases outwards from the centre. Blades are fixed at their inner ends on a circular rim.

They are also welded near their outer edge to another rim to provide a stable support.

The number of blades used ranges from 12 to 18.

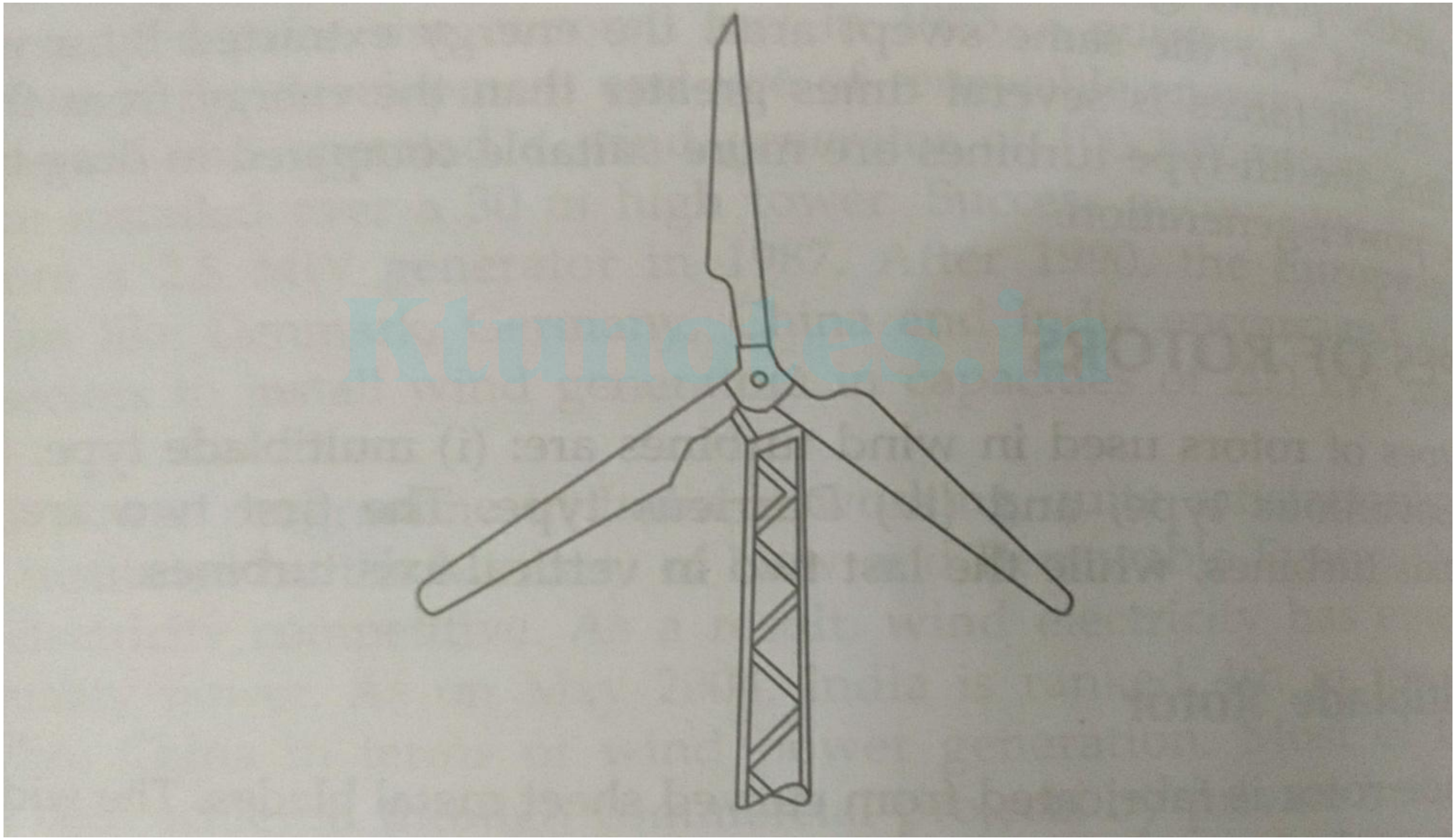


(ii) Propeller rotor

The propeller rotor comprises two or three aerodynamic blades made from strong but lightweight material such as fibre glass reinforced plastic.

The diameter of the rotor ranges from 2 m to 25 m.

Propeller rotor installed on a tower



(iii) Savonious rotor

It comprises two identical hollow semi-cylinders fixed to a vertical axis.

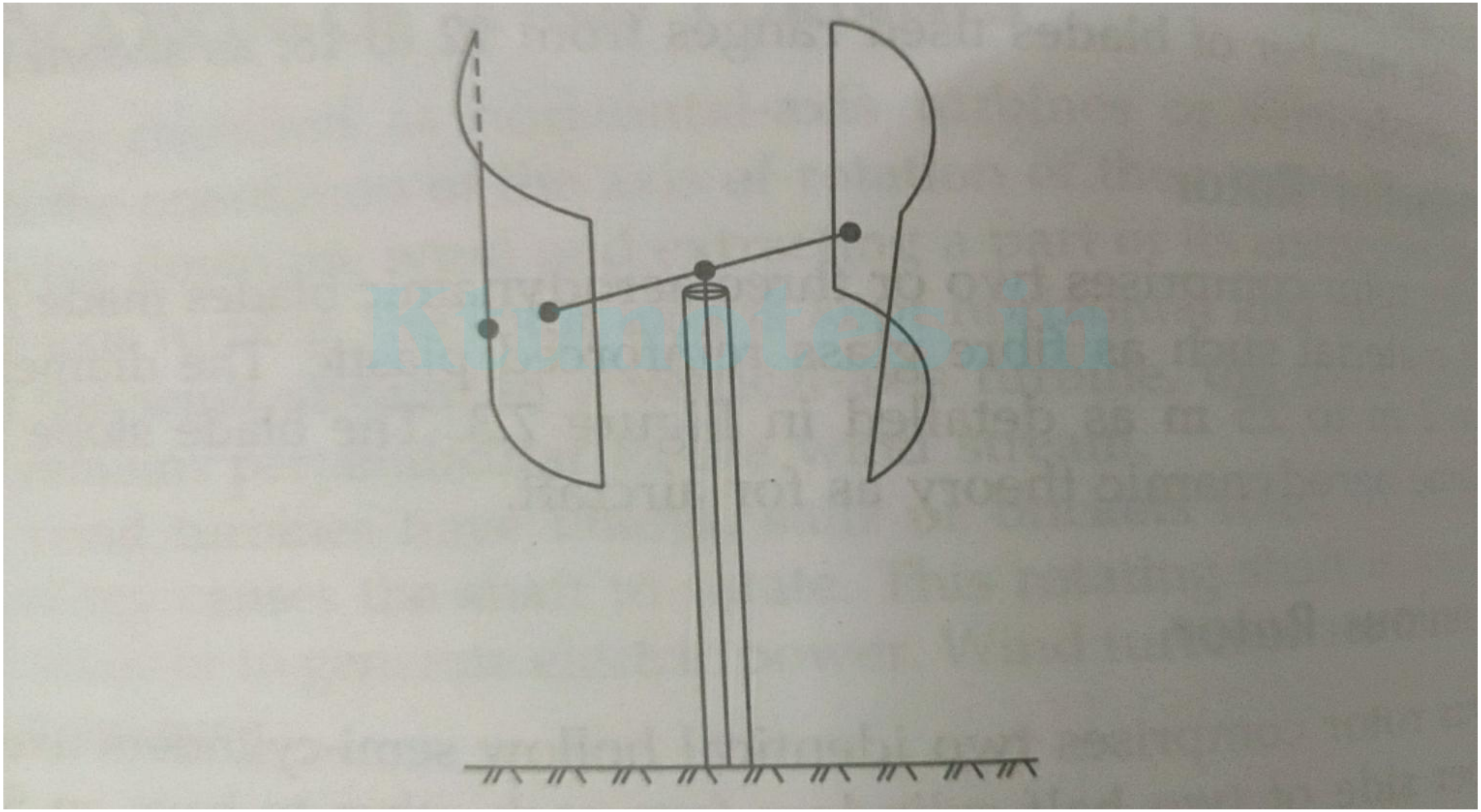
The inner side of two half cylinders face each other to have an S shaped cross section.

Irrespective of wind direction, the rotor rotates due to pressure difference between the two sides.

Driving force is mainly of drag type.

This rotor is suitable for water pumping.

Savonious vertical axis rotor



(iv) Darrieus rotor

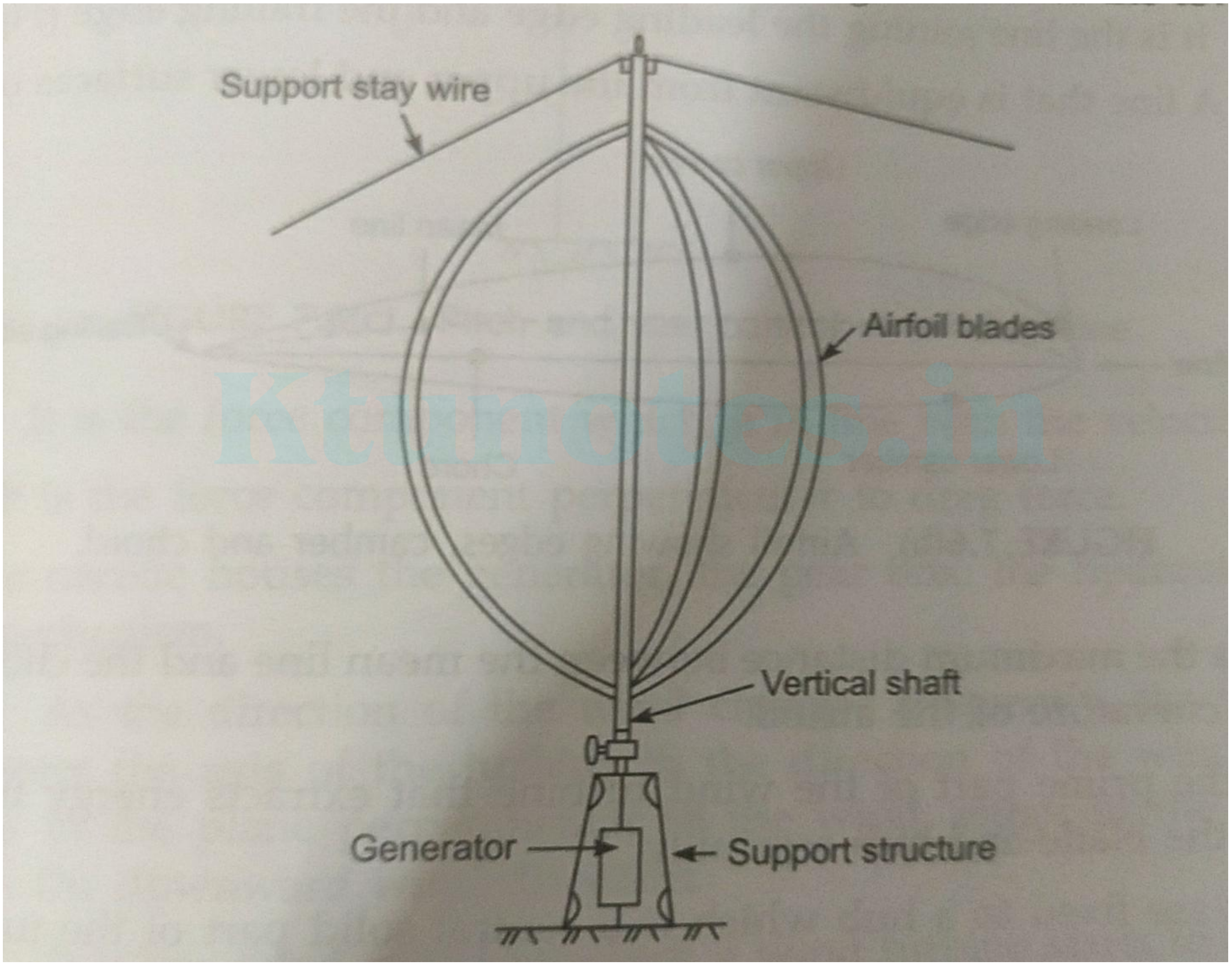
This rotor has two or three thin curved blades of flexible metal strips.

It looks like an egg beater and operates with the wind coming from any direction.

Both the ends of the blades are attached to a vertical shaft.

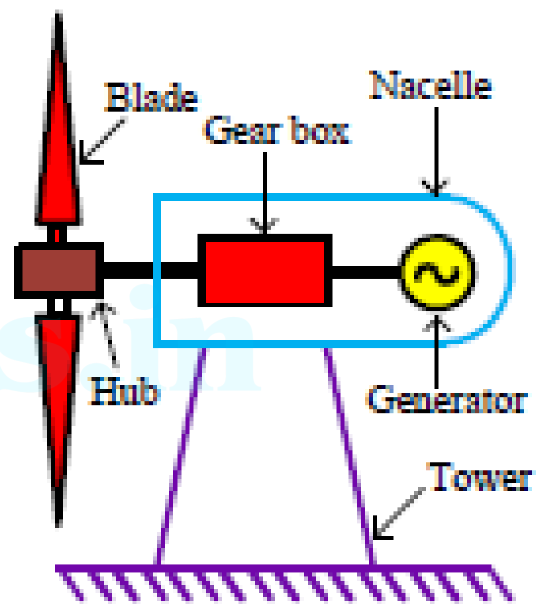
It has an advantage that it can be installed close to the ground eliminating the cost of the tower structure.

Darrieus rotor



Components of wind turbine

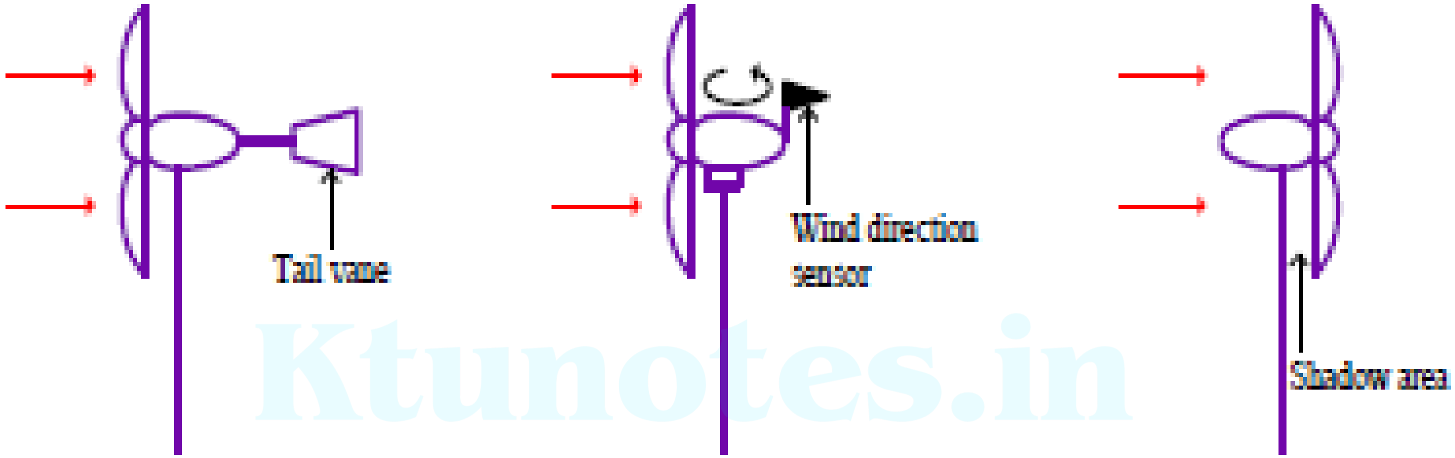
1. ***Hub*** *– The blades are attached to the hub.*
2. ***Rotor – Blades and hub*** *together is called the rotor. Rotor is attached to the slow speed shaft.*
3. ***Nacelle – Nacelle*** *is the cover housing that houses all of the generating components in a wind turbine, including the generator, gearbox, drive train, and brake assembly.*
4. ***Tower*** *– The tower of the wind turbine carries the nacelle and the rotor. Towers may be made from steel or concrete.*



Horizontal axis wind power plant (Propeller type)

5. ***Gears*** *– Gears connect the low-speed shaft attached to the hub to the high-speed shaft attached to the generator and increase the rotational speed.*

Upwind and downwind machines



Yaw control in upwind and downwind machines

- *Upwind machines are those machines that have rotor facing the wind. In these machines the wind meets the rotor first and then leaves from the direction in which the nacelle is located.*
- *In a downwind machine, the rotor is located downwind of (behind) the tower as shown in the figure. This means the nacelle comes first in the path of the wind and then the blades.*

Vertical-Axis Turbines

Advantages

- Omni-directional
  - accepts wind from any direction
- Components can be mounted at ground level
  - ease of service
  - lighter weight towers
- Can theoretically use less materials to capture the same amount of wind

Disadvantages

- Rotors generally near ground where wind is poorer
- Centrifugal force stresses blades
- Poor self-starting capabilities
- Requires support at top of turbine rotor
- Requires entire rotor to be removed to replace bearings
- Overall poor performance and reliability

Vertical-axis machines have blades that go from top to bottom and the most common type, the Darrieus wind turbine, looks like a giant, two-bladed eggbeater. This type of vertical wind turbine typically is 100 feet tall and 50 feet wide. New design concepts come to market on a regular basis. They make up only a very small percent of the wind turbines used today.

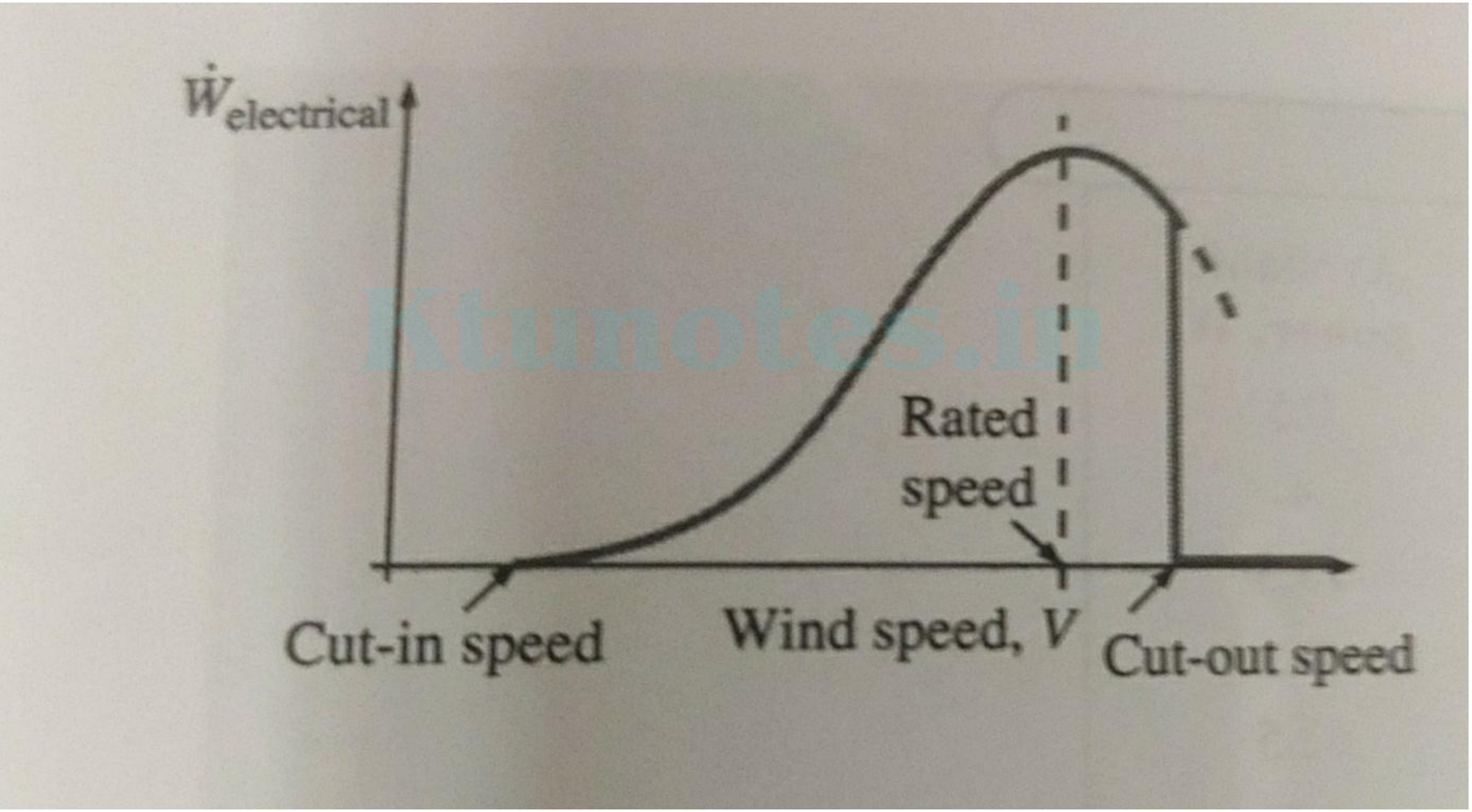
Comparing HWT and VWT

Parameter	***HWT***	***VWT***
Tip speed ratio	High and hence noisy.	Low and hence less noisy.
Application	Large scale electricity generation.	Small scale electricity generation.
Yawing	Yawing is required, as HWTs are dependent of wind direction.	Yawing is not required, as HWTs are independent of wind direction, but are affected by wind speed.
Torque	Low.	More at lower wind speeds.
Maintenance	Difficult.	Easier, as heavy components can be located at the ground level.
Stability	More stable and hence large sized turbines can be constructed.	Less stable.

Wind turbine Performance curve

- The electrical power output is plotted as a function of wind speed at the height of the turbine’s axis.
- Three key locations on the wind-speed scale
- Cut in speed is the maximum speed at which useful power can be generated.
- Rated speed is the wind speed that delivers the rated power, usually the maximum power.

Typical qualitative wind-turbine power performance curve with definitions of cut in, rated and cut-out speeds



- Cut-out speed is the maximum wind speed at which the wind turbine is designed to produce power.
- At wind speed greater than cut-out speed, the turbine blades are stopped by some type of braking mechanism to avoid damage and safety issues.
- The short section of dashed curve line indicates the power that would be produced if cut-out were not implemented.

- The design of horizontal axis wind turbine blades includes tapering and twist to maximise performance.
- The power performance curve influenced by electrical generator, the gearbox, and structural issues.

Wind power potential

- The mechanical energy can be defined as the form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine.
- The mechanical energy of a flowing fluid can be expressed as

$$\dot{E}_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

Wind power potential

- Where P/ρ is the flow energy, $V^2/2$ is the kinetic energy, and gz is the potential energy of the fluid, all per unit mass and m is the mass flow rate of the fluid.
- The pressure at the inlet and exit of wind turbine are both equal to the atmospheric pressure, and the elevation does not change across a wind turbine.
- Therefore, flow and potential energy do not change across a wind turbine.

Wind power potential

- A wind turbine converts the kinetic energy of the fluid into power.
- If the wind is blowing at a location at a velocity of V, the available wind power is expressed as

$$\dot{W}_{\text{avalable}} = \frac{1}{2}\dot{m}V^2 \qquad \text{(kW)}$$

- This is the maximum power a wind turbine can generated for the given wind velocity V.
- The mass flow rate is given by

$$\dot{m} = \rho A V \qquad \text{(kg/s)}$$

Wind power potential

$$\dot{W}_{\text{available}} = \frac{1}{2}\rho A V^3$$

- The above equation indicates that the power potential of a wind turbine is proportional to the cubic power of the wind velocity.
- For example, consider a location where the wind with a density of 1.2 kg/m^3 is blowing at a velocity of 4 m/s. The maximum power a wind turbine with a rotor diameter of 1.03 m can generate is given by

$$\dot{W}_{\text{available}} = \frac{1}{2}\rho A V_1^3 = \frac{1}{2}(1.2\ \text{kg/m}^3)\frac{\pi(1.03\ \text{m})^2}{4}(4\ \text{m/s})^3\left(\frac{1\ \text{J/kg}}{1\ \text{m}^2/\text{s}^2}\right) = 32\ \text{W}$$

Wind power potential

- The doubling of wind velocity will increase the power potential by a factor of 8.
- The power potential of wind turbine is proportional to the density of air.
- As a result, cold air has a higher wind power potential than warm air.
- The density of air can be determined from the ideal gas relation $P=\rho RT$ when the pressure P and temperature T are known. R is the gas constant.

Wind power potential

- The disk area is equal to A= $\Pi D^2/4$, where D is the blade diameter.

$$\dot{W}_{\text{available}} = \frac{\pi}{8}\frac{PD^2V^3}{RT}$$

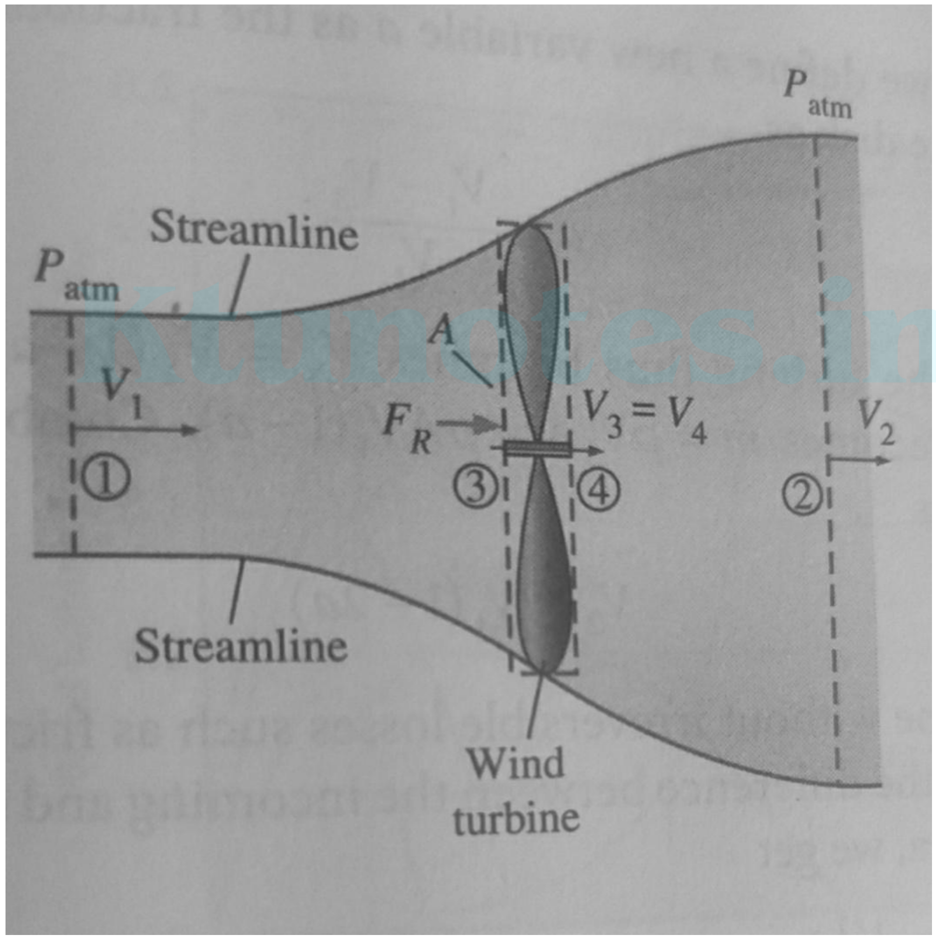
- The power potential of a wind turbine is proportional to the square of the blade diameter. As a result, doubling blade diameter increases the power potential by a factor of 4.

Betz limit theory

- A wind turbine converts the kinetic energy of air into work.
- This conversion is perfect under ideal conditions based on the second law of thermodynamics.

- The maximum possible efficiency of a wind turbine was first calculated by Albert Betz in the mid – 1920s.

The large and small control volumes for analysis of ideal wind turbine performance bounded by an axisymmetric stream tube



Betz limit theory

- Consider two control volumes surrounding the disk area- a large control volume and a small control volume with upstream wind speed V taken as V1
- The axisymmetric stream tube (enclosed by streamlines as drawn on the top and bottom) forming an imaginary duct for the flow of air through the turbine.
- Locations 1 and 2 are sufficiently far from the turbine, we take P1=P2=Patm, yielding no net pressure force on the control volume.

Betz limit theory

- Considering the velocity at inlet (1) and outlet (2) to be uniform at V1 and V2, respectively.
- The momentum equation is written as

$$F_R = \dot{m}(V_2 - V_1)$$

Where FR is the reaction force on the turbine.

The smaller control volume encloses the turbine, but A3= A4= A, since this control volume is infinitesimally thin in the limit.

Betz limit theory

- Since the air is considered to be incompressible, V3=V4.
- The wind turbine extracts energy from the air, causing a pressure drop. Thus P3 ≠ P4.
- Applying the streamwise components of the control volume momentum equation to the small control volume, we get

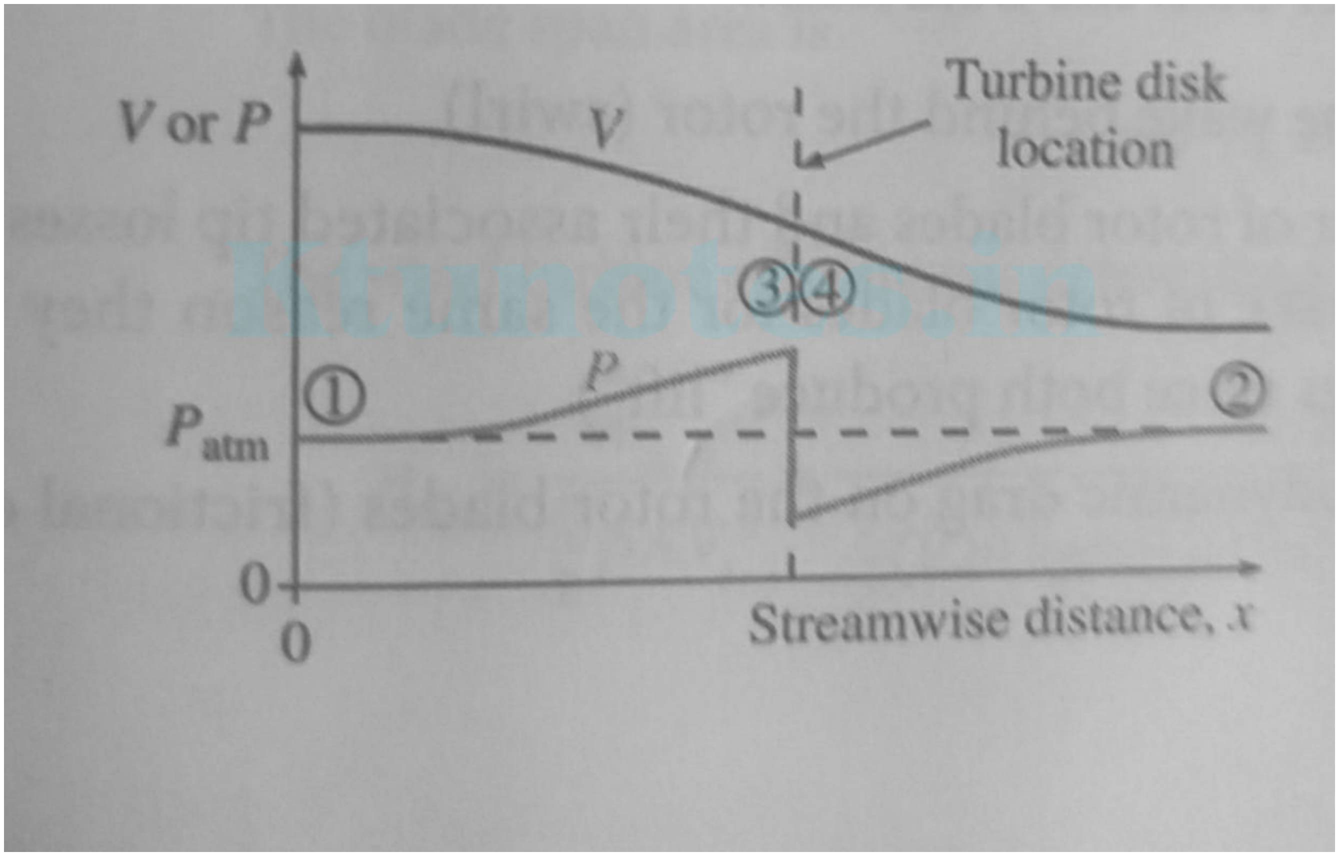
$$F_R + P_3A - P_4A = 0 \quad \rightarrow \quad F_R = (P_4 - P_3)A$$

Betz limit theory

- The Bernoulli equation is certainly not applicable across the turbine, since it is extracting energy from the air.
- However, it is a reasonable approximation between locations 1 and 3 and between locations 4 and 2:

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_3}{\rho g} + \frac{V_3^2}{2g} + z_3 \quad \text{and} \quad \frac{P_4}{\rho g} + \frac{V_4^2}{2g} + z_4 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2$$

Qualitative sketch of average streamwise velocity and pressure profiles through a wind turbine



- In this ideal analysis, the pressure starts at atmospheric pressure far upstream (P1=Patm), rises smoothly from P1 to P3, drops suddenly from P3 to P4 across the turbine disk and then rises smoothly from P4 to P2, ending at atmospheric pressure far downstream (P2= Patm).

$$\frac{V_1^2 - V_2^2}{2} = \frac{P_3 - P_4}{\rho}$$

$$V_3 = \frac{V_1 + V_2}{2}$$

- Thus, we conclude that the average velocity of air through an ideal wind turbine is the arithmetic average of the far upstream and far downstream velocities.

- For convenience, we define a new variable a as the fractional loss of velocity from far upstream to the turbine disk as

- The velocity through the runner thus becomes $V_3 = V_1(1-a)$, and the mass flow rate through the turbine becomes
- $V_2 = V_1(1-2a)$
- For an ideal wind turbine without irreversible losses such as friction, power generated by the turbine is simply the difference between the incoming and outgoing kinetic energies.

$$\dot{W}_{ideal} = \dot{m}\frac{V_1^2 - V_2^2}{2} = \rho A V_1 (1-a)\frac{V_1^2 - V_1^2(1-2a)^2}{2} = 2\rho A V_1^3 a (1-a)^2$$

- Again assuming no irreversible losses is transferring power from the turbine to the turbine shaft, the efficiency of the wind turbine is given by

$$\eta_{wt} = \frac{\dot{W}_{shaft}}{\frac{1}{2}\rho V_1^3 A} = \frac{\dot{W}_{ideal}}{\frac{1}{2}\rho V_1^3 A} = \frac{2\rho A V_1^3 a (1-a)^2}{\frac{1}{2}\rho V_1^3 A} = 4a(1-a)^2$$

$$\eta_{wt,max} = 4a(1-a)^2 = 4\frac{1}{3}\left(1-\frac{1}{3}\right)^2 = \frac{16}{27} = 0.5926$$

The maximum possible efficiency of any wind turbine is known as the Betz limit.

All real wind turbines have maximum achievable efficiency less than this due to irreversible losses, which have been ignored in this ideal analysis.

Tip speed ratio

- The tip speed ratio for wind turbines is the ratio between the tangential speed of the tip of a blade and the actual speed of the wind.
- The tip speed ratio is related to efficiency, with the optimum varying with blade design.
- Higher tips speeds results in higher noise levels and require stronger blades due to large centrifugal forces.

$$\lambda = \frac{\text{tip speed of blade}}{\text{wind speed}}$$

The tip speed of the blade can be calculated as w times R, where w is the rotational speed of the rotor in radians/second, and R is the rotor radius in metres. Therefore, we can also write.

$$\lambda = \frac{\omega R}{v}$$

- where v is the wind speed in metres/second at the height of the blade hub.

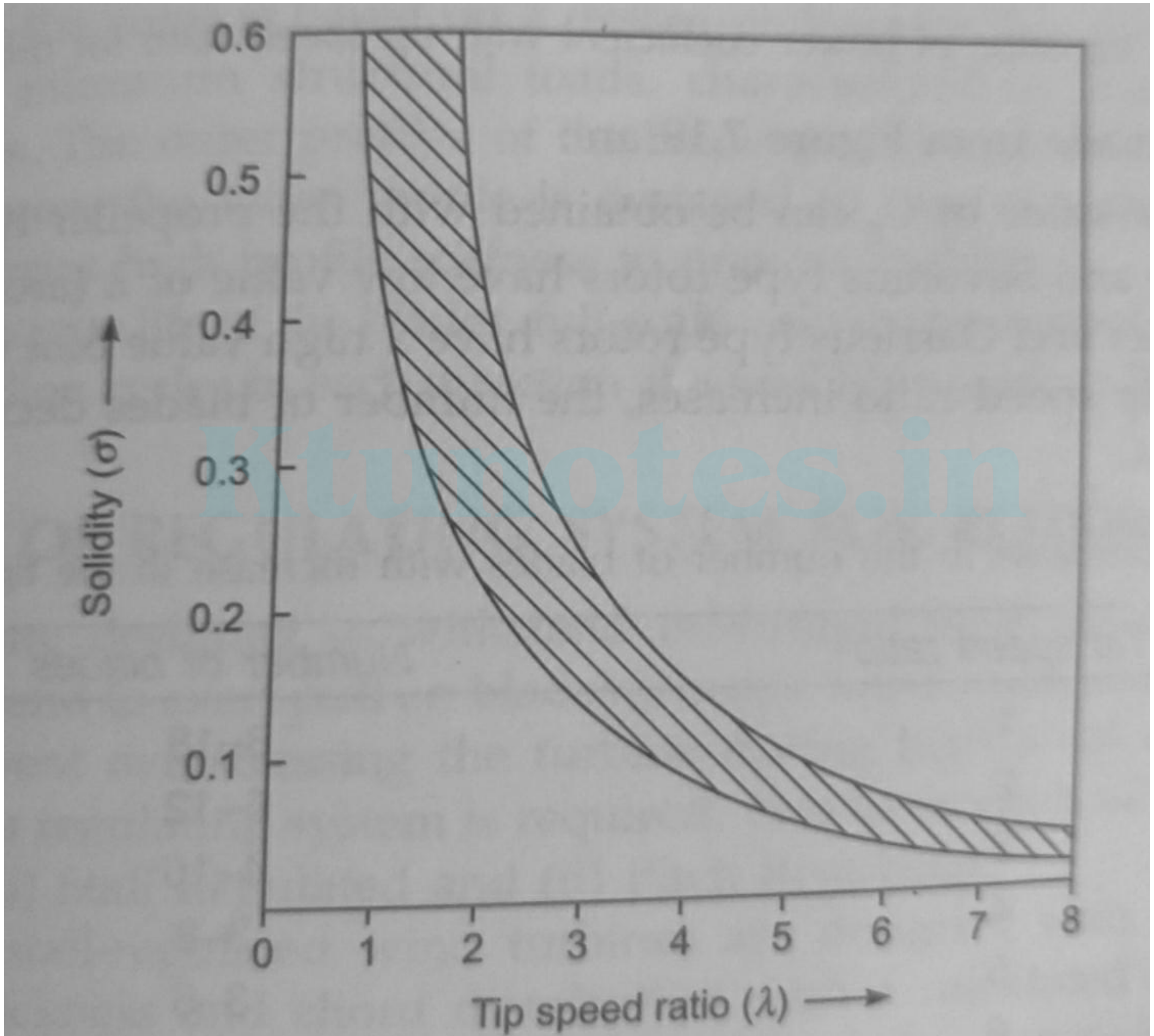
Solidity of turbine

- Solidity is defined as the ratio of the blade area to the circumference of the rotor.
- Solidity determines the quantity of blade material required to intercept a certain wind area.

$$\sigma = \frac{Nb}{2\pi R}$$

where N is the number of blades, b is the blade width and R is the blade radius.

Variation of solidity with tip speed ratio



Variation of solidity with tip speed ratio

- The following observations can be made

(i) A two or three bladed wind turbine has a low solidity and so needs to rotate faster to intercept and capture wind energy with aerofoil blades like aircraft.

(ii) Rotors having a high value of solidity like the multibladed wind water pump turbine, operate at low tip speed ratio. Such rotors needs a high starting torque.

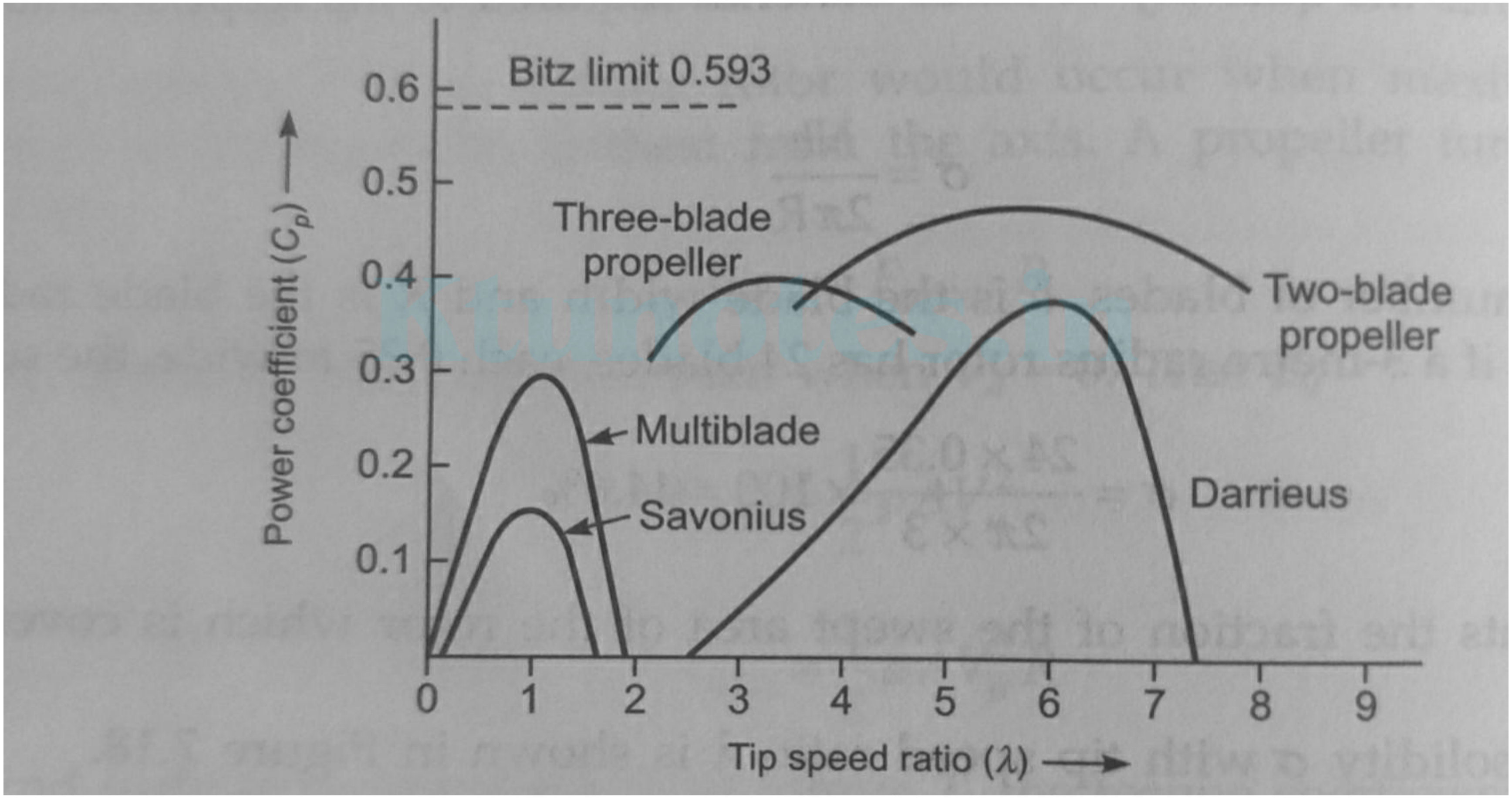
Wind power coefficients

- Power Coefficient (Cp) is a measure of wind turbine efficiency often used by the wind power industry.
- Cp is the ratio of actual electric power produced by a wind turbine divided by the total wind power flowing into the turbine blades at specific wind speed.
- The wind power coefficient represents the combined efficiency of the various wind power system components which include the turbine blades, the shaft bearings and gear train, the generator and power electronics.

Wind power coefficients

- The Cp for a particular turbine is measured or calculated by the manufacturer, and usually provided at various wind speeds.
- If you know the Cp at a given wind speed for a specific turbine you can use it to estimate the electrical power output.
- The Cp of a particular wind turbine varies with operating conditions such as wind speed, turbine blade angle, turbine rotation speed, and other parameters.

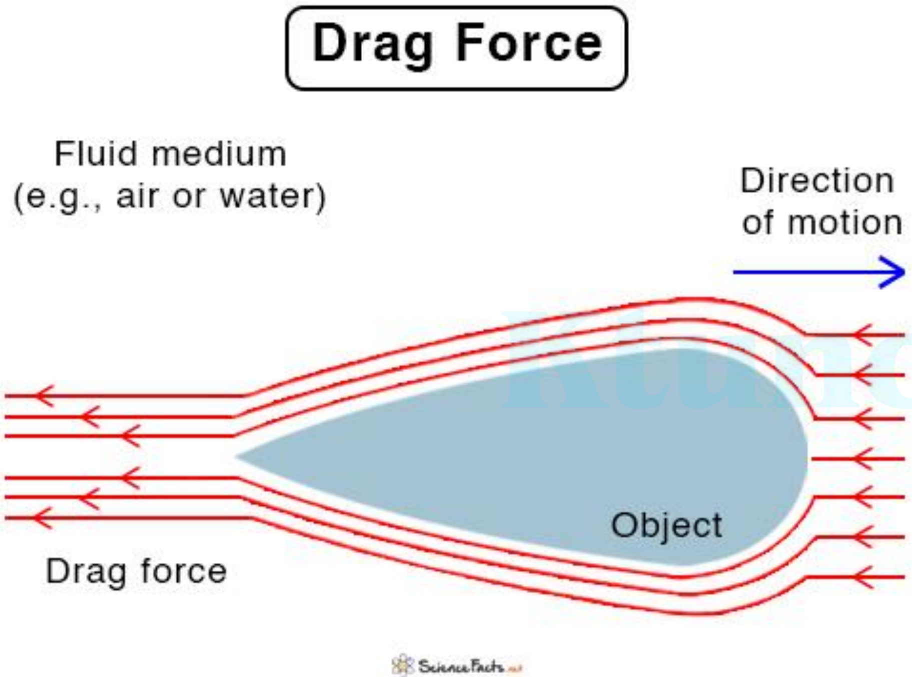
Variation of power coefficient with tip speed ratio for different rotors

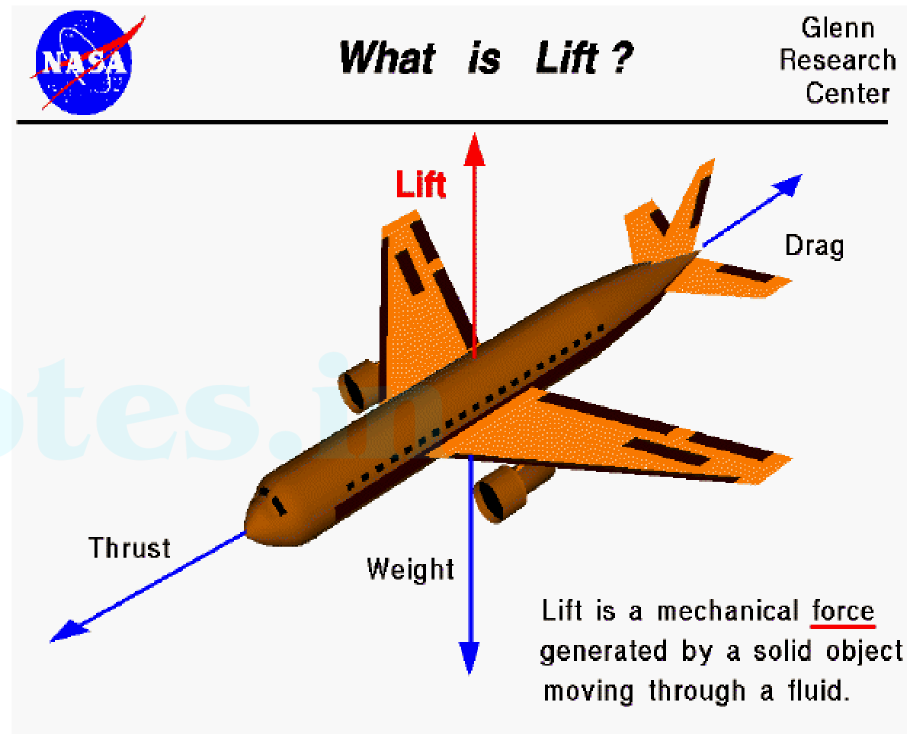


Basic principles of Wind Energy Conversion Systems

- The power in the wind is proportional to:
  - Area of windmill being swept by the wind
  - Cube of the wind speed
  - Air density - which varies with altitude
- 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).

Basic principles of Wind Energy Conversion Systems





- Drag forces provide the most obvious means of propulsion, these being the forces felt by a person (or object) exposed to the wind. Lift forces are the most efficient means of propulsion but being more subtle than drag forces are not so well understood.

- **The basic features that characterise lift and drag are:**
- Drag is in the direction of air flow
- Lift is perpendicular to the direction of air flow
- Generation of lift always causes a certain amount of drag to be developed
- With a good aerofoil, the lift produced can be more than thirty times greater than the drag
- Lift devices are generally more efficient than drag devices

Classifications of WECS

(1) Based on axis

(a) Horizontal axis machines

(b) Vertical axis machines

(2) According to size

(a) Small size machines (upto 2k W)

(b) Medium size machines (2 to 100k W)

(c) Large size machines (100k W and above)

Classifications of WECS

(3) Types of output

(a) DC output

i. DC generator

ii. Alternator rectifier

(b) AC output

i. Variable frequency, variable or constant voltage AC.

ii. Constant frequency, variable or constant voltage AC

Classifications of WECS

(4) According to the rotational speed of the area turbines

(1) Constant speed and variable pitch blades

(2) Nearly constant speed with fixed pitch blades

(3) Variable speed with fixed pitch blades

(a) Field modulated system

(b) Double output indication generator

(c) AC-DC-AC link

(d) AC commentator generator

Classifications of WECS

(4) As per utilization of output

(a) Battery storage

(b) Direct conversion to an electro magnetic energy converter

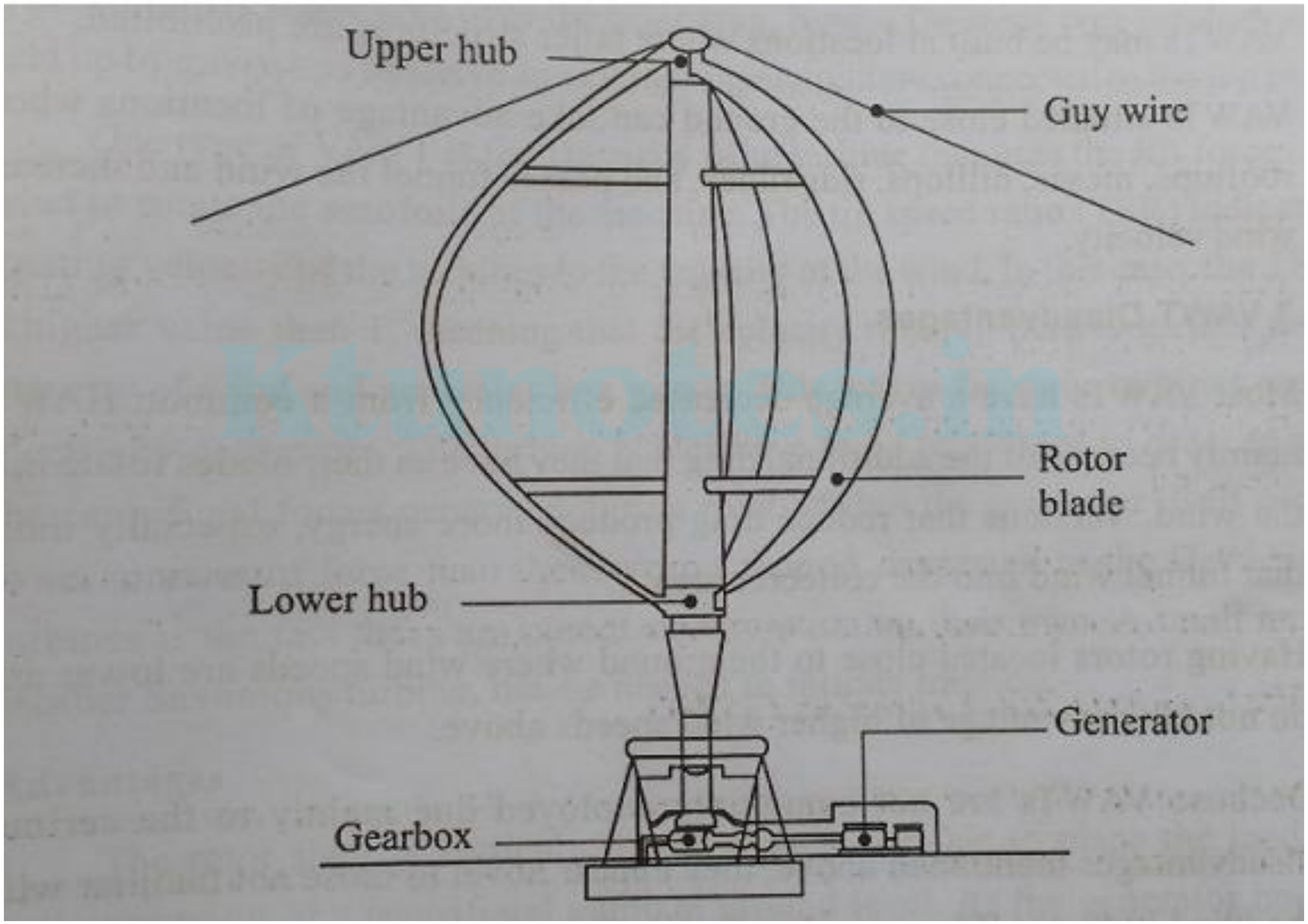
(c) Thermal potential

(d) Inter convention with conventional electric utility guides

Vertical Axis Wind Turbines(VAWT)

- The main advantage of this arrangement is that the wind turbine does not need to be pointed into the wind. This is an advantage on site where the wind direction is highly variable or has turbulent winds.
- With a vertical axis, the generator and other primary components can be placed near the ground, so the tower does not need to support it, also makes maintenance easier. The main drawback of a VAWT generally create drag when rotating into the wind.

Vertical Axis Wind Turbines(VAWT)



Vertical Axis Wind Turbines(VAWT)

- It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop.
- The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine.
- Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten its service life.

Vertical Axis Wind Turbines(VAWT)

- However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and this can double the wind speed at the turbine.
- If the height of the rooftop mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence.

Modes of Wind Power Generation

- Three modes

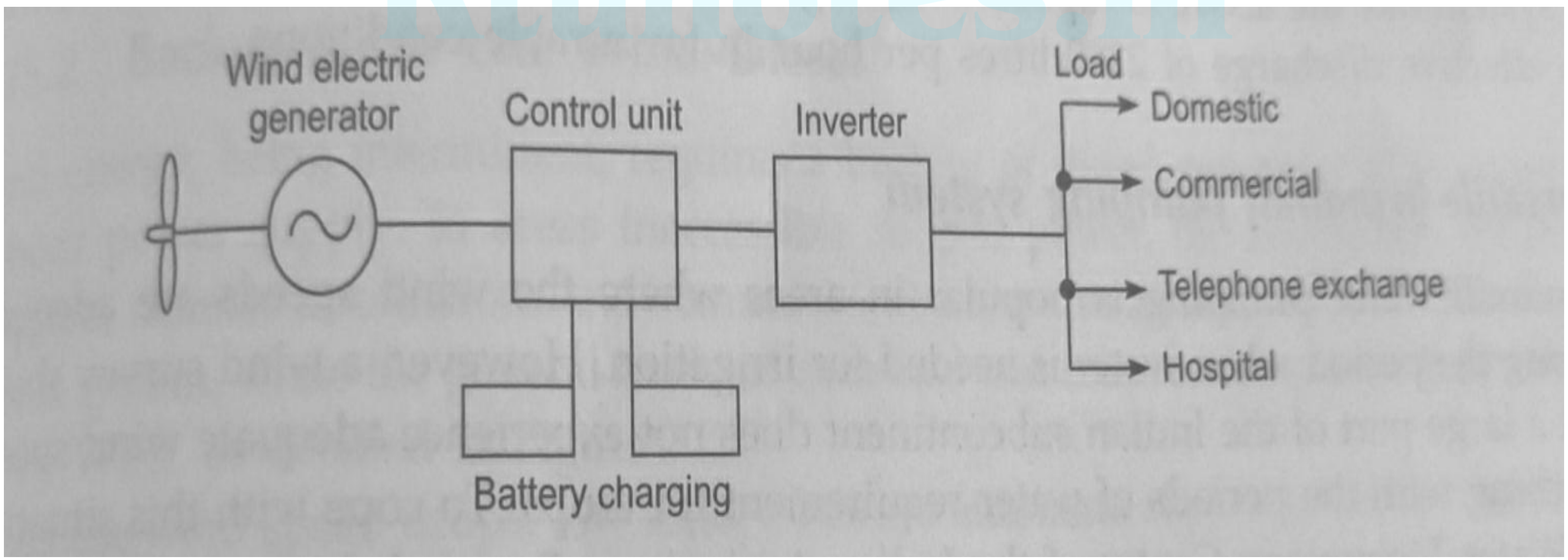
(a) Standalone mode

(b) Backup mode like wind-diesel

(c) Grid-connected mode

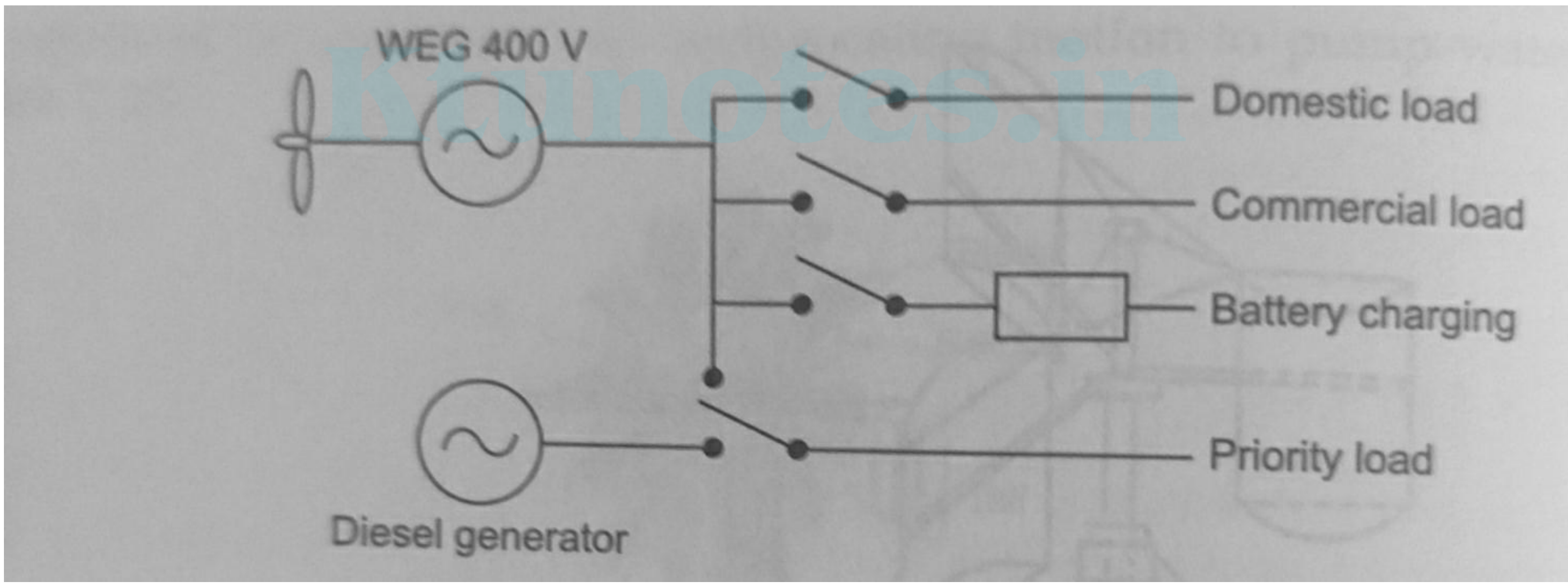
(a) Standalone mode

Represents decentralised application of wind energy and is characterised by the situation where an individual energy consumer or a group of consumers install their own wind turbine.



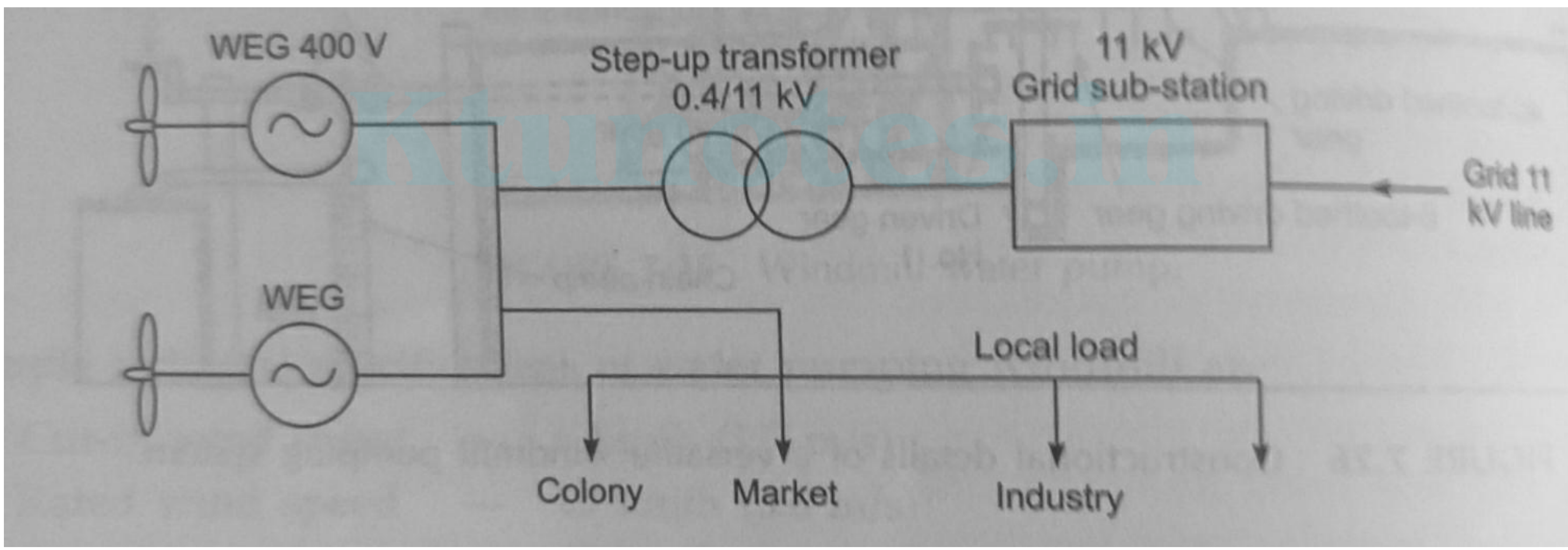
(b) Backup mode like wind-diesel

- Wind energy, being intermittent, requires a backup of diesel generator to maintain a 24 hour power supply.



(c) Grid-connected mode

- In this wind farms where the generated power is distributed among the nearby consumers and the excess power is exported to the grid.



Advantages of wind energy systems

1. Wind energy is renewable source of energy and can be tapped, free of fuel cost.
2. The wind turbine generator produces electricity in an environmental friendly way.
3. It can supply electric power to remote inaccessible areas like the Upper Himalayan range.
4. Wind power generation is cost effective.

Disadvantages of wind energy systems

1. Wind energy has low energy density and normally available at only selected geographical locations away from cities and load centres.
2. Wind speed being variable, wind energy is irregular, unsteady and erratic.
3. Wind energy storage require storage batteries which contribute to environmental pollution.
4. Wind farms are established in locations of favourable wind. These locations are in open areas away from load centres.

Thank you