NON CONVENTIONAL ENERGY SOURCES

(Course Code:18ME651)

Department of Mechanical Engineering
JSS Academy of Technical Education, Bangalore-560060

TEXT BOOKS

- **Non-Convention Energy Resources, B H Khan, McGraw Hill Education India Pvt. Ltd., 3rd Edition.**
- **Solar energy, Subhas P Sukhatme, Tata McGraw Hill, 2nd Edition, 1996.**
- **Non-Conventional Energy Sources, G.D Rai, Khanna Publishers, 2003.**

REFERENCE BOOKS:

- **Renewable Energy Sources and Conversion Technology, N.K.Bansal, Manfred Kleeman & Mechael Meliss, Tata McGraw Hill., 2004.**
- **Renewable Energy Technologies, Ramesh R & Kumar K U, Narosa Publishing House New Delhi.**
- **Non-Conventional Energy, Ashok V Desai, Wiley Eastern Ltd, New Delhi, 2003.**

NON CONVENTIONAL ENERGY SOURCES - MODULE 4

CHAPTER 1: Wind Energy, Tidal Power & Ocean Thermal Energy Conversion.

Module 4

- **Wind Energy** : Properties of wind, availability of wind energy in India, wind velocity and power from wind; major problems associated with wind power, wind machines; Types of wind machines and their characteristics, horizontal and vertical axis wind mills, elementary design principles; coefficient of performance of a wind mill rotor, aerodynamic considerations of wind mill design, numerical examples.
- **Tidal Power:** Tides and waves as energy suppliers and their mechanics; fundamental characteristics of tidal power, harnessing tidal energy, limitations.
- **Ocean Thermal Energy Conversion:** Principle of working, Rankine cycle, OTEC power stations in the world, problems associated with OTEC.

Wind Energy

- Wind energy is another potential source of energy. Winds are the motion of air caused by un-even heating of the earth‘s surface by the sun and rotation of the earth.
- It generates due to various global phenomena such as air-temperature difference‘ associated with different rates of solar heating.
- Since the earth‘s surface is made up of land, desert, water, and forest areas, the surface absorbs the sun‘s radiation differently.

- Wind, that is moving air, possesses some kinetic energy due to its high speed.
- Wind is a result of the solar energy, as heating of land results in movement of air.
- The most common application of wind could probably be kite flying! Or even paragliding, sail boats etc. Well these activities are definitely not possible without wind.
- Ever wondered what else it could be useful for?? Wind energy can be harnessed and used for generating electricity or for other smaller purposes by a windmill.
- In olden times, windmills were used to draw water out of wells or to grind flour etc. It is the rotatory motion of the shaft in a windmill that is used to rotate the turbine and convert it to the form of energy we need it in.

- The main advantage of wind energy is that harnessing it doesn’t disrupt natural processes or harm the environment, unlike a lot of other energy sources.

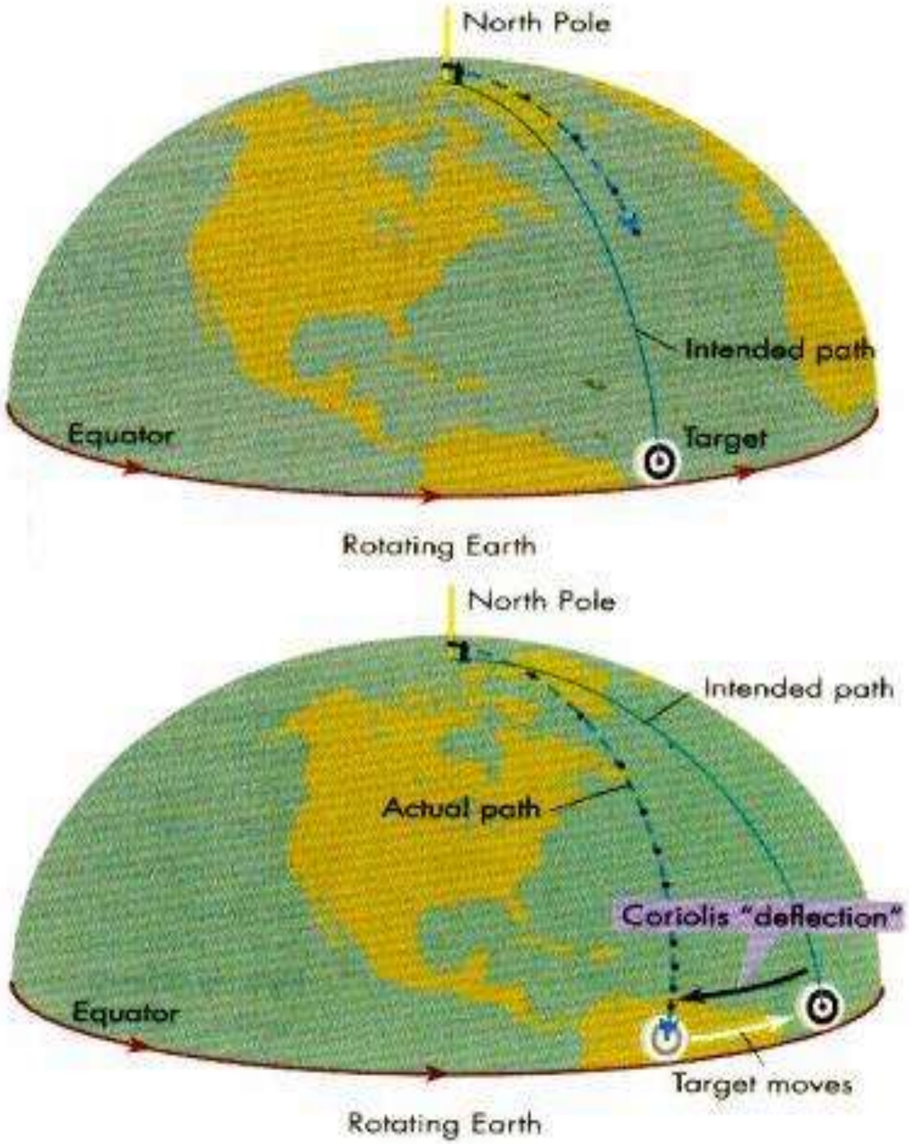
- To generate electricity on a large scale, a number of windmills are set up over a large area, called a wind energy farm. Such areas need a wind speed of 15kmph.

- Locally, the strong winds are created by sharp temperature difference between the land and the sea. Wind resources in India are tremendous.
- They are mainly located near the sea coasts. Its potential in India is estimated to be of 25×10^3 mW.
- According to a news release from American Wind Energy Association the installed wind capacity in India in the year 2000 was 1167 mW and the wind energy production was 2.33×10^6 mWh.
- This is 0.6% of the total electricity production

- The wind energy over earth is estimated to be 1.6×10^7 M.W, which is equivalent to the energy consumed. But, the wind energy is available in dilute form.
- The wind energy varies from time to time and place to place. Due to this reason some storage facility is required.
- The kinetic energy of wind is converted into useful shaft power by wind mills.
- General applications of wind mills are pumping water, fodder cutting, grain grinding, generation of power etc.

Generation of the Wind:

- **Wind is generated by,**
- Differential solar heating of locations at the equator and poles.
- Coriolis force due to earth‘s rotation.
- Friction between earth‘s surface and the wind.


North Pole
Intended path
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Target
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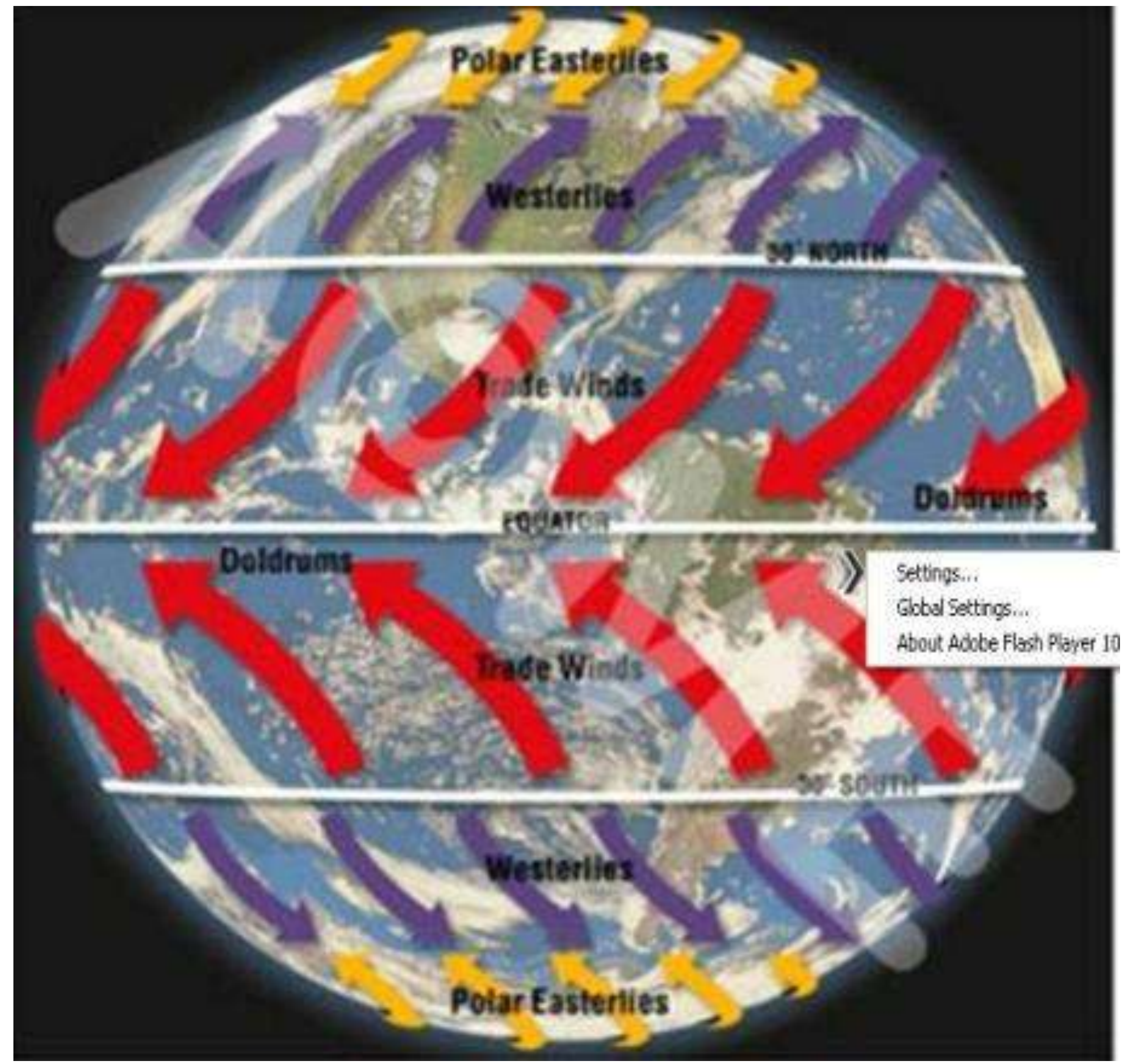
Polar Easterlies
Westerlies
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30° SOUTH
Westerlies
Polar Easterlies

Local winds:

- Differential heating of the land mass and nearby sea surface water creates local winds.
- During day land heats up faster rapidly compared with nearby sea water. Hence there tends to be surface wind flow from the water to the land.
- During night wind reverses because land surface cools faster than the water.
- Second mechanism of local winds is caused by hills and mountain sides. The air above the slopes heats up during the day and cools down at night, more rapidly than the air above the low lands.

Wind Energy is an indirect source of Solar Energy. Why?

- In India generally the wind speed is low. Therefore attempts are being made for development of low speed, low cost wind mills.
- Special focus is on development of mill for water pumping which can operate at low wind speed of 8-36 km/hr. Which can be utilised for providing drinking water in small rural area, irrigation of small farms.
- In India high speed winds are available in coastal areas of Saurashtra, Rajasthan and some parts of central India.

Characteristics of Wind Energy:

- It is a renewable source of energy.
- Wind power systems are non-polluting and has no adverse effects of the environment.
- Wind energy systems avoids fuel provision and transport.
- On small scale of up to few kilowatts, it is less costly. On large scale the costs are comparable with the costs of conventional energy sources, but low cost can be achieved by mass production.

The problems associated with Utilizing wind energy are that:

- Availability of wind is fluctuating or irregular in nature.
- Unlike water energy, it requires storage means because of irregular nature.
- Wind energy systems are noisy in operation; a large unit can be heard many km away.
- Large area is needed for installation of Wind Farms, for Electricity generation.
- The energy is available in dilute form, because of this conversion machines have to be necessarily large.
- The availability of the energy varies considerably over a day and with the seasons.
- For this reason some means of storage have to be devised if a continuous supply of power is required.

Availability of wind energy in India:

- In the early 1980s, the Indian government established the Ministry of Non-Conventional Energy Sources (MNES) to encourage diversification of the country's energy supply, and satisfy the increasing energy demand of a rapidly growing economy.
- In 2006, this ministry was renamed the Ministry of New and Renewable Energy (MNRE).
- Renewable energy is growing rapidly in India. With an installed capacity of 13.2 GW, renewable energy sources (excluding large hydro) currently account for 9% of India's overall power generation capacity.

- By 2012, the Indian government is planning to add an extra 14 GW of renewable sources.
- In its 10th Five Year Plan, the Indian government had set itself a target of adding 3.5 GW of renewable energy sources to the generation mix. In reality, however, nearly double that figure was achieved.
- In this period, more than 5.4 GW of wind energy was added to the generation mix, as well as 1.3 GW from other resources The total power in 2008-2012 was increased to 14 GW, 10.5 GW of which to be new wind generation capacity.

- The Indian Ministry of New and Renewable Energy (MNRE) estimates that there is a potential of around 90,000 MW for the country, including 48,561 MW of wind power, 14,294 MW of small hydro power and 26,367 MW of biomass.

- In addition, the potential for solar energy is estimated for most parts of the country at around 20 MW per square kilometre of open, shadow free area covered with 657 GW of installed capacity.

- The total potential for wind power in India was first estimated by the Centre for Wind Energy Technology (C-WET) at around 45 GW, and was recently increased to 48.5 GW. This figure was also adopted by the government as the official estimate.
- The C-WET study was based on a comprehensive wind mapping exercise initiated by MNRE, which established a country-wide network of 105O wind monitoring and wind mapping stations in 25 Indian States.
- This effort made it possible to assess the national wind potential and identify suitable areas for harnessing wind power for commercial use, and 216 suitable sites have been identified.

The power in the wind:

- Wind possesses energy by virtue of its motion. Any device capable of slowing down the mass of moving air can extract part of energy and convert it into useful work.
- Three factors determine the output from a wind energy converter.
  - The wind speed.
  - The cross section of wind swept by rotor.
  - The overall conversion efficiency of the rotor, transmission system and generator.

- It is not possible to convert all the wind energy to mechanical energy.
- Maximum of 60% of the wind energy can be converted to mechanical energy.
- Due to losses in gear box, transmission system and generator, maximum
- overall wind turbine efficiency is 35%.
- $KE=(1/2)mv^2$ $m=\varrho AV^2$
- $KE=(1/2)\ \varrho AV^3$ watts
- Surface area of rotor is normally circular, so $A=\pi D^2/4$
- Available wind energy, $KE=(1/2)\ \varrho\ \pi D^2/4V^3$
- $KE=(1/8)\ \varrho\ \pi D^2V^3$
- The equation tells us that maximum power available from the wind varies according to square of the diameter of the intercept area and cube of the wind velocity.

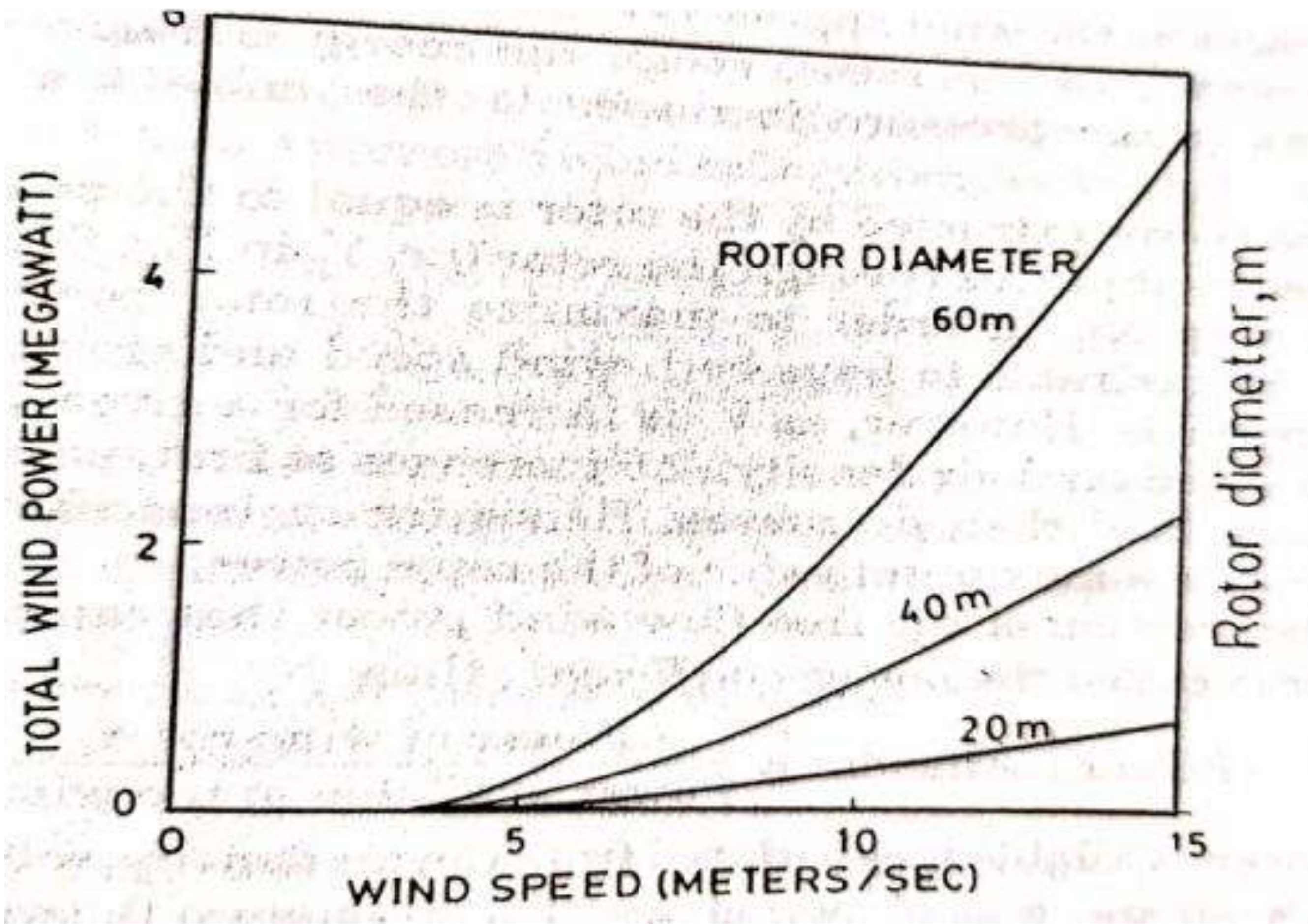


Fig: Dependence of wind rotor power on wind speed and rotor diameter

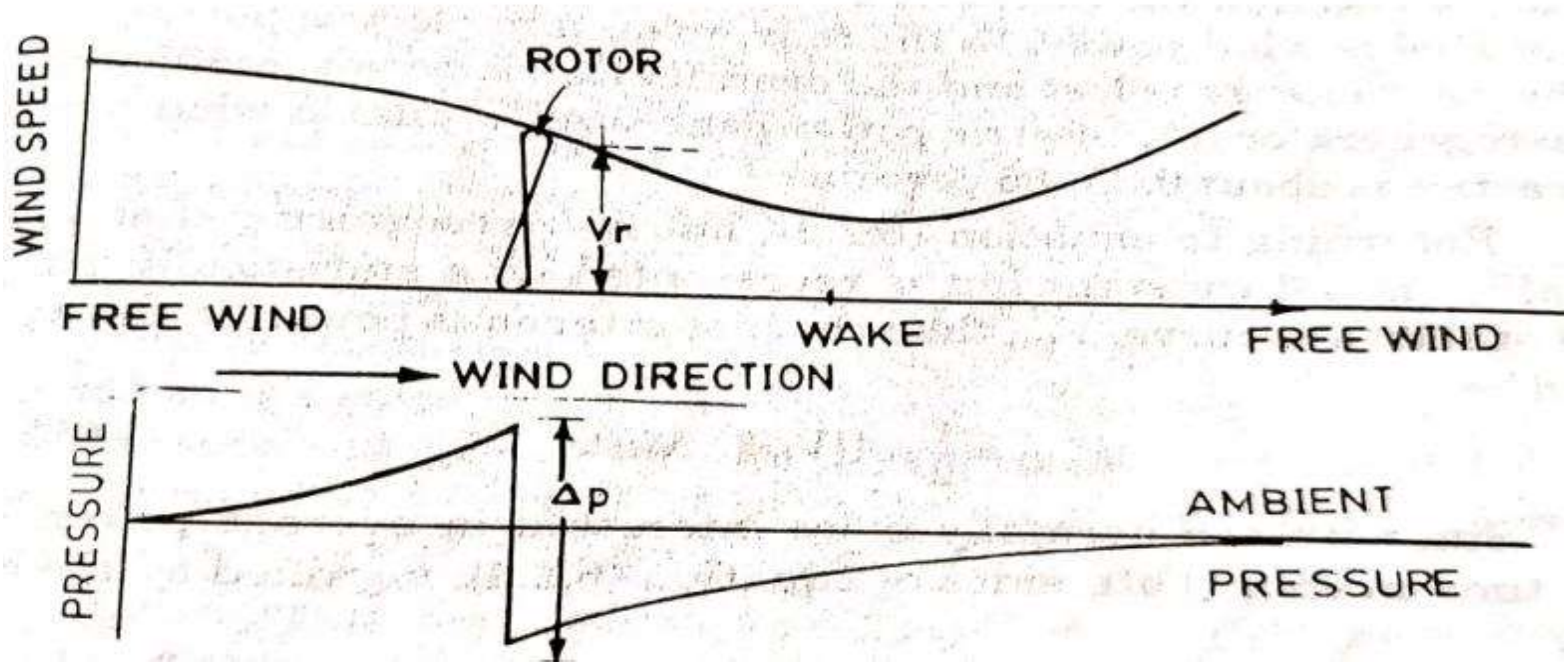


Fig: Conditions in traversing a wind rotor

- Conditions in traversing a wind rotor.
- Power extracted by rotor = $\Delta P. V_r$
- The fraction of the free flow wind power that can be extracted by a rotor is called power coefficient.
- power coefficient = power output from wind machine/Power available in the wind

Advantages of Wind Energy:

- Wind Energy is an inexhaustible source of energy and is virtually a limitless resource.
- Energy is generated without polluting environment.
- This source of energy has tremendous potential to generate energy on large scale.
- Like solar energy and hydropower, wind power taps a natural physical resource.
- Windmill generators don’t emit any emissions that can lead to acid rain or greenhouse effect.
- Wind Energy can be used directly as mechanical energy.
- In remote areas, wind turbines can be used as great resource to generate energy.
- In combination with Solar Energy they can be used to provide reliable as well as steady supply of electricity.
- Land around wind turbines can be used for other uses, e.g. Farming.

Disadvantages of Wind Energy:

- Wind energy requires expensive storage during peak production time.
- It is unreliable energy source as winds are uncertain and unpredictable.
- There is visual and aesthetic impact on region.
- Requires large open areas for setting up wind farms.
- Noise pollution problem is usually associated with wind mills.
- Wind energy can be harnessed only in those areas where wind is strong enough and weather is windy for most parts of the year.
- Usually places, where wind power set-up is situated, are away from the places where demand of electricity is there. Transmission from such places increases cost of electricity.

- The average efficiency of wind turbine is very less as compared to fossil fuel power plants. We might require many wind turbines to produce similar impact.
- It can be a threat to wildlife. Birds do get killed or injured when they fly into turbines.
- Maintenance cost of wind turbines is high as they have mechanical parts which undergo wear and tear over the time.
- Even though there are advantages of wind energy, the limitations make it extremely difficult for it to be harnessed and prove to be a setback.

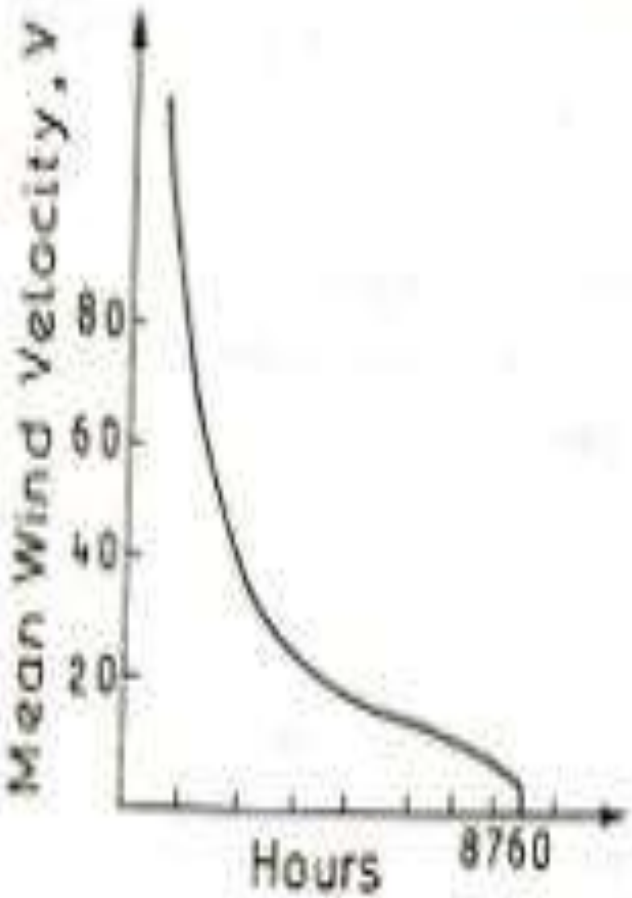
Energy Estimation

- The basic wind data of hourly mean wind velocity is recost into,

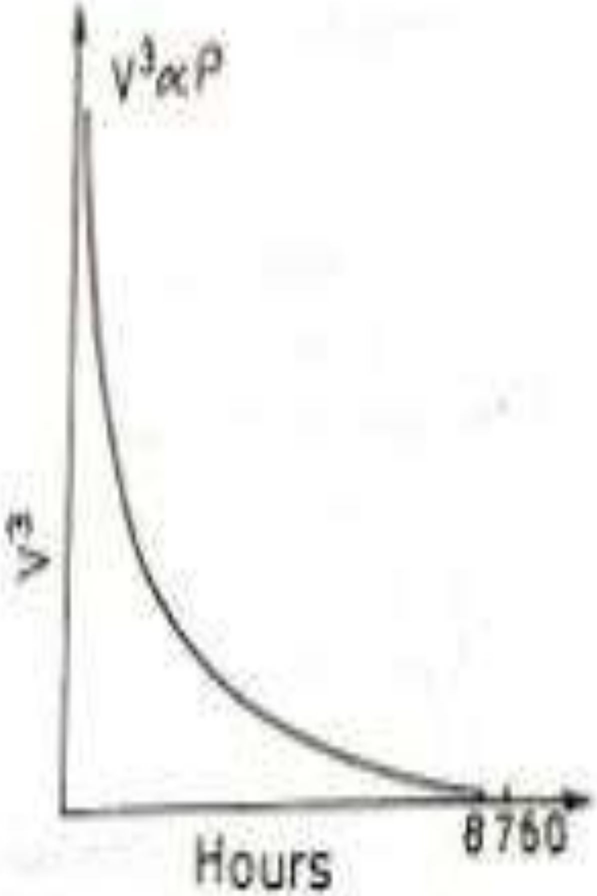
  - Number of hours in the year for which the speed equals or exceeds each particular value.

  - Annual hours of duration of various wind speed.

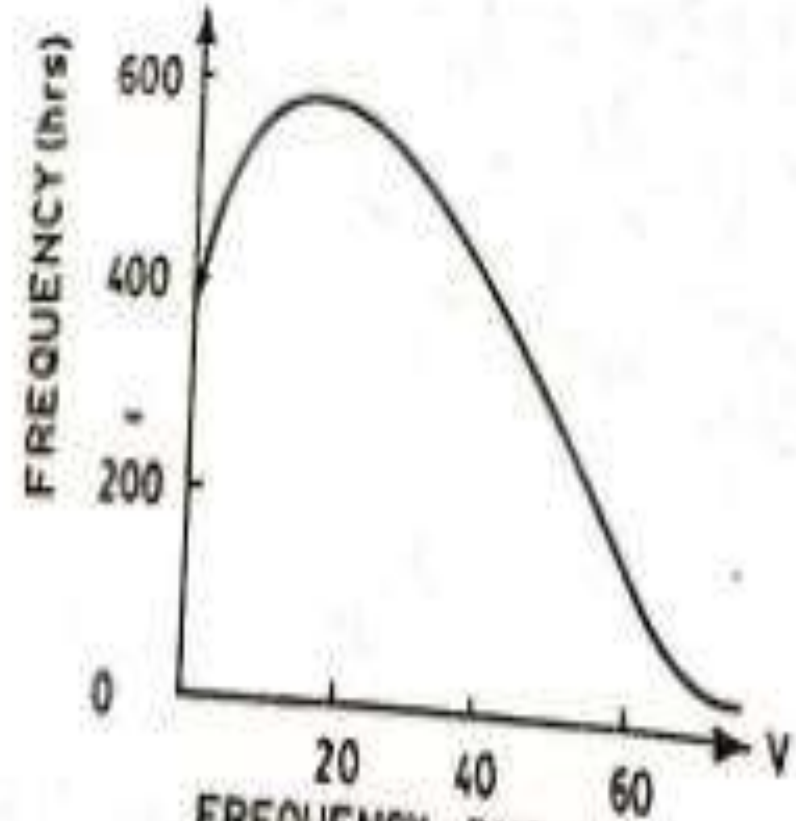
- The first of these plotted the hours in the year called the velocity- duration curve, the replot of this on V^3 basis is called the power duration curve (V^3 being proportional to P).
- These curves are useful for establishing the wind energy potential of a place, and the design wind speed.



(a) Velocity duration curve



(b) Power duration curve



FREQUENCY–DURATION CURVE

Site Selection Consideration:

1. High annual average wind speed.
2. Availability of anemometry data.
3. Availability of wind curve at proposed site.
4. Wind structure at proposed site.
5. Altitude of site.
6. Terrain and its aerodynamics.
7. Local ecology.
8. Distance to roads railways.
9. Nearness of site to users.
10. Nature of ground.
11. Favorable land cost.
12. Salt spray, blowing dust.

Basic components of wind energy conversion system:

- The main components of WECS are shown in the figure 6.5.1.

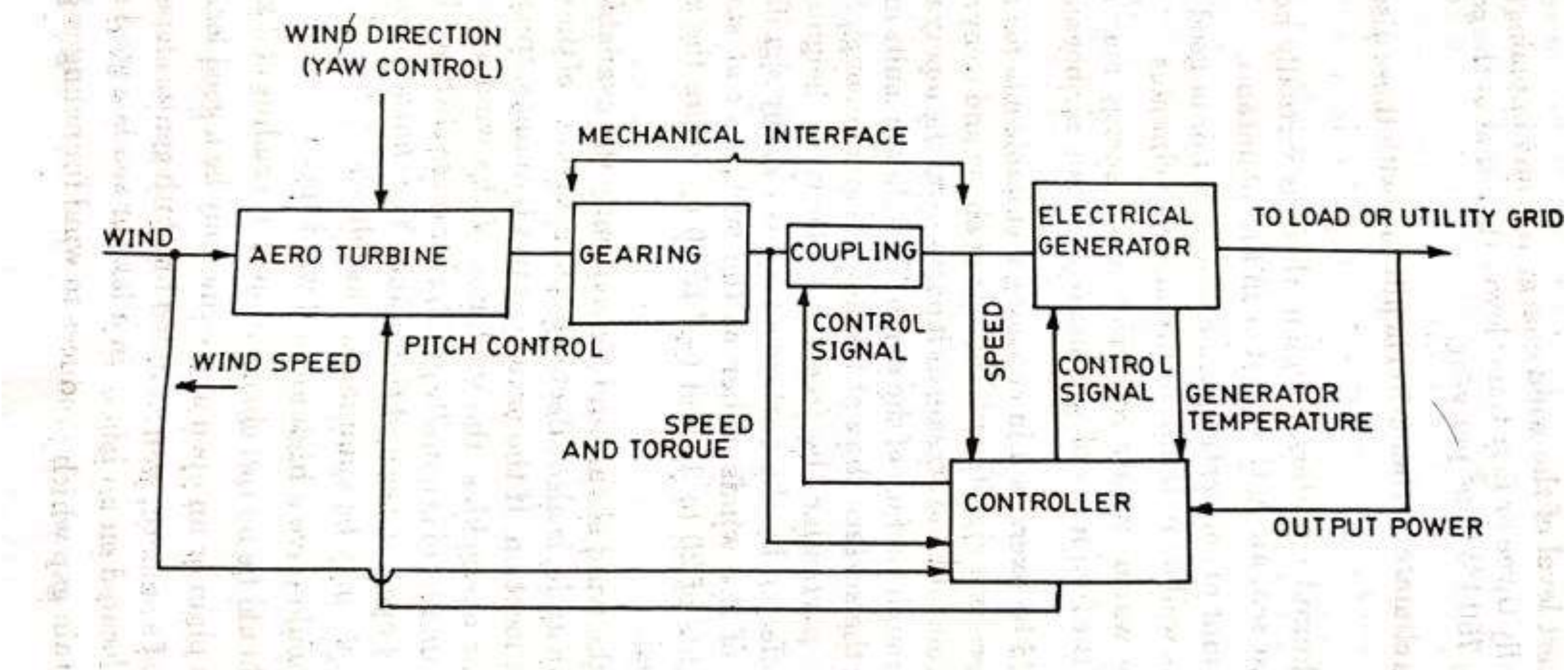


Fig. 6.5.1. Basic components of a Wind Electric System.

- Aeroturbine converts energy in the moving air to rotary mechanical energy. In general, they require “pitch control” and “yaw control” (only in case of horizontal or wind axis machine) for proper operation.
- **Yaw Control:** rotor which can be in a fixed orientation with the swept area perpendicular to the predominant wind direction, such a machine is said to be *yaw* fixed.
- Most of the turbines are yaw active, as the direction of the wind changes motor rotates the turbine slowly about the vertical axis so as to face the blades into the wind.

Wind Turbine:

- A **wind turbine** is a device that converts kinetic energy from the wind into mechanical energy. If the mechanical energy is used to produce electricity, the device may be called a **wind generator** or **wind charger**.
- If the mechanical energy is used to drive machinery, such as for grinding grain or pumping water, the device is called a windmill or wind pump.
- Developed for over a millennium, today's wind turbines are manufactured in a range of vertical and horizontal axis types.
- The smallest turbines are used for applications such as battery charging or auxiliary power on sailing boats; while large grid-connected arrays of turbines are becoming an increasingly large source of commercial electric power.

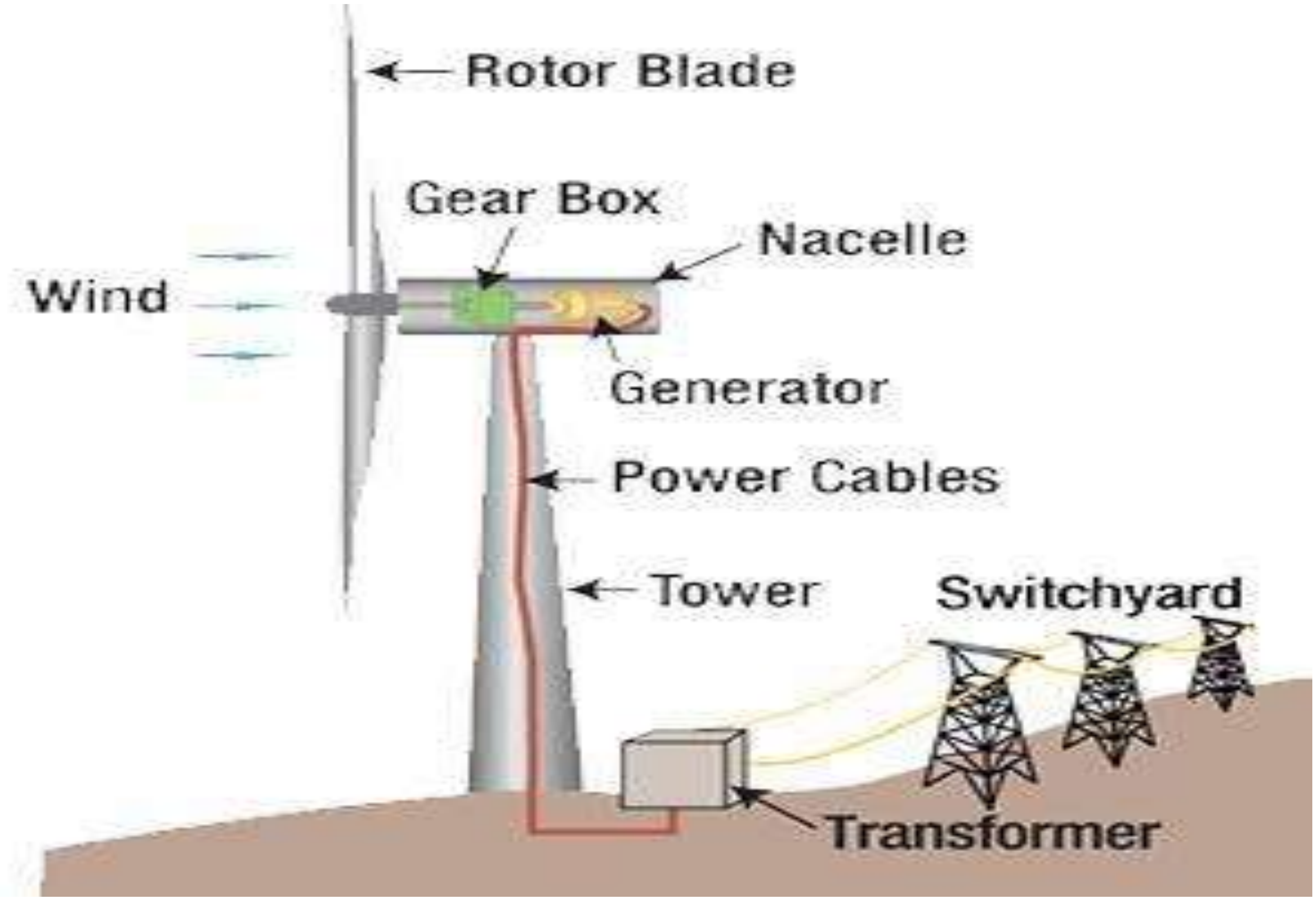


Fig: Wind Turbine

- The physical embodiment for wind turbine is shown in the above figure, the sub-components of the wind mill/turbine are:

➢ Wind turbine.

➢ Wind mill head.

➢ Transmission & control.

➢ Supporting structure.

1) Rotor are mainly two types,

➢ Horizontal axis rotor and

➢ Vertical axis rotor.

2) The windmill head - supports the rotor, housing the rotor bearings.

- It also houses the control mechanism incorporated like changing the pitch of the blades for safety devices.

3) Transmission.

4) Generator.

5) Controls.

6) Towers.

Classification of WECS:

1. Two broad classification

(i) Horizontal axis machines (ii) Vertical axis machines

2. According to size,

(i) Small scale- up to 2 kW – for farms and places requiring relatively low power

(ii) Medium scale, 2-100 kW for several residences

(iii) Large scale- >100 kW for distribution in central power grids

3. Based on output,

(i) DC output (ii) AC output

4. Rotational speed,

(i) Constant speed – variable pitch blades

(ii) Variable speed – fixed pitch blades

5. Utilization of output,

(i) Battery storage.

(ii) Thermal potential of storage.

(iii) Direct connection with electromagnetic energy converter.

(iv) Interconnection with conventional electric utility grids.

Wind Energy Collector:

- A windmill is a machine for wind energy conversion. A wind turbine converts kinetic energy of the wind’s motion to mechanical energy transmitted by the shaft, which in turn can be converted into electricity by means of a generator.
- There are essentially two types of wind turbines:
  - The horizontal-axis variety, and the vertical axis design.

Wind Turbine Classification:

- Horizontal Axis Machines: Machines with rotors that move in a plane perpendicular to the direction of the wind. A farmer‘s windmill, for example.

- Vertical Axis Machines: Machines that have the working surfaces traveling in the direction of the wind. These machines are sometimes called- “Panemones”.

Types of Wind turbines:

Horizontal axis:

- Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind.
- Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor.
- Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator.
- Since a tower produces turbulence behind it, the turbine is usually positioned upwind of its supporting tower.

Horizontal axis type wind mill

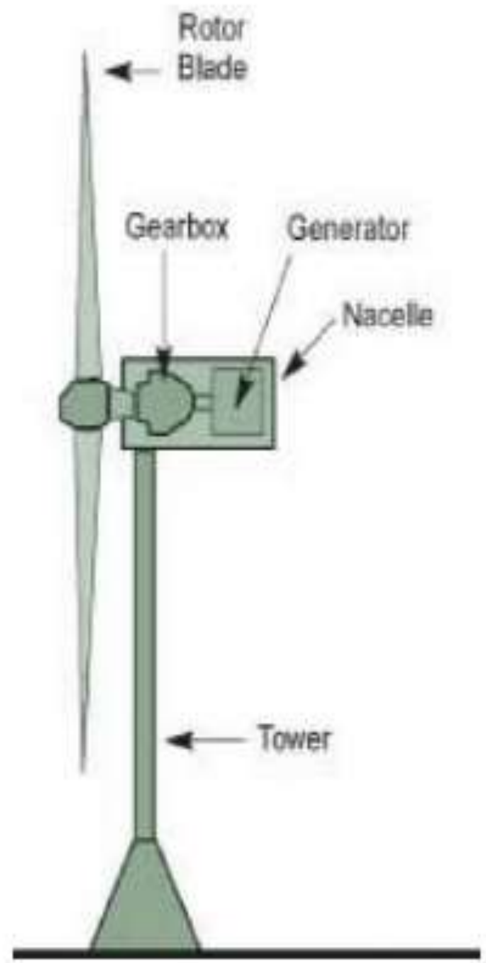
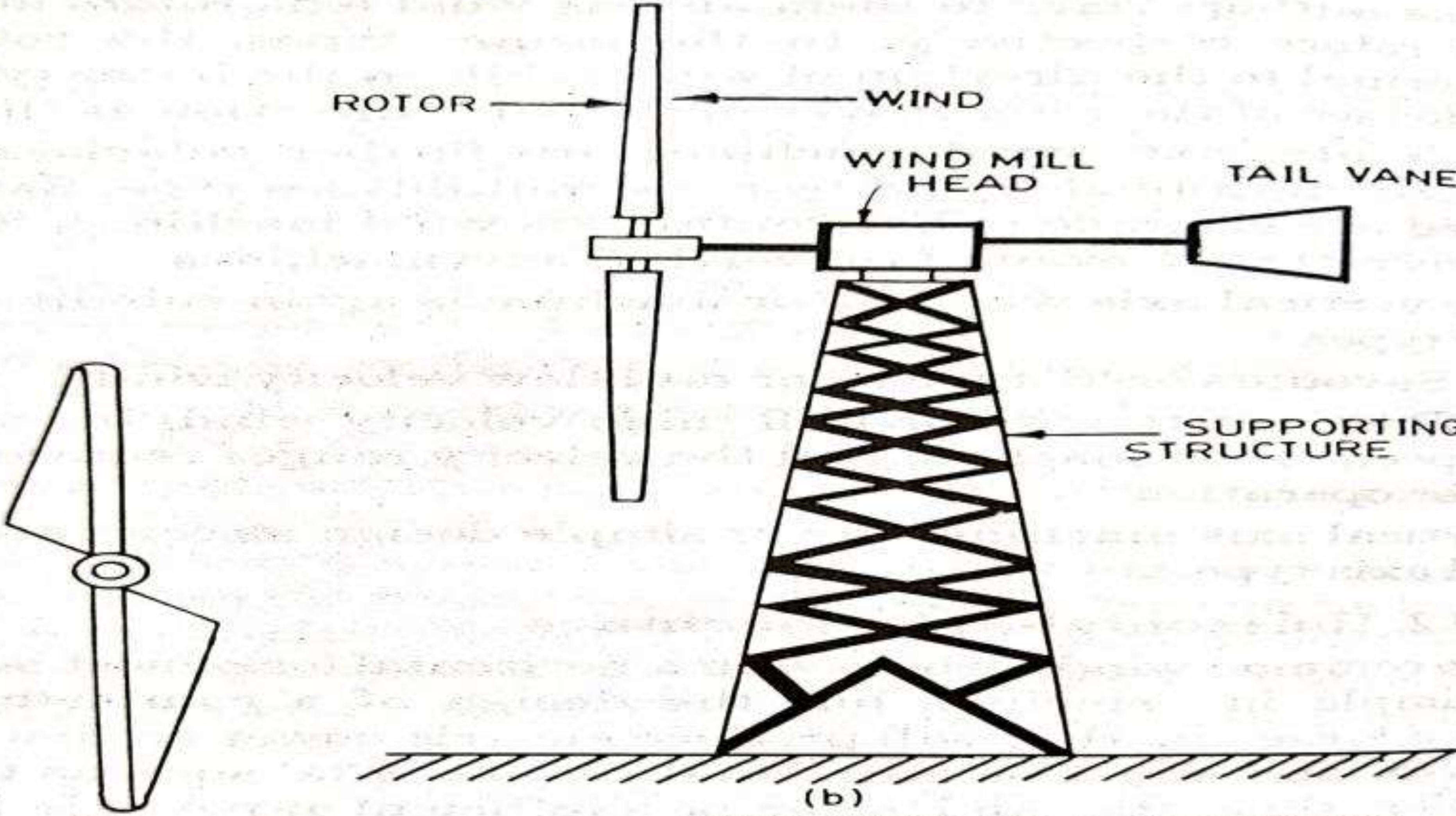


Fig: Horizontal-axis wind turbines



(a)
TWO BLADE PRUFILE

(b)
SCHEMATIC OF A HORIZANTAL
AXIS TYPE WIND MILLS

Fig 6.8.1

- Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds.
- Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted forward into the wind a small amount.
- Downwind machines have been built, despite the problem of turbulence (mast wake), because they don't need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance.
- Since cyclical (that is repetitive) turbulence may lead to fatigue failures, most HAWTs are of upwind design.

Horizontal axis single blade wind mill

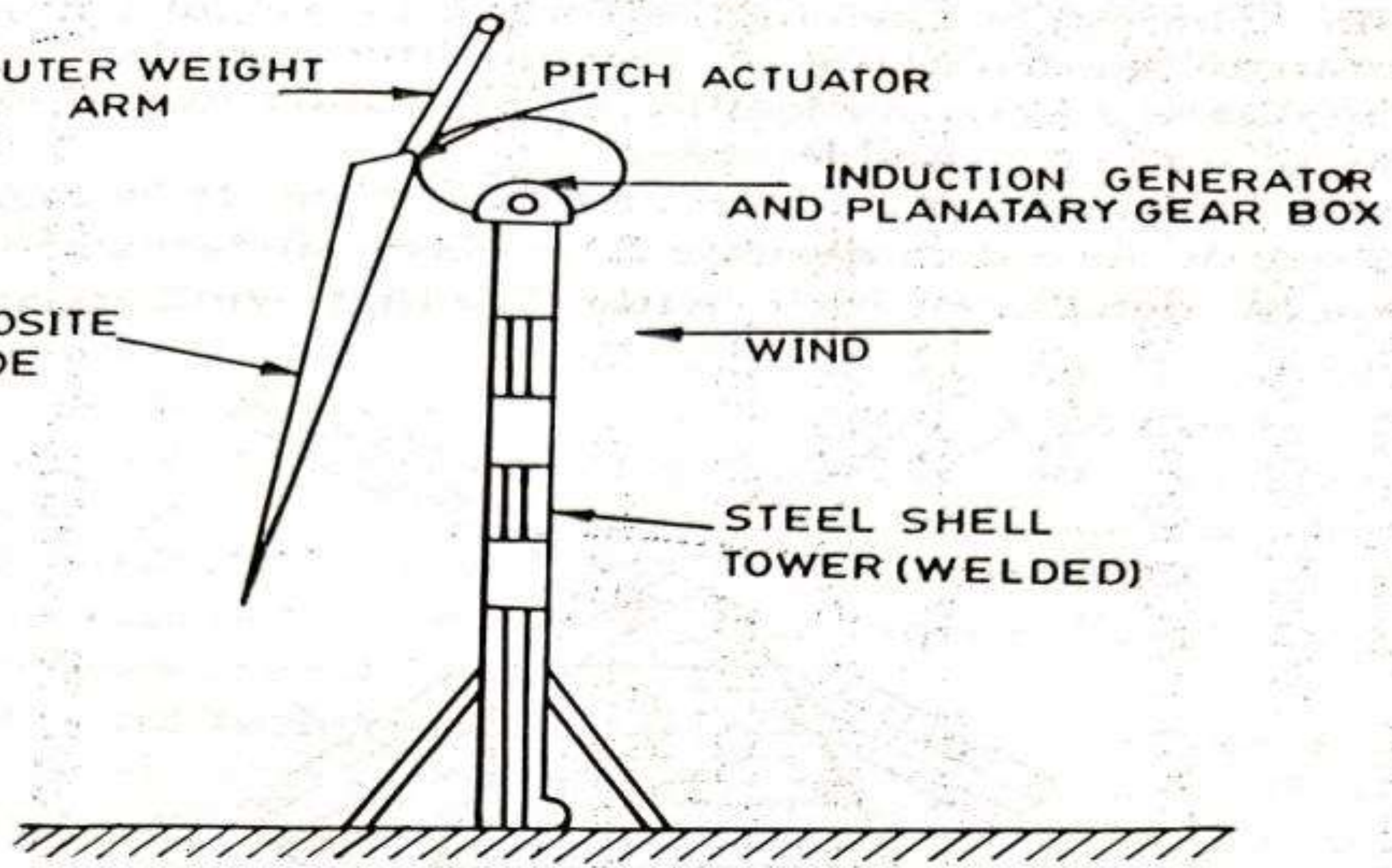


Fig. 6.8.2. Horizontal axis single blade wind mill.

- In this type a long blade is mounted on a rigid hub, induction generator and gear box is also shown.
- Long blades (say 60m) are mounted on rigid hub.
- To reduce rotor cost, use of low cost counter weight is recommended.
- Simple blade controls.
- Counter weight cost less than a second blade.
- Pitch bearings do not carry centrifugal force.

Horizontal axis mutlibladed type

- This type of design is shown in figure 6.8.3,

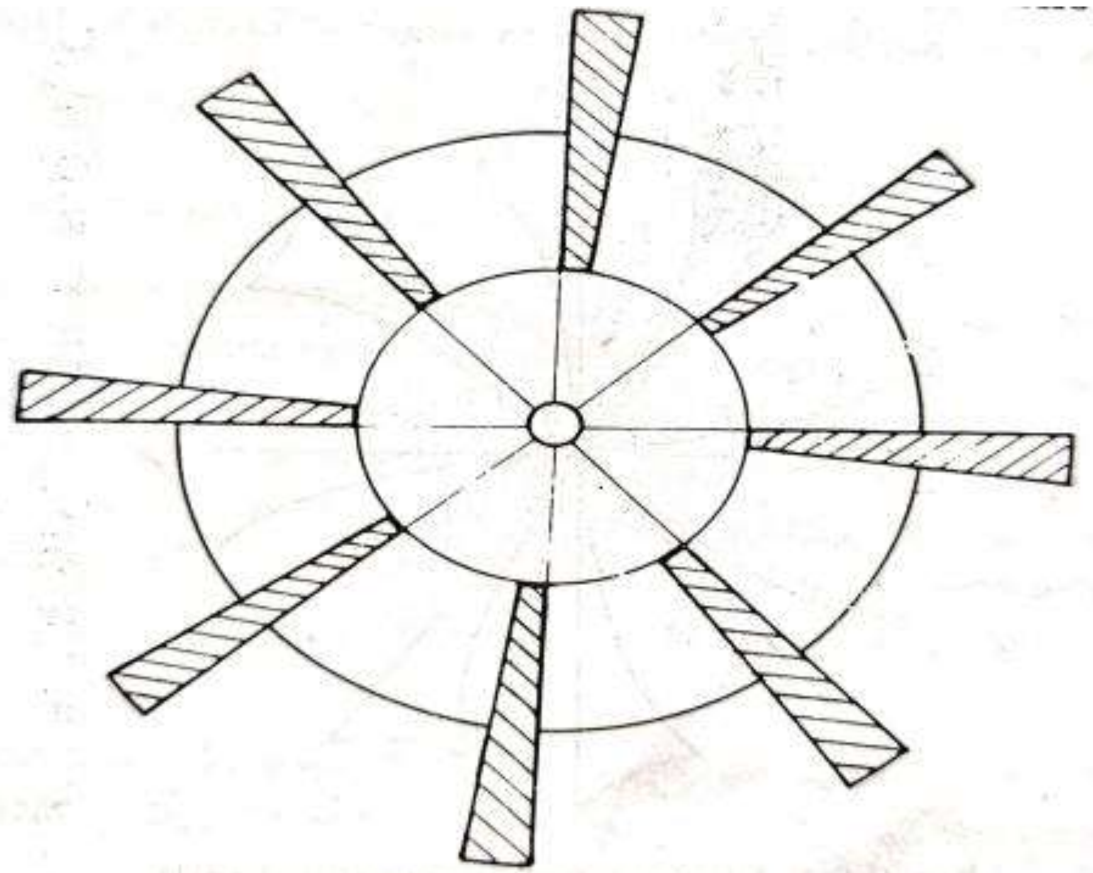
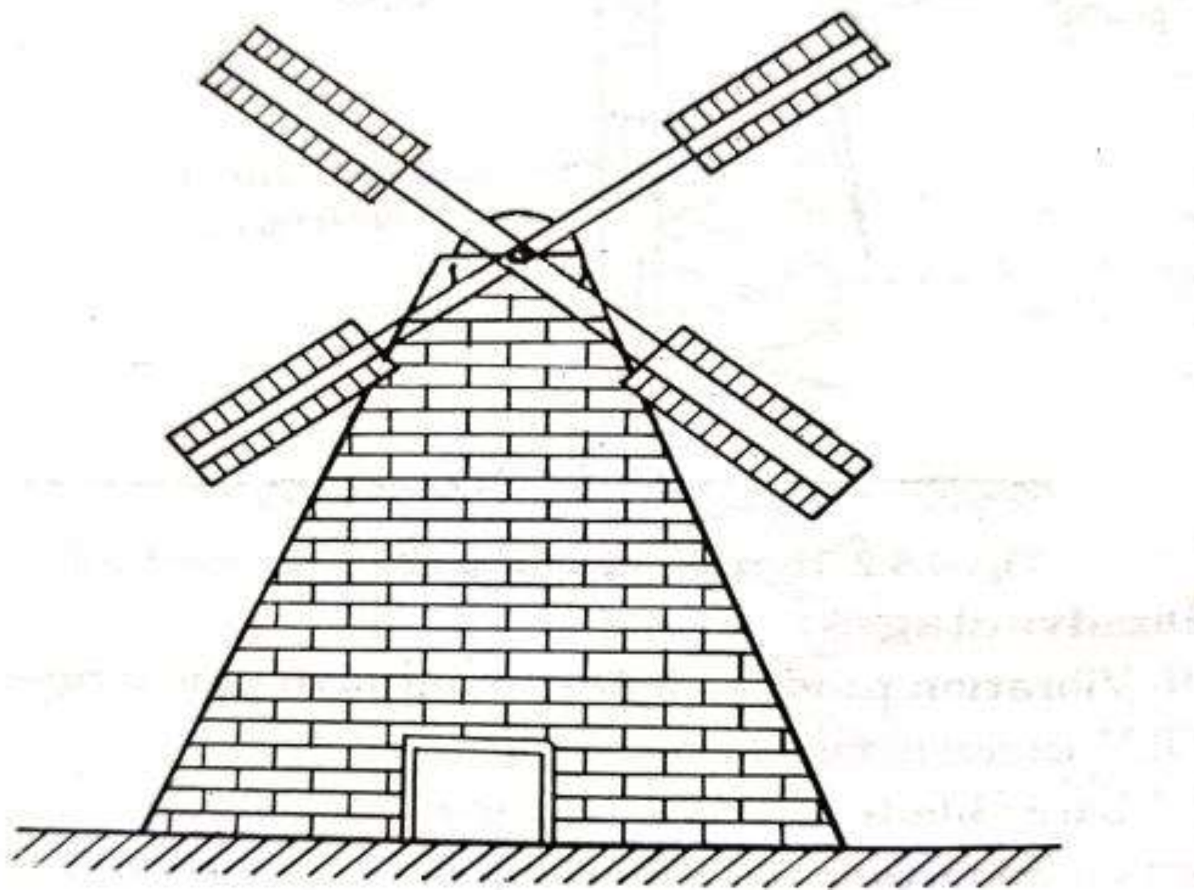


Fig. 6.8.3. Multiblade propeller.

Horizontal axis wind mill- Dutch type

- It is one o the oldest designs. The blade surfaces are made from an array of wooden slats which feather at high wind speeds



Sail type wind mill

- Its blade are shown in figure 6.8.5. It is of recent origin and the blade surface is made from cloth, nylon or plastics arranged as sailwings.

sails used.

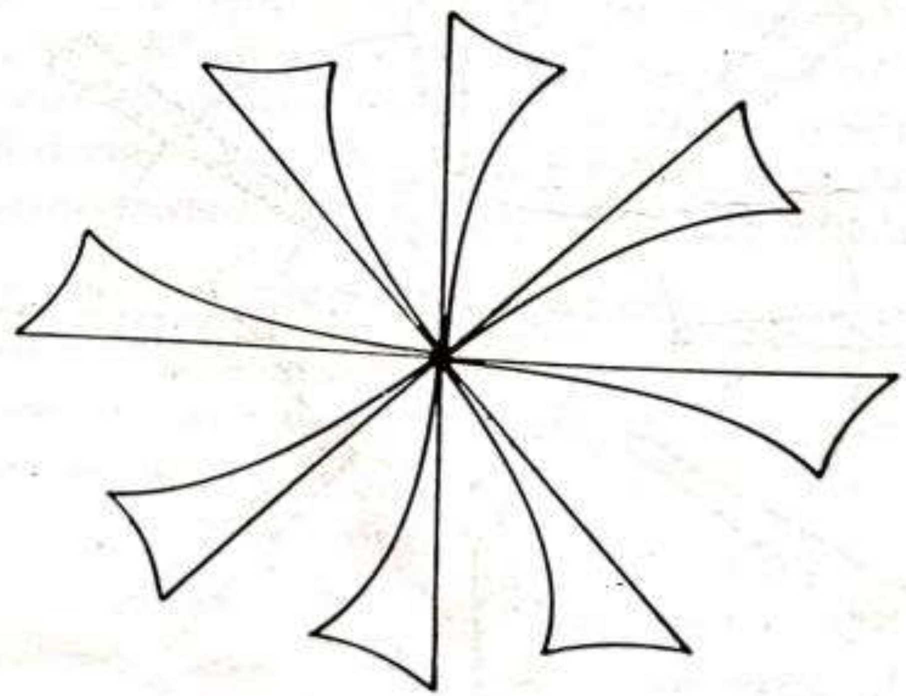


Fig. 6.8.5. Blades of sail type wind mill.

Vertical axis:

- Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable, for example when integrated into buildings.

Vertical Axis wind mill

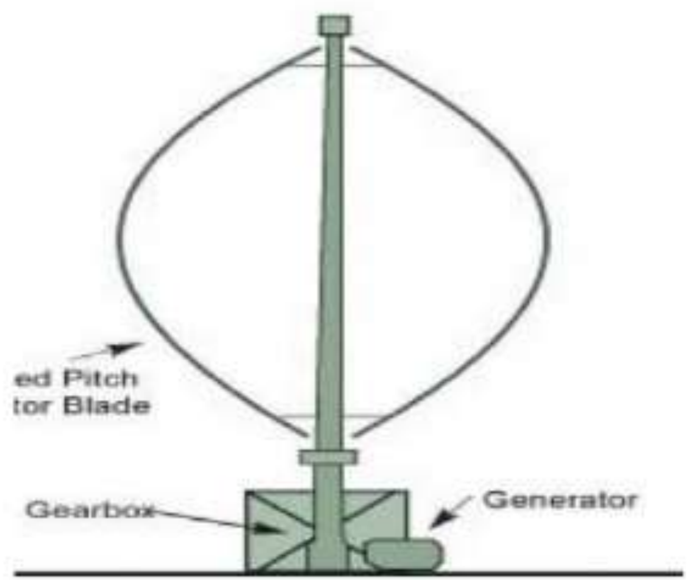


Fig: Vertical-axis wind turbine

- The key disadvantages include the low rotational speed with the consequential higher torque and hence higher cost of the drive train.
- The inherently lower power coefficient, the 360 degree rotation of the aero foil within the wind flow during each cycle and hence the highly dynamic loading on the blade,
- The pulsating torque generated by some rotor designs on the drive train, and the difficulty of modeling the wind flow accurately and hence the challenges of analyzing and designing the rotor prior to fabricating a prototype.

- With a vertical axis, the generator and gearbox can be placed near the ground, using a direct drive from the rotor assembly to the ground-based gearbox, hence improving accessibility for maintenance.
- When a turbine is mounted on a rooftop, the building generally redirects wind over the roof and these can double the wind speed at the turbine.
- If the height of the roof top mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence.

- A wind mill converts the kinetic energy of moving air into mechanical energy that can be either used directly to run the machine or to run the generator to **“*Produce Electricity*”.**

Wind Mill Types:

1. Multi-blade type Wind Mill
2. Sail type
3. Propeller type
4. Savonius type
5. Darrieus type

Horizontal Axis

Vertical Axis

Subtypes of Vertical Axis Wind Mill (VAWM):

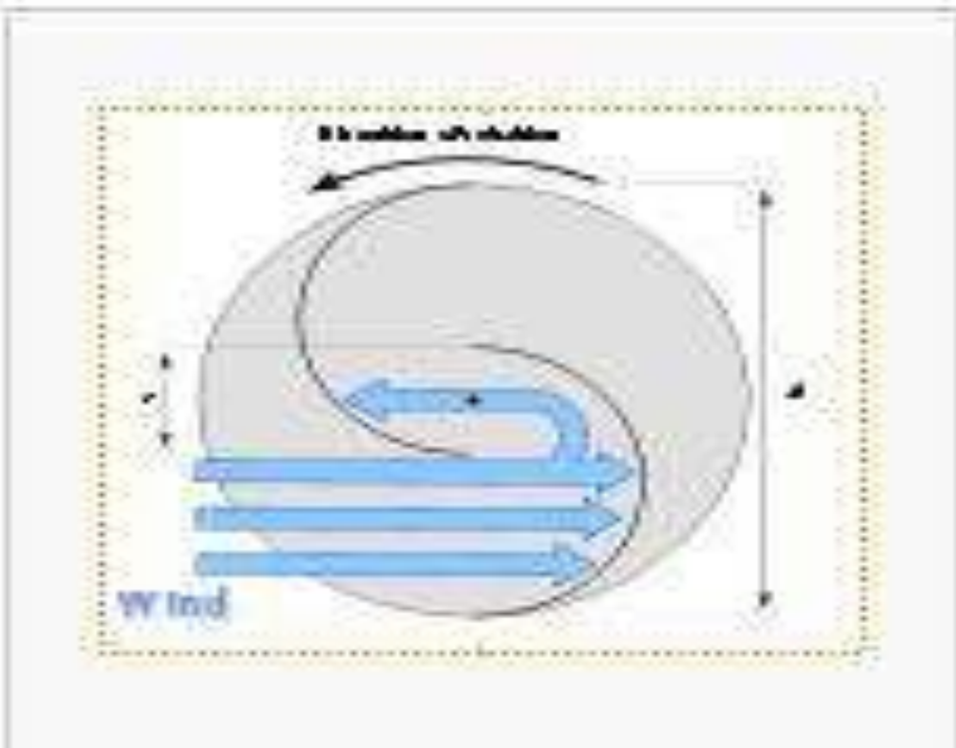
Darrieu's wind turbine:

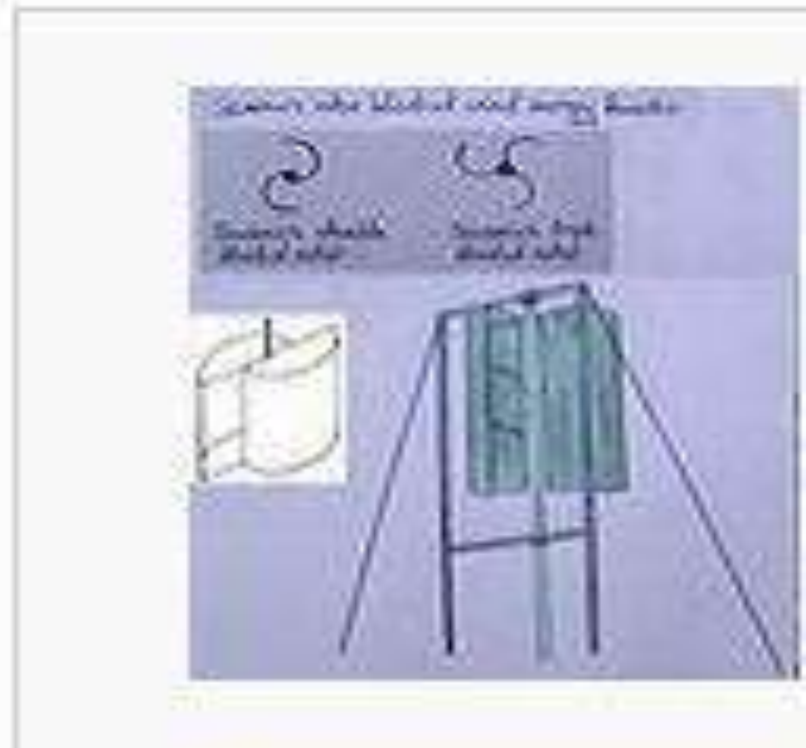
- Eggbeater turbines, or Darrieu's turbines, were named after the French inventor, Georges Darrieus. They have good efficiency, but produce large torque ripple and cyclical stress on the tower, which contributes to poor reliability.

- They also generally require some external power source, or an additional Savonius rotor to start turning, because the starting torque is very low.
- The torque ripple is reduced by using three or more blades which results in greater solidity of the rotor.
- Solidity is measured by blade area divided by the rotor area.
- Newer Darrieus type turbines are not held up by guy-wires but have an external superstructure connected to the top bearing.

Savonius Wind Turbine:

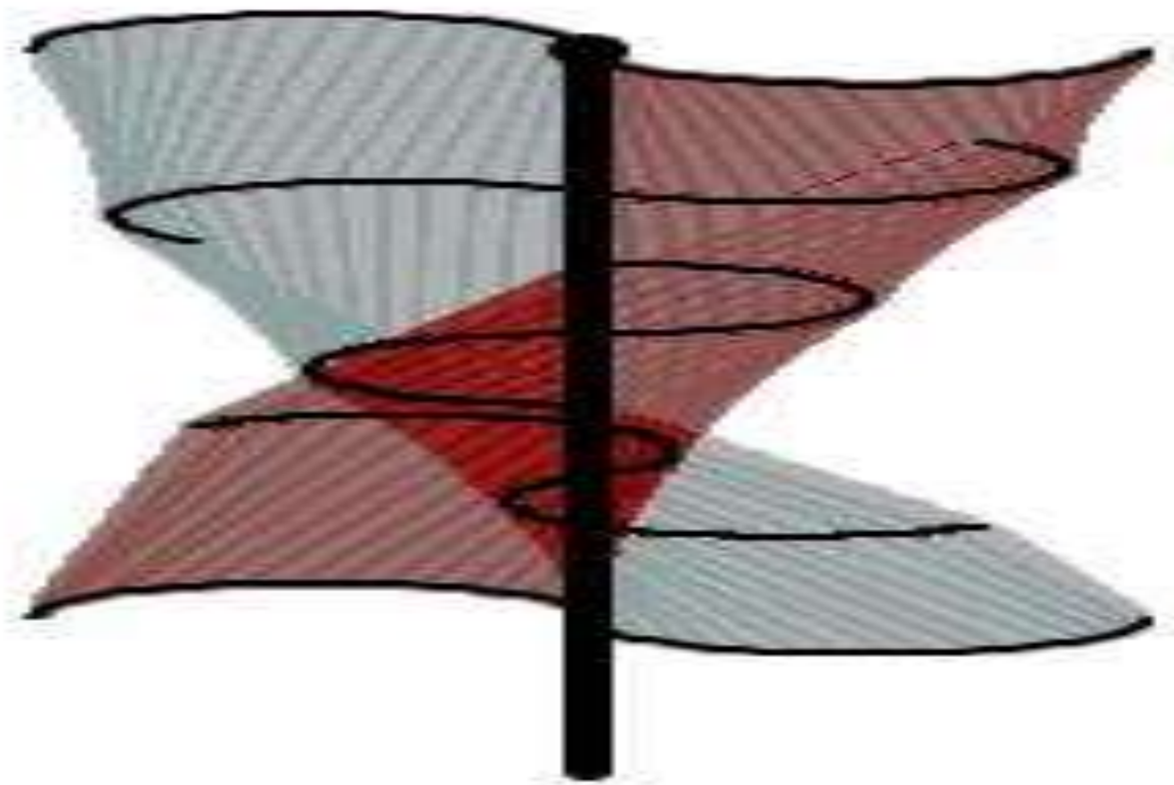
- These are drag-type devices with two (or more) Scoops. They are always self-starting if there are at least three scoops.





Twisted Savonius:

- Twisted Savonius is a modified Savonius, with long helical scoops to give a smooth torque, this is mostly used as roof wind turbine or on some boats.



Subtypes of Horizontal axis wind mills:

- Single blade rotor:

  – Rotor must move more rapidly to capture same amount of wind.

  – Gearbox ratio reduced.

  – Added weight of counterbalance negates some benefits of lighter design.

  – Higher speed means more noise, visual, and wildlife impacts.

- Blades easier to install because entire rotor can be assembled on ground
- Captures 10% less energy than two blade design.

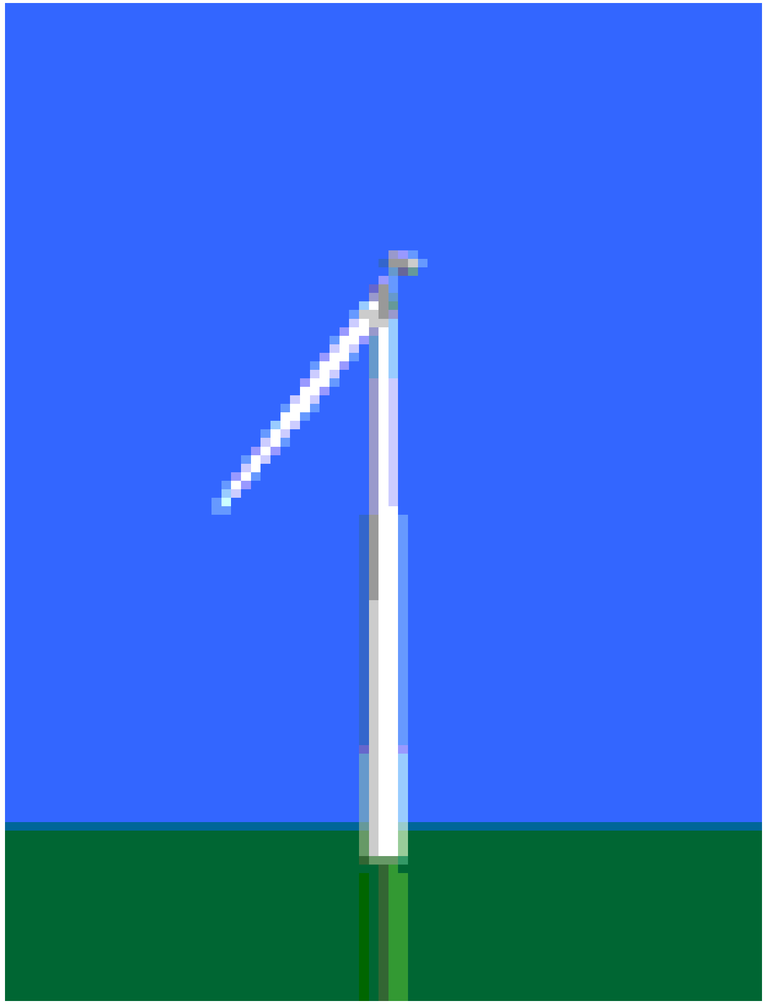


Fig: Single Blade Rotor

Two bladed rotor:

- Advantages & disadvantages similar to one blade.
- Need teetering hub and or shock absorbers because of gyroscopic imbalances.
- Capture 5% less energy than three blade designs.

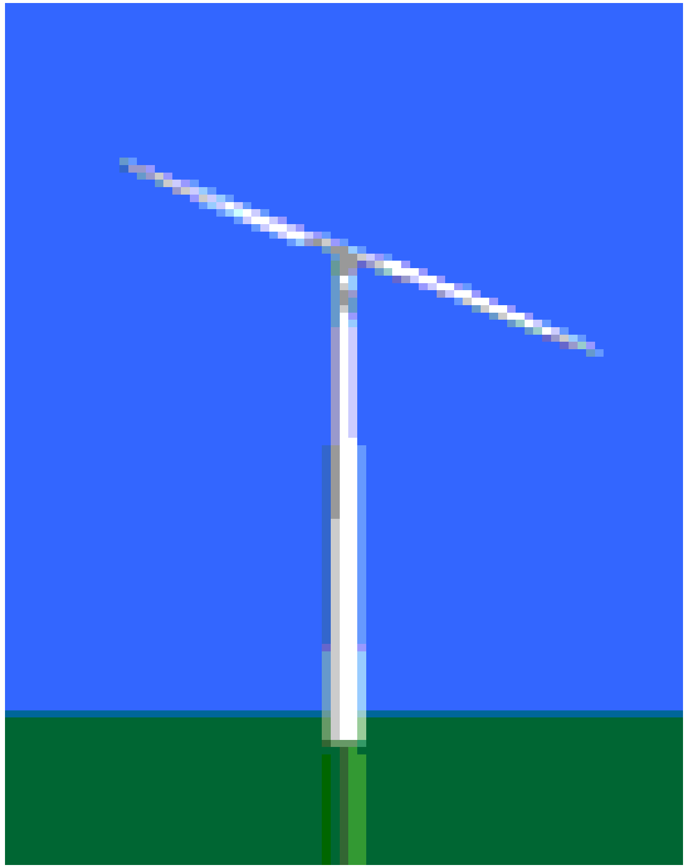


Fig: Two Blade Rotor

Three bladed rotor:

- Balance of gyroscopic forces
- Slower rotation
  - – increases gearbox & transmission costs
  - – More aesthetic, less noise, fewer bird strikes

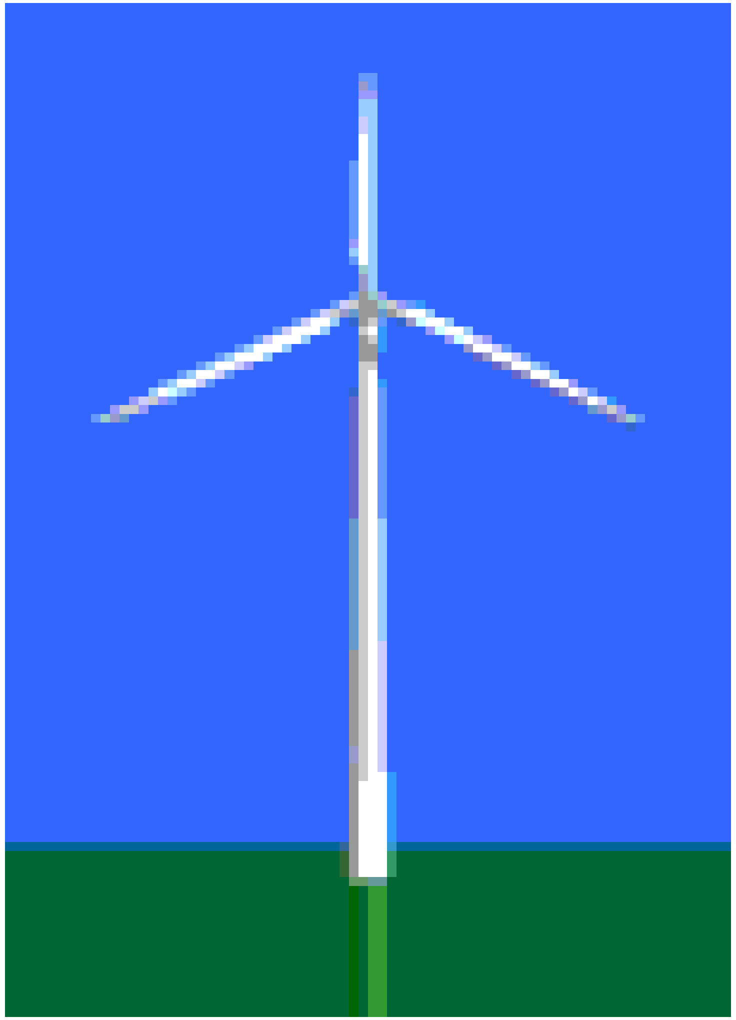
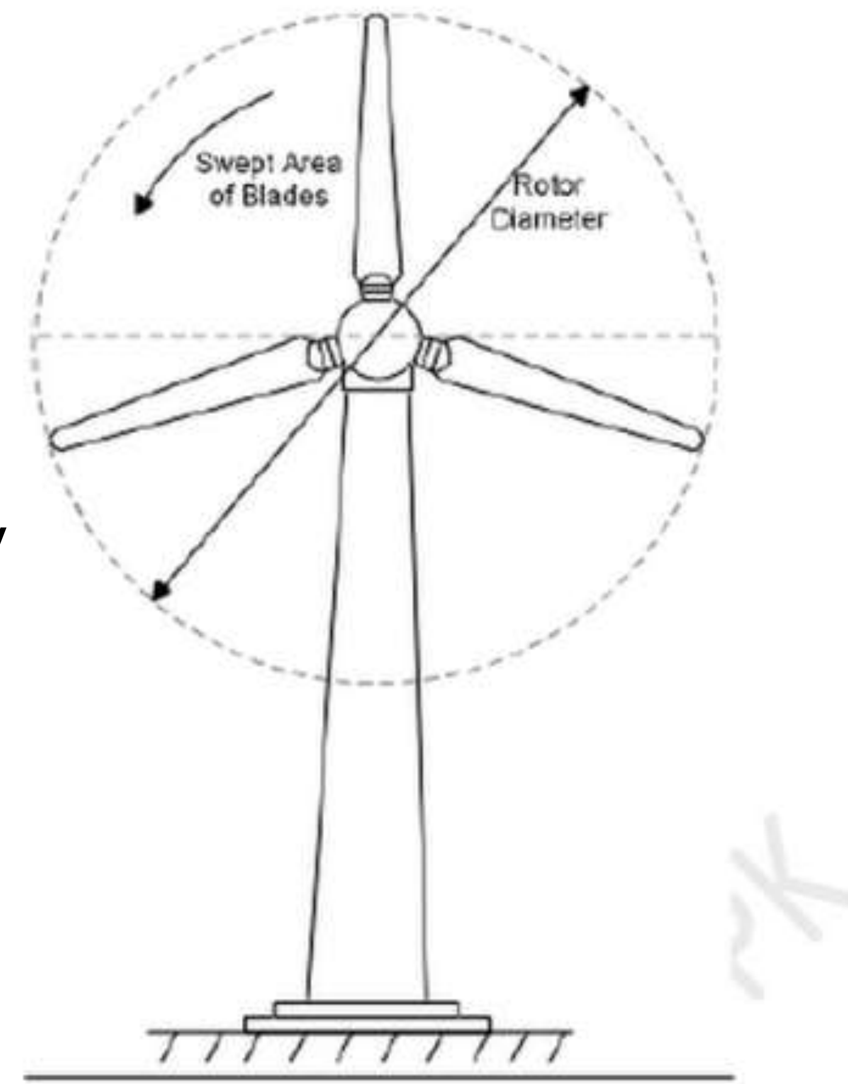


Fig: Three Blade Rotor

Calculation of Wind Power:

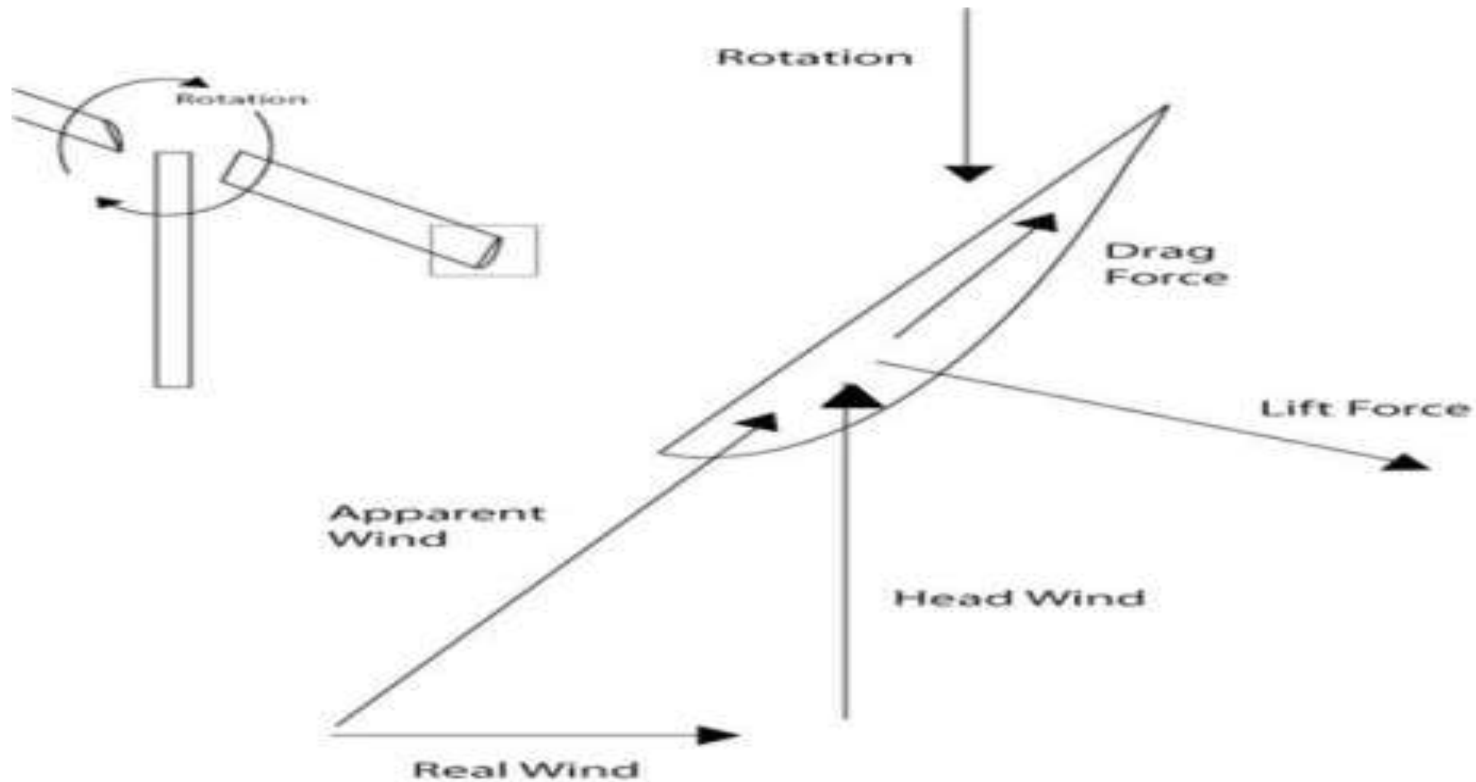
- **Power in the Wind = $\frac{1}{2}\rho A V^3$**
  - – Effective swept area, A
  - – Effective wind speed, V
  - – Effective air density, ρ

– Swept Area: $A = \pi R^2$ Area of the circle swept by the rotor (m^2).



Lift/Drag Forces Experienced by Turbine Blades:

- There are two primary mechanisms for producing forces from the wind. Lift and drag. Lift force act perpendicular to air flow and drag force act in the direction of flow.



TIP-SPEED RATIO (TSR):

- Tip-speed ratio is the ratio of the speed of the rotating blade tip to the speed of the free stream wind. There is an optimum angle of attack which creates the highest lift to drag ratio. Because angle of attack is dependent on wind speed, there is an optimum tip-speed ratio.

$$\mathrm{TSR} = \frac{\Omega R}{V}$$

Where,

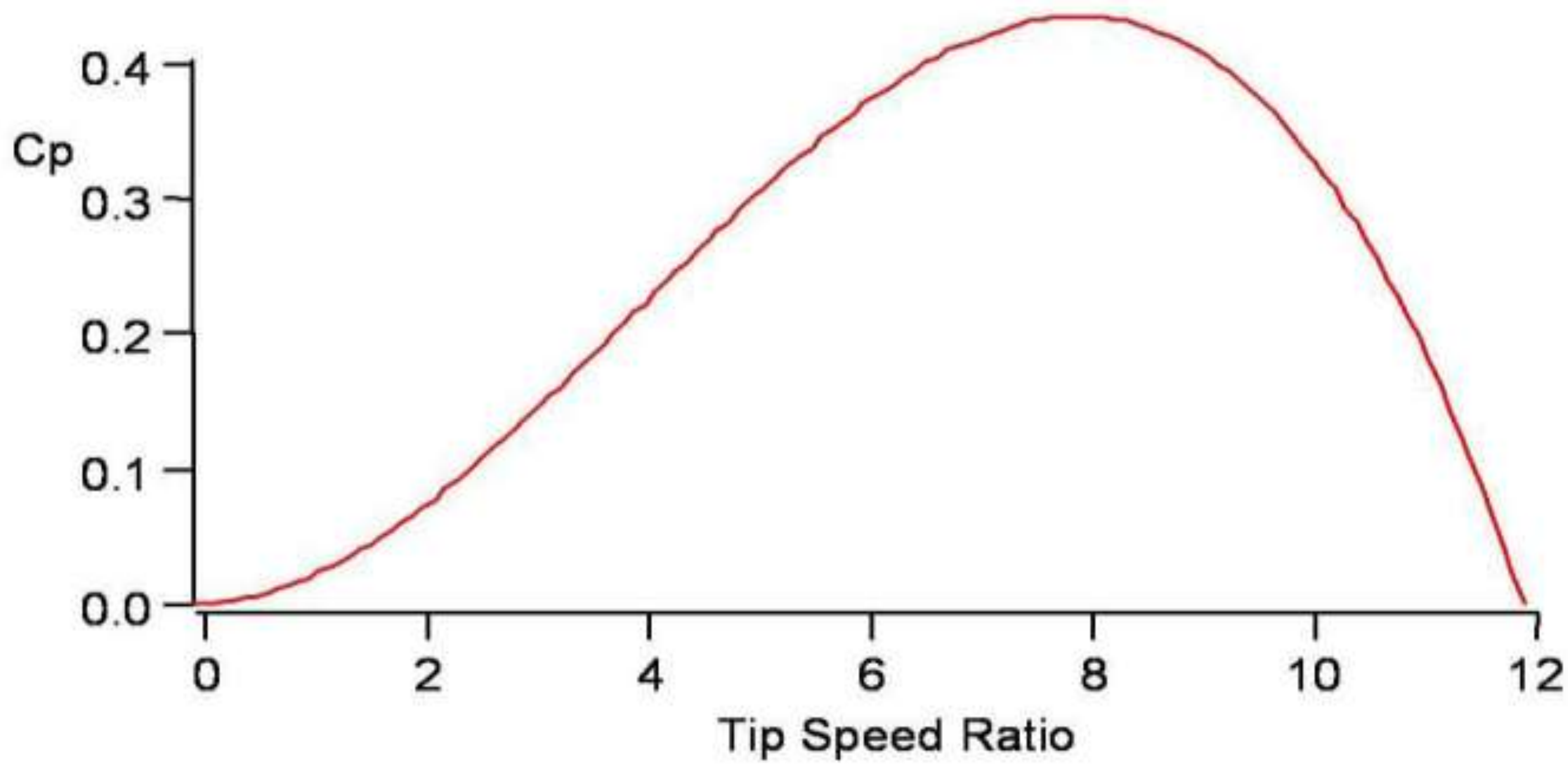
Ω = rotational speed in radians /sec

R = Rotor Radius

V = Wind “Free Stream” Velocity

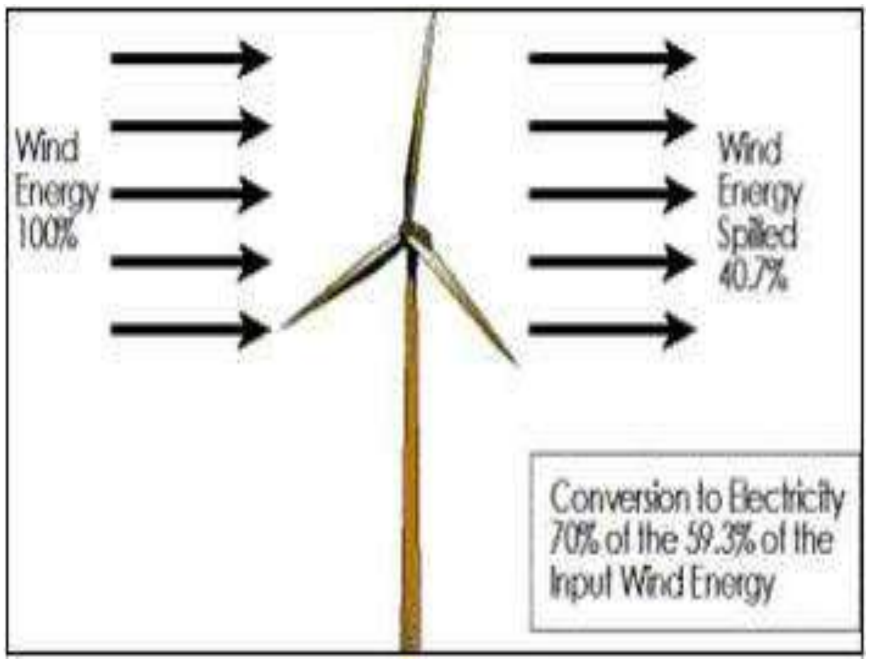
Performance Over Range of Tip Speed Ratios:

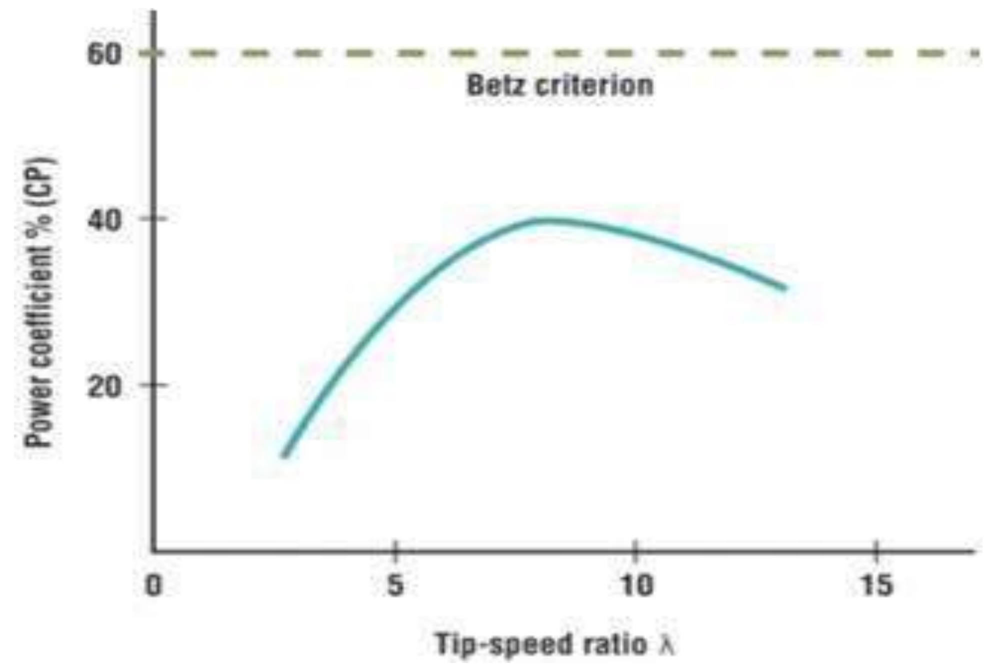
- Power Coefficient Varies with Tip Speed Ratio ,Characterized by Cp vs Tip Speed Ratio Curve.



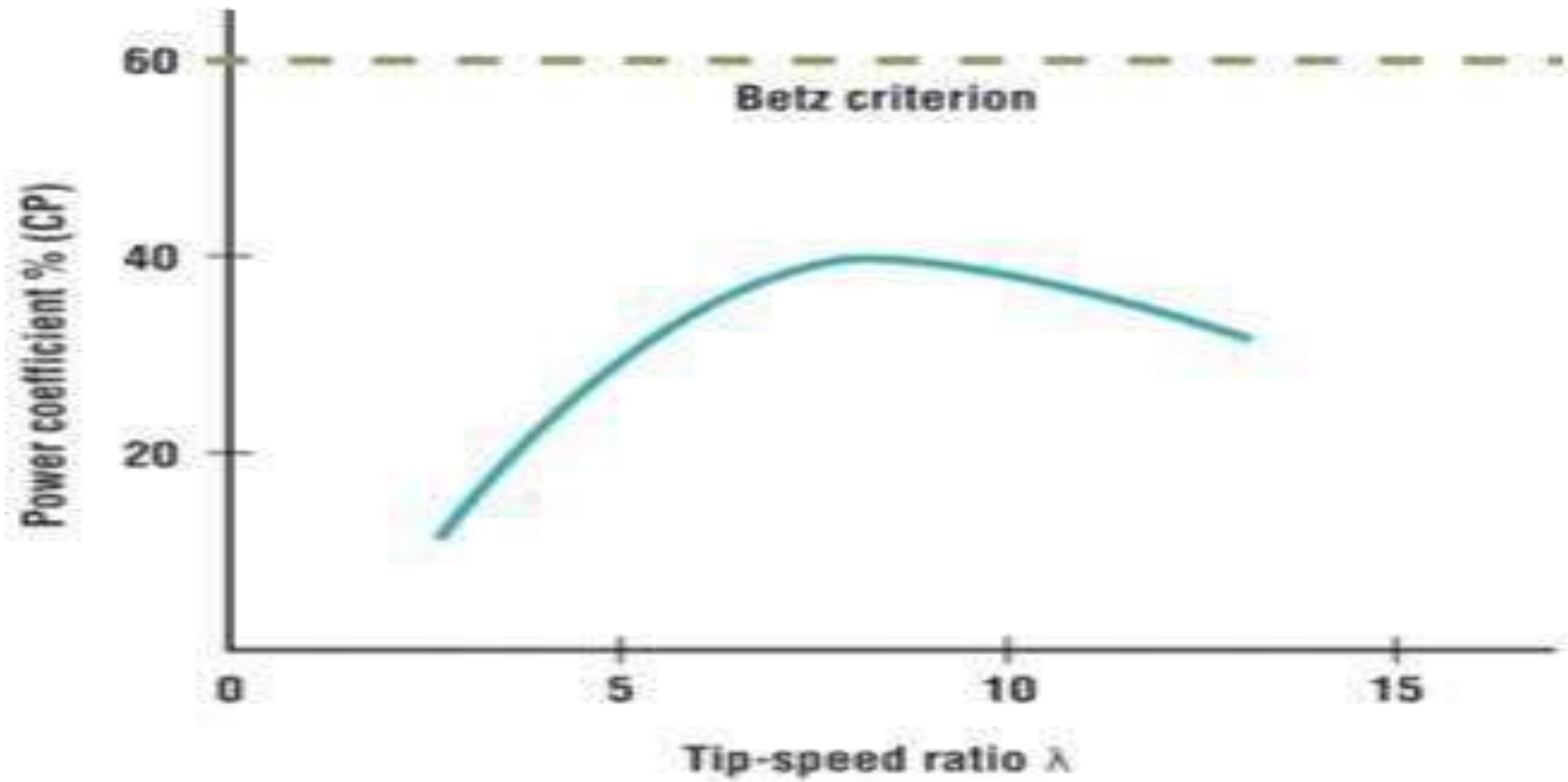
Betz Limit:

- All wind power cannot be captured by rotor or air would be completely still behind rotor and not allow more wind to pass through. Theoretical limit of rotor efficiency is 59%.Most modern wind turbines are in the 35 – 45% range.

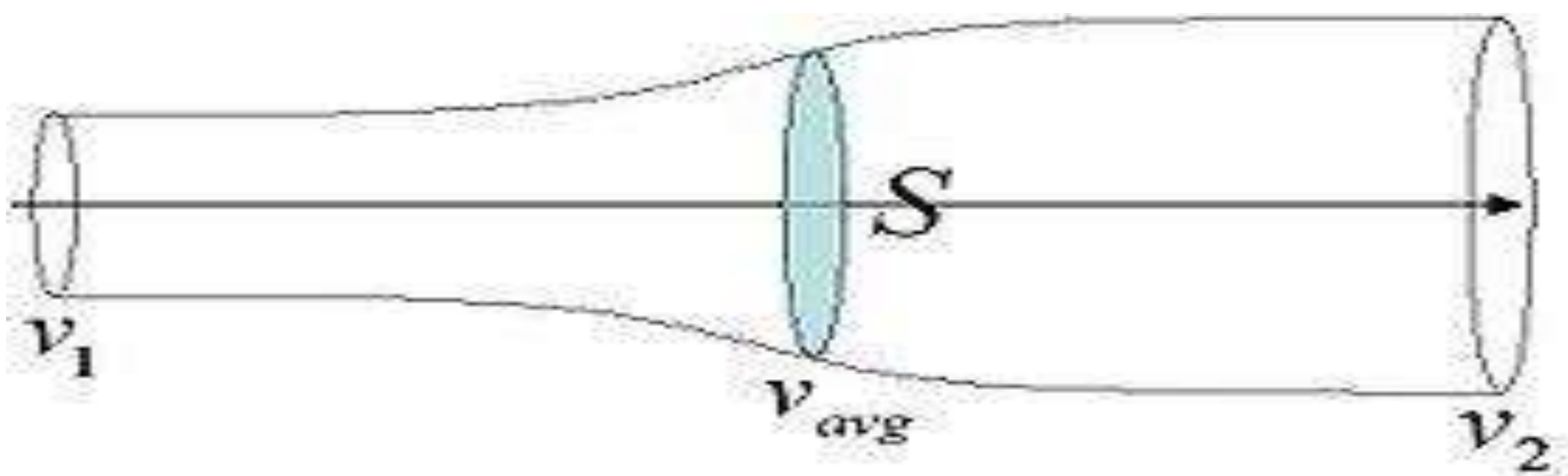




- All wind power cannot be captured by rotor or air would be completely still behind rotor and not allow more wind to pass through. Theoretical limit of rotor efficiency is 59%.Most modern wind turbines are in the 35 – 45% range.



- It shows the maximum possible energy — known as the **Betz limit** — that may be derived by means of an infinitely thin rotor from a fluid flowing at a certain speed.
- In order to calculate the maximum theoretical efficiency of a thin rotor (of, for example, a windmill) one imagines it to be replaced by a disc that withdraws energy from the fluid passing through it. At a certain distance behind this disc the fluid that has passed through flows with a reduced velocity.



Assumptions:

- The rotor does not possess a hub, this is an ideal rotor, with an infinite number of blades which have no drag. Any resulting drag would only lower this idealized value.
- The flow into and out of the rotor is axial. This is a control volume analysis, and to construct a solution the control volume must contain all flow going in and out, failure to account for that flow would violate the conservation equations.
- This is incompressible flow. The density remains constant, and there is no heat transfer from the rotor to the flow or vice versa.

- The rotor is also massless. No account is taken of angular momentum imparted to either the rotor or the air flow behind the rotor, i.e., no account is taken of any wake effect.

- **Application of conservation of mass (continuity equation):**

Applying conservation of mass to this control volume, the mass flow rate (the mass of fluid flowing per unit time) is given by:

$$\dot{m} = \rho \cdot A_1 \cdot v_1 = \rho \cdot S \cdot v = \rho \cdot A_2 \cdot v_2$$

where v_1 is the speed in the front of the rotor and v_2 is the speed downstream of the rotor, and v is the speed at the fluid power device. ρ the fluid density, and the area of the turbine is given by S. The force exerted on the wind by the rotor may be written as

$$\begin{aligned} F &= m \cdot a \\ &= m \cdot \frac{dv}{dt} \\ &= \dot{m} \cdot \Delta v \\ &= \rho \cdot S \cdot v \cdot (v_1 - v_2) \end{aligned}$$

Power and work

The work done by the force may be written incrementally as

$$dE = F \cdot dx$$

and the power (rate of work done) of the wind is

$$P = \frac{dE}{dt} = F \cdot \frac{dx}{dt} = F \cdot v$$

Now substituting the force F computed above into the power equation will yield the power extracted from the wind:

$$P = \rho \cdot S \cdot v^2 \cdot (v_1 - v_2)$$

However, power can be computed another way, by using the kinetic energy. Applying the conservation of energy equation to the control volume yields

$$\begin{aligned} P &= \frac{\Delta E}{\Delta t} \\ &= \frac{1}{2} \cdot \dot{m} \cdot (v_1^2 - v_2^2) \end{aligned}$$

Looking back at the continuity equation, a substitution for the mass flow rate yields the following

$$P = \frac{1}{2} \cdot \rho \cdot S \cdot v \cdot (v_1^2 - v_2^2)$$

Both of these expressions for power are completely valid, one was derived by examining the incremental work done and the other by the conservation of energy. Equating these two expressions yields

$$P = \frac{1}{2} \cdot \rho \cdot S \cdot v \cdot (v_1^2 - v_2^2) = \rho \cdot S \cdot v^2 \cdot (v_1 - v_2)$$

Therefore, the wind velocity at the rotor may be taken as the average of the upstream and downstream velocities. This is often the most argued against portion of Betz' law, but as it can be seen from the above derivation, it is indeed correct.

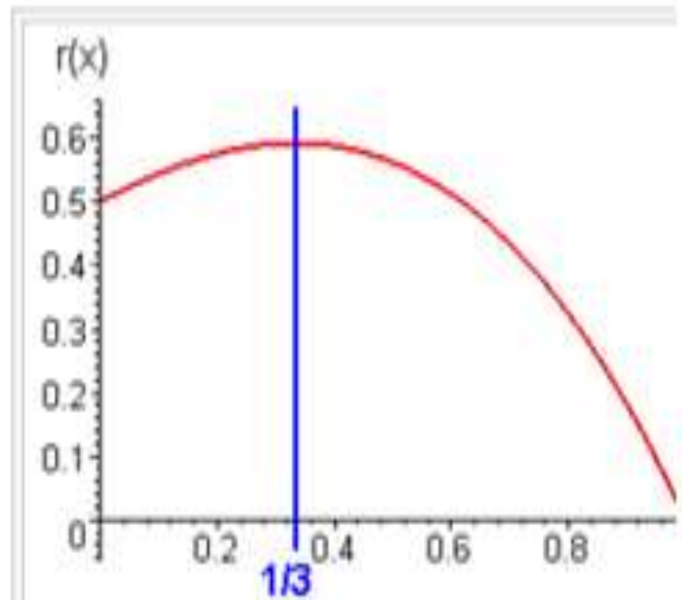
$$v = \frac{1}{2} \cdot (v_1 + v_2)$$

Betz' law and coefficient of performance

Returning to the previous expression for power based on kinetic energy:

$$\begin{aligned}\dot{E} &= \tfrac{1}{2}\cdot\dot{m}\cdot(v_1^2 - v_2^2)\\ &= \tfrac{1}{2}\cdot\rho\cdot S\cdot v\cdot(v_1^2 - v_2^2)\\ &= \tfrac{1}{4}\cdot\rho\cdot S\cdot(v_1 + v_2)\cdot(v_1^2 - v_2^2)\\ &= \tfrac{1}{4}\cdot\rho\cdot S\cdot v_1^3\cdot\left(1 - \left(\frac{v_2}{v_1}\right)^2 + \left(\frac{v_2}{v_1}\right) - \left(\frac{v_2}{v_1}\right)^3\right).\end{aligned}$$

By differentiating (through careful application of the chain rule) $\dot{E}$ with respect to $\frac{v_2}{v_1}$ for a given fluid speed v_1 and a given area S one finds the *maximum* or *minimum* value for $\dot{E}$. The result is that $\dot{E}$ reaches maximum value when $\frac{v_2}{v_1} = \frac{1}{3}$.



Substituting this value results in:

$$P_{\max} = \tfrac{16}{27}\cdot\tfrac{1}{2}\cdot\rho\cdot S\cdot v_1^3.$$

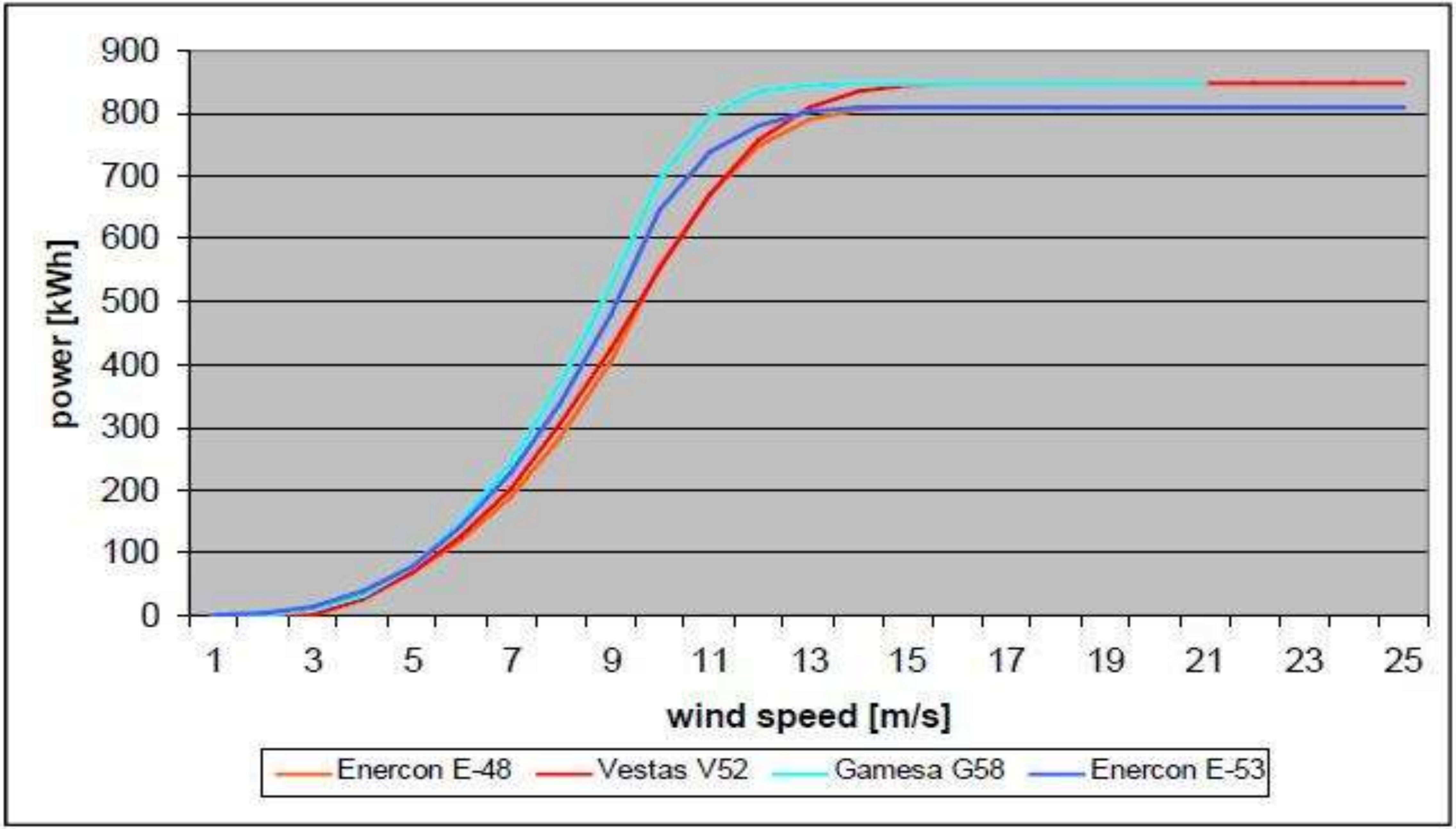
The work rate obtainable from a cylinder of fluid with cross sectional area S and velocity v_1 is:

$$P = \tfrac{1}{2}\cdot\rho\cdot S\cdot v_1^3\cdot C_{\mathrm{p}}.$$

- The *"power coefficient"* C_p (= P/P_{wind}) has a maximum value of: $C_{p.max}$ = 16/27 = 0.593 (or 59.3%; however, coefficient of performance are usually expressed as a decimal, not a percentage).

Wind Power Curve:

- The Power curve of a wind turbine is an important parameter, describing the relation between the wind speed on site and the respective electrical energy output.
- Power curves and ct-values (a parameter for the calculation of the wake effect) of the turbines under consideration are applied for the energy calculation.
- Power curves which had been measured by independent institutions are of higher quality than calculated ones.
- Due to the fluctuations of both the characteristics of the wind turbine components, and the measuring conditions power curves of different measurements differing slightly between each other.



900
800
700
600
500
400
300
200
100
0
power [kWh]
1
3
5
7
9
11
13
15
17
19
21
23
25
wind speed [m/s]
Enercon E-48
Vestas V52
Gamesa G58
Enercon E-53

- During the calculation of the energy yield, the power curves, given for the standard conditions of air density = 1.225 kg/m^3 are adapted to the air density of each individual turbine location at hub height, with the transformed power curves for the average air density.
- The air density can be calculated for each individual wind turbine according to the site conditions, height above sea level plus the hub height of the turbines (e.g. 57 m/60 m) and an annual average temperature level.
- As verification, the calculated adaptations for air density at the turbine sites should be compared to information provided by nearby meteorological stations. Figure next shows the power curves of several wind turbines at an air density of $\rho = 1{,}225 kg / m^3$.

Forces on blades and thrust on turbines:

- There are two types of forces that acting on the blades

1. Circumferential force acting in the direction of wheel rotation that provide torque.

2. Axial force acting in the wind stream that provides axial thrust that must be counteracted by the proper mechanical design

- The circumferential force, or torque T can be obtained from,

$$T = \frac{P}{\omega} = \frac{P}{\pi D N}$$

Where

T=Torque in Newton

ω=angular velocity in m/s

D=diameter of the turbine wheel

$$D = \sqrt{\frac{4}{\pi} A.m}$$

N= wheel revolution per unit time

$$real\ effieciency\ \eta = \frac{P}{P_{total}}$$

$$P = \eta P_{total}$$

For a turbine operating at power P, the expression for torque becomes

$$T = \eta \frac{\rho A}{2g_c} \frac{V_i^3}{\pi D N}$$

$$T = \eta \frac{1}{2g_c} \frac{\rho \pi}{4} \frac{D^2}{\pi D N} V_i^3 = \eta \frac{1}{8g_c} \frac{\rho D V_i^3}{N}$$

At maximum effciency i.e,59.3%, Torque has maximum value given by,

$$T_{max} = \frac{2}{27g_c} \frac{\rho D V_i^3}{N}$$

- Axial Thrust given by,

$$F_x = \frac{1}{2g_c}\rho A(V_i^2 - v_e^2)$$

$$= \frac{\pi}{8g_c}\rho D^2(V_i^2 - v_e^2)$$

The axial force on a turbine wheel operating at maximum efficiency is given by,

$$F_{x,max} = \frac{\pi}{g\, g_c} \cdot \rho A V_1^2$$

$$F_{x.max} = \frac{\pi}{9\, g_c} \cdot \rho \cdot D^2 V_1^2$$

- It can be seen that axial forces are proportional to the square of the diameter of turbine wheel, this limits the turbine wheel diameter of large size.

Example 6.2.1. Wind at 1 standard atmospheric pressure and 15°C has velocity of 15 m/s calculate :

(*i*) the total power density in the wind stream,

(*ii*) the maximum obtainable power density,

(*iii*) a reasonally obtainable power density,

(*iv*) the total power, and

(*v*) the torque and axial thrust.

Given : turbine diameter = 120 m, and turbine operating speed = 40 r.p.m. at maximum efficiency. Propeller type wind turbine is considered.

Solution.

For air, the value of gas constant

$$R = 0.287 \text{ kJ/kg K}$$

$$1 \text{ atm.} = 1.01325 \times 10^5 \, P_a.$$

Air density $\rho = \dfrac{P}{RT}$

$$\rho = \frac{1.01325 \times 10^5}{287(288)} = 1.226 \text{ kg/m}^3$$

(i) Total power $P_{total} = \dfrac{\rho A V_i^{\,3}}{2g_c}$

Power density $= \dfrac{P_{total}}{A}$

$$= \frac{1}{2g_c} \cdot \rho\, V_i^3 = \frac{1}{2 \times 1}\, 1.226 \times 15^3$$

$$= \mathbf{2068.87\ W/m^2.\ Ans.}$$

(ii) Maximum power density

$$= \frac{P_{max}}{A} = \frac{8}{27 g_c}\, \rho A V_i^{\,3}$$

$$= \frac{8}{27 \times 1}\, 1.226 \times 15^3$$

$$= \mathbf{1226\ W/m^2.\ Ans.}$$

(iii) Assuming $n = 35\%$

$$\therefore \quad \frac{P}{A} = n\, \frac{P_{total}}{A}$$

$$= 0.35 \times 2068.87 = \mathbf{724\ W/m^2.\ Ans.}$$

(iv) Total Power P = Power density × Area

$$= 724 \times \frac{\pi}{4} D^2 \text{ watt}$$

$$= 0.724 \times \frac{\pi}{4} \times 120^2 \text{ kW}$$

$$= \mathbf{8184\ kW.\ Ans.}$$

(v) Torque at maximum efficiency

$$T_{max} = \frac{2}{27 g_c} \times \frac{\rho D V_i^{\,3}}{N}$$

$$= \frac{2}{27 \times 1} \times \frac{1.226 \times 120 \times 15^3}{40/60}$$

$$= \mathbf{55170\ Newton.\ Ans.}$$

and maximum axial thrust

$$F_{x\,max} = \frac{\pi}{9 g_c}\, \rho D^2 V_i^{\,2}$$

$$= \frac{\pi}{9 \times 1}\, 1.226 \times 120^2 \times 15^2$$

$$= \mathbf{1385{,}870\ Newton.\ Ans.}$$

TIDAL POWER

TIDAL POWER PLANTS - INTRODUCTION

- The periodic rise and fall of the water level of sea which are carried by the action of the sun and moon on water of the earth is called the 'tide'.
- Tidal energy can furnish a significant portion of all such energies which are renewable in nature. The large scale up and down movement of sea water represents an unlimited source of energy.
- If some part of this vast energy can be converted into electrical energy, it would be an important source of hydropower.

- The main feature of the tidal cycle is the difference in water surface elevations at the high tide and at the low tide.
- If this differential head could be utilized in operating a hydraulic turbine, the tidal energy could be converted into electrical energy by means of an attached generator.

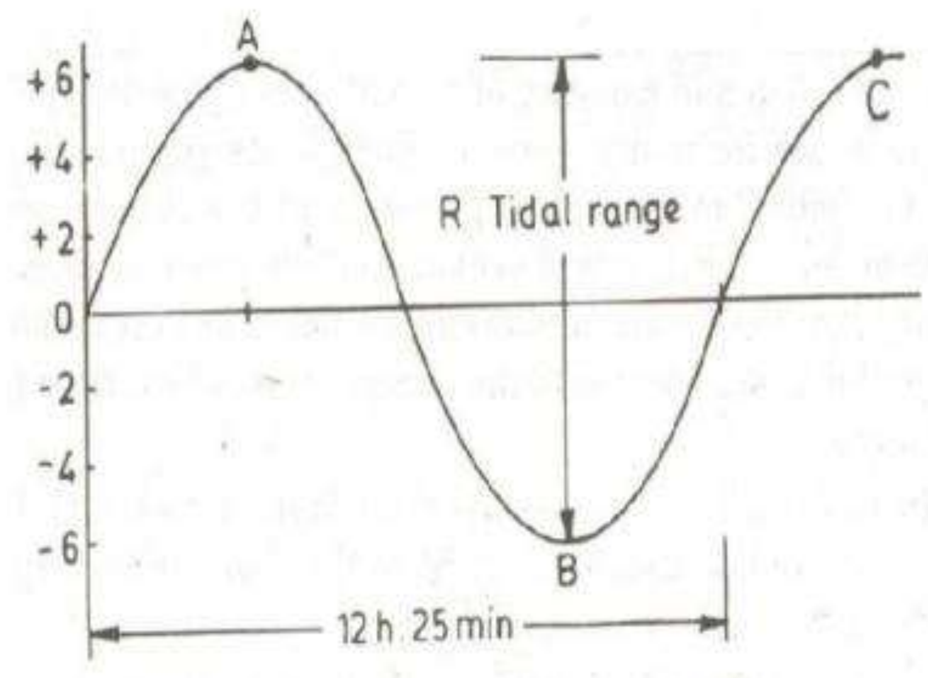
TIDAL POWER PLANT

- The periodic rise and fall of the water level of sea which are carried away by the gravitational action of sun and moon is called tide.
- The energy generated by these tides is called tidal energy.
- To harness the tidal energy, the difference in water surface elevations at high tide and low tide is utilized to operate a hydraulic turbine.
- A generator is attached to the turbine to generate electricity.
- The rising water or high tides are called floods and low tides are called ebbs.
- These tides can be used to produce electrical power which is known as tidal power.

- They are mainly caused by the gravitational attraction of the moon & Sun on the water of solid earth & Oceans. 70% of tides are produced by the force due to moon. Moon is the major factor in the tide.
- Two tidal cycles occurs during a lunar day of 24Hrs 50 Minutes. They are two high tides and two low tides. Time between high tides & Low tides at any given location is a little over 6 Hrs.
- A High tide will be experienced at a point which is directly under the moon. At the Same time, a diametrically opposite point on the earth‘s surface also experience a high tide due to dynamic balancing. Hence the Full moon as well as a No moon produce a high tide.

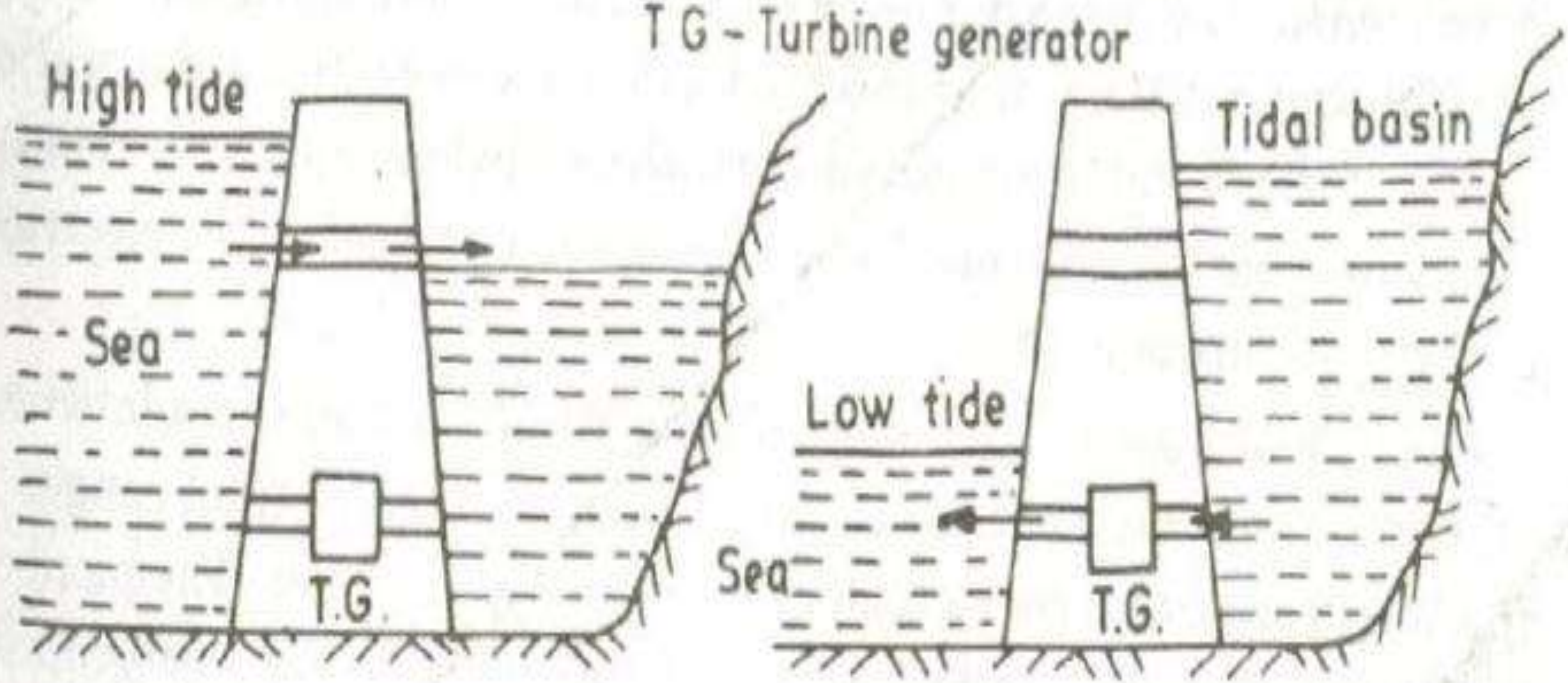
- The Rise & Fall of water level follows a Sinusoidal curve. Tides are periodical phenomenon. No two tides are alike, since the relative positions of sun & moon and their distances are continuously changing.

Tides of sea



Basic Principle of Tidal Power Plant

- A dam is constructed in such a way that a basin gets separated from the sea and a difference in the water level is obtained between the basin and sea.
- The constructed basin is filled during high tide and emptied during low tide passing through sluices and turbine respectively.
- The Potential energy of the water stored in the basin is used to drive the turbine which in turn generates electricity as it is directly coupled to an alternator.

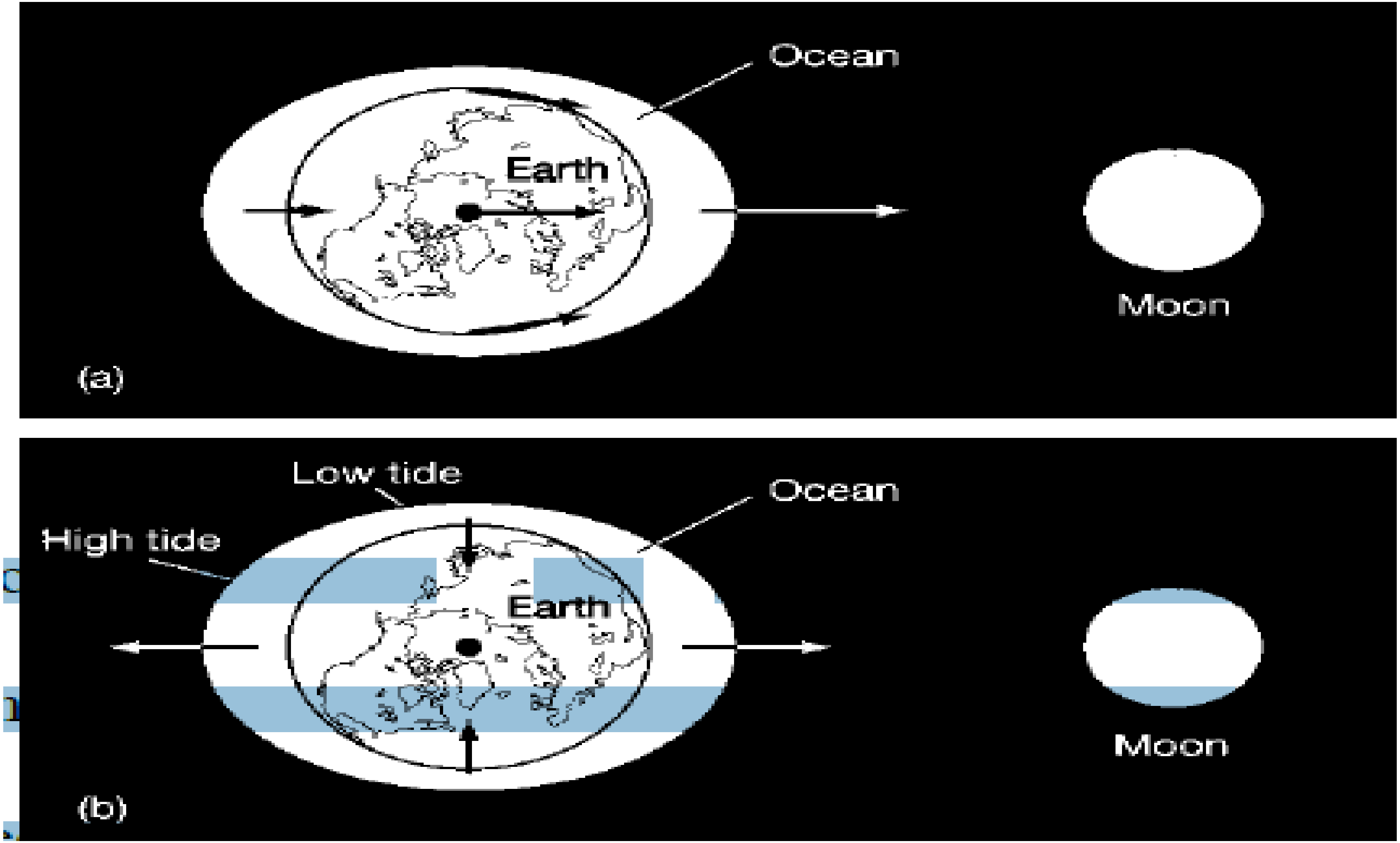


T G - Turbine generator
High tide
Sea
T.G
Tidal basin
Low tide
Sea
T.G.

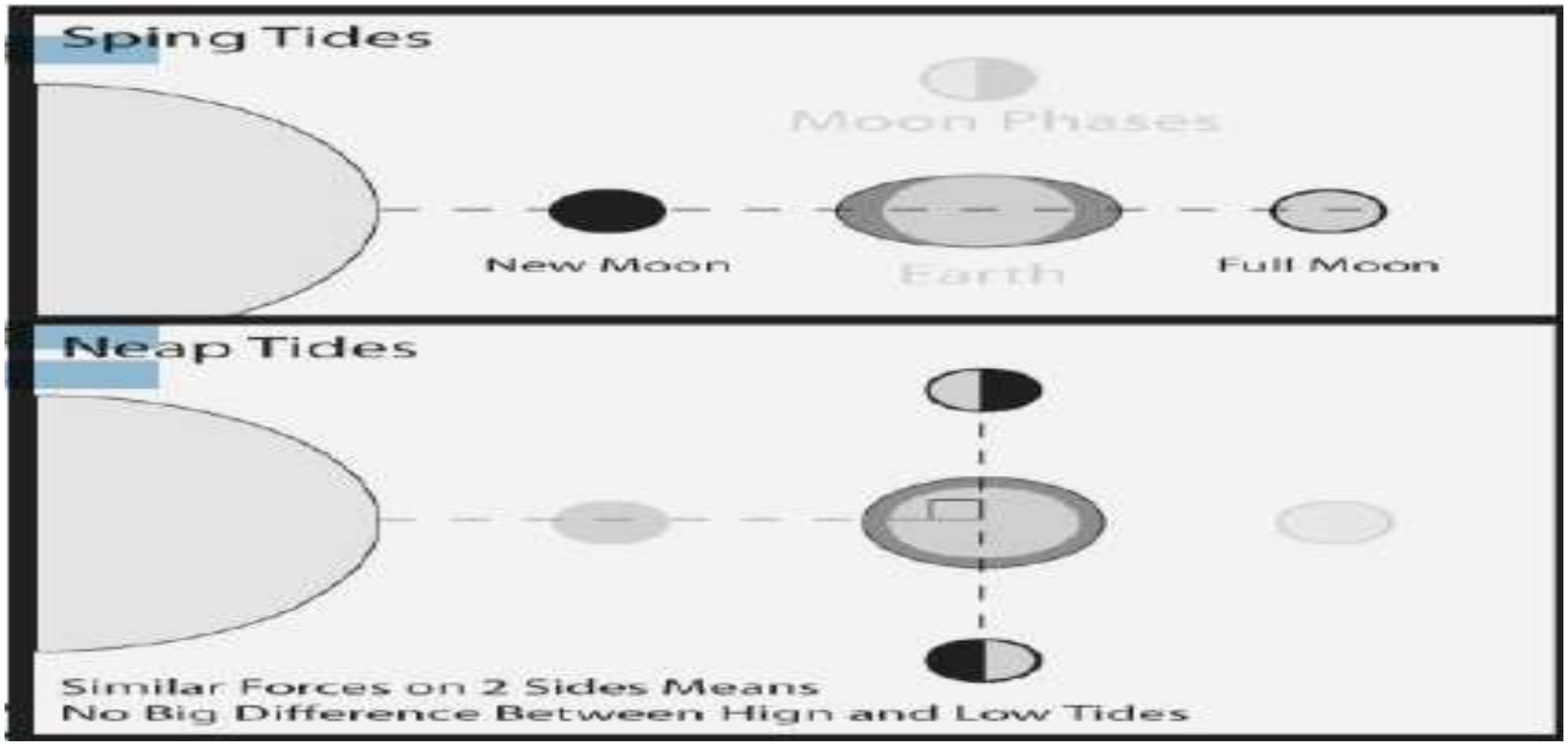
BASIC PRINCIPLE OF TIDAL POWER

- The gravitational attraction of moon and the sun on the water present on the earth produces tides.
- The magnitude of attraction depends on the mass and its distance, which is given by Newton’s law of gravitation.
- It states that “every object in the universe attracts the other object with a force”
- The gravitational force of attraction between two bodies is directly proportional to the product of their masses.
- The gravitational force of attraction between two bodies is inversely proportional to the square of the distance between their centers.

- Though the moon has less mass compared to the sun, the moon has greater effect of attraction than sun because the distance between the moon and earth is very less.
- The gravitational force of the moon causes the oceans to bulge along an axis pointing directly at the moon as shown in the figure.


Ocean
Earth
Moon
(a)
Low tide
Ocean
High tide
Earth
Moon
(b)

- When the sun and the moon are in line, their gravitational attraction on the earth combine and cause a spring tide.
- When the sun and moon are at 90˚, their gravitational attraction each pulls water in different directions and cause a neap tide.



Tidal Power:

- When a basin exists along the shores with high tides, the power in the tide can be hydroelectrically utilized.
- This can be realized by having a long dam across the basin and locating two sets of turbines underneath the dam. As the tide comes in water flows into the basin one set of turbines. At low tide the water flows out of the basin operating another set of turbines.

Components of Tidal Power Plants.

- The following are the components of a tidal power plant:
- There are three main Components of a tidal Power plant.
- Dam or barrage.
- Sluice-ways from the basins to the sea and vice versa.
- Power house.

Dam or Barrage:

- The function of dam to form a barrier between the sea and basin or between one basin and the other in case of multiple basins.
- Dam and barrage are synonymous terms. The function of dam is to form a barrier between the sea and the basin or between one basin and the other in case of multiple basins.
- Tidal power barrages have to resist waves whose shock can be severe and where pressure changes sides continuously. The barrage needs to provide channels for the turbines in reinforced concrete.
- The location of the barrage is important, because the energy available is related to the size of trapped basin and to the square of the tidal range.

- The nearer it is built to the mouth of bay, the larger the basin, but the smaller the tidal range. A balance must also be struck between increased output and increased material requirements and construction costs.
- Tidal barrages require sites where there is a sufficiently high tidal range to give a good head of water – the minimum useful range is around three meters.

Gates and Locks:

- The sluice ways are used either to fill the basin during the high tide or empty the basin during the low tide, as per operational requirement.
- Gate structures can be floated as modular units. Though, in existing plants, vertical lift gates have been used.
- The technology is about ready to substitute a series of flap gates. Flap gates are gates operated by water pressure that are positioned so as to allow water in to the holding basin and require no mechanical means of operation.
- The flap gates allow only in the direction of the sea to basin. Hence, the basin level rises well above to sea level as ebb flow area is far less than flood flow area.

Power House:

- The turbines, electric generators and other auxiliary equipment’s are the main components of a power house.
- For small head, large size turbines are needed; hence, the power house is also a large structure.
- Both the French and Soviet operating plants use the bulb type of turbine of the propeller type, with revisable blades, bulbs have horizontal shafts coupled to a single generator.

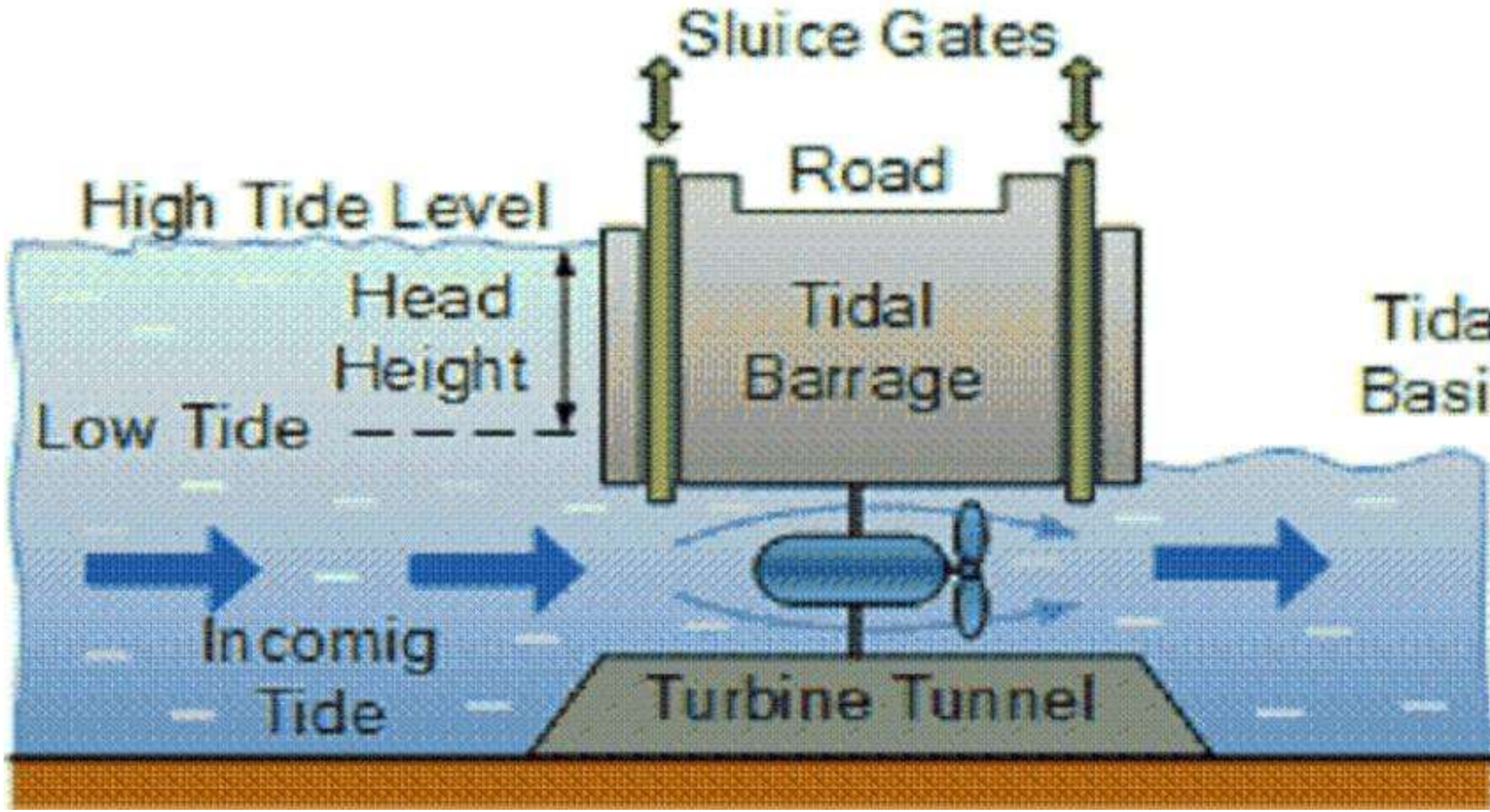
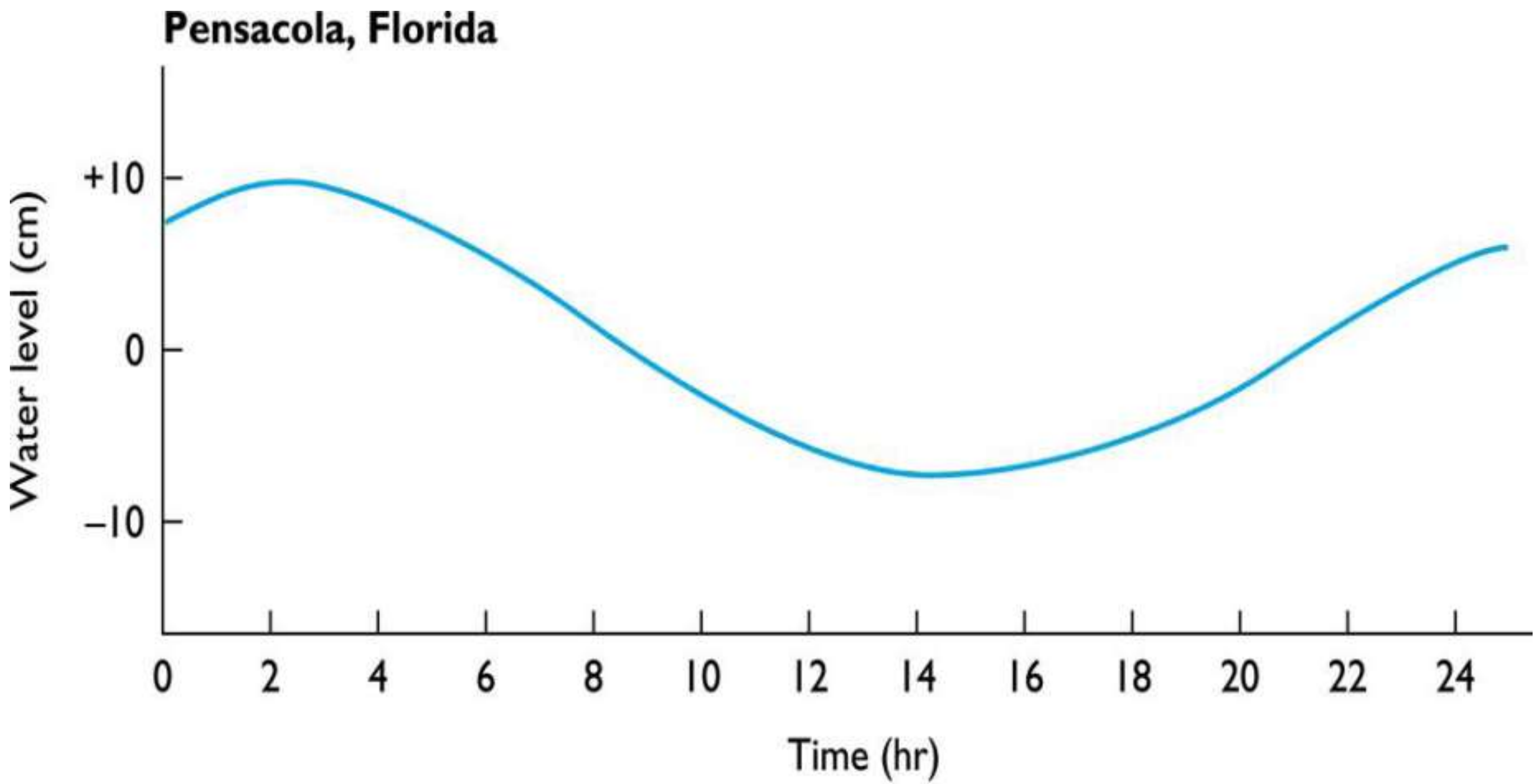


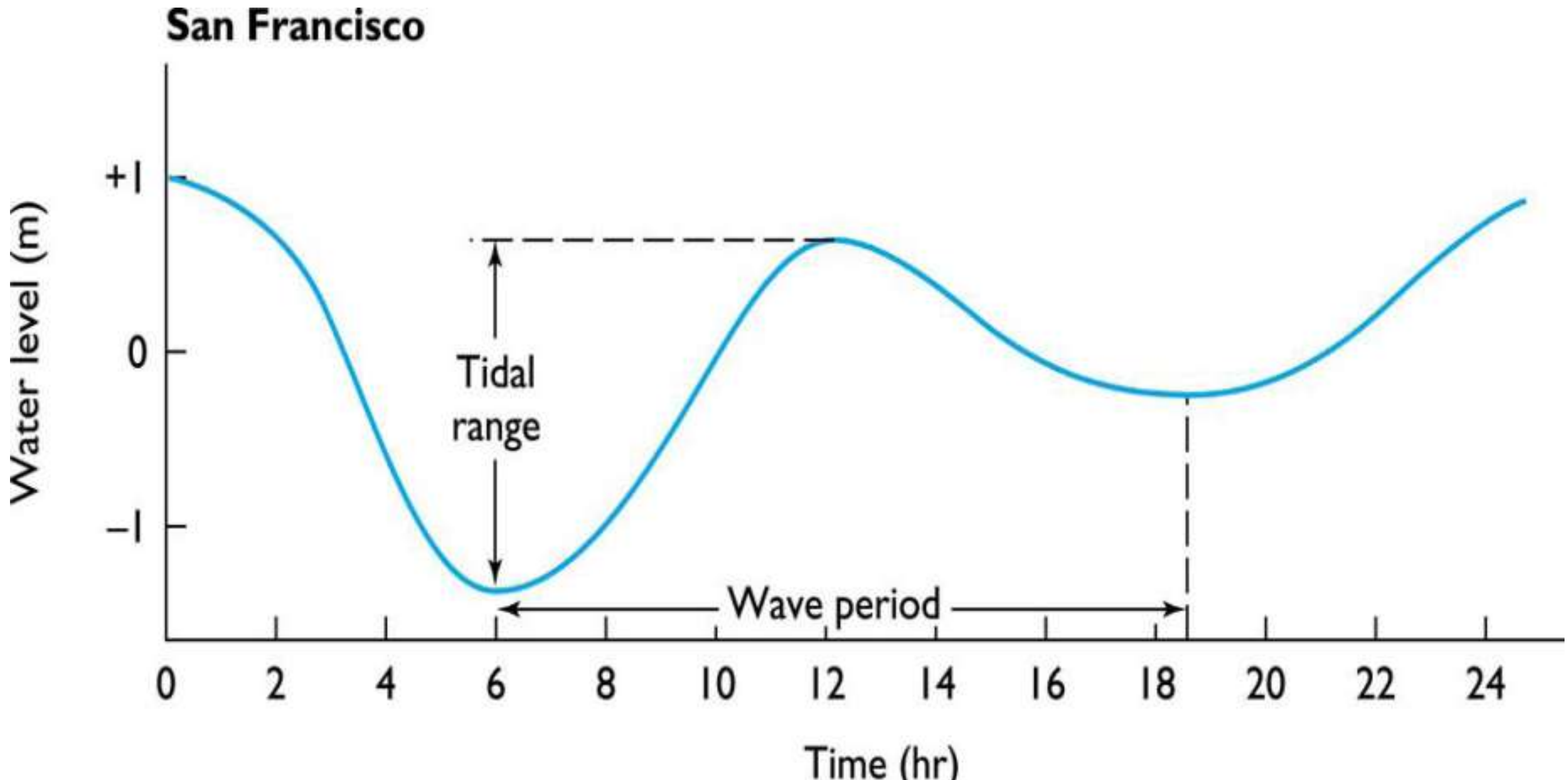
Fig: Schematic Layout of Tidal Power House

- The design cycle may also provide for pumping between the basin and the sea in either direction.
- If reversible pump turbines are provided, the pumping operation can be taken over at any time by the same machine.
- The modern tubular turbines are so versatile that they can be used either as turbines or as pumps in either direction of flow.
- In addition, the tubular passages can also be used as sluice-ways by locking the machine in to a standstill.
- As compared to conventional plants, this, however, imposes a great number of operations in tidal power plants.

- Tides have a wave form, but differ from other waves because they are caused by the interactions between the ocean, Sun and Moon.
  - Crest of the wave form is high tide and trough is low tide.
  - The vertical difference between high tide and low tide is the tidal range.
  - Tidal period is the time between consecutive high or low tides and varies between 12 hrs 25 min to 24 hrs 50 min.
  - There are three basic types of daily tides defined by their period and regularity: Diurnal tides, Semidiurnal tides, and Mixed tides.



(a) DIURNAL TIDE


San Francisco
Water level (m)
+1
0
–1
Tidal
range
Wave period
0
2
4
6
8
10
12
14
16
18
20
22
24
Time (hr)

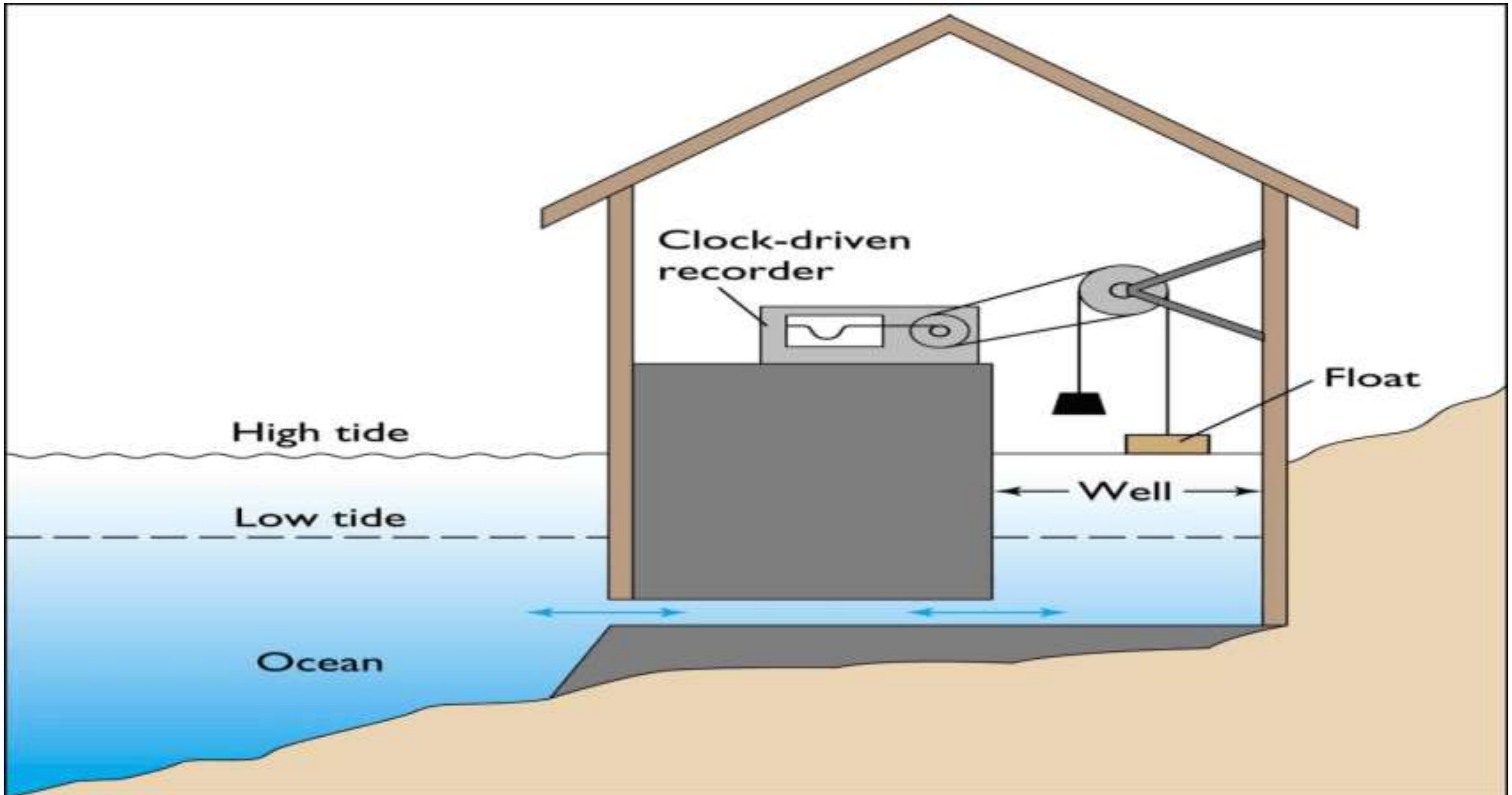
(b) MIXED TIDE

Note:

1. Over a month the daily tidal ranges vary systematically with the cycle of the Moon.

2. Tidal range is also altered by the shape of a basin and sea floor configuration.

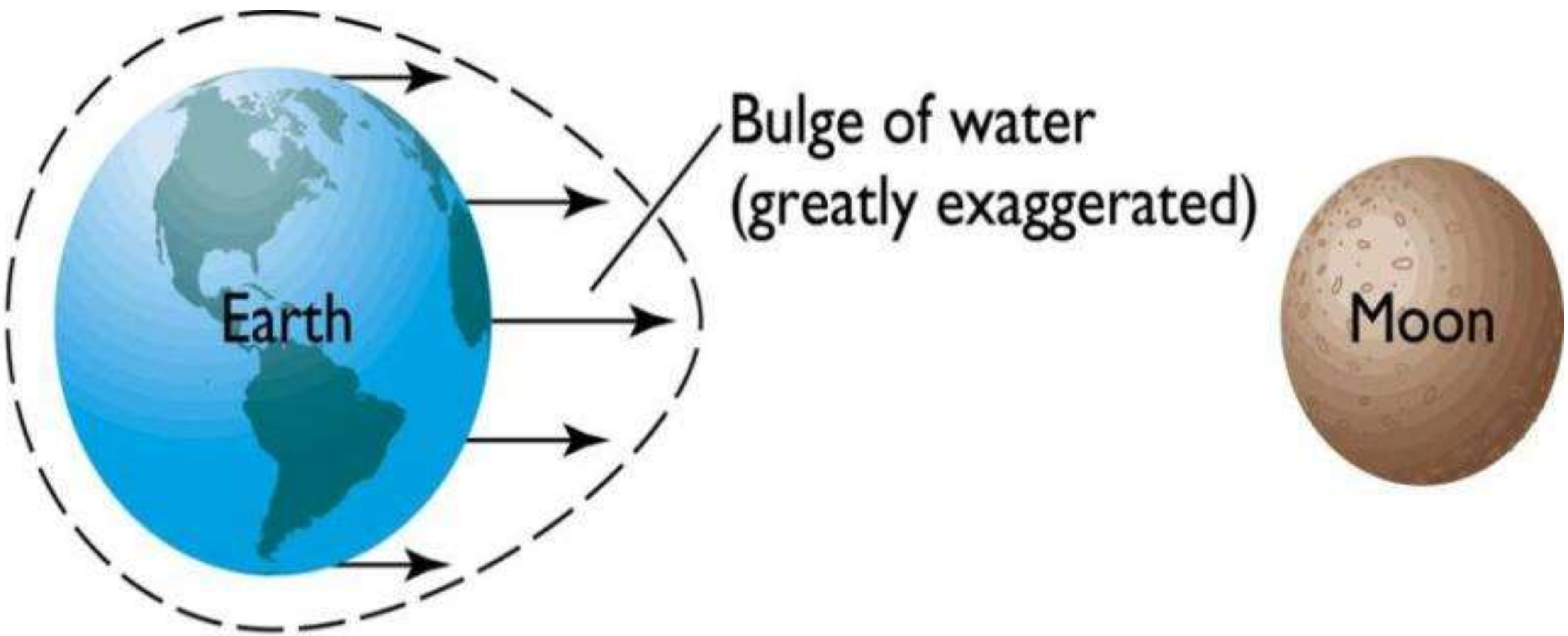
- **Following figure shows a tide gauging station:**



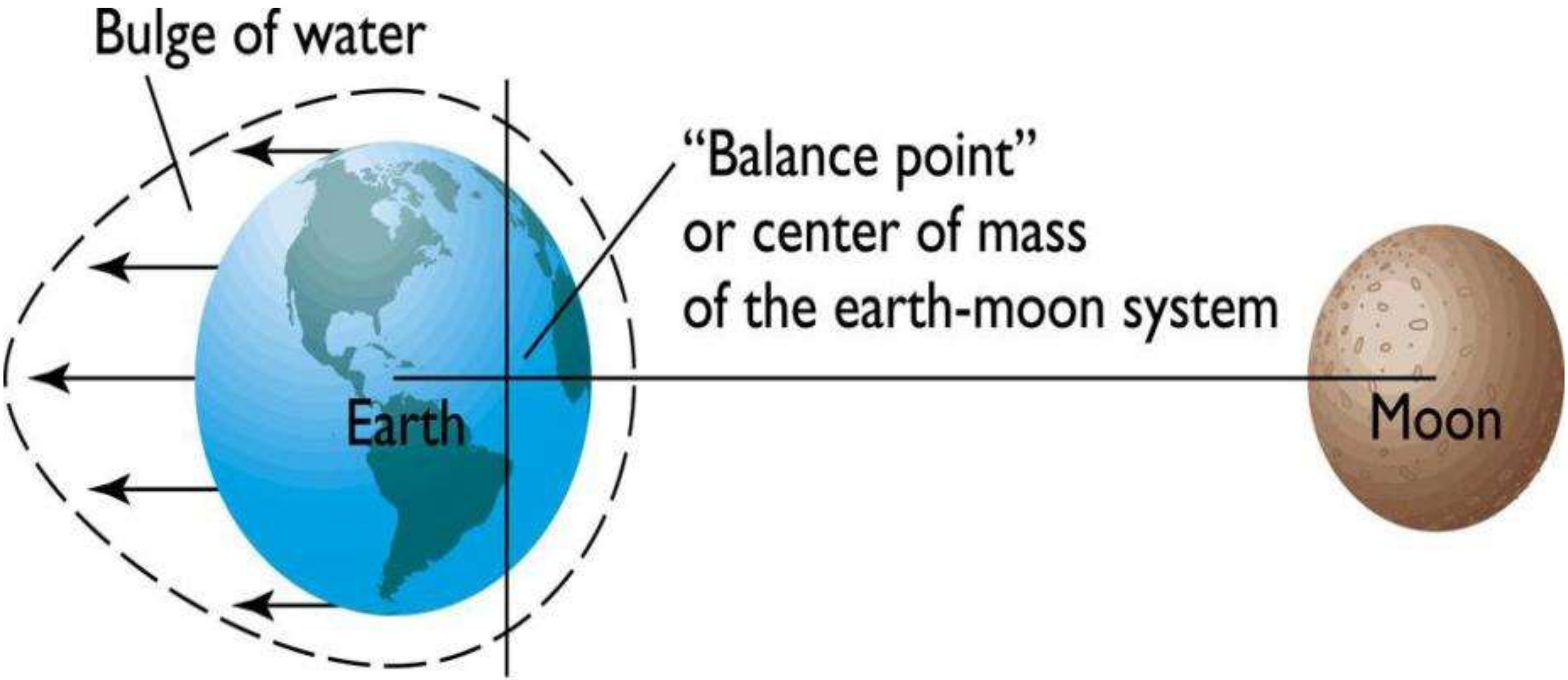
(a) TIDE-GAUGE STATION

- Tides result from gravitational attraction and centrifugal effect.
- Gravity varies directly with mass, but inversely with distance.
- Although much smaller, the Moon exerts twice the gravitational attraction and tide-generating force as the Sun because the Moon is closer.
- Gravitational attraction pulls the ocean towards the Moon and Sun, creating two gravitational tidal bulges in the ocean (high tides).
- Centrifugal effect is the push outward from the center of rotation.

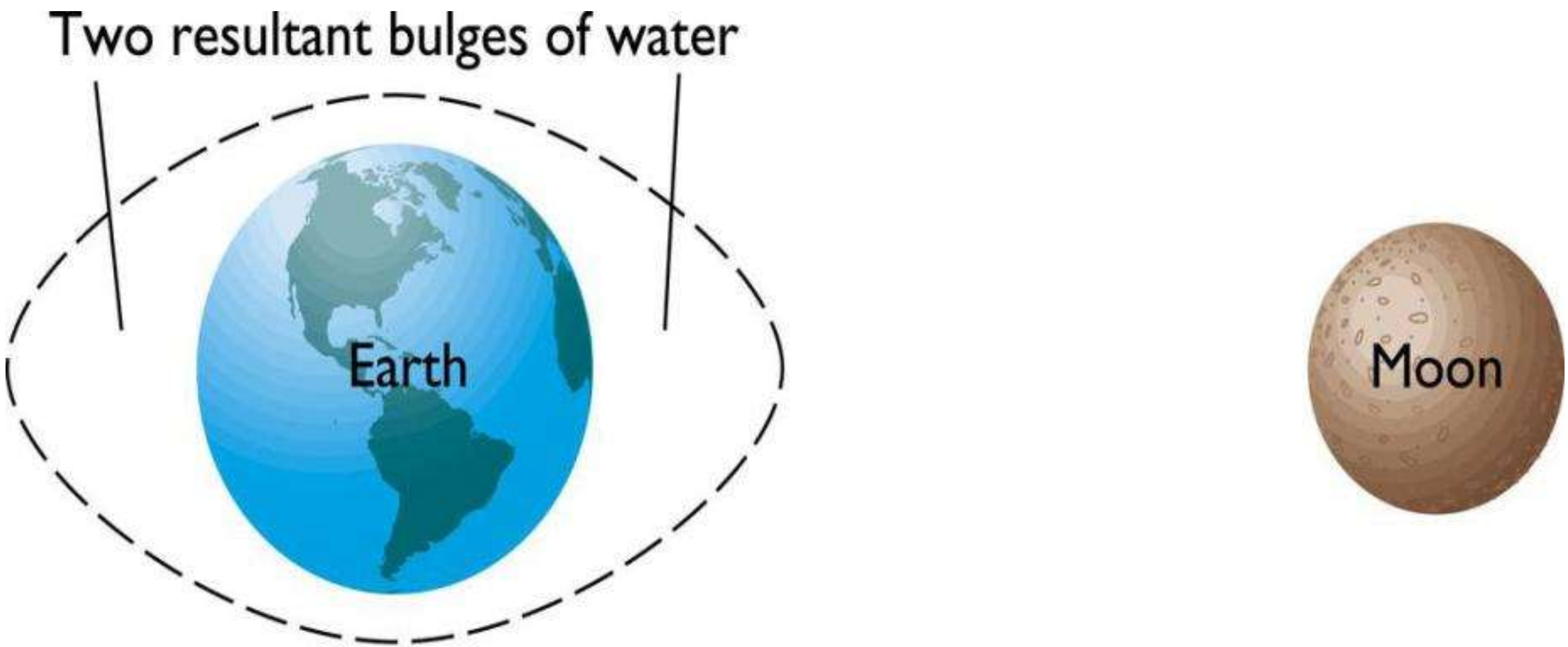
- Following figures show how the gravitational forces and centrifugal forces create tides.



(a) GRAVITATIONAL FORCE



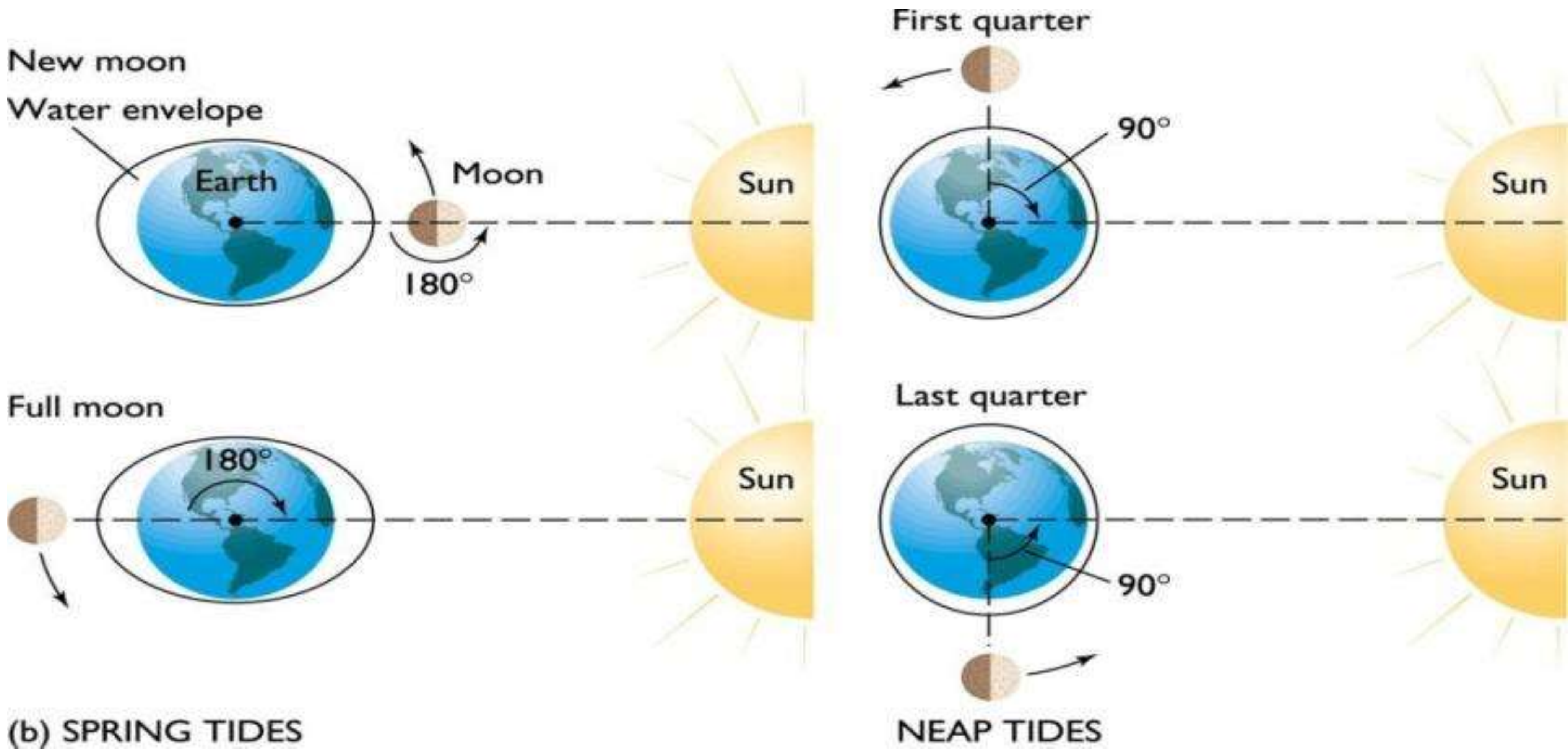
(b) CENTRIFUGAL FORCE

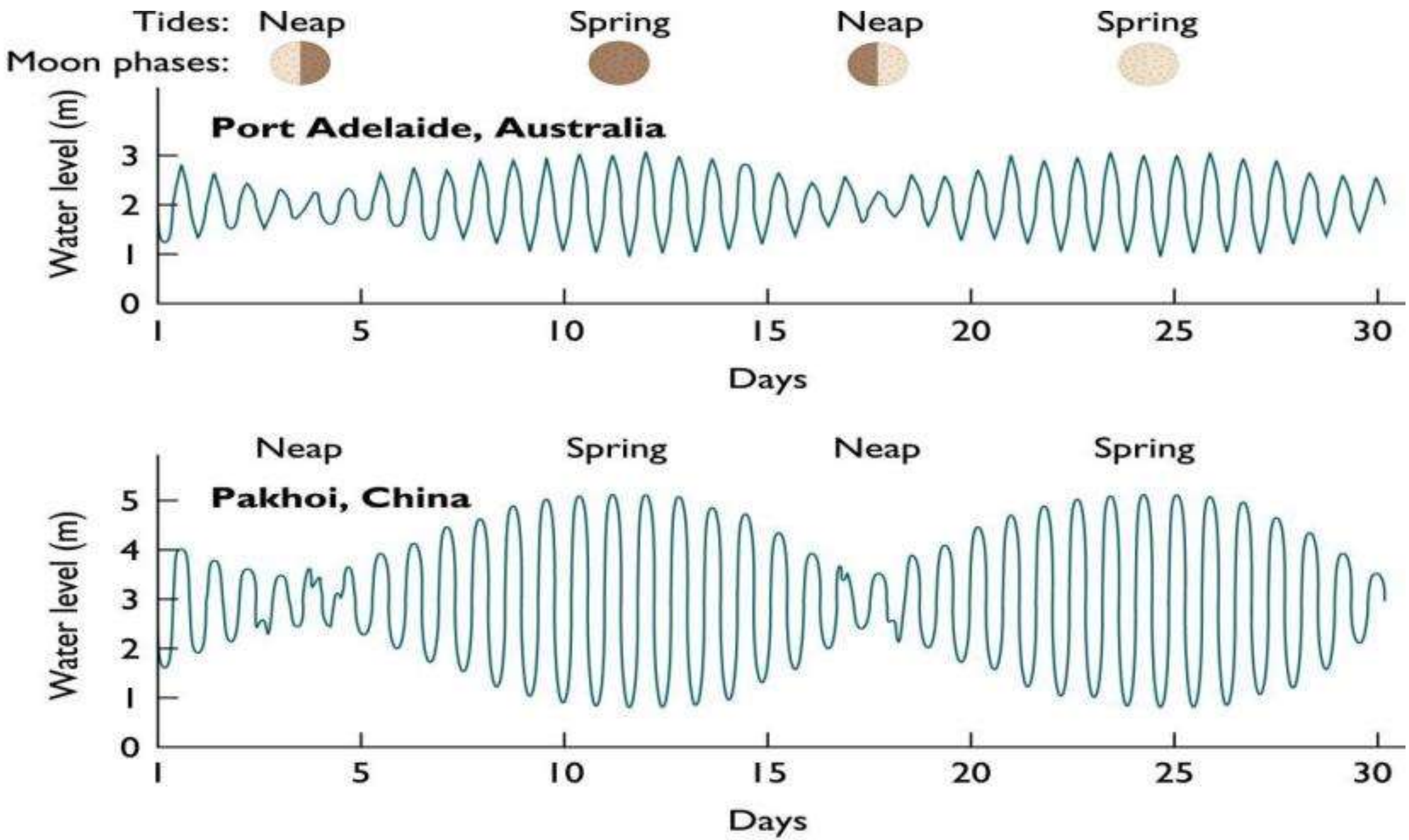


(c) GRAVITATIONAL AND CENTRIFUGAL FORCE

- Latitude of the tidal bulges is determined by the declination, the angle between Earth‘s axis and the lunar and solar orbital plane.
- Spring tides occur when Earth, Moon and Sun are aligned in a straight line and the tidal bulges display constructive interference, producing very high, high tides and very low, low tides.
- Spring tides coincide with the new and full moon.
- Neap tides occur when the Earth, Moon and Sun are aligned forming a right angle and tidal bulges displaying destructive interference, producing low high tides and high low tides.
- Neap tides coincide with the first and last quarter moon.

- Earth on its axis and the Moon in its orbit both revolve eastward and these causes the tides to occur 50 minutes later each day.





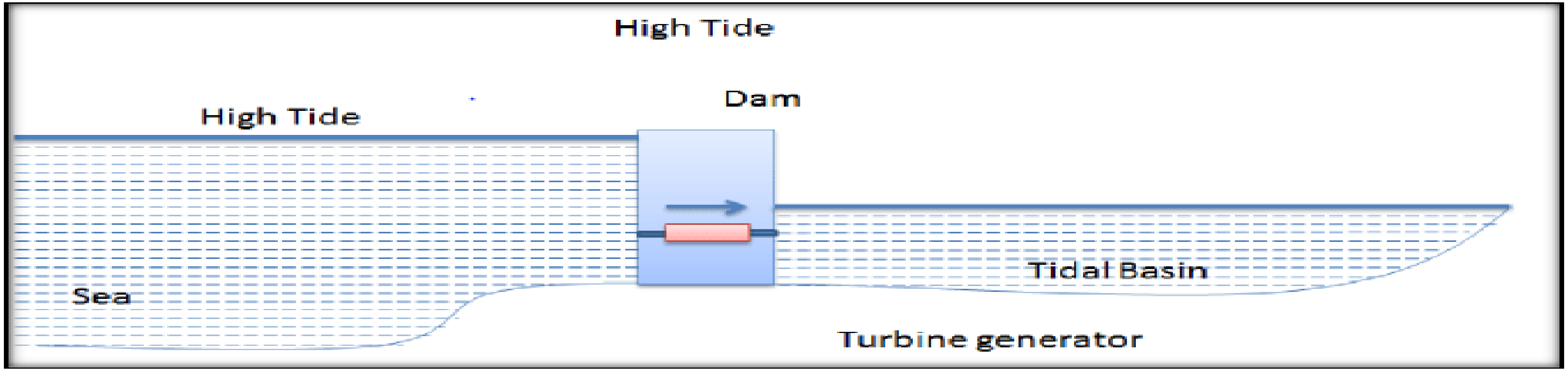
(a) VARIATIONS IN TIDAL RANGE

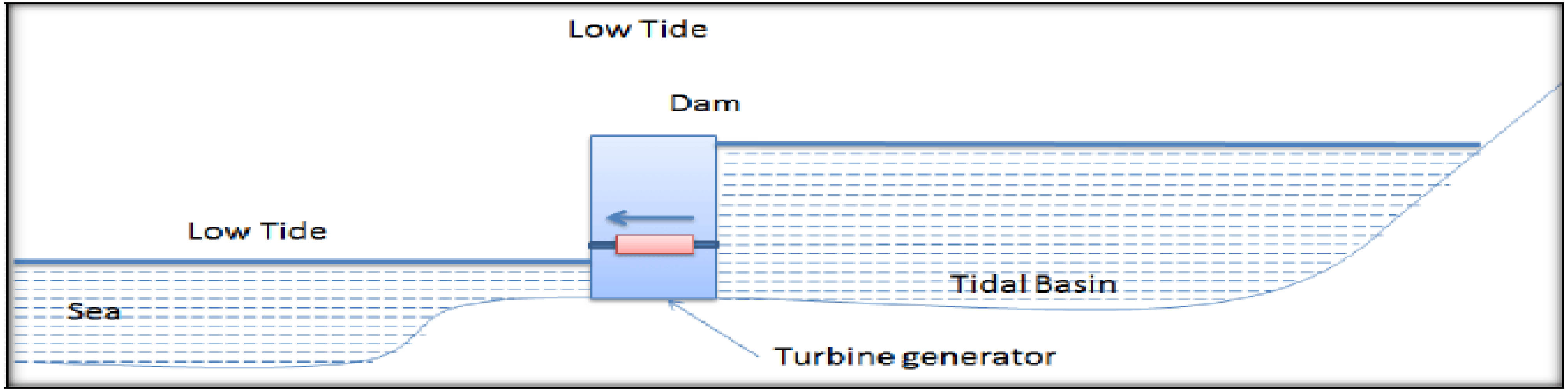
Tidal Power Stations:

- Classification and Operation of Tidal Power Plants Tidal power plants are classified as follows:

1. Single basin arrangement
   (i) Single ebb-cycle system.
   (ii) Single tide-cycle system.
   (iii) Double cycle system.
2. Double basin arrangement.

- **Single basin arrangement :**





- The general arrangement of a single basin system is shown above.
- Since only one basin interacts with the sea, power can be generated at regular intervals.
- A dam separates basin and sea. The power house is installed inside the dam.
- During High Tide, i.e., when the sea level rises, the turbine valves are opened and the sea water flows into
- the basin through the turbine generating power.
- The power is generated till the level of sea water and basin is equal.
- The water is allowed to pass into the basin, till the level reaches its maximum position.

- During low tide, the level of basin is more than the level of seawater.
- After attaining sufficient head, the turbine valves are opened and water flows from basin to sea through the turbine generating power.
- Tidal power plants normally use reversible water turbines, such that power is generated in both the directions.

A Single basin arrangement system can be classified as:

1) Single -ebb system: Water is stored during High tide in the basin and power is generated only during low tide.

2) Single -Tide system: Power is generated only during High tide and it fills the basin. The water is drained out during low tide.

3) Double cycle system: Power is generated during both high tide and low tide as explained above.

Single basin-One-way cycle

- This is the simplest form of tidal power plant. In this system, a basin is allowed to get filled during flood tide and during the ebb tide.
- The water flows from the basin to the sea passing through the turbine and generates power. The power is available for a short duration during ebb tide .
- Fig1. Shows a single tide basin before the construction of dam and Fig.2 shows the diagrammatic representation of a dam at the mouth of the basin and power generation during the falling tide.

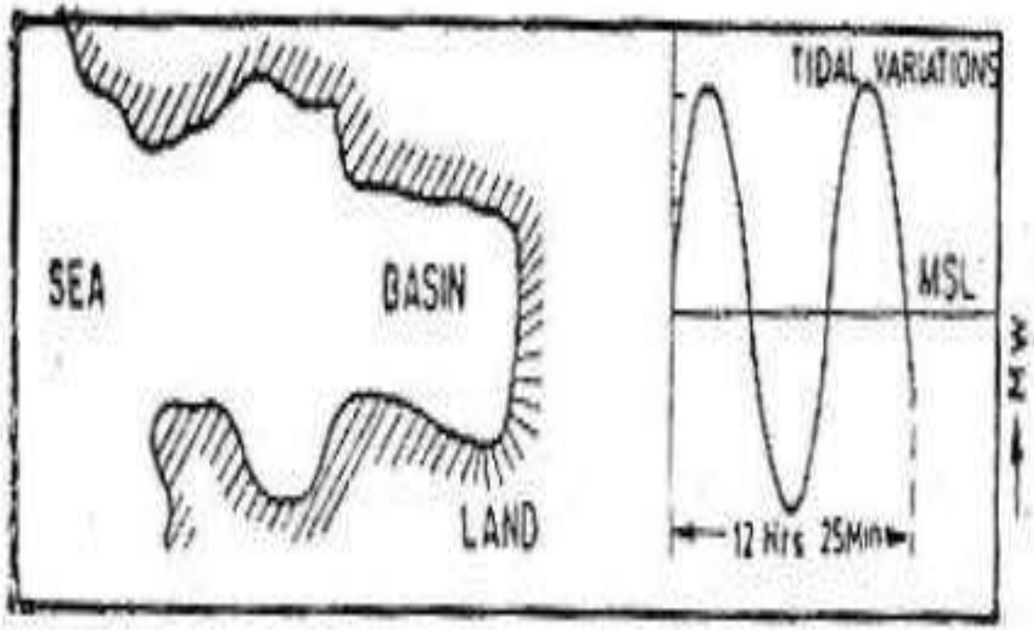
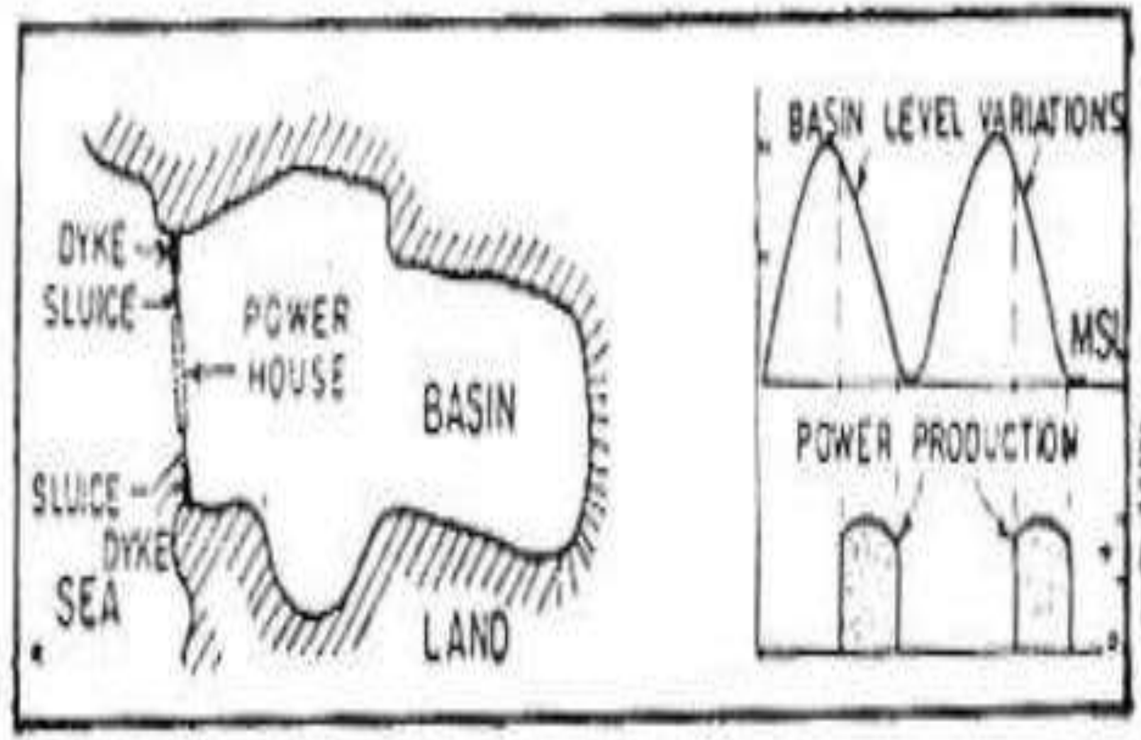


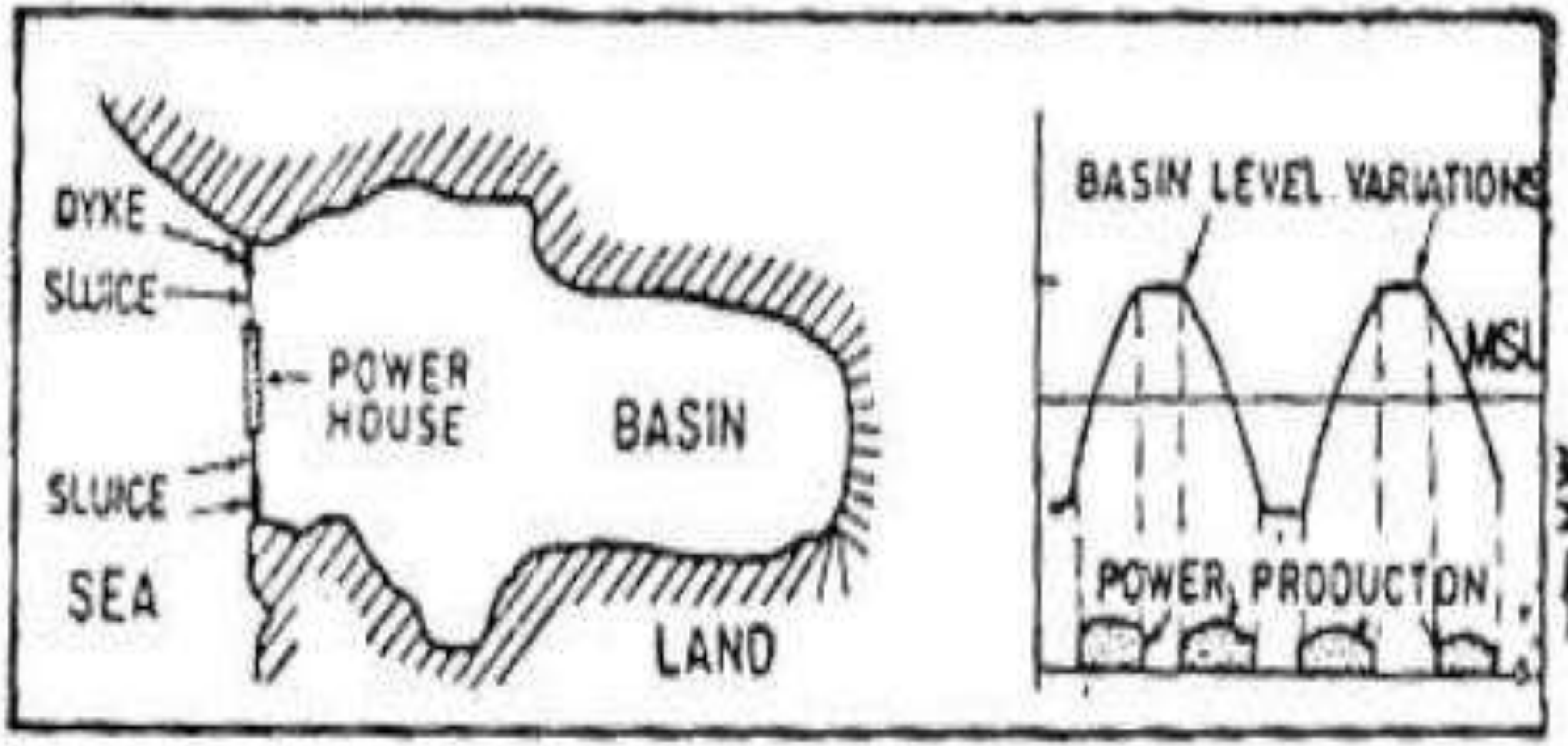
Fig1. Single basin Tidal Power Plant



(b) Single basin, one-way tidal power plant.

Single-basin two-way cycle:

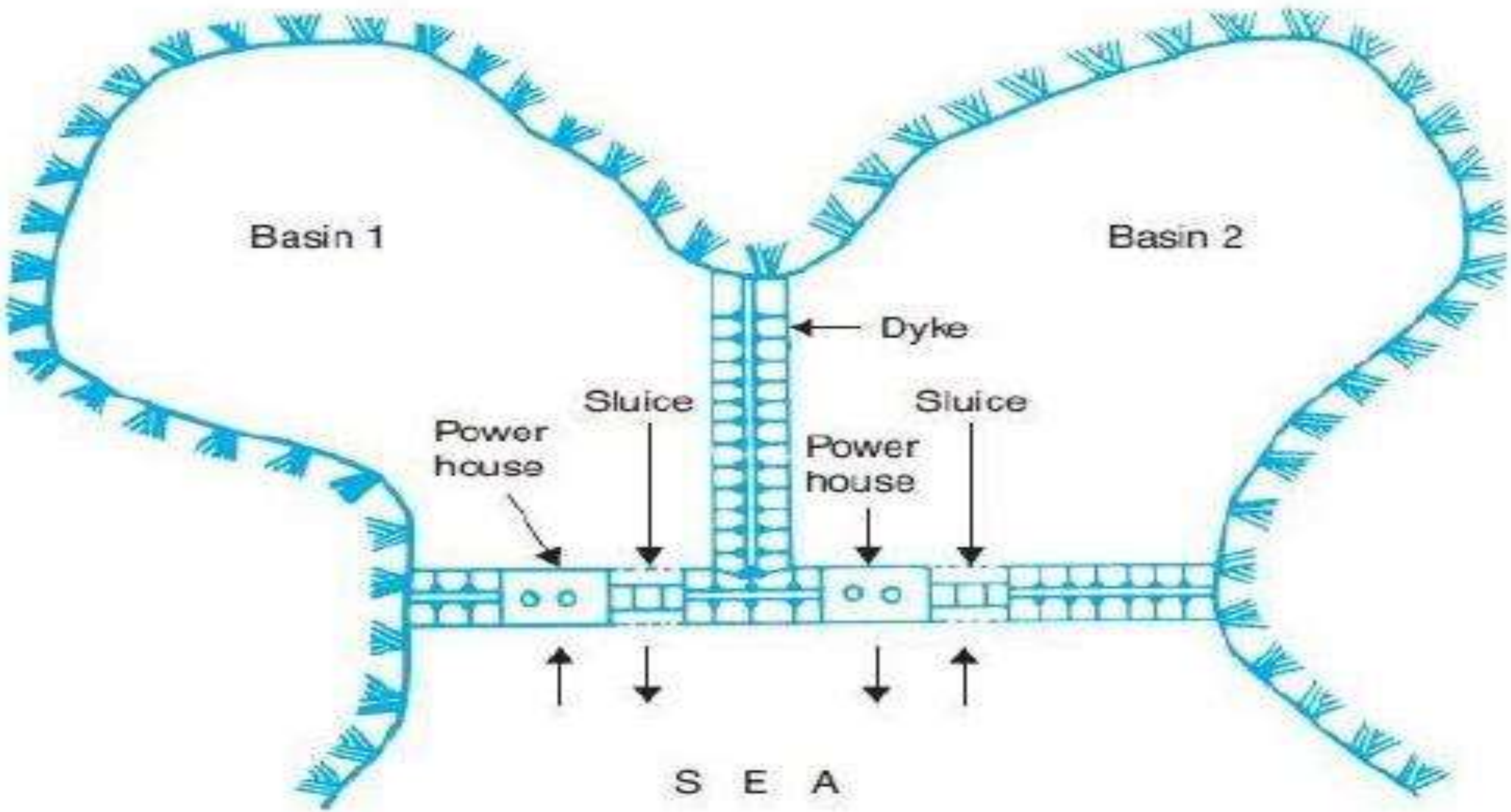
- In this arrangement power is generated both during flood tide as well as ebb tide also.
- The power generation is also intermittent but generation period is increased compared with one-way cycle.
- However the peak power obtained is less than the one-way cycle. The arrangement of the basin and the power cycle is shown in Fig.3.
- The main difficulty with this arrangement, the same turbine must be used as Prime mover as ebb and tide flows pass through the turbine in opposite directions. Variable pitch turbine and dual rotation generator are used for such schemes.



Single-basin two-way tidal power plant.

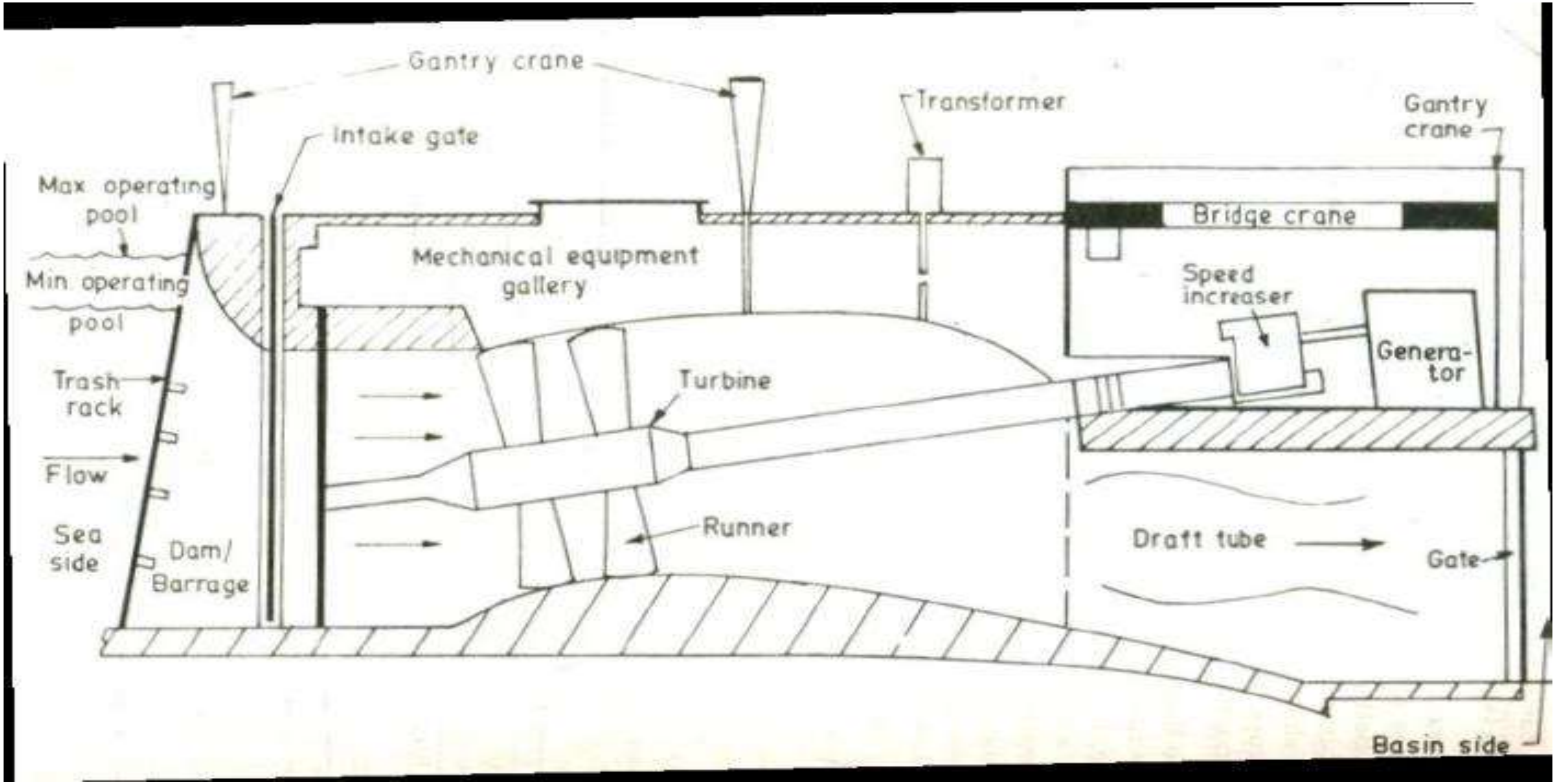
- **Double Basin Tidal System:** another form of energy barrage configuration is that of the dual basin type.
- With two basins, one is filled at high tide and the other is emptied at low tide. Turbines are placed between the basins.
- Two-basin schemes offer advantages over normal schemes in that generation time can be adjusted with high flexibility and it is also possible to generate almost continuously.
- In normal estuarine situations, however, two-basin schemes are very expensive to construct due to the cost of the extra length of barrage. There are some favourable geographies, however, which are well suited to this type of scheme.

DOUBLE BASIN ARRANGEMENT



- Figure above shows a schematic diagram of two-basin system.
- In the system, the two basins close to each other operate alternatively.
- One basin generates power when the tide is rising (basin getting filled up) and the other basin generates power while the tide is falling (basin getting emptied).
- The two basins may have a common power house or may have separate power house for each basin.
- In both the cases, the power can be generated continuously.

Components of a Tidal Power Station:



- The following are the main components of the tidal power station,

  (i) Power House.

  (ii) The Dam or Barrage.

  (iii) Sluice ways from basin to sea and vice versa.

DAM (Barrage):

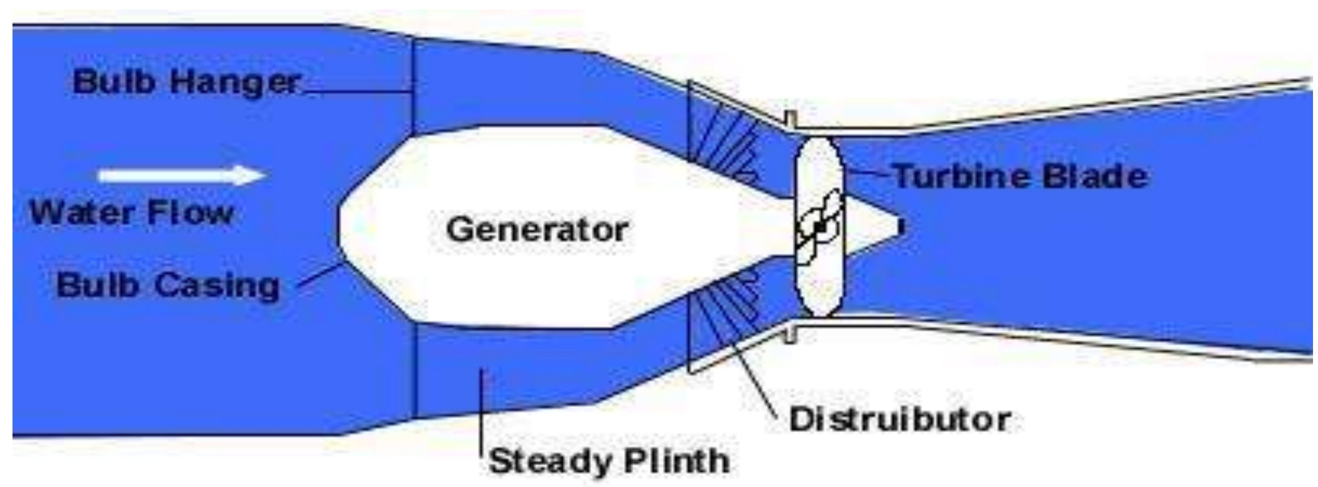
- The barrages store water behind them. The barrages should provide channels for the turbines, gates and locks. The tidal power barrages should be of shorter length.
- The length should be less than resonant length of tidal waves. The tidal barrages require sites where a sufficiently high tidal range is available. The barrages require flat bottom.

POWER HOUSE:

- Large size turbines are needed to because of small head available. Hence power house will also be large structure. The types of turbines used are,

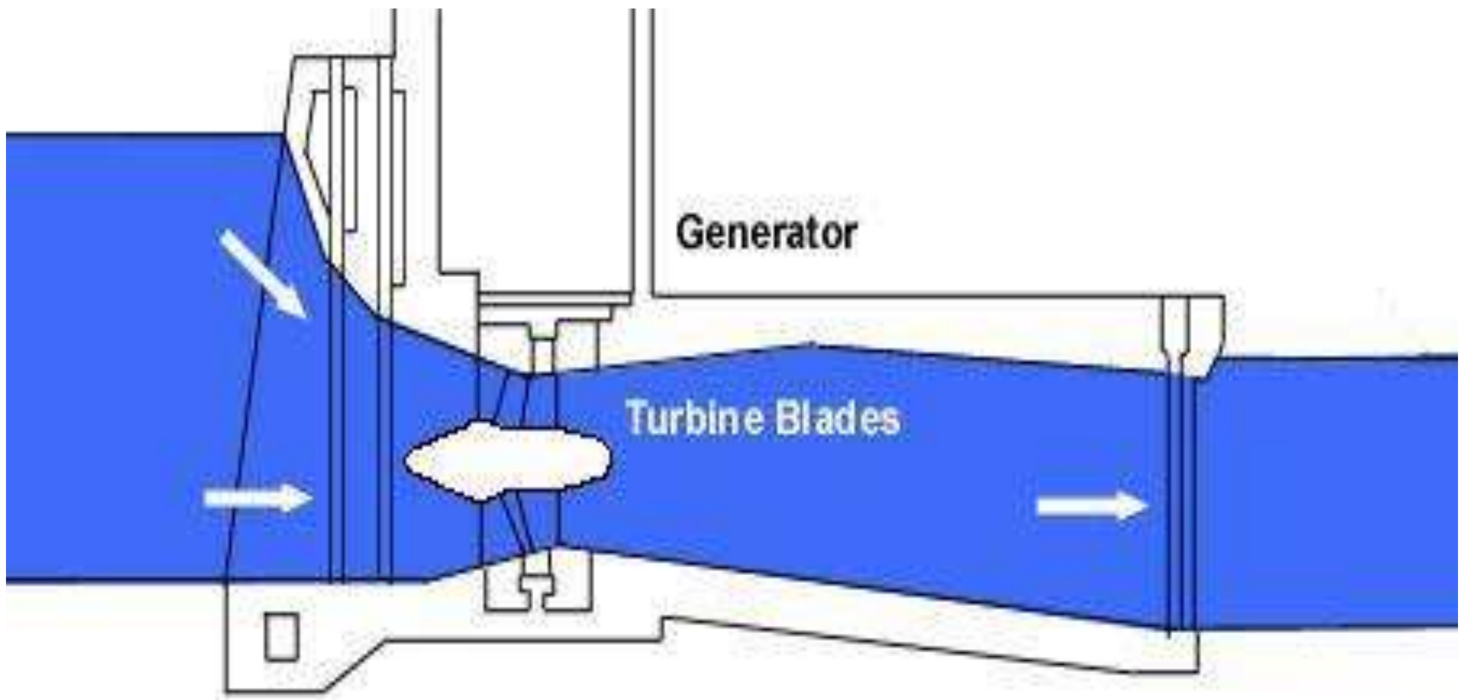
(I) Bulb Type:

- In systems with a bulb turbine, water flows around the turbine, making access for maintenance difficult, as the water must be prevented from flowing past the turbine.



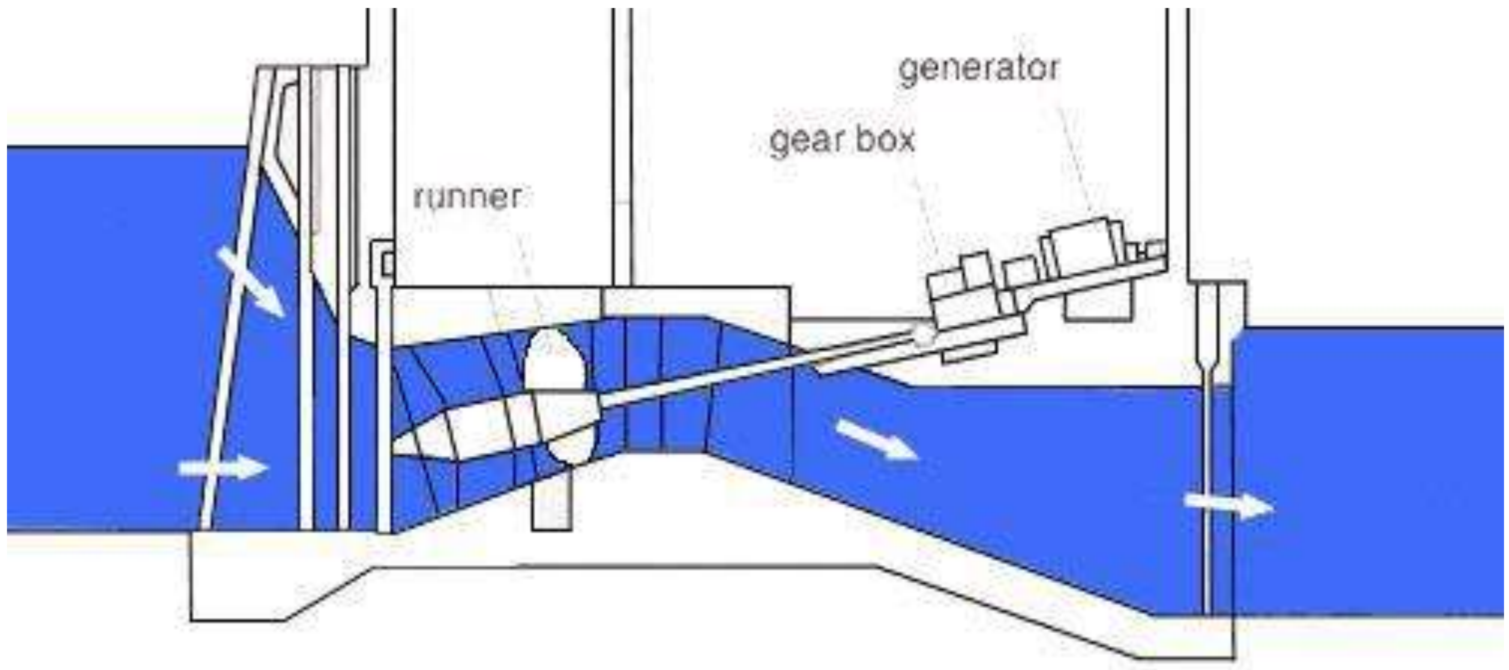
(ii) Rim Type:

- Rim turbines reduce these problems as the generator is mounted in the barrage, at right angles to the turbine blades. Unfortunately, it is difficult to regulate the performance of these turbines and it is unsuitable for use in pumping.

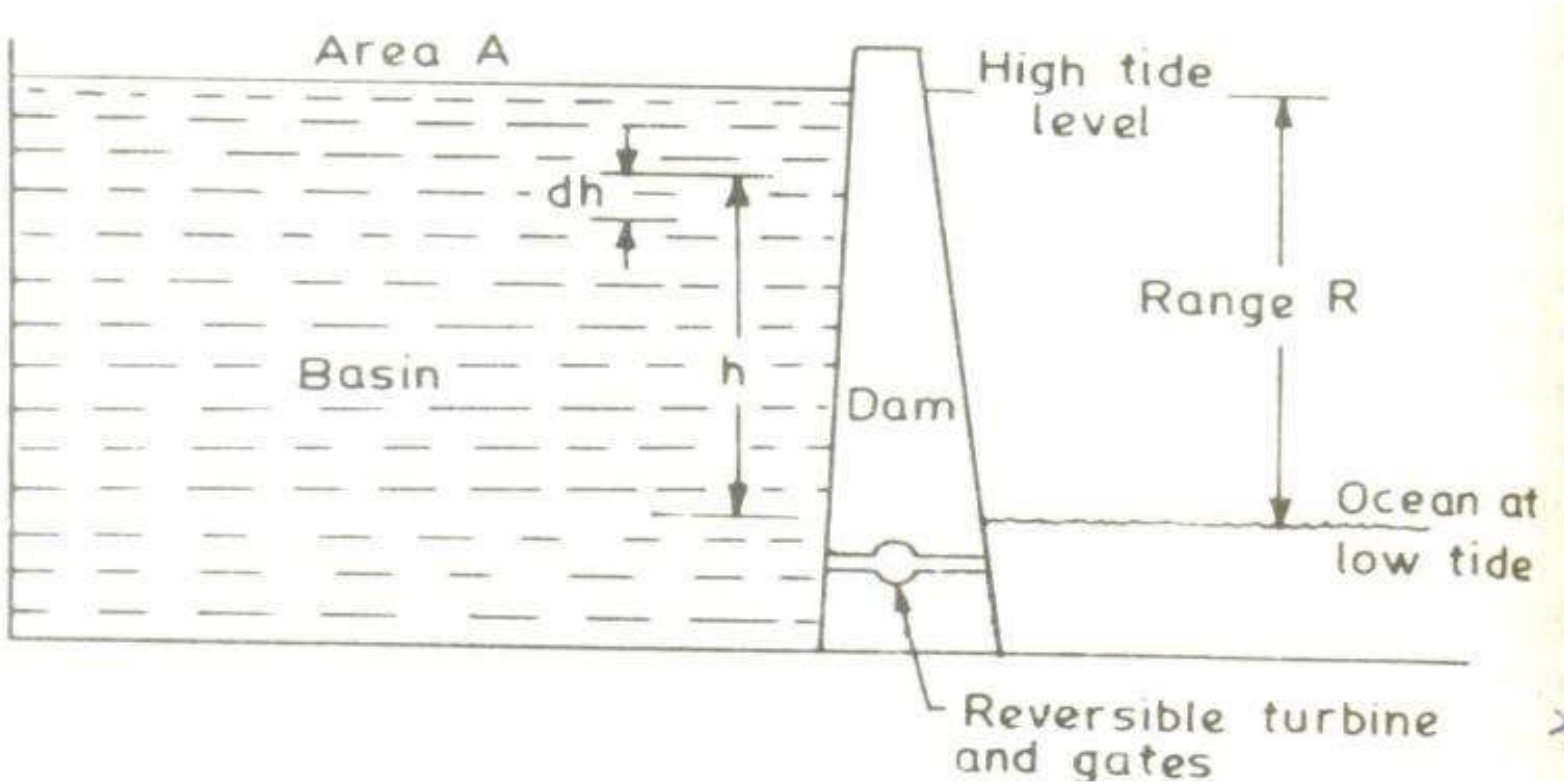


(iii)Tubular Type:

- Tubular turbines have been proposed for use some UK projects. In this configuration, the blades are connected to a long shaft and orientated at an angle so that the generator is sitting on top of the barrage.



- **Estimation of tidal power:**
- **Single basin system:**



- We can write,

$$\sim dw = dm.\ g.h$$

$$\sim dm = -\rho A\ d\ h$$

$$\sim dw = -\rho A\ d\ h\ g\ h$$

Where,

- W= work done by water in joules
- g= gravitational constant
- m= mass flowing through the turbine, Kg
- h= head. m
- ρ= water density, Kg/m^3
- A= basin surface area in m^2.

- The total amount of work during a full emptying or filling is given by,

$$W = \int_R^0 dw = -g\rho A \int_R^0 h\, dh$$

$$= \frac{1}{2} g\rho A\, R^2$$

- The power is rate of doing work. The time taken for producing power once is tidal period. Tidal wave has period equal to 6h,12.5 min i.e, 22350 seconds.

$$P_{av} = \frac{W}{Time} = \frac{\frac{1}{2}}{22350} g\rho A\, R^2$$

$$= \frac{1}{44700}\, g\rho A\, R^2$$

- Assuming an average water density as 1025Kg/m³, The average power per unit basin area is given by,

$$\frac{P_{av}}{A} = \frac{1}{44700} \times 9.81 \times 1025 \times R^2$$

$$= 0.225R^2 \text{ watts/m}^2$$

Example Problem:

- A Tidal power plant of the simple single basin type has a basin area of $30X10^{6}$ m^{2}. The tide has a range of 12m. The turbine however stops operating when the head falls below three meters. Calculate the energy generated in one filling(or emptying) process, in KW hours if the generator efficiency is 0.73.

Solution

The total theoretical Work $W = \int_R^r dw$

Here R=12m

R=the head below turbine stops operating=3m

$$W = \int_R^r -g\rho Ah\, dh = -g\rho A \int_R^r h\, dh$$

$$=\frac{1}{2}\,g\rho A(R^2-r^2)$$

Thus the average power

$$P_{av}=\frac{W}{time}$$

$$=\frac{\frac{1}{2}\,g\rho A(R^2-r^2)}{44700}$$

The average power generated

$$=\frac{1}{44700}\times 9.81\times 1025\times 30\times 10^6\times(12^2-3^2)Watts$$

$$=\frac{1}{44700}\times 9.81\times 1025\times 30\times 10^6\times 135\,watts$$

$$=911.25 \times 10^6 \text{ watts} = \frac{911.25}{1000} \times 3600 \times 10^6 \text{kWh}$$

$$= 3280.5 \times 10^6 kWh$$

Considering turbine generator efficiency, the energy generated

$$= 3280.5 \times 10^6 \times 0.73 = 2395 \times 10^6 \; kWh$$

Ocean Thermal Energy Conversion (OTEC)

- This is also as indirect source of Solar Energy.
- The tropical oceans absorb a large amount of solar energy. The surface of ocean acts as collector of heat, while the temperature in the depths is 20-25 ^{o}c lower.
- This difference in temperature is used to obtain energy.
- The surface water, which is heated, is used to heat some low boiling organic fluid such as ammonia, propane, R-12, R-22, etc.
- Then the vapour produced will run the heat engine.

- The exit vapour is condensed using cold ocean water of deeper regions.
- Several such plants were build in France with capacity upto7.5 MW.
- The OTEC works in Closed Rankine Cycle.
- In India the Department of Non-Conventional Energy Sources (DNES) has proposed to set up a 1 MW OTEC plant in Lakshadweep Island.

Ocean Power

What is OTEC?

- OTEC, or Ocean Thermal Energy Conversion, is an energy technology that converts solar radiation to electric power.
- OTEC systems use the ocean's natural thermal gradient—the fact that the ocean's layers of water have different temperatures—to drive a power-producing cycle.
- As long as the temperature between the warm surface water and the cold deep water differs by about 20°C (36°F), an OTEC system can produce a significant amount of power with a maximum “Carnot Efficiency” of about 6.7%.

Lambert’s Law:

- Solar Energy absorption by the water takes place according to Lambert‘s Law of absorption, which states that each layer of equal thickness absorbs the same fraction of light that passes through it.

$$\frac{-dI_{(x)}}{dx} = kI$$

$$I_{(x)} = I_0 e^{-kx}$$

- Where I_o and $I_{(x)}$ are intensities of radiation at the surface(x=0) and at a distance x below the surface. K is the extinction coefficient and it has the value $0.05 m^{-1}$ for very clear fresh water, 0.27 for turbid fresh water and $0.5 m^{-1}$ for very salty water.

Consequences of Lambert's Law:

- Intensity decreases exponentially with depth and depending upon K value almost all the absorption takes place very close to the surface water. Maximum temperature occur just below the top surface of water.
- Deep water remains cool.
- There will not be thermal convection currents between the warmer, lighter surface water and cool heavier water at the depth.
- In the tropics, the ocean surface temperature often exceeds 25^0C while 1Km below temperature is not higher than 10^0C.
- A heat engine can be made to work between these two temperatures and power can be obtained.

OTEC POWER PLANTS:

- **Open-Cycle (Claude Cycle):**
- Open-cycle OTEC uses the tropical oceans' warm surface water to make electricity. When warm seawater is placed in a low-pressure container, it boils.
- The expanding steam drives a low-pressure turbine attached to an electrical generator.
- The steam, which has left its salt behind in the low pressure container, is almost pure fresh water. It is condensed back into a liquid by exposure to cold temperatures from deep-ocean water.

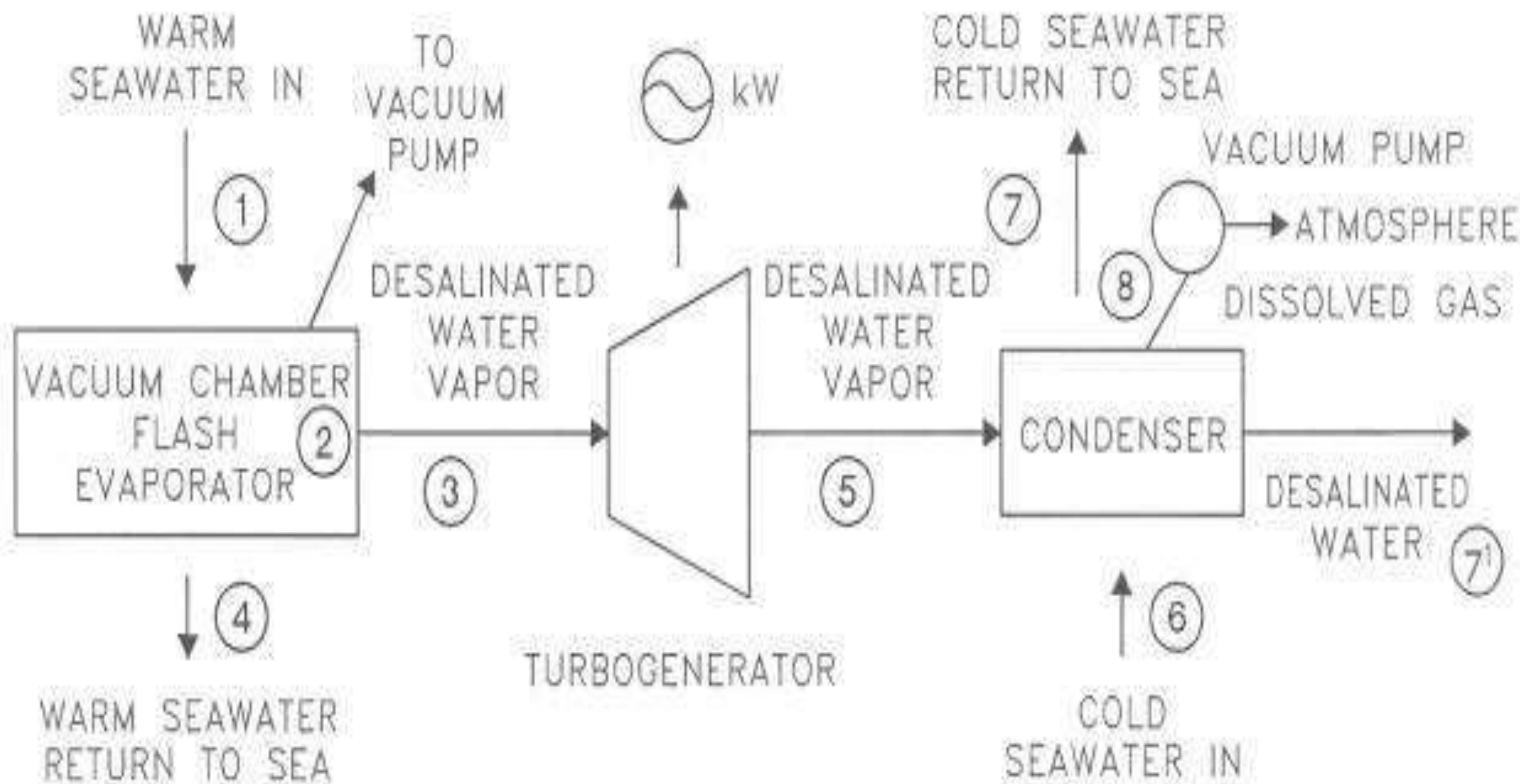
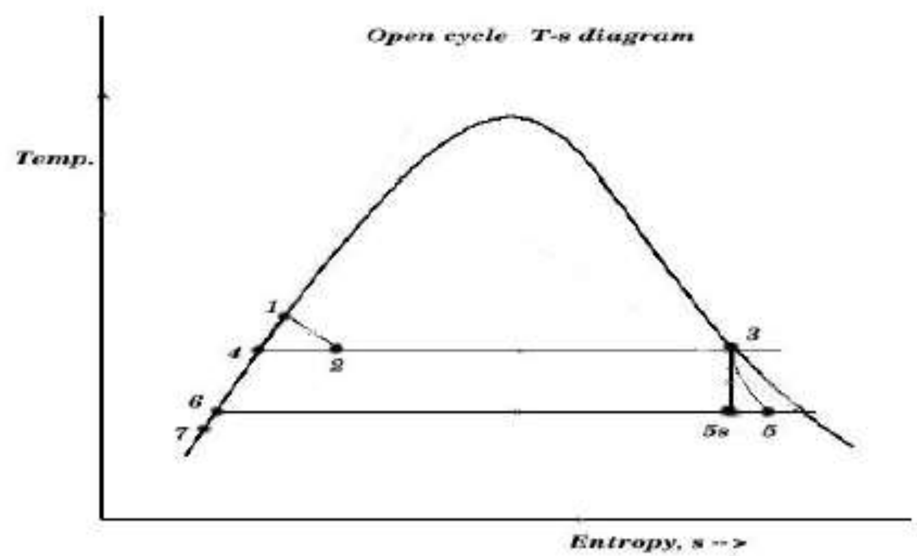


Fig: Open-Cycle (Claude Cycle):

Open cycle thermodynamic analysis:

- In this scheme, warm surface water at around 27°C (81°F) enters an evaporator at pressure slightly below the saturation pressure causing it to vaporize. $H_1 = H_f$

Where H_f is enthalpy of liquid water at the inlet temperature, T_1.



- This water undergoes volume boiling as opposed to pool boiling in conventional boilers where the heating surface is in contact. Thus the water partially flashes to steam with two-phase equilibrium prevailing.
- Suppose that the pressure inside the evaporator is maintained at the saturation pressure, T_2.

$$H_2 = H_1 = H_f + x_2 H_{fg}$$

Here, x_2 is the fraction of water by mass that vaporizes. The warm water mass flow rate per unit turbine mass flow rate is $1/x_2$.

- The low pressure in the evaporator is maintained by a vacuum pump that also removes the dissolved non-condensable gases from the evaporator.
- The evaporator now contains a mixture of water and steam of very low vapour quality (steam content).
- The steam is separated from the water as saturated vapour.
- The remaining water is saturated and is discharged to the ocean in the open cycle. The steam is a low pressure/high specific volume working fluid. It expands in a special low pressure turbine,

$$H_3 = H_g$$

Here, H_g corresponds to T_2.

For an ideal isentropic (reversible adiabatic) turbine,

$$S_{5s} = S_3 = S_f + x_{5s} S_{gf}$$

The above equation corresponds to the temperature at the exhaust of the turbine, T_5. $x_{5,s}$ is the mass fraction of vapor at state 5.

The enthalpy at T_5 is,

$$H_{5s} = H_f + x_{5s} H_{fg}$$

This enthalpy is lower. The adiabatic reversible turbine work = H_3-$H_{5,s}$.

Actual turbine work W_T = (H_3-$H_{5,s}$) x *polytropic efficiency*

$$H_5 = H_3 - \text{ actual work}$$

- The condenser temperature and pressure are lower. Since the turbine exhaust is to be discharged back into the ocean, a direct contact condenser is used to mix the exhaust with cold water, which results in a near-saturated water. That water is now discharged back to the ocean.

H_6=H_f, at T_5. T_7 is the temperature of the exhaust mixed with cold sea water, as the vapour content now is negligible

$$H_7 \approx H_f \ \ at \ T_7$$

The temperature differences between stages include that between warm surface water and working steam, that between exhaust steam and cooling water, and that between cooling water reaching the condenser and deep water. These represent external irreversibility that reduce the overall temperature difference.

The cold water flow rate *per* unit turbine mass flow rate,

$$m_c = \frac{\dot{H}_5 - H_6}{H_6 - H_7}$$

Turbine mass flow rate,

$$\dot{M}_T = \frac{\text{turbine work required}}{W_T}$$

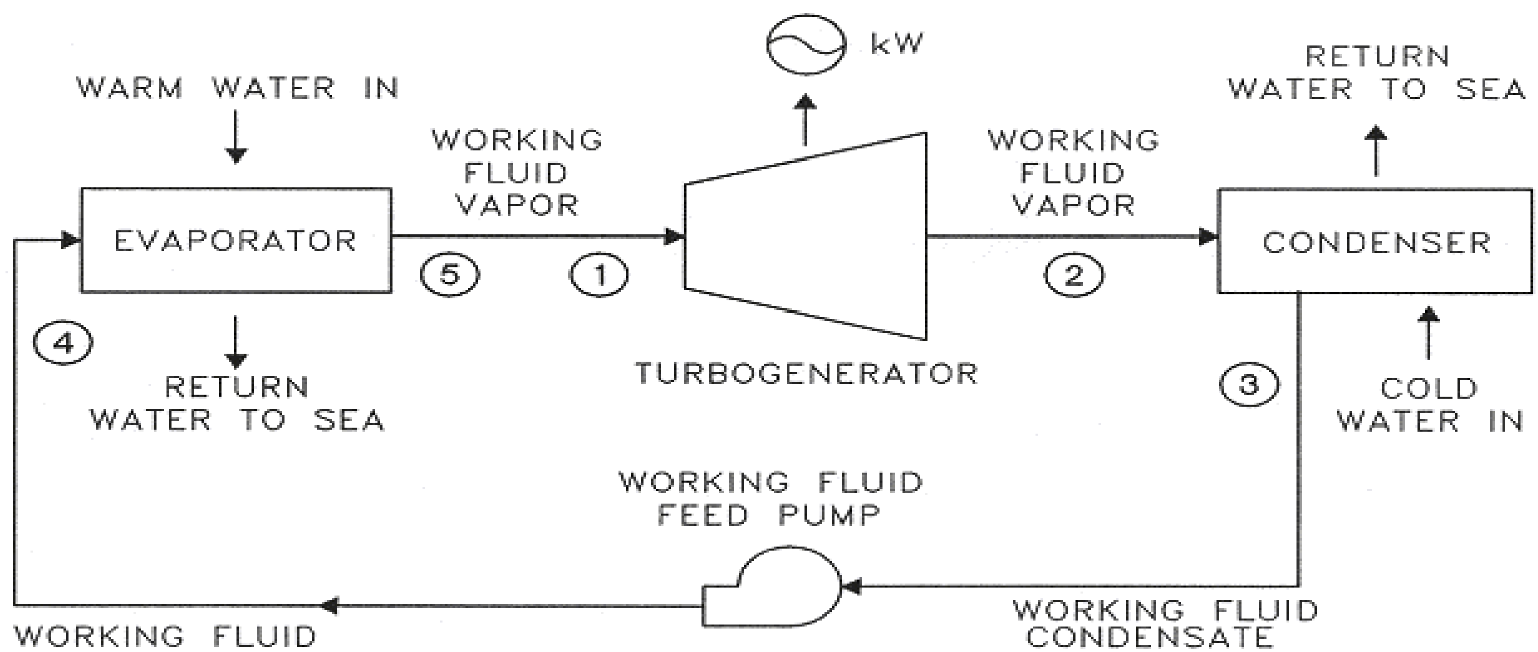
Warm water mass flow rate,

$$\dot{M}_w = M_T \dot{m}_w$$

Cold water mass flow rate

$$\dot{M}_c = \dot{M}_T \dot{m}_C$$

- **Closed-Cycle (Rankine):**
- The Natural Energy Laboratory along with several private-sector partners carried out the mini OTEC experiment in 1979 which successfully achieved the production of net electrical power at sea with the help of closed-cycle OTEC.
- In 1999, the Natural Energy Laboratory experimented with a 250-kW pilot OTEC closed-cycle plant, which is the largest of its kind.



- Closed-cycle systems use fluid with a low-boiling point, such as ammonia, to rotate a turbine to generate electricity. Here's how it works.
- Warm surface seawater is pumped through a heat exchanger where the low-boiling-point fluid is vaporized.
- The expanding vapour turns the turbo-generator. Then, cold, deep seawater—pumped through a second heat exchanger—condenses the vapour back into a liquid, which is then recycled through the system.

Thermodynamic analysis:

- In this cycle, Q_H is the heat transferred in the evaporator from the warm sea water to the working fluid. The working fluid exits the evaporator as a gas near its dew point.
- The high-pressure, high-temperature gas then is expanded in the turbine to yield turbine work, W_T.
- The working fluid is slightly superheated at the turbine exit and the turbine typically has an efficiency of 90% based on reversible, adiabatic expansion.

- From the turbine exit, the working fluid enters the condenser where it rejects heat, $-Q_C$, to the cold sea water.
- The condensate is then compressed to the highest pressure in the cycle, requiring condensate pump work, W_C.
- Thus, the Anderson closed cycle is a Rankine-type cycle similar to the conventional power plant steam cycle except that in the Anderson cycle the working fluid is never superheated more than a few degrees Celsius.
- Owing to viscous effects, working fluid pressure drops in both the evaporator and the condenser. This pressure drop, which depends on the types of heat exchangers used, must be considered in final design calculations but is ignored here to simplify the analysis.

- Thus, the parasitic condensate pump work, W_C, computed here will be lower than if the heat exchanger pressure drop was included. The major additional parasitic energy requirements in the OTEC plant are the cold water pump work, W_{CT}, and the warm water pump work, W_{HT}. Denoting all other parasitic energy requirements by W_A, the net work from the OTEC plant, W_{NP} is,

$$W_{NP} = W_T + W_C + W_{CT} + W_{HT} + W_A$$

- The thermodynamic cycle undergone by the working fluid can be analysed without detailed consideration of the parasitic energy requirements. From the first law of thermodynamics, the energy balance for the working fluid as the system is, where $W_N = W_T + W_C$, is the net work for the thermodynamic cycle.

$$W_N = Q_H + Q_C$$

- For the idealized case in which there is no working fluid pressure drop in the heat exchangers, and so that the net thermodynamic cycle work becomes,

$$Q_H = \int_H T_H ds$$

and

$$Q_C = \int_C T_C ds$$

so that the net thermodynamic cycle work becomes

$$W_N = \int_H T_H ds + \int_C T_C ds$$

- Sub cooled liquid enters the evaporator. Due to the heat exchange with warm sea water, evaporation takes place and usually superheated vapour leaves the evaporator. This vapour drives the turbine and the 2-phase mixture enters the condenser.
- Usually, the sub cooled liquid leaves the condenser and finally, this liquid is pumped to the evaporator completing a cycle.

Hybrid System:

- Hybrid systems combine the features of both the closed-cycle and open cycle systems. In a hybrid system, warm seawater enters a vacuum chamber where it is flash-evaporated into steam, similar to the open cycle evaporation process. The steam vaporizes a low-boiling-point fluid (in a closed-cycle loop) that drives a turbine to produces electricity.

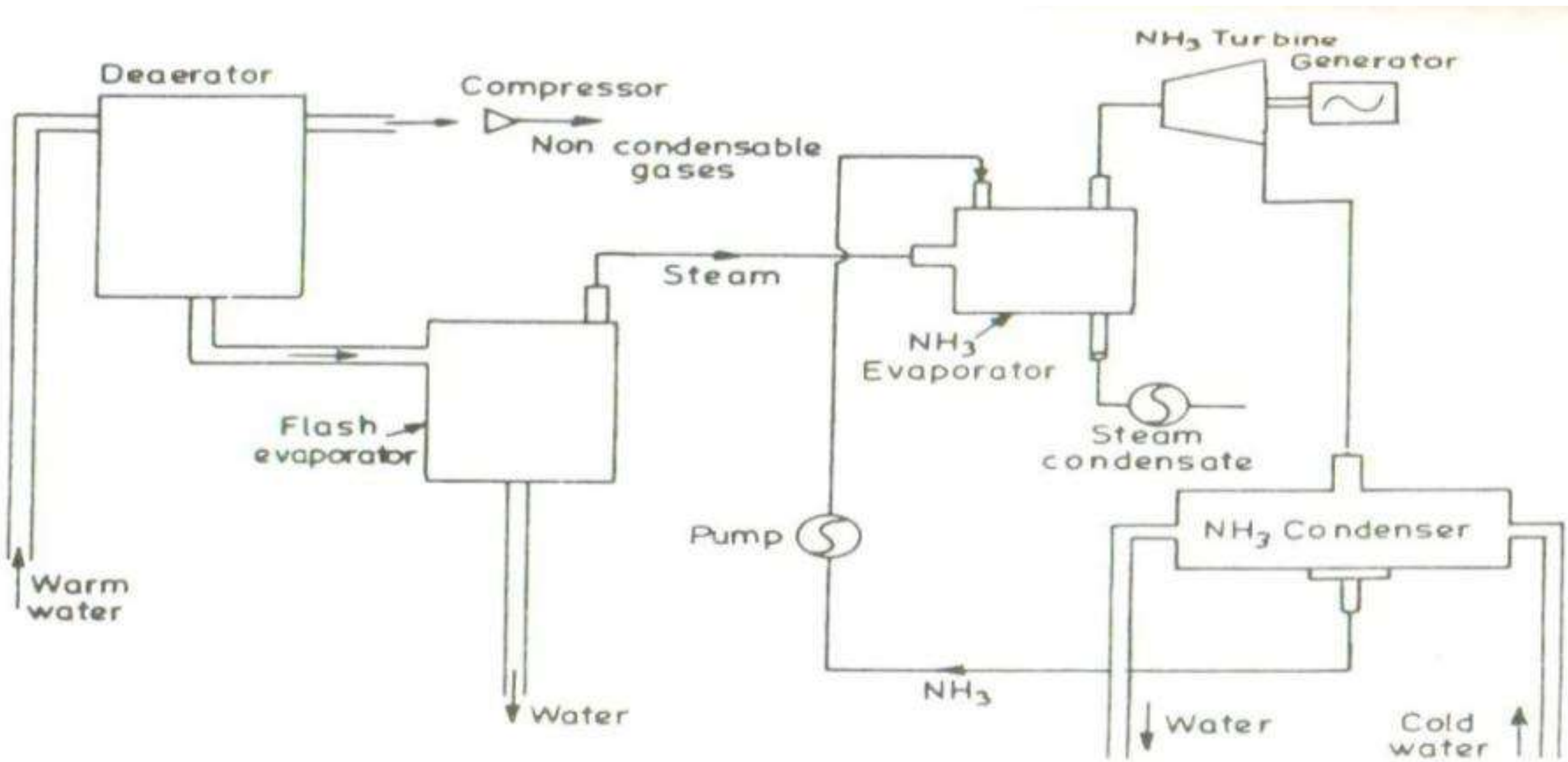


Fig: Hybrid System

Advantages:

- **Low Environmental Impact:**
- The distinctive feature of OTEC energy systems is that the end products include not only energy in the form of electricity, but several other synergistic products.
- **Fresh Water:**
- The first by-product is fresh water. A small 1 MW OTEC is capable of producing some 4,500 cubic meters of fresh water per day, enough to supply a population of 20,000 with fresh water.

Food:

- A further by-product is nutrient rich cold water from the deep ocean. The cold "waste" water from the OTEC is utilised in two ways.
- Primarily the cold water is discharged into large contained ponds, near shore or on land, where the water can be used for multi-species “Mari culture” (shellfish and shrimp) producing harvest yields which far surpass naturally occurring cold water upwelling zones, just like agriculture on land.

Minerals:

- OTEC may one day provide a means to mine ocean water for 57 trace elements.
- Most economic analyses have suggested that mining the ocean for dissolved substances would be unprofitable because so much energy is required to pump the large volume of water needed and because of the expense involved in separating the minerals from seawater. But with
- OTEC plants already pumping the water, the only remaining economic challenge is to reduce the cost of the extraction process.

- OTEC systems produce fresh water and electricity as well, which is highly beneficial for island regions where fresh water availability is limited.
- It makes use of renewable, clean, natural resources. Fossil fuels are replaced by warm surface seawater and cold water from deep sea to generate electricity.
- OTEC plants do not pollute the environment by releasing carbon dioxide emissions or other polluting substances.
- It helps reduce the country’s dependence on imported fossil fuels.

Disadvantages of OTEC:

- Some of the major drawbacks of OTEC include the following:
- Construction of OTEC plants and pipes in ocean may cause damage to onshore marine ecosystems and reefs.
- As this technology has been tested only in small-scale, it is not feasible for an energy company to invest in this project.
- Electricity produced from OTEC would currently cost more than that produced from fossil fuels.
- Discharging of cold and warm sea water needs to be carried out several metres away from the shore to avoid any dwelling impact on marine ecosystems.
- Energy required to pump the sea water from depths may be huge, which otherwise need a diesel generator.

- **Problems associated with OTEC.**
- OTEC process is not altogether a very clean process unless certain precautions are taken, otherwise there may be pollution and relative effects.
- Fortunately all these precautions can be easily taken and without spending large amounts of money.
- For all this it is necessary first to be aware of the possible sources of OTEC pollution and to avoid these, following are discussed briefly.

- Solid particles and non condensable gases.
- Re-injection.
- Land erosion.
- Noise.
- Water-borne poisons.
- Heat pollution.
- Silica.
- Subsidence.
- Seismicity.
- Escaping Steam.

Solid particles and non condensable gases.

- Steam and water from both hydrothermal system contain, besides the dissolved solids in the water, entrained solids are removed, usually by centrifugal separators at the well head.
- H_2S is almost always present in OTEC field. This if present in excess quantities may cause harmful effects on the bearings. This also attacks electrical equipments and it may adverse effects on crops and on river life.
- At power plants it occurs in high concentration at the gas ejector points. At some places H_2S are being trapped and the gas is being burned to form SO_2 , which is then scrubbed with cooling water tower.

Re-injection:

- It would avoid discharging large quantity of heat into rivers, with consequent hazards to fisheries and would also avoid infecting rivers and stream with toxic substances emitted from the bores which would endanger down stream drinking water supplies.

Land Erosion:

- Close control, replanting of shrubs an trees, more careful site selection and improved construction methods are helping to solve this problem.

Noise:

- Noise pollution is another problem. Exhausts, blow-downs and centrifugal separation are some of the sources of noise that necessitate the installation of silencers on some equipment.

Water-borne poisons:

- The water phase in wet fields sometimes contain toxic mercury, arsenic, ammonia etc., which if discharged could contaminate water downstream.

Air-borne poisons:

- From various plants harmful substances may escape into the air thermal sites. This may contain radioactive materials also.

Heat pollution.

- The necessary adoption of relatively low temperature for OTEC power production results in low efficiencies and emission of huge quantities of waste heat.
- Heat pollution in river water can damage fisheries and encourage growth of unwanted water weeds.

Silica:

- Silica can be particularly troublesome with distinct heating systems.
- Re-injection of silicon loaded waters could flow up to the permeability level.

Subsidence:

- The withdrawal of huge quantities of underground fluids from a wet field can cause substantial ground subsidence, which could cause fitting and stressing of pipelines and surface structures.

Seismicity:

- Some fears have been expressed that prolonged OTEC exploitation could trigger off earthquakes where fairly large temperature differentiation occur.

Escaping Steam:

- Huge volumes of flash steam escaping into the air could cause dense fog to occur, which may drift across in causing the pollution.

Current operating Plants of OTEC:

- In March 2013, Makai installed and operate a 100 kilowatt (which is sufficient to power 120 homes in Hawaii) turbine on the OTEC Heat Exchanger Test Facility, and connect OTEC power to the grid.
- Okinawa Prefecture announced the start of the OTEC operation testing at Kume Island on April 15, 2013. The plant consists of two units; one includes the 50 kW generator while the second unit is used for component testing and optimization.
- In July 2014, DCNS group partnered with Akuo Energy announced their NEMO project. If successful, the 16MW gross 10MW net offshore plant will be the largest OTEC facility to date.

END