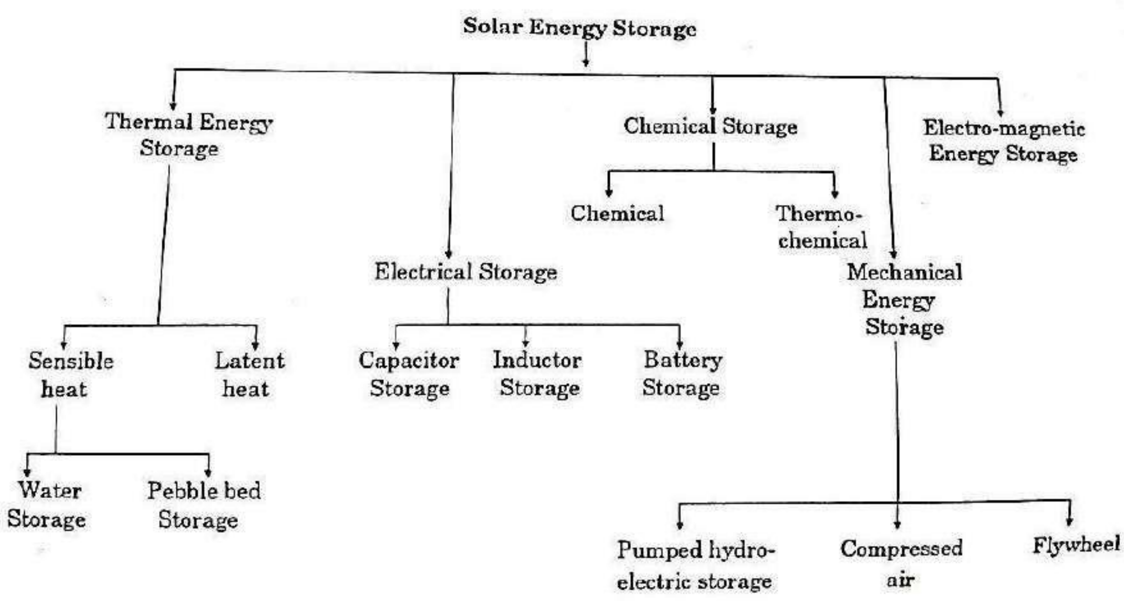
UNIT-III SOLAR ENERGY STORAGE AND APPLICATIONS

The thermal energy of sun can be stored in a well-insulated fluids or solids. It is either stored as i) sensible heat – by virtue of the heat capacity of the storage medium, or as ii) Latent heat – by virtue of the latent heat of change of phase of the medium or both.

In the first type of storage the temp of the medium changes during charging or discharging of the storage whereas in the second type the temp of the medium remains more or less constant since it undergoes a phase transformation.

An overview of the major techniques of storage of solar energy is as shown in the fig. A wide range of technical options are available for storing low temp thermal energy as shown. Some of the desired characteristics of the thermal energy as shown below. Some of the different storage techniques and their main features are compared in the next table. Desired properties of phase change heat storage materials are also listed in subsequent table.

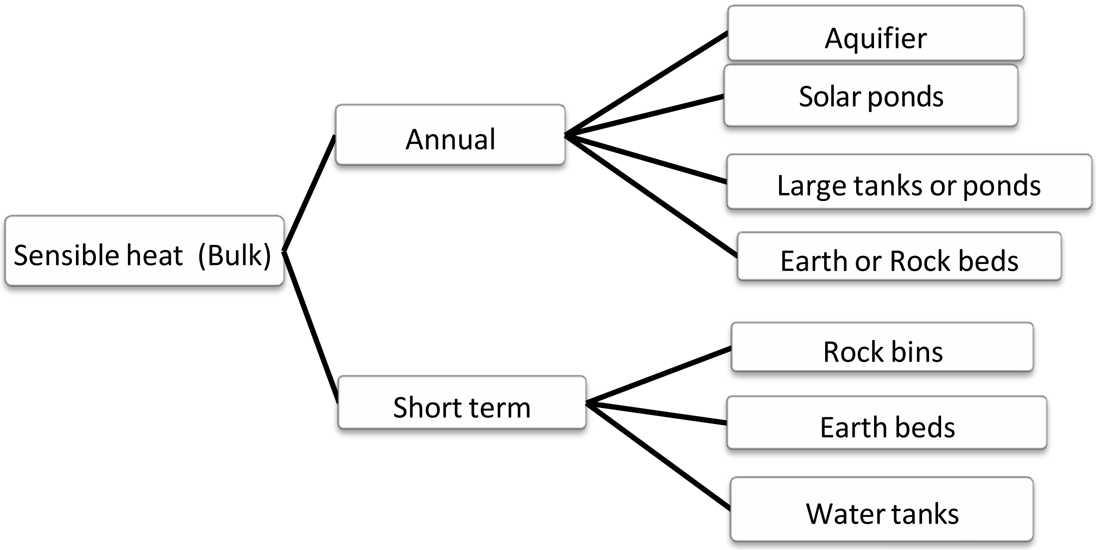


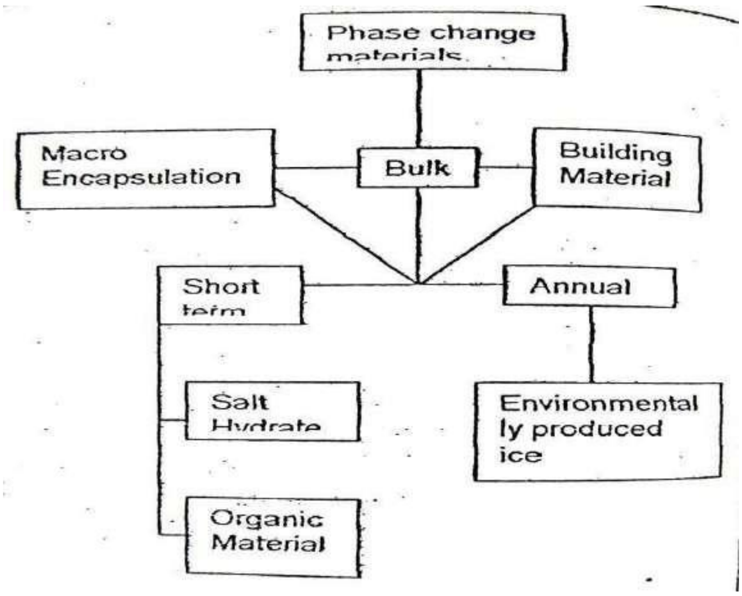
There are four main factors affecting the cost affecting the cost of solar thermal energy storage systems. They are,

1) Thermal heat storage materials,
2) Insulating material,
3) Space occupied by the storage device,
4) Heat exchange for charging and discharging the storage.

The following chart shows the different storage systems used as per the required capacity. Depending on the available energy one can select the particular storage system thus optimizing the cost and the efficiency of the storage system.

Low Temperature solar thermal energy storage technology classification:





Desired characteristics of a thermal storage system:

1) Compact, large storage capacity per unit mass and volume,
2) High storage efficiency,
3) Heat storage medium with suitable properties in the operating temperature range,
4) Uniform temperature,
5) Capacity to charge and discharge with the largest input/output rates but without temperature gradients,

6) Complete reversibility,
7) Ability to undergo large number of charges and discharge cycles without loss of performance and storage capacity,
8) Small self-discharging rates,
9) Quick charging and discharging,
10) Long life,
11) Inexpensive,
12) Non corrosive,
13) No fire and toxic hazards.

In smaller heat storage, the surface area to volume ratio is large and hence the cost of insulating is an important factor. Phase change storages with higher energy densities are more attractive for small storage. In larger heat storage, on the other hand, the cost of storage material is more important and sensible heat storage like water is very attractive.

Comparison of different storage techniques for solar space heating

Property	Sensible Heating Water	Rock	Latent heat storage (solid – liquid0
Temperature Range	$0 - 100^0$ c	Large	Large, depends on the material
Specific heat	High	low	Medium
Thermal conductvity	Low	Low	Very-low (insulating)
Storage capacity /unit mass/unit vol	Low	Low	High
Stability to thermal cycling	Good	Good	Insufficient data
Availability	Good	Good	Depend on the choice of the material
Cost	Inexpensive	Inexpensive	Expensive
Heat exchanger geometry	Simple	Simple	Complex
Temp. gradient during charging/discharging	Large	Large	Small
Simultaneous charging/discharging	Possible	Not possible	Possible with appropriate H.E.
Cost of accessories	low	High	Low
Corrosion	Corrosive	Non corrosive	Insufficient data
Life	long	long	long

Photovoltaic Solar Systems

What is a solar cell?

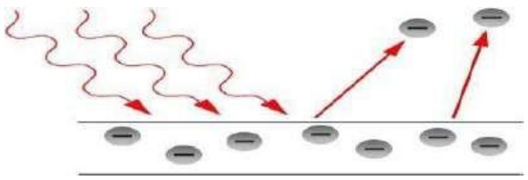
- Solid state device that converts incident solar energy directly into electrical energy

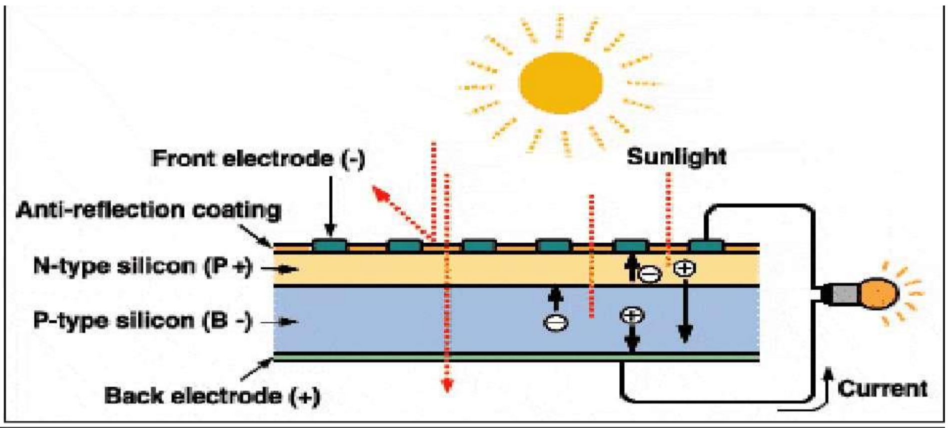
Advantages:

1. Efficiencies from a few percent up to 20-30%
2. No moving parts
3. No noise
4. Lifetimes of 20-30 years or more

How Does It Work?

- The junction of dissimilar materials (n and p type silicon) creates a voltage
- Energy from sunlight knocks out electrons, creating a electron and a hole in the junction
- Connecting both sides to an external circuit causes current to flow
- In essence, sunlight on a solar cell creates a small battery with voltages typically 0.5 v. DC

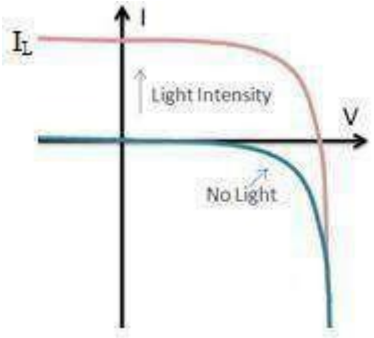


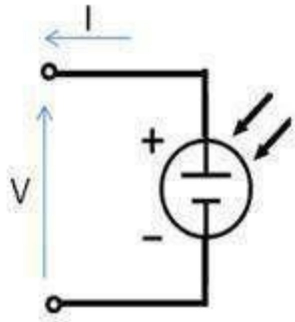


charecteristics of a solar cell:

Theory of I-V Characterization:

PV cells can be modeled as a current source in parallel with a diode. When there is no light present to generate any current, the PV cell behaves like a diode. As the intensity of incident light increases, current is generated by the PV cell, as illustrated in Figure.





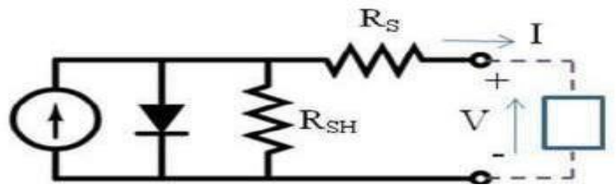
- In an ideal cell, the total current I is equal to the current I_ℓ generated by the photoelectric effect minus the diode current I_D, according to the equation:

$$I = I_\ell - I_D = I_\ell - I_o\left(e^{\frac{qV}{kT}} - 1\right)$$

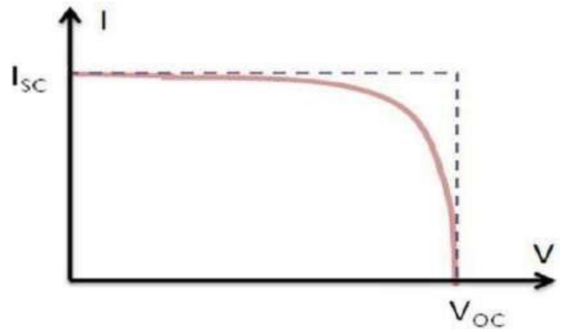
- where I_0 is the saturation current of the diode, q is the elementary charge 1.6×10^{-19} Coulombs, k is a constant of value 1.38×10^{-23} J/K, T is the cell temperature in Kelvin, and V is the measured cell voltage that is either produced (power quadrant) or applied (voltage bias).

- Expanding the equation gives the simplified circuit model shown below and the following associated equation, where n is the diode ideality factor (typically between 1 and 2), and R_S and R_{SH} represents the series and shunt resistances that are described in further detail later in this document:

$$I = I_l - I_0\left(exp^{\frac{q(V+I\cdot R_S)}{n\cdot k\cdot T}} - 1\right) - \frac{V + I\cdot R_S}{R_{SH}}$$



The I-V curve of an illuminated PV cell has the shape shown in the following Figure as the voltage across the measuring load is swept from zero to V_{OC},



Short Circuit Current (I_{SC}):

The short circuit current I_{SC} corresponds to the short circuit condition when the impedance is low and is calculated when the voltage equals 0.

I (at V=0) = I_{SC}

I_{SC} occurs at the beginning of the forward-bias sweep and is the maximum current value in the power quadrant. For an ideal cell, this maximum current value is the total current produced in the solar cell by photon excitation.

$I_{SC} = I_{MAX} = I_\ell$ for forward-bias power quadrant

Open Circuit Voltage (V_{OC}):

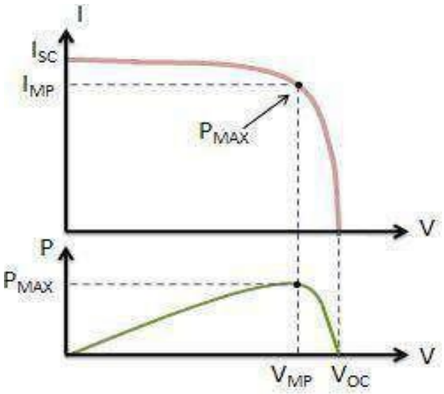
The open circuit voltage (V_{OC}) occurs when there is no current passing through the cell.

V (at I=0) = V_{OC}

V_{OC} is also the maximum voltage difference across the cell for a forward-bias sweep in the power quadrant.V_{OC}= V_{MAX} for forward-bias power quadrant

Maximum Power (P_{MAX}), Current at P_{MAX} (I_{MP}), Voltage at P_{MAX} (V_{MP}):

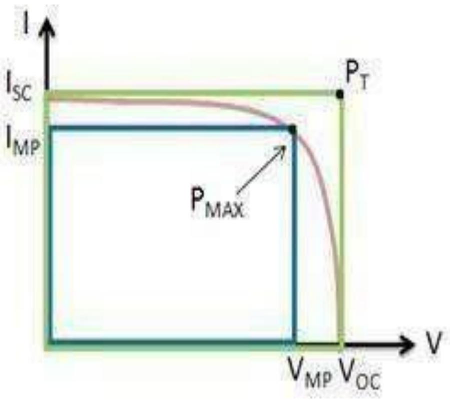
The power produced by the cell in Watts can be easily calculated along the I-V sweep by the equation $P=IV$. At the I_{SC} and V_{OC} points, the power will be zero and the maximum value for power will occur between the two. The voltage and current at this maximum power point are denoted as V_{MP} and I_{MP} respectively.



Fill Factor:

The Fill Factor (FF) is essentially a measure of quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power (P_T) that would be output at both the open circuit voltage and short circuit current together. FF can also be interpreted graphically as the ratio of the rectangular areas depicted in Figure

$$FF = \frac{P_{MAX}}{P_T} = \frac{\boxed{I_{MP} \cdot V_{MP}}}{\boxed{I_{SC} \cdot V_{OC}}}$$



A larger fill factor is desirable, and corresponds to an I-V sweep that is more square-like. Typical fill factors range from 0.5 to 0.82. Fill factor is also often represented as a percentage.

Efficiency (η):

Efficiency is the ratio of the electrical power output P_{out}, compared to the solar power input, P_{in}, into the PV cell. P_{out} can be taken to be P_{MAX} since the solar cell can be operated up to its maximum power output to get the maximum efficiency.

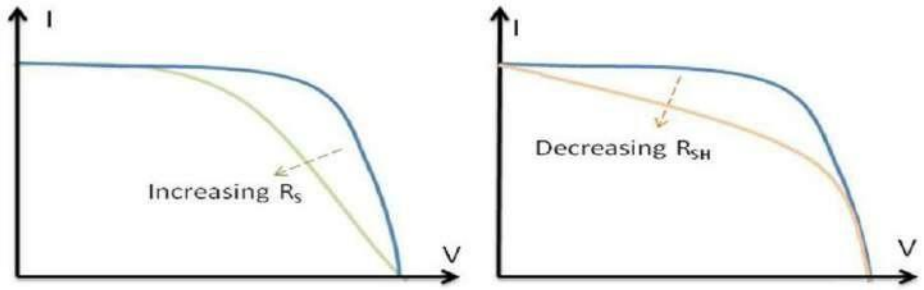
$$\eta = \frac{P_{out}}{P_{in}} \Rightarrow \eta_{MAX} = \frac{P_{MAX}}{P_{in}}$$

Shunt Resistance (R_{SH}) and Series Resistance (R_S):

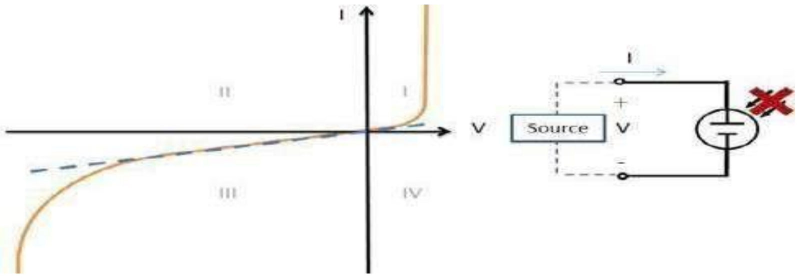
During operation, the efficiency of solar cells is reduced by the dissipation of power across internal resistances. These parasitic resistances can be modeled as a parallel shunt resistance (R_{SH}) and series resistance (R_S), as depicted in Figure previously.

For an ideal cell, R_{SH} would be infinite and would not provide an alternate path for current to flow, while R_S would be zero, resulting in no further voltage drop before the load.

Decreasing R_{SH} and increasing R_s will decrease the fill factor (FF) and P_{MAX} as shown in Figure 6. If R_{SH} is decreased too much, V_{OC} will drop, while increasing R_S excessively can cause I_{SC} to drop instead.



If incident light is prevented from exciting the solar cell, the I-V curve shown in following Figure can be obtained. This I-V curve is simply a reflection of the ―No Light‖ curve from Figure 1 about the V-axis. The slope of the linear region of the curve in the third quadrant (reverse-bias) is a continuation of the linear region in the first quadrant, which is the same linear region used to calculate R_{SH} in Figure. It follows that R_{SH} can be derived from the I-V plot obtained with or without providing light excitation, even when power is sourced to the cell. It is important to note, however, that for real cells, these resistances are often a function of the light level, and can differ in value between the light and dark tests.


I
II
I
III
IV
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+
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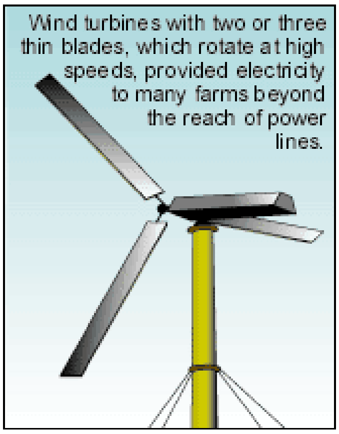
WIND ENERGY

History of Wind-Mills:

- The wind is a by-product of solar energy. Approximately 2% of the sun's energy reaching the earth is converted into wind energy.
- The surface of the earth heats and cools unevenly, creating atmospheric pressure zones that make air flow from high-to low-pressure areas.
- The wind has played an important role in the history of human civilization .
- The first known use of wind dates back 5,000 years to Egypt, where boats used sails to travel from shore to shore.
- The first true windmill, a machine with vanes attached to an axis to produce circular motion, may have been built as early as 2000 B.C.
- In ancient Babylon. By the 10th century A.D., windmills with wind-catching surfaces having 16 feet length and 30 feet height were grinding grain in the areas in eastern Iran and Afghanistan.
- The earliest written references to working wind machines in western world date from the 12th century.
- These too were used for milling grain. It was not until a few hundred years later that windmills were modified to pump water and reclaim much of Holland from the sea.
- The multi-vane "farm windmill" of the American Midwest and West was invented in the United States during the latter half ofthe l9th century.
- In 1889 there were 77 windmill factories in the United States, and by the turn of the century, windmills had become a major American export.
- Until the diesel engine came along, many transcontinental rail routes in the U.S. depended on large multi-vane windmills to pump water for steam locomotives.
- Farm windmills are still being produced and used, though in reduced numbers.
- They are best suited for pumping ground water in small quantities to livestock water tanks.
- In the 1930s and 1940s, hundreds of thousands of electricity producing wind turbines were built in the U.S.
- They had two or three thin blades, which rotated at high speeds to drive electrical generators.
- These wind turbines provided electricity to farms beyond the reach of power lines and were typically used to charge storage batteries, operate radio receivers and power a light bulb.
- By the early 1950s, however, the extension of the central power grid to nearly every American household, via the Rural Electrification Administration, eliminated the market for these machines. Wind turbine development lay nearly dormant for the next 20 years.

- A typical modern windmill looks as shown in the following figure.
- The wind-mill contains three blades about a horizontal axis installed on a tower. A turbine connected to a generator is fixed about the horizontal axis.



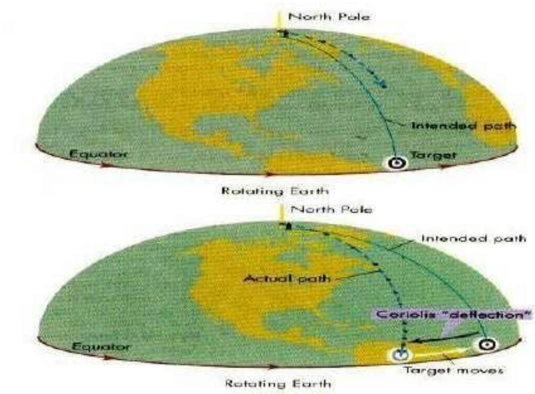
- Like the weather in general, the wind can be unpredictable. It varies from place to place, and from moment to moment.
- Because it is invisible, it is not easily measured without special instruments.
- Wind velocity is affected by the trees, buildings, hills and valleys around us.
- Wind is a diffuse energy source that cannot be contained or stored for use elsewhere or at another time.

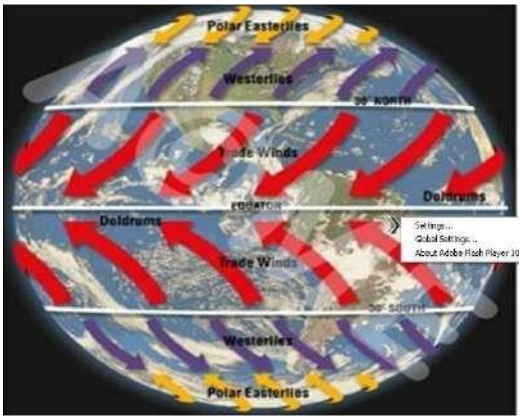
Generation of the Wind(Origin of Winds):

Planetory winds:

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
  - Planetory winds are caused because of the above





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 mountainsides. The air above the slopes heats up during the day and cools down at night, more rapidly than the air above the low lands. This causes heated air in the day to raise along the slopes and relatively heavy air to flow down at night.

Note: It has been estimated that 2% of solar radiation falling on the earth‘s face is converted into kinetic energy in the atmosphere. About 30% of this is available in the lowest 1000m from the earth‘s surface. This is sufficient many times than the need of a country. Direct solar radiation is predictable and dependable whereas wind is erratic, unsteady and not reliable except in some areas.

Wind Data

All countries have national meteorological services that record and publish weatherrelated data including wind speed and direction. Wind speed is measured byanemometer and wind direction is measured by wind vane attached to a directionindicator. Anemometers work on one of the following principles.

(i) The oldest and simplest anemometer is a swinging plate hung vertically and hinged along its top edge. Wind speed is indicated by the angle of deflection of the plate with respect to vertical.

(ii) Cup anemometer consists of three or four cups mounted symmetrically about a vertical axis. The speed of rotation indicates wind speed.

(iii) Wind speed can also be recorded by measuring the wind pressure on a flat plate.

(iv) Hot wire anemometer measures the wind speed by recording cooling effect of the wind on hot wire. The heat is produced by passing an electric current through the wire.

(v) An anemometer can also be based on sonic effect. Sound travels through still air at a known speed. However, if the air is moving, the speed decreases or increases accordingly.

(vi) The other more novel techniques include the laser anemometer, the ultrasonic anemometer and the SODAR Doppler anemometer.

Figure 7.2 shows the typical anemograph of wind speed recorded at three heights, 10 m, 50 m and 150 m during strong winds. These records demonstrate the main characteristics of the flow in the region near ground. Main conclusions may be drawn as:

(i) Wind speed increases with height.

(ii) Wind speed is fluctuating with time, i.e. turbulences are present at the site.

(iii)The turbulence is spread over a broad range of frequencies.

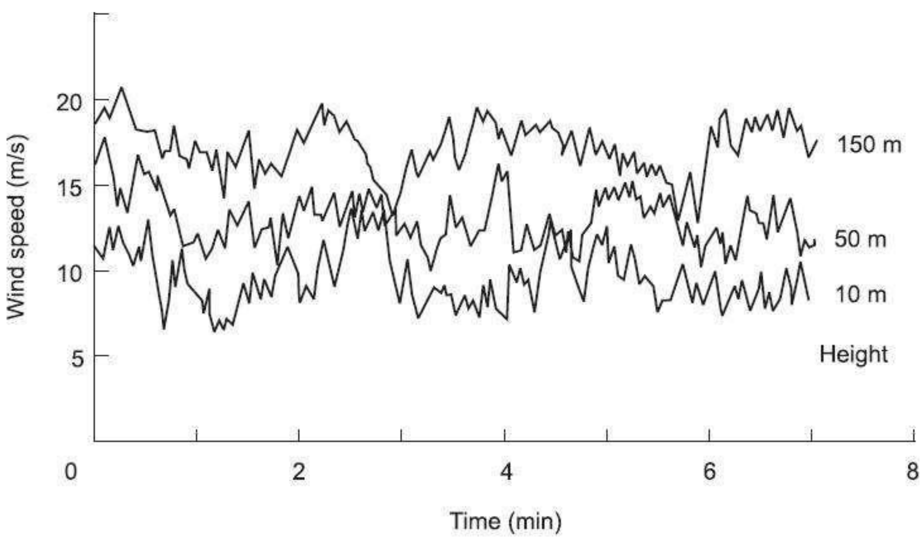


Figure 7.2 Wind speed recording

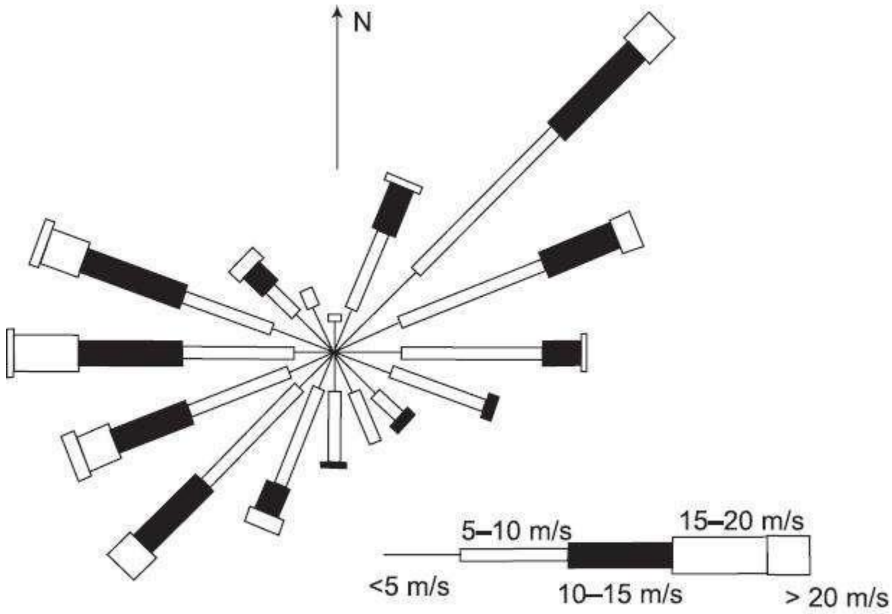


Figure 7.3 A typical wind rose

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.

Process of Wind Creation

- Wind is caused by differences in the atmospheric pressure. When a difference in atmospheric pressure exists, air moves from the higher to the lower pressure area, resulting in winds of various speeds.

- The two major driving factors of wind patterns are the differential heating between the equator and the poles (difference in absorption of solar energy) and the rotation of the planet.

- Each second, the sun releases an enormous amount of radiant energy into the solar system.

- Some of it reaches the earth:
  - strikes the equator directly (giving it the most radiation)
  - diffuses along the Northern and Southern Hemisphere
  - the poles receive the lowest amount of radiation

- The radiation from the sun heats the Earth's surface.

- Heating process creates temperature differences between the Land, Water, Air due to their different physical properties i.e.
  - Density

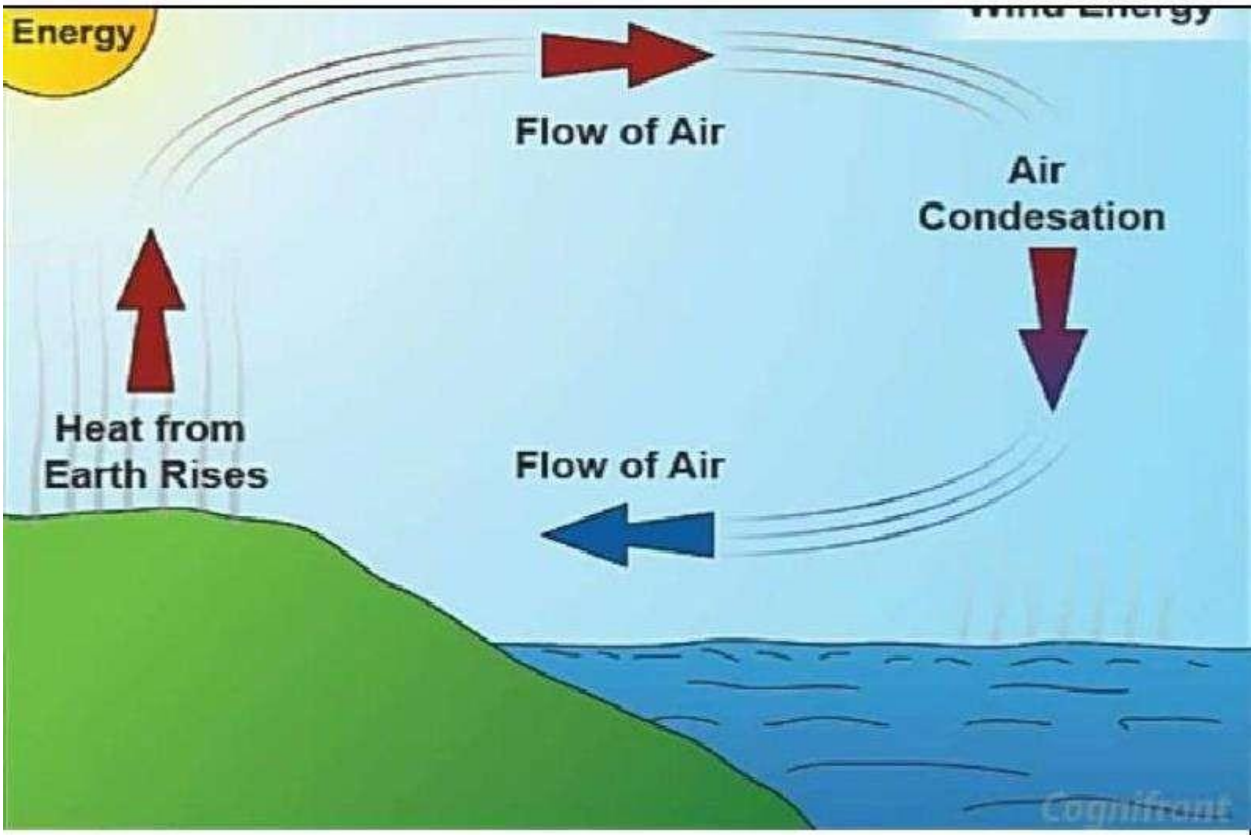
- Hot air rises, it expands, becomes less dense, and is then replaced by denser, cooler air.

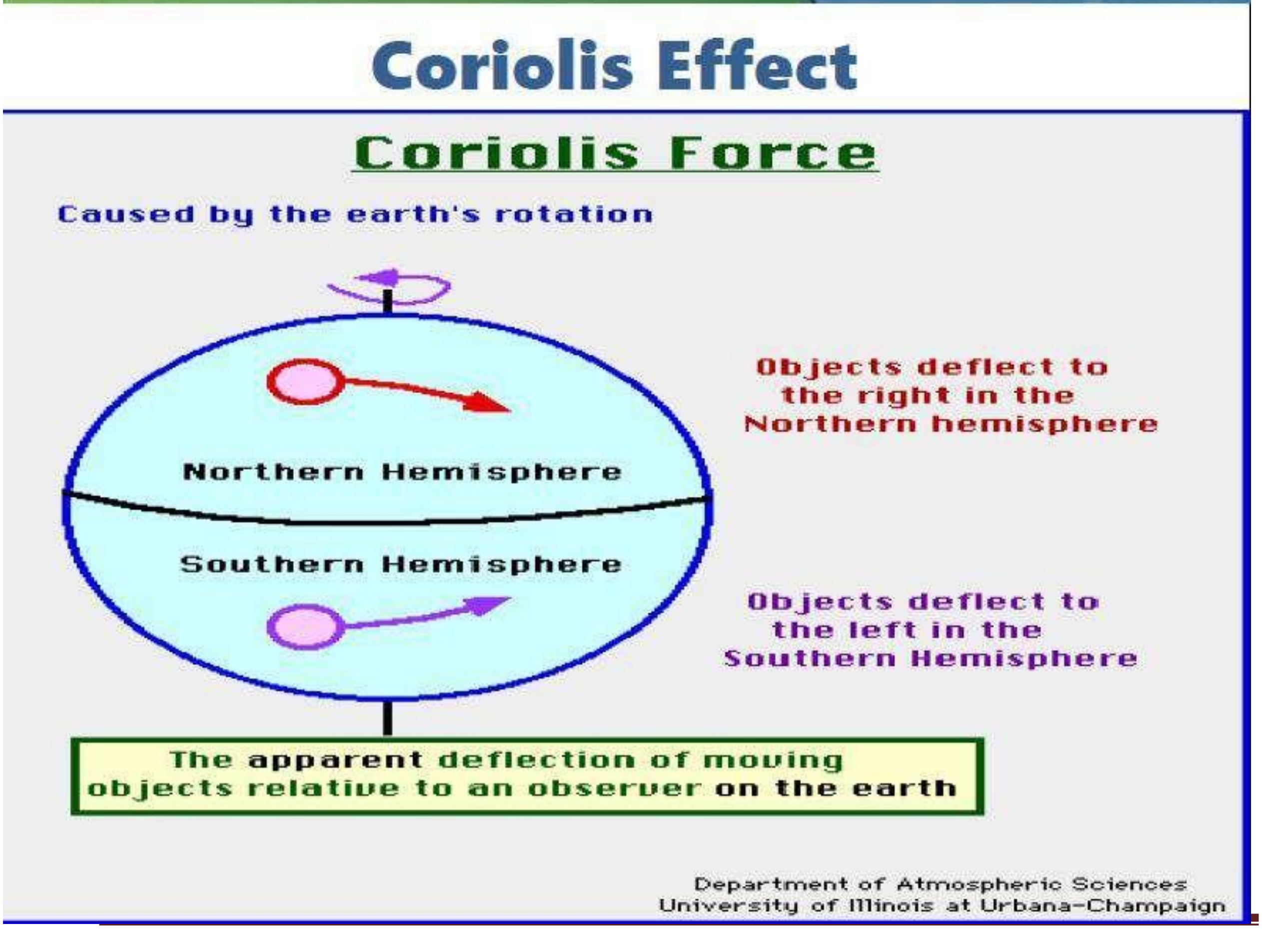
- Heated air rises from equator.

- Moves north and south in the upper levels of the atmosphere and circulates above cooler air.

- Wind is formed due to the phenomena called ***Coriolis Effect*** " the tendency for any moving body on or above the earth's surface to drift sideways from its course because of the earth's rotation".

Wind formation





Wind Turbines

- Rotating machines that can be used to generate electricity from the kinetic power of the wind.

- Alike aircraft propeller, turn in moving air, power the electric generator, supply electric current.

- For fan Electricity → Wind
- For turbines Wind → Electricity

- Wind rotates the turbine blades
  - spins a shaft connected to a generator
  - The spinning of the shaft in the generator makes electricity

- Efficiency depends on number of blades in windmill.

  Efficiency↑ as Blades↑ .

Blades

One

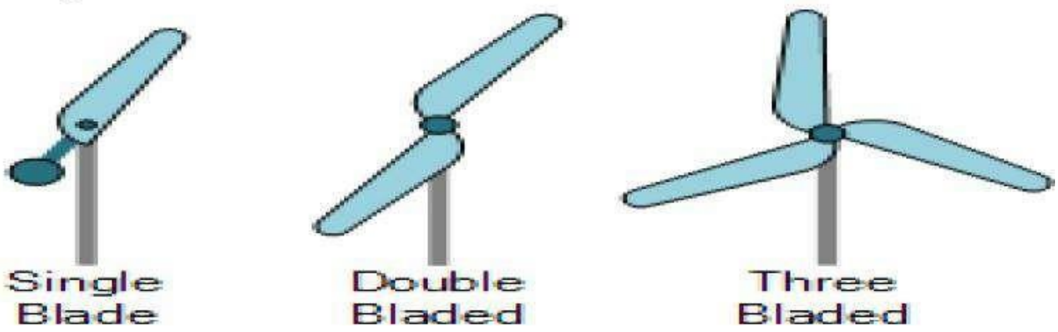
- Rotor must move more rapidly .
- Gearbox ratio reduced.
- Higher speed means more noise and other impacts.
- Captures 10% less energy than 2 blades design.
- Ultimately provide no cost savings.

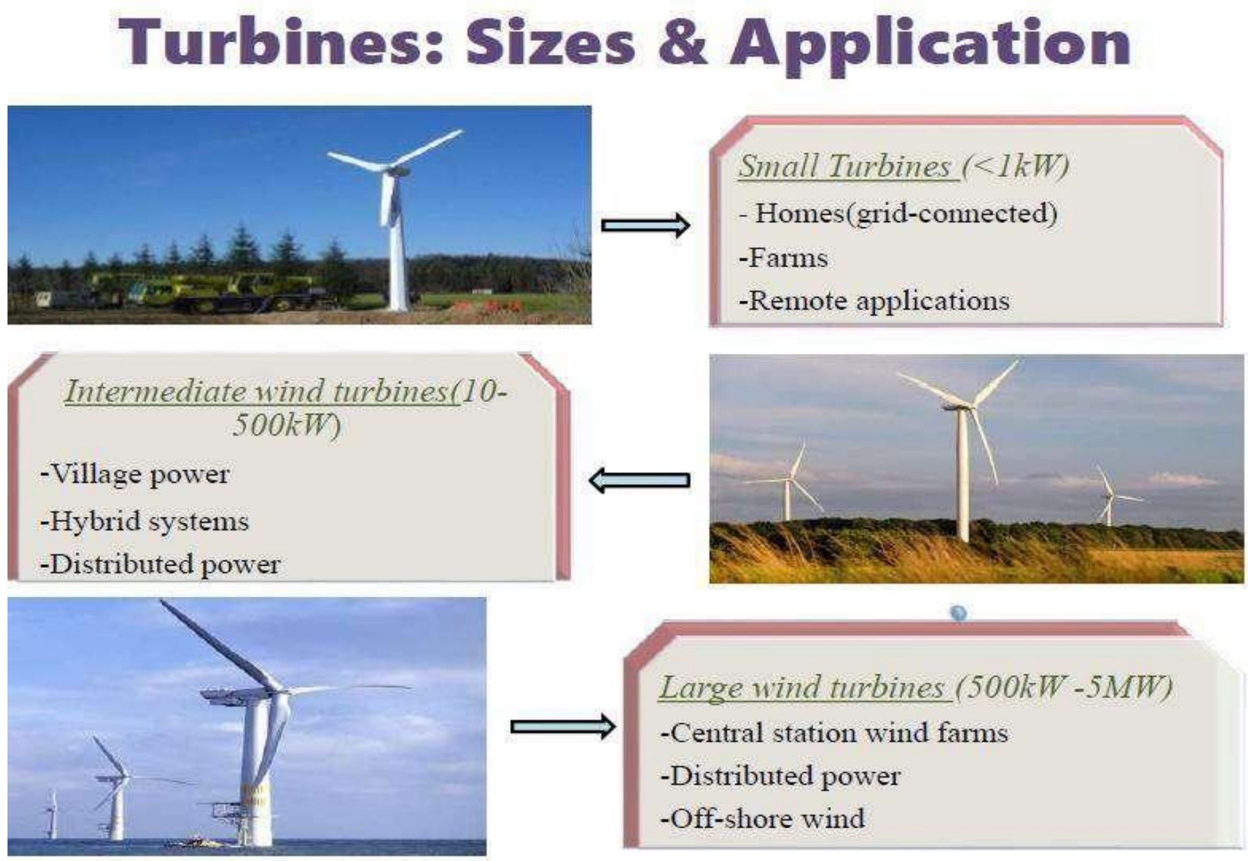
Two

- Rotor must move more rapidly.
- Higher speed means more noise and other impacts.
- Needs shock absorber because of gyroscopic imbalances.
- Captures 5% less energy than three blades design.

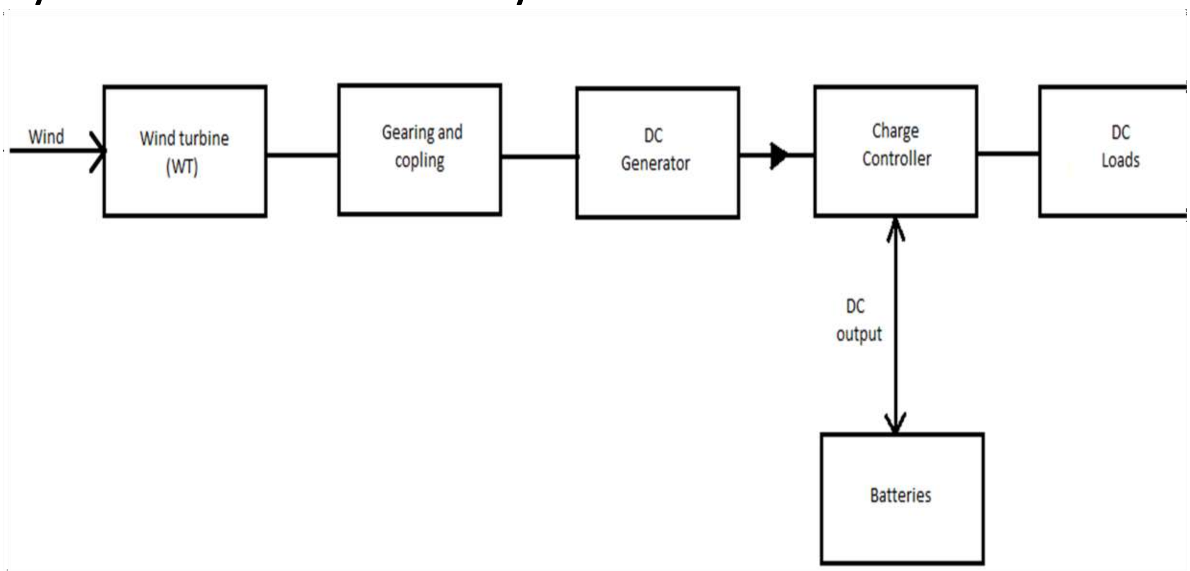
Three

- Balances of gyroscopic forces.
- Slower rotation
- Increases gearbox and transmission cost
- More aesthetic, less noise , fewer bird strikes.





How do you convert wind into electricity???

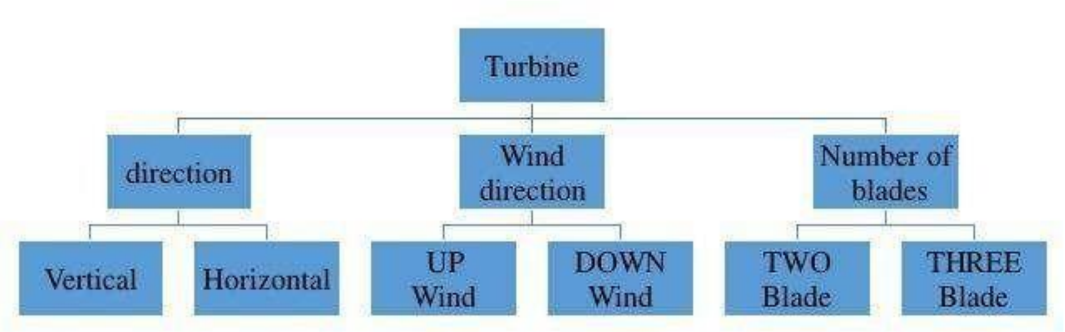


Wind turbines are classified into two general types: Horizontal axis and Vertical axis.

- A horizontal axis machine has its blades rotating on an axis parallel to the ground as shown in the above figure.

- A vertical axis machine has its blades rotating on an axis perpendicular to the ground.
- There are a number of available designs for both and each type has certain advantages and disadvantages.
- However, compared with the horizontal axis type, very few vertical axis machines are available commercially.

Classification of turbines By Mechanical features



1.Based on the direction

a. Horizontal axis wind mills:

i.Single Blade

ii.Double Blade

iii.Three Blade

b.Vertical Axis wind mills

i.Savonius

ii.Darrieus

2.Based on power out put

(i) Small wind power plants

Power output:10-50 kw,Rotor Dia.:1-16m.

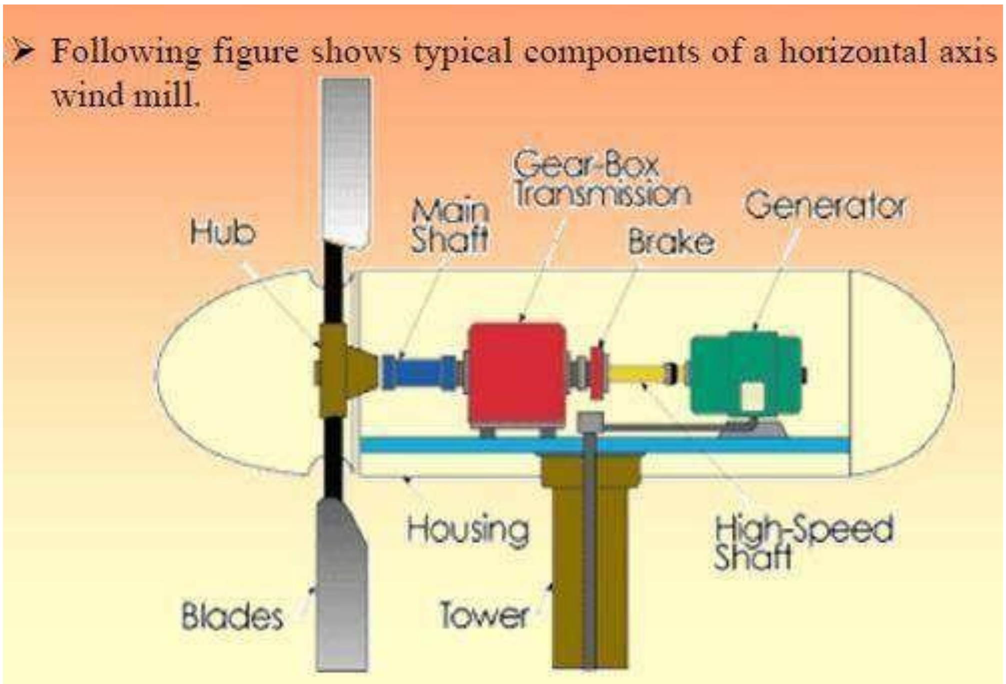
(ii)Medium size wind power plants

Power output:50-500 kw,Rotor Dia.:16-50m.

(iii) Large wind power plants

Power output:500-5000 kw,Rotor Dia.:50-130m

Main Components of a wind-mill



Rotor:

- The portion of the wind turbine that collects energy from the wind is called the rotor.
- The rotor usually consists of two or more wooden, fiberglass or metal blades which rotate about an axis (horizontal or vertical) at a rate determined by the wind speed and the shape of the blades.
- The blades are attached to the hub, which in turn is attached to the main shaft.

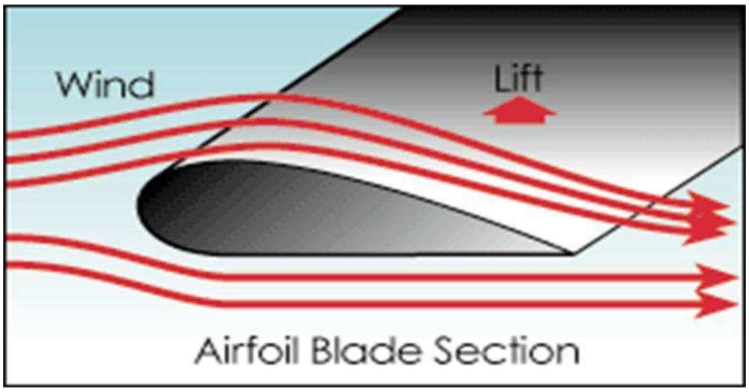
Drag Design:

- Blade designs operate on either the principle of drag or lift.
- For the drag design, the wind literally pushes the blades out of the way.
- Drag powered wind turbines are characterized by slower rotational speeds and high torque capabilities.

Lift Design:

- The lift blade design employs the same principle that enables airplanes, kites and birds to fly.
- The blade is essentially an airfoil, or wing.
- When air flows past the blade, a wind speed and pressure differential is created between the upper and lower blade surfaces.
- The pressure at the lower surface is greater and thus acts to "lift" the blade.
- When blades are attached to a central axis, like a wind turbine rotor, the lift is translated into rotational motion.
- Lift-powered wind turbines have much higher rotational speeds than drag types and therefore well suited for electricity generation.

- Following figure gives an idea about the drag and lift principle.



Tip Speed Ratio:

- The tip-speed is the ratio of the rotational speed of the blade to the wind speed.
- The larger this ratio, the faster the rotation of the wind turbine rotor at a given wind speed.
- Electricity generation requires high rotational speeds.
- Lift-type wind turbines have maximum tip-speed ratios of around 10, while drag-type ratios are approximately 1.
- Given the high rotational speed requirements of electrical generators, it is clear that the lift-type wind turbine is most practical for this application.
- The number of blades that make up a rotor and the total area they cover affect wind turbine performance.
- For a lift-type rotor to function effectively, the wind must flow smoothly over the blades.
- To avoid turbulence, spacing between blades should be great enough so that one blade will not encounter the disturbed, weaker air flow caused by the blade which passed before it.
- It is because of this requirement that most wind turbines have only two or three blades on their rotors.

Generator:

- The generator is what converts the turning motion of a wind turbine's blades into electricity.
- Inside this component, coils of wire are rotated in a magnetic field to produce electricity.
- Different generator designs produce either alternating current (AC) or direct current (DC), and they are available in a large range of output power ratings.
- The generator's rating, or size, is dependent on the length of the wind turbine's blades because more energy is captured by longer blades.
- It is important to select the right type of generator to match intended use.
- Most home and office appliances operate on 240 volt, 50 cycles AC.
- Some appliances can operate on either AC or DC, such as light bulbs and resistance heaters, and many others can be adapted to run on DC.
- Storage systems using batteries store DC and usually are configured at voltages of between 12 volts and 120 volts.
- Generators that produce AC are generally equipped with features to produce the correct voltage of 240 V and constant frequency 50 cycles of electricity, even when the wind speed is fluctuating.
- DC generators are normally used in battery charging applications and for operating DC appliances and machinery.
- They also can be used to produce AC electricity with the use of an inverter, which converts DC to AC.

Transmission:

- The number of revolutions per minute (rpm) of a wind turbine rotor can range between 40 rpm and 400 rpm, depending on the model and the wind speed.
- Generators typically require rpm's of 1,200 to 1,800.
- As a result, most wind turbines require a gear-box transmission to increase the rotation of the generator to the speeds necessary for efficient electricity production.
- Some DC-type wind turbines do not use transmissions.
- Instead, they have a direct link between the rotor and generator.
- These are known as direct drive systems.
- Without a transmission, wind turbine complexity and maintenance requirements are reduced.
- But a much larger generator is required to deliver the same power output as the AC-type wind turbines.

Tower:

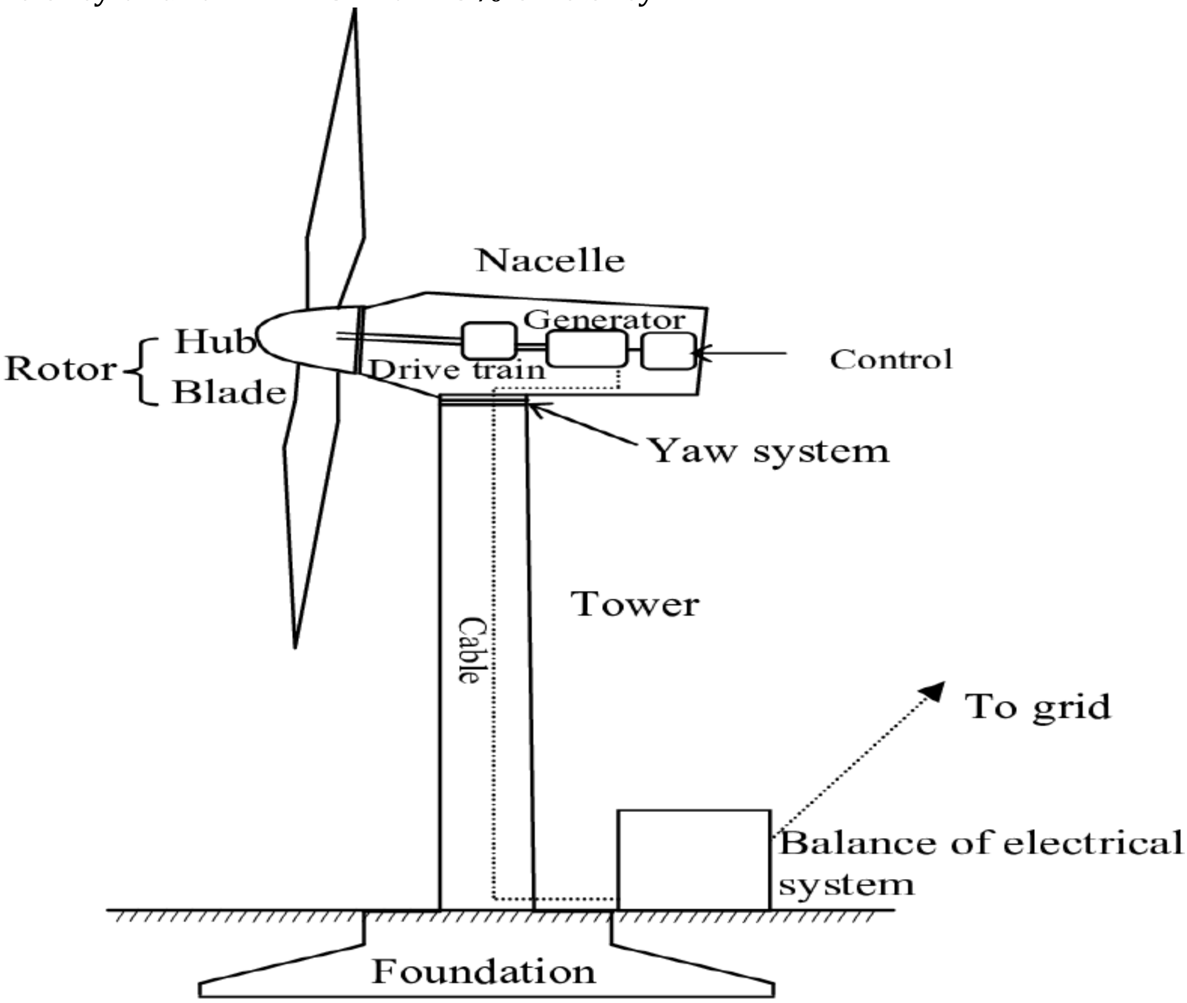
- The tower on which a wind turbine is mounted is not just a support structure.
- It also raises the wind turbine so that its blades safely clear the ground and so it can reach the stronger winds at higher elevations.
- Maximum tower height is optional in most cases, except where zoning restrictions apply.
- The decision of what height tower to use will be based on the cost of taller towers versus the value of the increase in energy production resulting from their use.
- Studies have shown that the added cost of increasing tower height is often justified by the added power generated from the stronger winds.
- Larger wind turbines are usually mounted on towers ranging from 40 to 70 meters tall.
- Towers for small wind systems are generally "guyed" designs.
- This means that there are guy wires anchored to the ground on three or four sides of the tower to hold it erect.
- These towers cost less than freestanding towers, but require more land area to anchor the guy wires.
- Some of these guyed towers are erected by tilting them up.
- This operation can be quickly accomplished using only a winch, with the turbine already mounted to the tower top.
- This simplifies not only installation, but maintenance as well. Towers can be constructed of a simple tube, a wooden pole or a lattice of tubes, rods, and angle iron.
- Large wind turbines may be mounted on lattice towers, tube towers or guyed tilt-up towers.

Horizontal Axis Wind Turbine(HAWT):

- This is the most common wind turbine design.
- In addition to being parallel to the ground, the axis of blade rotation is parallel to the wind flow.
- Some machines are designed to operate in an upwind mode, with the blades upwind of the tower.
- In this case, a tail vane is usually used to keep the blades facing into the wind.
- Other designs operate in a downwind mode so that the wind passes the tower before striking the blades.
- Some very large wind turbines use a motor-driven mechanism that turns the

machine in response to a wind direction sensor mounted on the tower.

Commonly found horizontal axis wind mills are aero-turbine mill with 35% efficiency and farm mills with 15% efficiency.



- Most have a gearbox, which turns the slow rotation of the blades into a high speed rotation that is more suitable for driving an electrical generator.
- Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Turbine blades are made stiff to prevent the blades from being pushed into 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 do not require 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 cyclic turbulence may lead to fatigue failure most HAWTs are upwind machines.
- Turbines used in wind farms for commercial production of electrical energy are usually three-bladed and pointed into the wind by computer-controlled motors. These have high tip speeds of over 320 kmph, high efficiency and low torque ripple, resulting in good reliability.
- The blades are usually coloured light gray to blend in with the clouds and range in length from 20 to 40 m or more.
- The tubular steel towers range from 60 to 90 m tall. The blades rotate at 10-22 rpm. At 22 rpm, the tip speed exceeds 90 m/s.

- A gear box is commonly used for stepping up the speed of the generator, although designs may also use direct drive of an annular generator.

HAWT Advantages:

- The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every ten meters up the wind speed can increase by 20% and the power output by 34%.
- High efficiency, since the blades always move perpendicularly to the wind, receiving power through the whole rotation. In contrast, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to backtrack against the wind for part of the cycle. Backtracking against the wind leads to inherently lower efficiency.

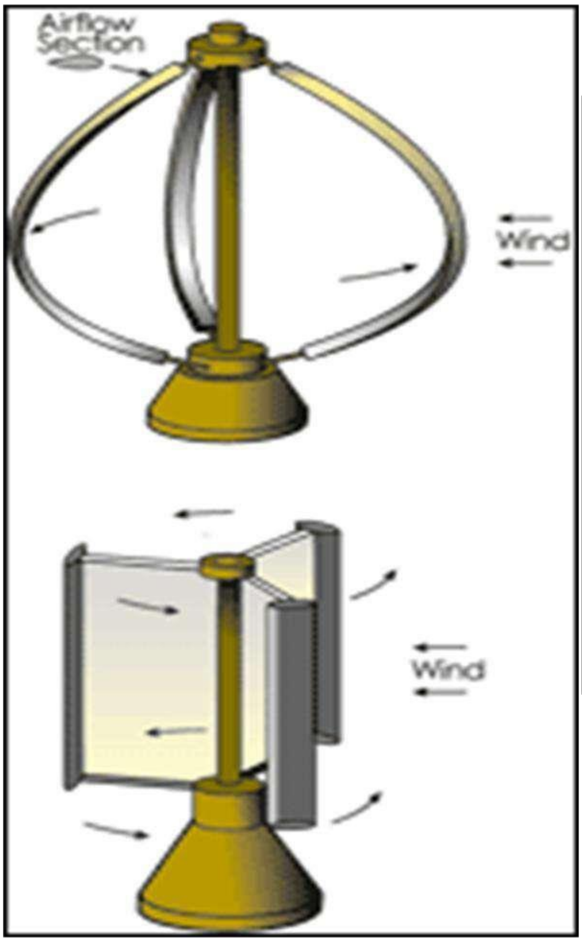
HAWT Disadvantages:

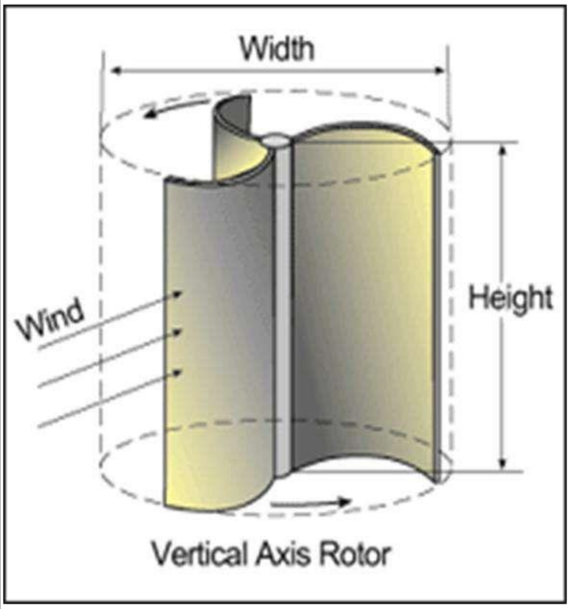
- Massive tower construction is required to support the heavy blades, gearbox, and generator.
- Components of a horizontal axis wind turbine (gearbox, rotor shaft and brake assembly) being lifted into position.
- Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.
- Downwind variants suffer from fatigue and structural failure caused by turbulence when a blade passes through the tower's wind shadow (for this reason, the majority of HAWTs use an upwind design, with the rotor facing the wind in front of the tower).
- HAWTs require an additional yaw control mechanism to turn the blades toward the wind.
- HAWTs generally require a braking or yawing device in high winds to stop the turbine from spinning and destroying or damaging itself.
- Cyclic Stresses & Vibration – When the turbine turns to face the wind, the rotating blades act like a gyroscope. As it pivots, gyroscopic precession tries to twist the turbine into a forward or backward somersault. For each blade on a wind generator's turbine, force is at a minimum when the blade is horizontal and at a maximum when the blade is vertical. This cyclic twisting can quickly fatigue and crack the blade roots, hub and axle of the turbines.

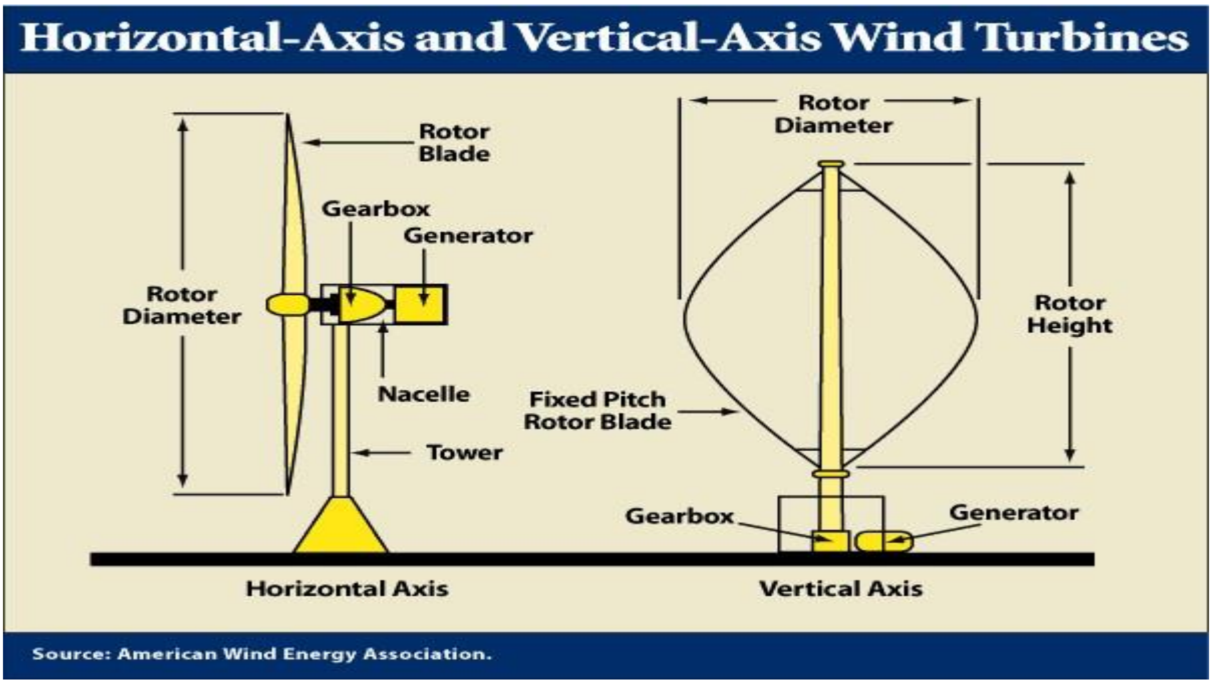
Vertical AxisWind Turbine (VAWT):

- Although vertical axis wind turbines have existed for centuries, they are not as common as their horizontal counterparts.
- The main reason for this is that they do not take advantage of the higher wind speeds at higher elevations above the ground as well as horizontal axis turbines.
- The basic vertical axis designs are the Darrieus, which has curved blades and efficiency of 35%, the Giromill, which has straight blades, and efficiency of 35%, and the Savonius, which uses scoops to catch the wind and the efficiency of 30%.
- A vertical axis machine need not be oriented with respect to wind direction.
- Because the shaft is vertical, the transmission and generator can be mounted at ground level allowing easier servicing and a lighter weight, lower cost tower.
- Although vertical axis wind turbines have these advantages, their designs are not as efficient at collecting energy from the wind as are the horizontal machine designs.
- There is one more type of wind-mill called Cyclo-gyro wind- mill with very high efficiency of about 60%. However, it is not very stable and is very sensitive to

wind direction. It is also very complex to build.
The following figures show all the above mentioned mills







Eggbeater or Darrieus Turbine:

- Eggbeater or Darrieus turbines have good efficiency but develop large torque ripple and cylindrical stress on the tower that results in poor reliability. They also usually need some external power source or an additional Savonius rotor to start turning due to poor starting torque. The torque ripple is reduced by using 3 or more blades resulting in a higher solidity for the rotor. Newer Darrieus type turbines are not held up by guy-wires but have an external superstructure connected to the top bearing.

- Giromill is subtype of Darrieus turbines with straight, as opposed to curved, blades. The cycloturbine has variable pitch in order to reduce the torque pulsation and is self-starting. The advantages of variable pitch are- high starting torque; a wide, relatively flat torque curve; a lower blade speed ratio, a higher coefficient of performance; more efficient in turbulent winds; and a lower blade speed ratio resulting in lower blade bending stresses. Straight Vee or curved blades may be used.
- **Savonius wind turbines** are drag type devices with two or more long helical scoops to provide a smooth torque.

VERTICAL AXIS WIND MILL ADVANTAGES:

- They can produce electricity in any wind direction.
- Strong supporting tower in not needed because generator, gearbox and other components are placed on the ground.
- Low production cost as compared to horizontal axis wind turbines.
- As there is no need of pointing turbine in wind direction to be efficient so yaw drive and pitch mechanism is not needed.
- Easy installation as compared to other wind turbine.
- Easy to transport from one place to other.
- Low maintenance costs.
- They can be installed in urban areas.
- Low risk for human and birds because blades moves at relatively low speeds.
- They are particularly suitable for areas with extreme weather conditions, like in the mountains where they can supply electricity to mountain huts.

VAWT Disadvantages

- Only one blade of the wind turbine works at a time, efficiency is very low compared to HAWTS.
- They need an initial push to start; this initial push that to make the blades start spinning on their own must be started by a small motor.
- When compared to horizontal axis wind turbines they are very less efficient because of the additional drag created when their blades rotate.
- They have relative high vibration because the air flow near the ground creates turbulent flow.
- Because of vibration, bearing wear increases which results in the increase of maintenance costs.
- They can create noise pollution.
- VAWTs may need guy wires to hold it up (guy wires are impractical and heavy in farm areas).

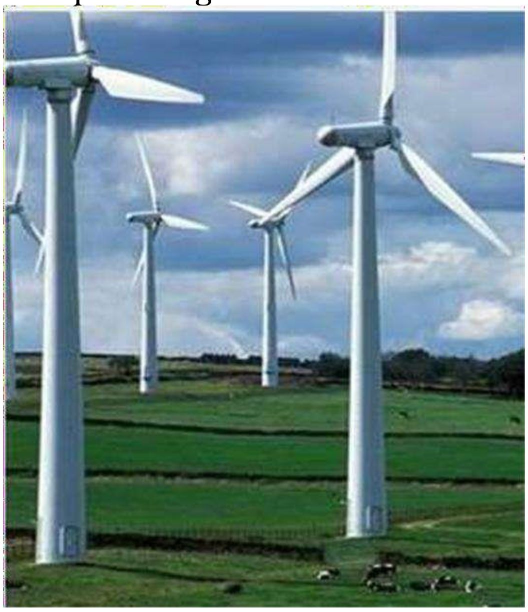
Differentiate between Horizontal and Vertical Axis Wind Turbine

Horizontal Axis	Vertical Axis
1. Major components at height	1. Major components at ground level
2. Rotating Speed -High	2. Rotating Speed -Low
3. Maintenance- High	3. Maintenance- Low
4. Cable standing Problem	4. No Cable standing Problem
5. Less life span	5. Long Life Span
6. Installation cost is High	6. Installation cost is Low
7. It run on high wind speed	7. It can run on lower wind speed
8. High tip to wind speed ration so high power output	8. Low tip to wind speed ration so low power output
9. Starting torque is less	9. Starting torque is high
10.Rotation is parallel to the wind direction.	10. Rotation is perpendicular to the wind direction

Onshore wind turbine:

Onshore advantages:

1. Normally it takes about 2-3 months before the wind turbine has paid itself back.
2. This also includes the energy, which were used to produce, install, maintain and remove the wind turbine.
3. Cheaper foundation
4. Cheaper integration with electrical- grid network



Onshore disadvantages:

1. Wind turbines are noisyEach one can generate the same level of noise as a family car travelling 70 mph
2. Some people thinks that the large towers of wind turbines destroys the view of the landscape

Offshore wind turbine:

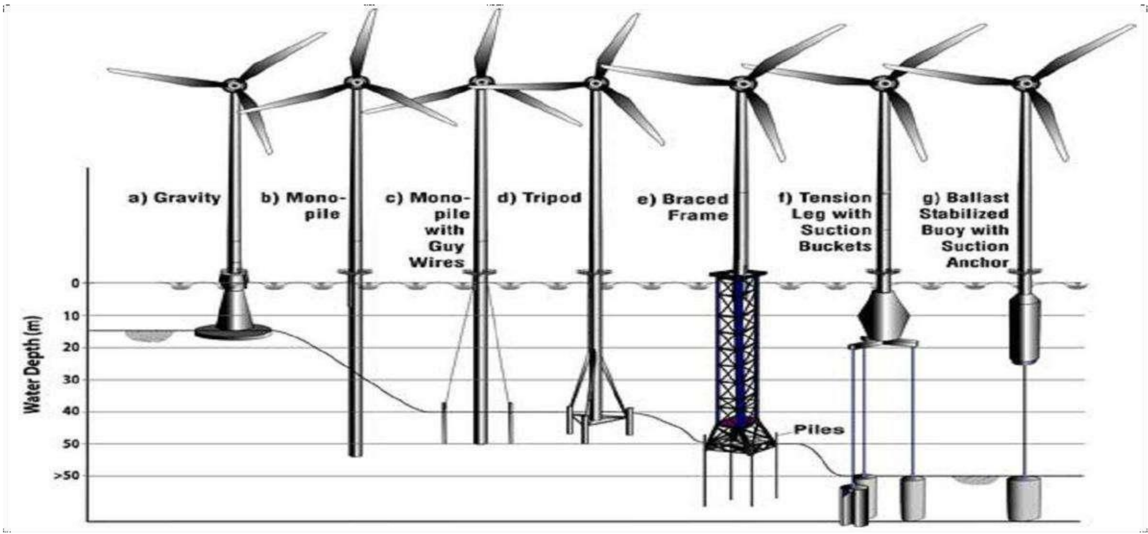
<u>Offshore advantages:</u>

1. A offshore wind turbine is stronger than a onshore turbine. It lasts around 25-30 years, and produces about 50 % more energy than a onshore turbine.
2. When a strong wind blows, it produces around 3-5 MW per hour.
3. Higher and more constant wind speed

<u>Offshore disadvantages:</u>

1. More expensive to built
2. More difficult to maintain and access

OFFSHORE FOUNDATION OPTIONS:



Operating Characteristics of wind mills

- All wind machines share certain operating characteristics, such as cut-in, rated and cut-out wind speeds.

  Cut-in Speed:
- Cut-in speed is the minimum wind speed at which the blades will turn and generate usable power.
- This wind speed is typically between 10 and 16 kmph.

  Rated Speed:
- The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power.

  For example, a "10 kilowatt" wind turbine may not generate 10 kilowatts until wind speeds reach 40 kmph.
- Rated speed for most machines is in the range of 40 to 55 kmph.
- At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind increases.

- The output of most machines levels off above the rated speed. Most manufacturers provide graphs, called "power curves," showing how their wind turbine output varies with wind speed.

Cut-out Speed:

- At very high wind speeds, typically between 72 and 128 kmph, most wind turbines cease power generation and shut down.
- The wind speed at which shut down occurs is called the cut-out speed.
- Having a cut-out speed is a safety feature whichprotects the wind turbine from damage.
- Shut down may occur in one of several ways. In some machines an automatic brake is activated by a wind speed sensor.
- Some machines twist or "pitch" the blades to spill the wind.
- Still others use "spoilers," drag flaps mounted on the blades or the hub which are automatically activated by high rotor rpm's, or mechanically activated by a spring loaded device which turns the machine sideways to the wind stream.
- Normal wind turbine operation usually resumes when the wind drops back to a safe level.

Betz Limit:

- It is the flow of air over the blades and through the rotor area that makes a wind turbine function.
- The wind turbine extracts energy by slowing the wind down.
- The theoretical maximum amount of energy in the wind that can be collected by a wind turbine's rotor is approximately 59%.
- This value is known as the Betz limit. If the blades were 100% efficient, a wind turbine would not work because the air, having given up all its energy, would entirely stop.
- In practice, the collection efficiency of a rotor is not as high as 59%. A more typical efficiency is 35% to 45%.
- A complete wind energy system, including rotor, transmission, generator, storage and other devices, which all have less than perfect efficiencies, will deliver between 10% and 30% of the original energy available in the wind.

Main considerations in selection of site for WECS

The power available in wind increases rapidly with wind speed. Therefore main consideration for locating a wind power generation plant is the availability of strong and persistent wind. A suitable site should preferably have some of the following features:

1. No tall obstructions for some distance (about 3 km) in the upwind direction (i.e. the direction of incoming wind) and also as low a roughness as possible in the same direction
2. A wide and open view, i.e. open plain, open shoreline or offshore locations
3. Top of smooth well-rounded hill with gentle slopes (about 1:3 or less) on a flat plain
4. An island in a lake or the sea
5. A narrow, mountain gap through which wind is channeled
6. The site should be reasonably close to power grid
7. The soil conditions must be such that building of foundations of the turbines and transport of road construction material loaded on heavy trucks must be feasible
8. If there are already wind turbines in the area, their production results are an excellent guide to local wind conditions.

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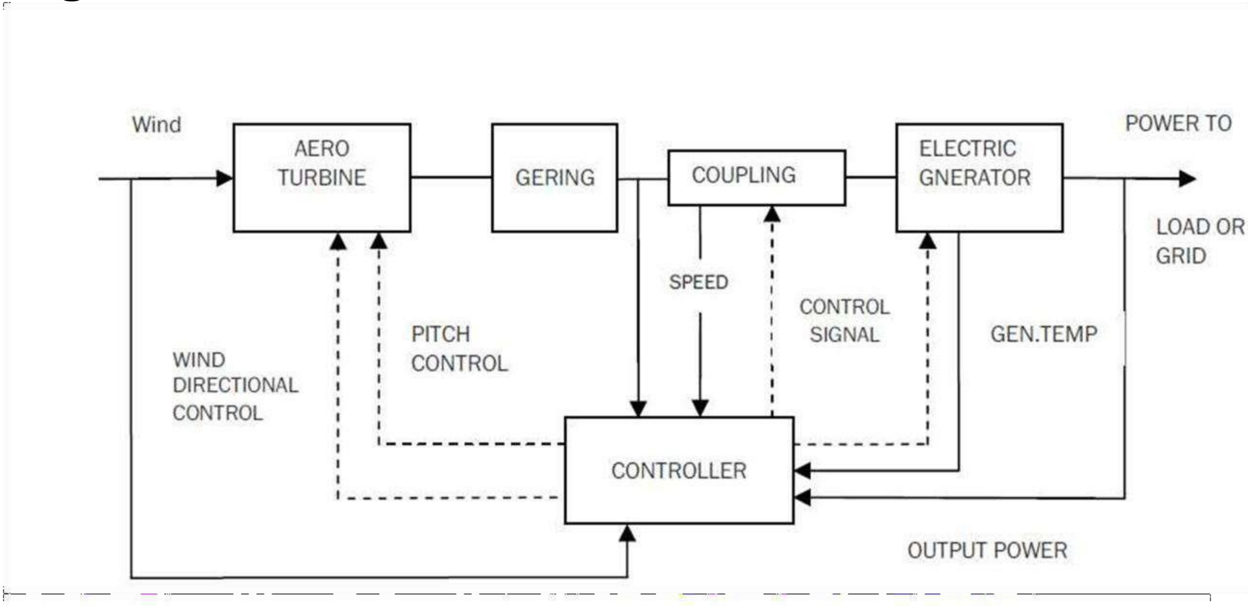
Explain various components of wind energy conversion system with diagram.



Rotor blades - capture wind's energy and convert it to rotational energy of shaft

Shaft - transfers rotational energy into generator

Nacelle - casing that holds:

Gearbox - increases speed of shaft between rotor hub and generator

Generator - uses rotational energy of shaft to generate electricity using electromagnetism

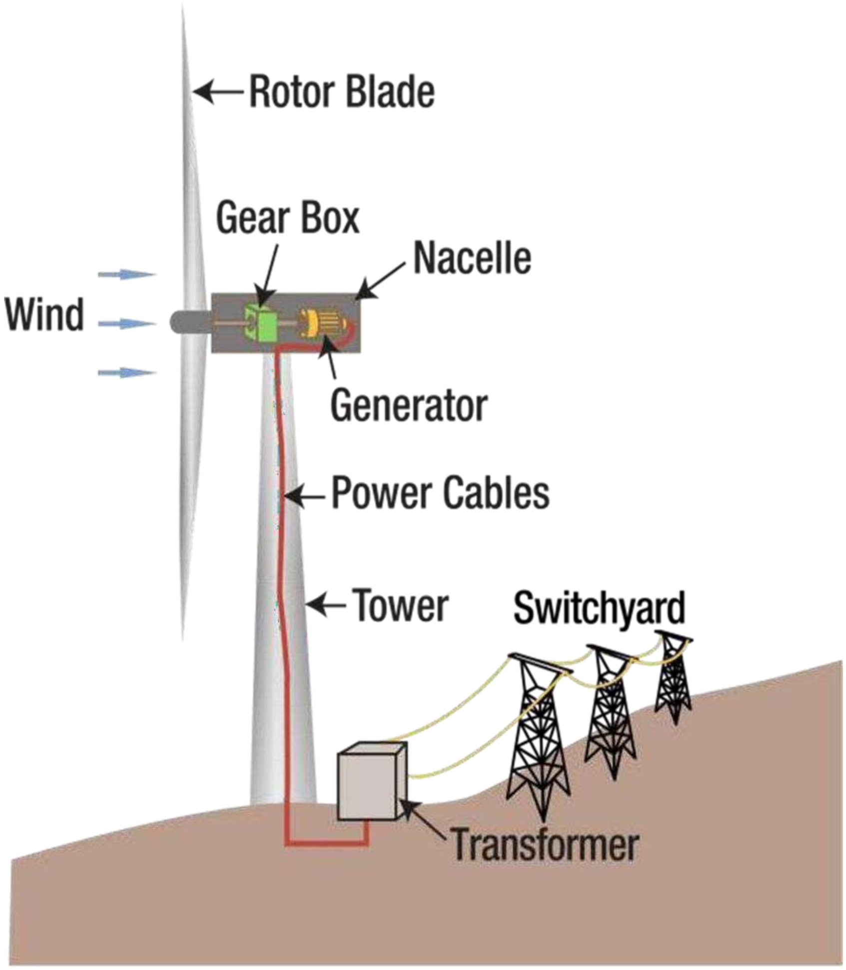
Electronic control unit (not shown) - monitors system, shuts down turbine in case of malfunction and controls yaw mechanism

Yaw controller (not shown) - moves rotor to align with direction of wind

Brakes - stop rotation of shaft in case of power overload or system failure

Tower - supports rotor and nacelle and lifts entire setup to higher elevation where blades can safely clear the ground

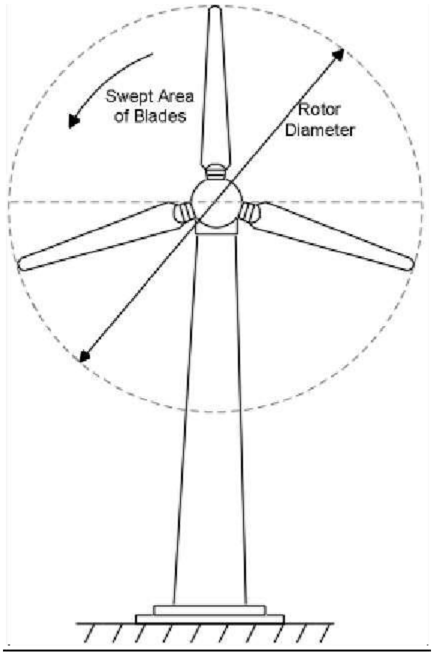
Electrical equipment - carries electricity from generator down through tower and controls many safety elements of turbine



Calculation of Wind Power:

Power in the Wind = $\frac{1}{2}\rho AV^3$

- Effective swept area, A
- Effective wind speed, V
- Effective air density, ρ



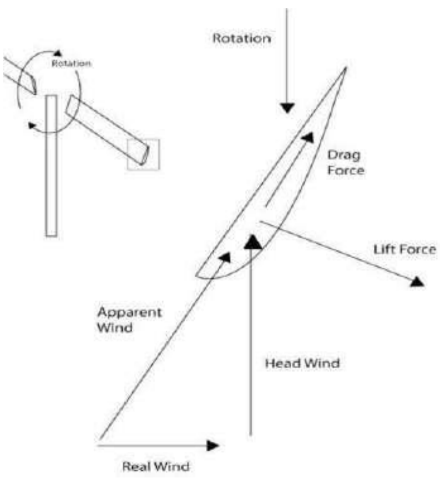
– Swept Area: $A = \pi R^2$ Area of the circle swept by the rotor (m^2).

PowerCoefficient(Cp): It 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.

$$Cp = \frac{\text{Actual Electrical Power Produced}}{\text{Wind Power into Turbine}} = \frac{P_{out}}{P_{in}}$$

Lift/Drag Forces Experienced by Turbine Blades



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

Where,

Ω = rotational speed in radians /sec

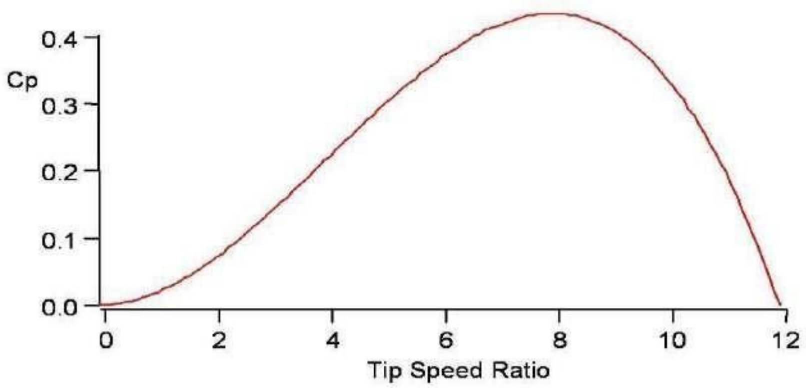
R = Rotor Radius

V = Wind —Free Stream|| Velocity

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

Performance Over Range of Tip Speed Ratios:

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

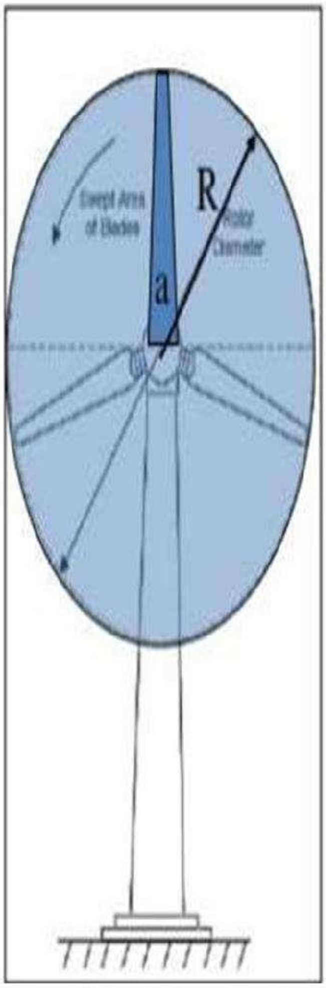


Rotor

Solidity is the ratio of total rotor plan form area to total swept area

Low solidity (0.10) = high speed, low torque

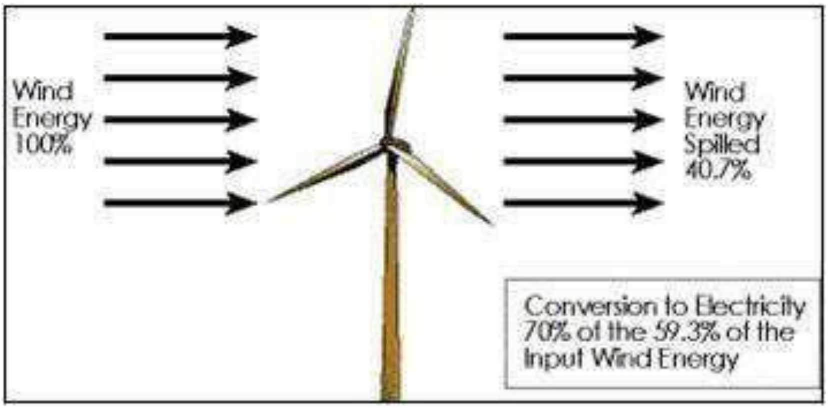
High solidity (>0.80) = low speed, high torque



Ratio of the blade area to the swept frontal area of wind turbine.

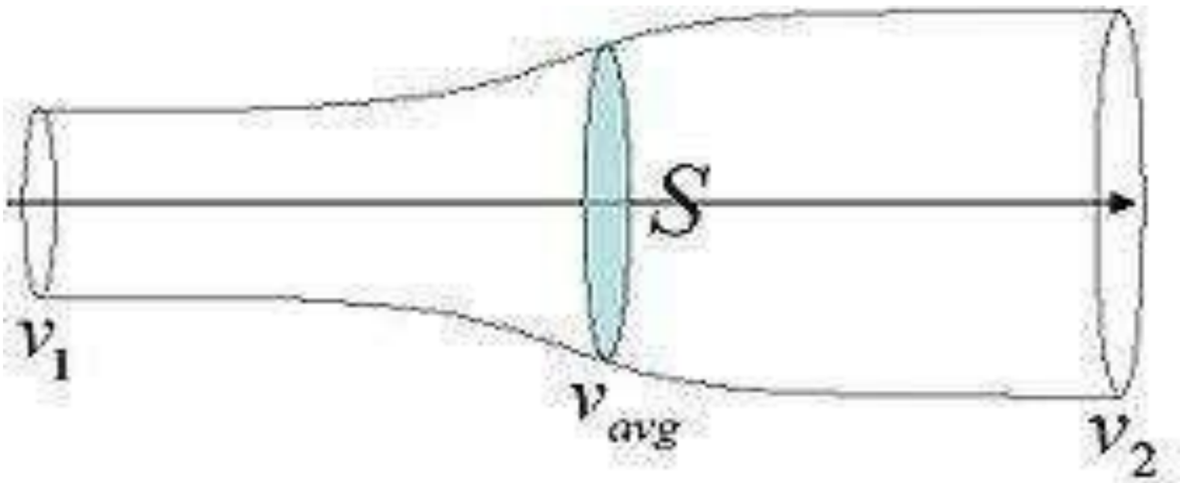
$$Solidity(\Upsilon) = \frac{Blade\ area}{Swept\ area} = \frac{nC}{R}$$

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.

Proof:



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.

2. 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.

3. This is incompressible flow. The density remains constant, and there is no heat transfer from the rotor to the flow or vice versa.

4. 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.

Speed Control Strategies for Wind Turbine

Various options are available for speed control of a turbine. The particular control strategy depends on the size of the turbine. Small machines use simple, low cost methods while large machines use more sophisticated methods incorporating pitch control along with power electronic circuit. These methods may be grouped in the following categories:

(i) No speed control at all. Various components of the entire system are designed to withstand extreme speed under gusty wind.

(ii) Yaw and tilt control, in which the rotor axis is shifted out of wind direction, either by yaw control or by tilting the rotor plane with respect to normal vertical plane when the wind exceeds the design limit.

(iii) Pitch control, in which the pitch of the rotor blades is controlled to regulate the speed.

(iv) Stall control, in which the blades are shifted to a position such that they stall when wind speed exceeds the safe limit.

MAJOR APPLICATIONS OF WIND POWER

Wind turbines have been built in power output range from a kilowatt to few MW to suit wide range of applications. Major applications may be grouped in three categories.

1. Applications Requiring Mechanical Power

(i) *Wind pumps*: Low power turbines are used for producing mechanical power for pumping water in remote areas. These are also known as wind pumps. Simple and reliable traditional reciprocating pumps or centrifugal pumps are used. These wind pumps are used to supply water for livestock, small-scale irrigation, low head pumping for aquatic breeding and domestic water supply. Mechanical power is also used to operate farm appliances.

(ii) *Heating*: The direct dissipation of mechanical power produces heat with 100 per cent efficiency using paddlewheel and other turbulent fluid systems. The available hot water is used as such or employed for space heating.

(iii) *Sea transport:* The old square-rigged sailing ships were inefficient as they were operated by drag forces (to be discussed later). Modern racing yachts, with a subsurface keel, harness lift forces and are much more efficient and can sail faster than the wind. Large cargo ships requiring power in MW range, driven by improved efficient sails are now being designed. Also wind turbines are installed onboard to power propellers in ferries operating on short routes.

2. As Off Grid Electrical Power Source

(i) Machines of low power with a rotor diameter of about 3 m and 40–1000 W rating can generate sufficient electrical energy for space heating and cooling of homes, water heating, battery charging, and for operating domestic appliances such as fan, light and small tools.

(ii) Applications for somewhat more powerful turbines of about 50 kW are: producing electrical power for navigation signal (e.g. lighthouse), remote communication, weather stations and offshore oil drilling platforms.

(iii) Intermediate power range, roughly 100 to 250 kW aero-generators can supply power to isolated populations, farm cooperatives, commercial refrigeration, desalination and to other small industries. The generator may operate in stand-alone mode or may be connected to a mini-grid system.

(iv) For lifting water to a hill, aero-generator is installed on the top of hill and electrical energy is transmitted to a pump fixed at a lower level. Same principle is utilized to store excess generated power using pumped storage system, to be utilized later during no wind periods.

3. As Grid Connected Electrical Power Source

Large aero-generators in the range of few hundred kW to few MW are planned for supplying power to a utility grid. Large arrays of aero-generators, known as *wind farms* are being deployed in open plains or offshore in shallow water for this purpose.

Specifications of wind turbine:

- **Turbine type:** RRB Energy PS500 – 500kW (50Hz) – (also available in 60Hz configuration)
- **Nominal Output:** 500 kW (50Hz & 60Hz)
- **Rotor diameter**: 47m
- **Tower Height:** 33m – 40m – 46m & 65m (3 sections)
- **Type:** Pitch controlled

Turbine:

Configuration: 3 Blades Horizontal Axis, Upwind Rated Power: 500kW

Cut in Wind Speed: 4 m/s Cut out Wind Speed: 25 m/s Nominal Wind Speed: 14 m/s Survival Wind Speed: 70 m/s

Rotor:

Rotor Diameter: 47m

Rotor RPM: 33 rpm / 43 rpm Swept Area: 1735 m2

Blade Material: Fiber glass / reinforced polyester

Generator:

Rated Power: 500kW

Type: Single Wound Asynchronous Frequency: 50HZ (60Hz also available) Voltage: 690 V – 3 phase

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

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

Examining the two equated expressions yields an interesting result, mainly

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

or

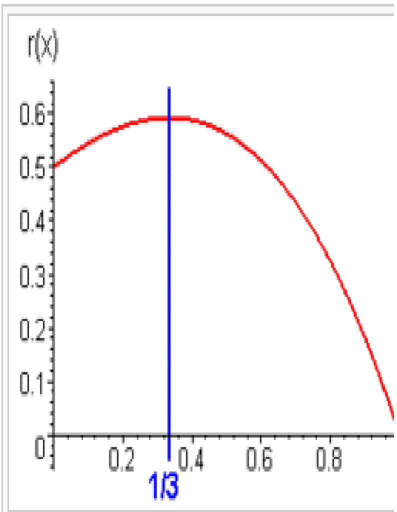
$$v = \frac{1}{2} \cdot (v_1 + v_2)$$

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.

Betz' law and coefficient of performance

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

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



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 $\frac{v2}{v1} = \frac{1}{3}$.

Substituting this value results in:

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

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

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

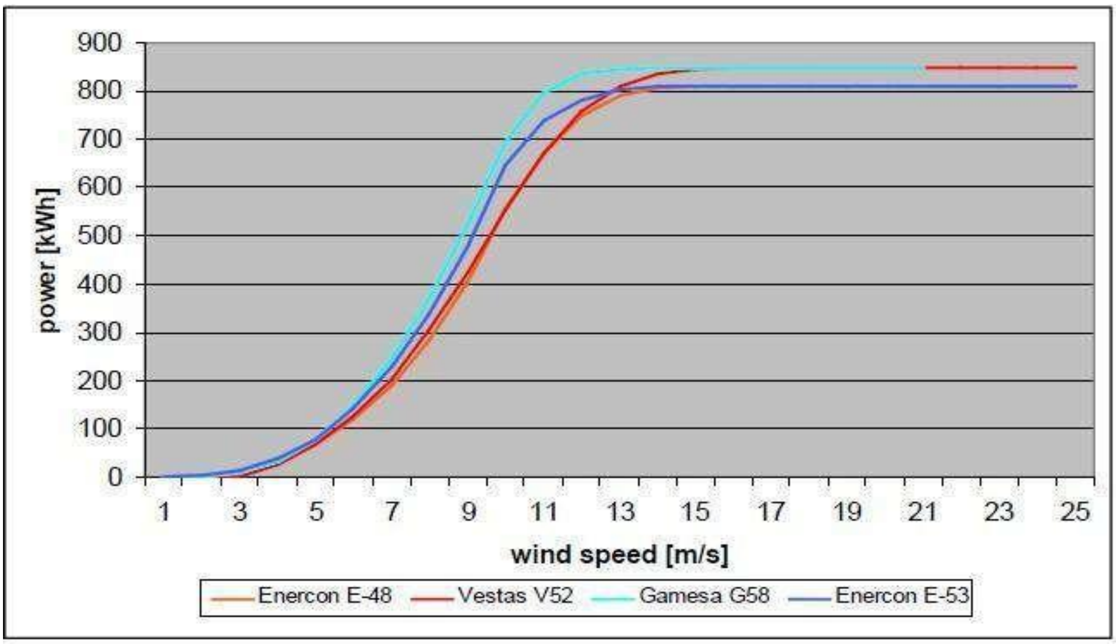
The *"power coefficient"* C_{p} (= P/P_{wind}) has a maximum value of: $C_{\mathrm{p.max}}$ = 16/27 = 0.593 (or 59.3%; however, coefficients of performance are usually expressed as a decimal, not a percentage).

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.

Several manufacturers are thus providing power curves which are calculated from the results of several measured ones; the performance of these calculated power curves might be contractually guaranteed by the manufacturers.

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,

$$T = \frac{P}{\omega} = \frac{P}{\pi DN}$$

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

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

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

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,

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

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

On substituting $v_e = 1/3\ v_i$

$$F_{x\,max} = \frac{4}{9g_c}\rho A V_i^2$$

$$= \frac{\pi}{9g_c}\rho D^2 V_i^2$$

- 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.

Wind Energy – 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 RE ssurces The total power in2008-2012 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 kilometer of open, shadow free area covered with 657 GW of installed capacity.

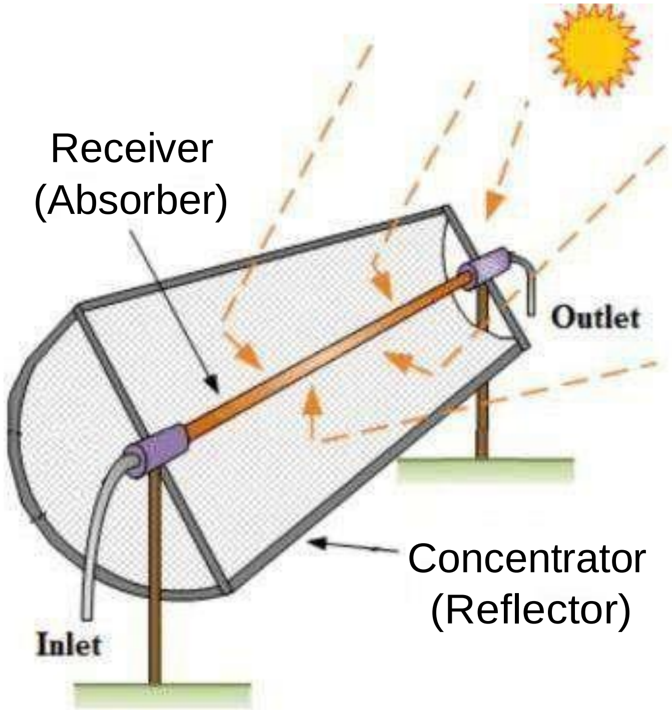
The total potential for wind power in India was first estimated by the Centre for Wind Energy Technology (C-WET) at around 45 GW, and was recently increased to 48.5 GW. This figure was also adopted by the government as the official estimate.

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.

However, the wind measurements were carried out at lower hub heights and did not take into account technological innovation and improvements and repowering of old turbines to replace them with bigger ones At heights of 55-65 meters, the Indian Wind Turbine Manufacturers Association (IWTMA) estimates that the potential for wind development in India is around 65-70 GW. The World Institute for Sustainable Energy, India (WISE) considers that with larger turbines, greater land availability and expanded resource exploration, the potential could be as big as 100 GW.

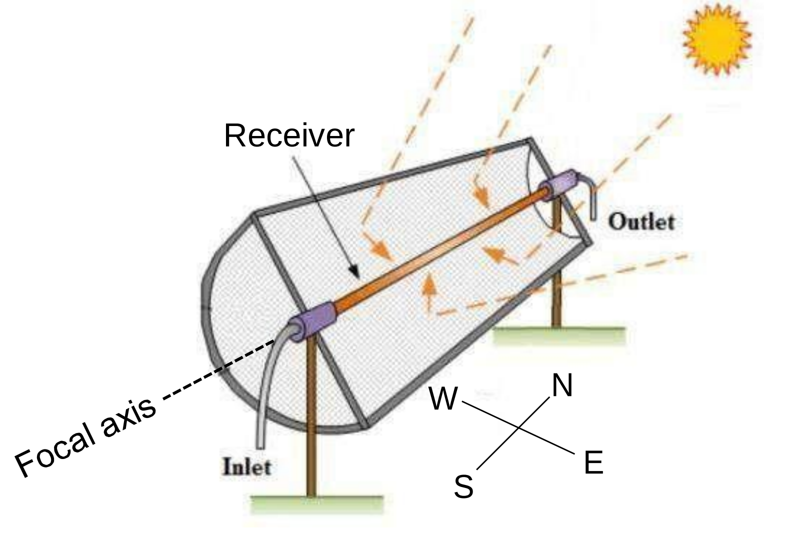
Concentrating Solar Collector

- Concentrating solar collectors are used to obtain energy at temperatures higher than those possible with flat plate solar collectors.
- The energy at high temperature can be obtained by increasing the solar radiation intensity (solar energy per unit area) falling on the absorber surface. This can be achieved by using large reflective surface, called concentrator or reflector, to concentrate sunlight onto a small area (receiver or absorber) as shown in the figure.

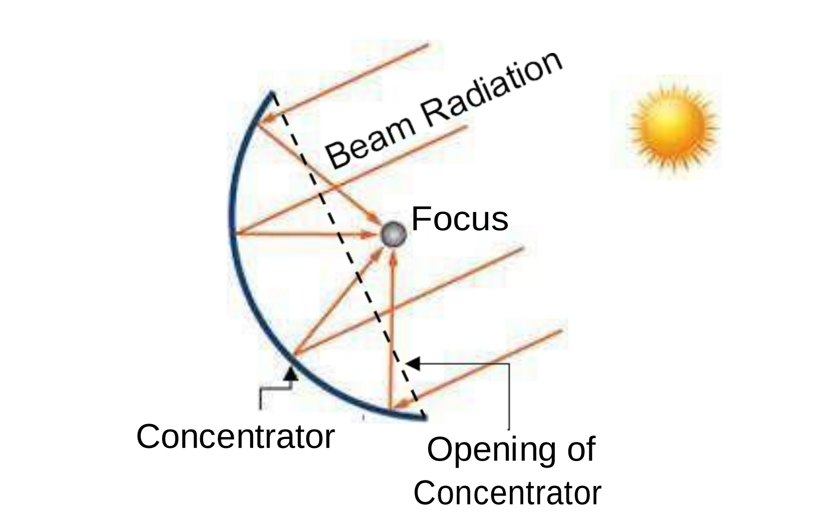


Concentrating Solar Collector

The reflecting surface (concentrator) focuses the beam radiation to the receiver only when the beam radiation enters perpendicularly through the opening of concentrator and receiver (absorber) is placed at focal axis of concentrator.

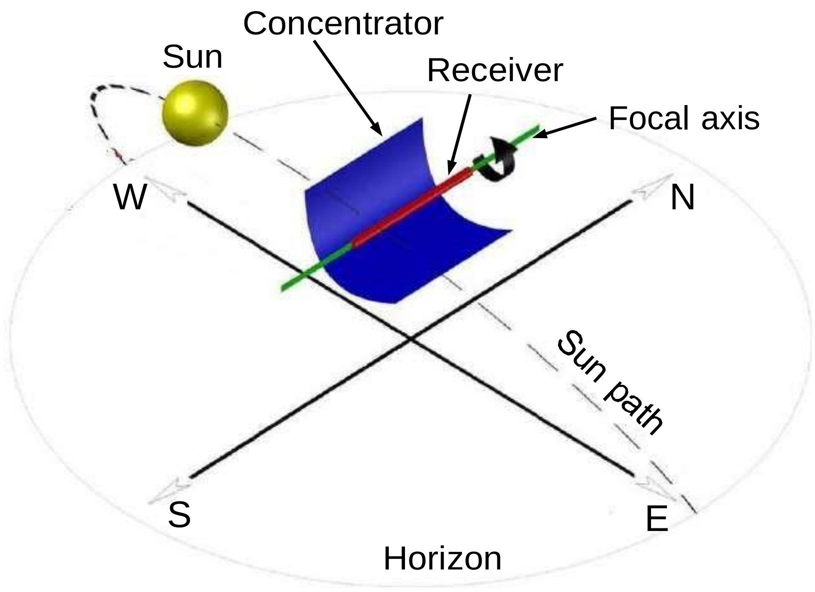


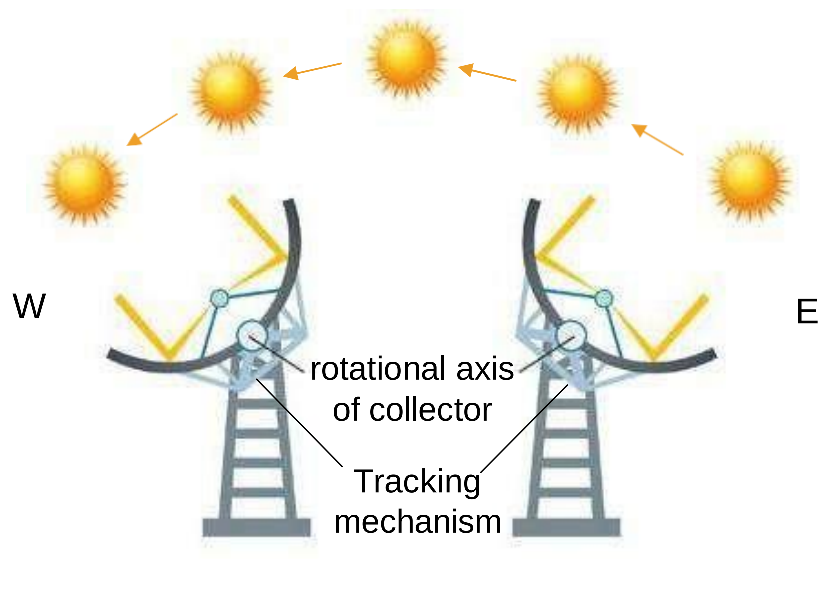
Concentrating solar collector



Cross-section of concentrator

Hence concentrating collectors should always be oriented towards sun by using sun tracking mechanism so that beam radiation always enters perpendicularly through the opening of concentrator.

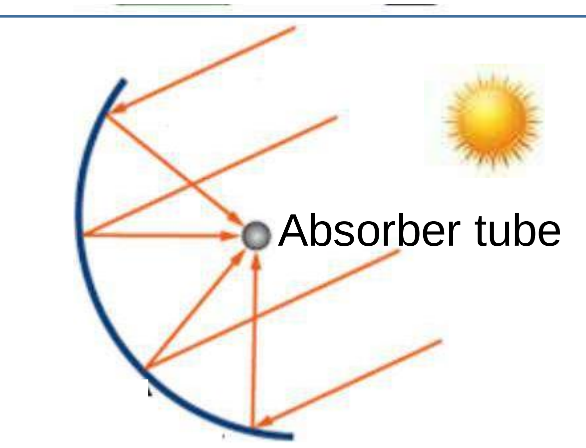


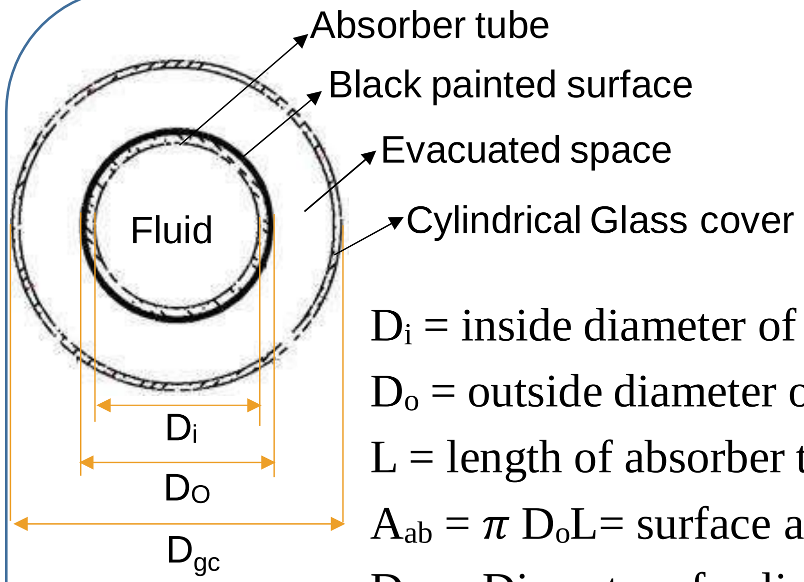


Basic terms and definitions related with concentrating collector

Receiver

- The component of concentrating collector system which receives the concentrated solar radiation is called receiver. It is used to convert the solar radiation energy into thermal energy.
- It consists of a cylindrical shaped absorber tube. The absorber tube is generally made of stainless steel or copper.
- The outside surface of absorber tube is painted carbon black in order to enhance the absorption of solar radiation falling on it.
- The cylindrical shaped absorber tube is surrounded by an evacuated cylindrical glass cover to reduce thermal losses from absorber tube surface.
- A working fluid usually synthetic oil or water flows through the absorber tube. The reflected solar radiation striking the absorber tube surface is absorbed into the working fluid, which transfers the absorbed solar energy for some useful application such as conversion of water into steam in the generator/boiler of solar energy based thermal power plant to produce electricity using steam turbine.





D_i = inside diameter of absorber tube

D_o = outside diameter of absorber tube

L = length of absorber tube

$A_{ab} = \pi D_o L$ = surface area of absorber

D_{gc} = Diameter of cylindrical glass cover

Cross section of absorber tube

Basic terms and definitions related with concentrating collector

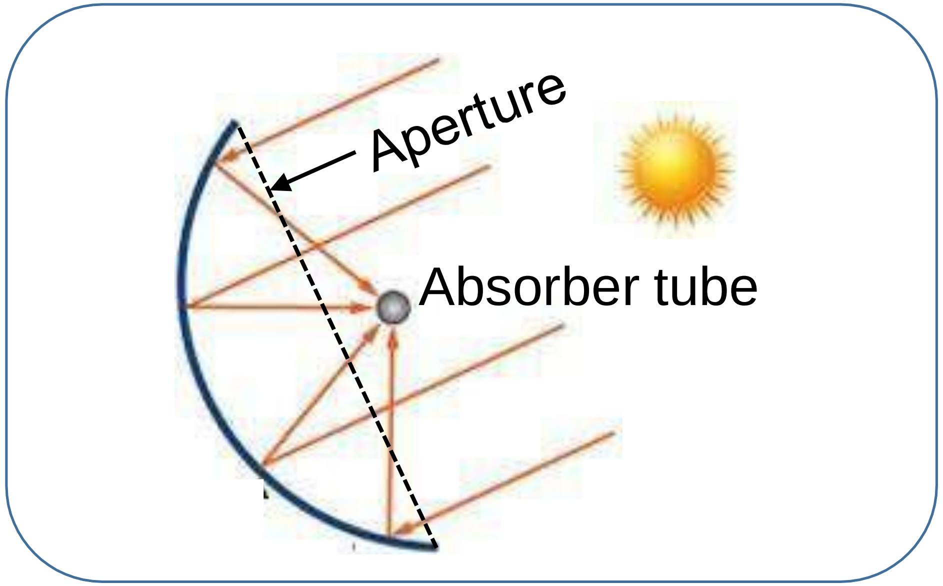
Aperture of Concentrator

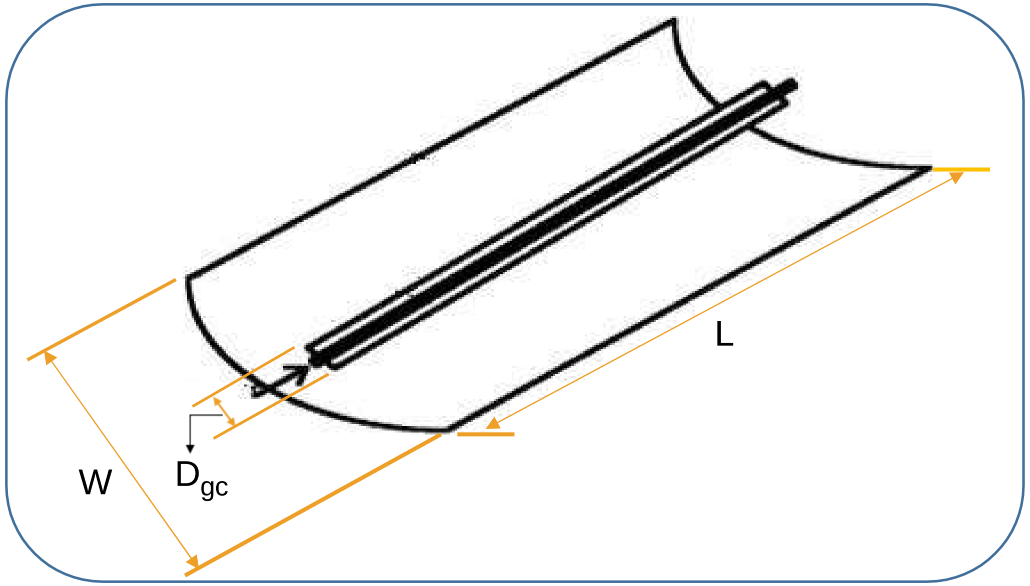
- The aperture of concentrator is the opening through which solar radiation enters the concentrator and the area of this concentrator opening is called aperture area.

- As shown in Fig. below, a small portion of this opening area is blocked due to presence of receiver, hence aperture area, by taking into account the shading of central part of the collector by receiver, is given by:

Aperture area (A_{ap}) = concentrator opening area – area blocked by receiver

$$A_{ap} = W \times L - D_{gc} \times L = \left(W - D_{gc}\right) \times L$$





Basic terms and definitions related with concentrating collector

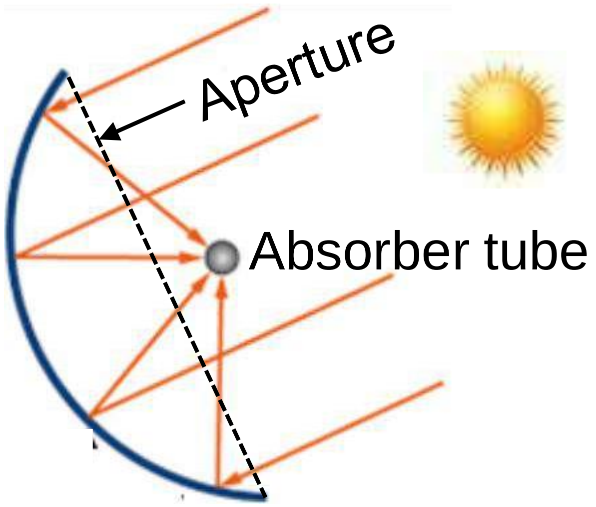
Absorbed radiation flux (S)

- For concentrating collector, the solar radiation absorbed by absorber tube is expressed in terms of absorbed radiation flux per unit aperture area and this is known as absorbed radiation flux. For example:

Let us say, for a given concentrating collector system:

Absorbed radiation flux (S) is 500 W/m^2, and aperture area (A_{ap}) is 2 m^2

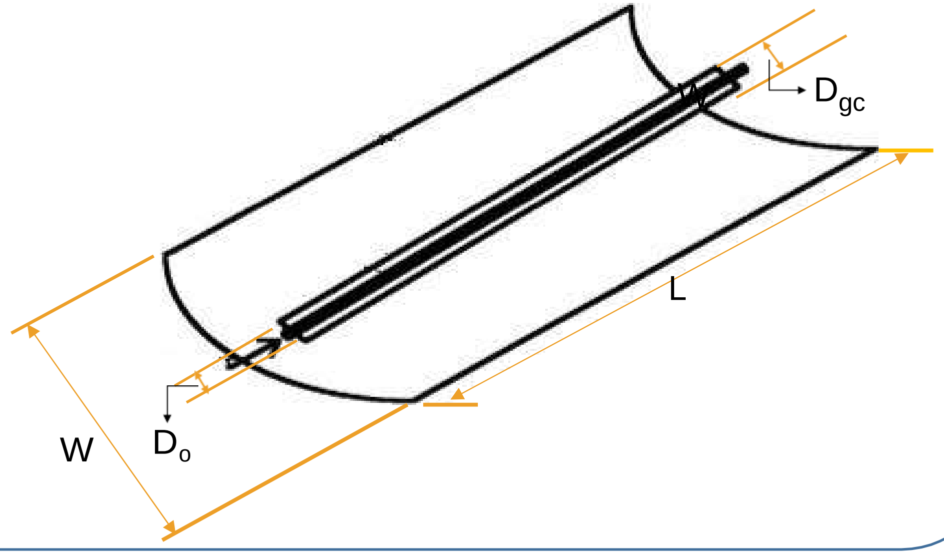
It means total energy absorbed by absorber tube surface per unit time is 500×2 =10000 W



Concentration ratio (C)

- Concentration ratio is the ratio of aperture area to the surface area of the absorber, i.e.,

$$C = \frac{Aperture\ area}{Absober\ tube\ surface\ area} = \frac{(W - D_{gc}) \times L}{\pi D_o L}$$



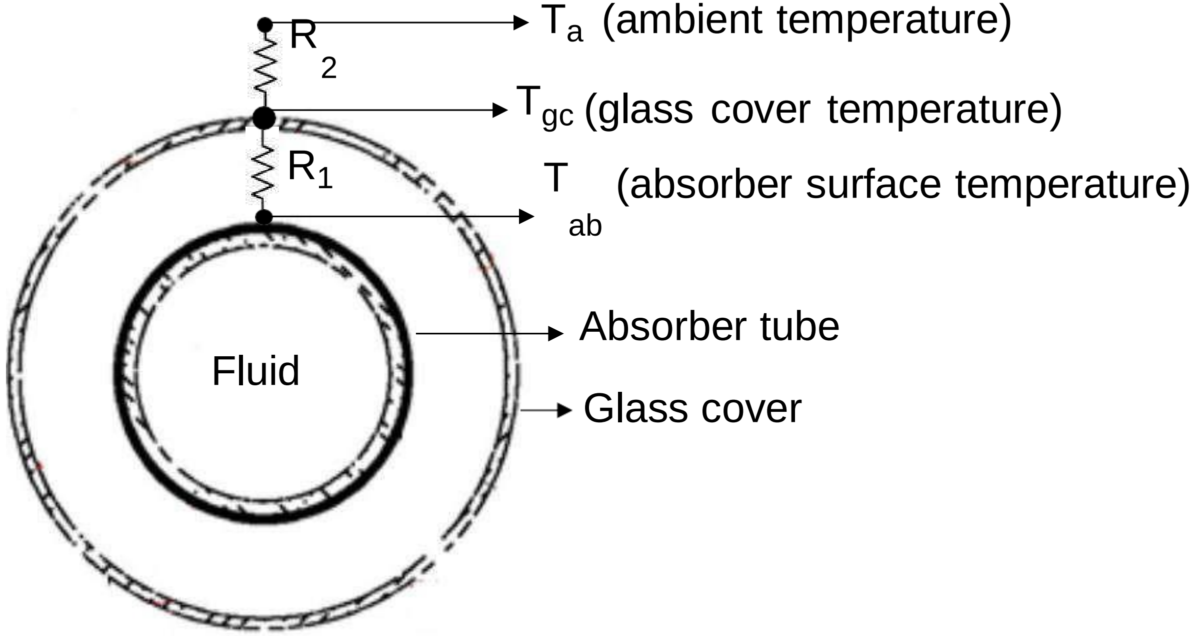
Basic terms and definitions related with concentrating collector

Overall loss coefficient (U_L)

- Overall loss coefficient is the overall heat transfer coefficient corresponding to thermal energy loss from absorber tube surface to surroundings and it can be estimated by using thermal network approach, as shown in Fig below. By using Fig. given below, heat loss rate from unit area of absorber surface to surrounding can be written as:

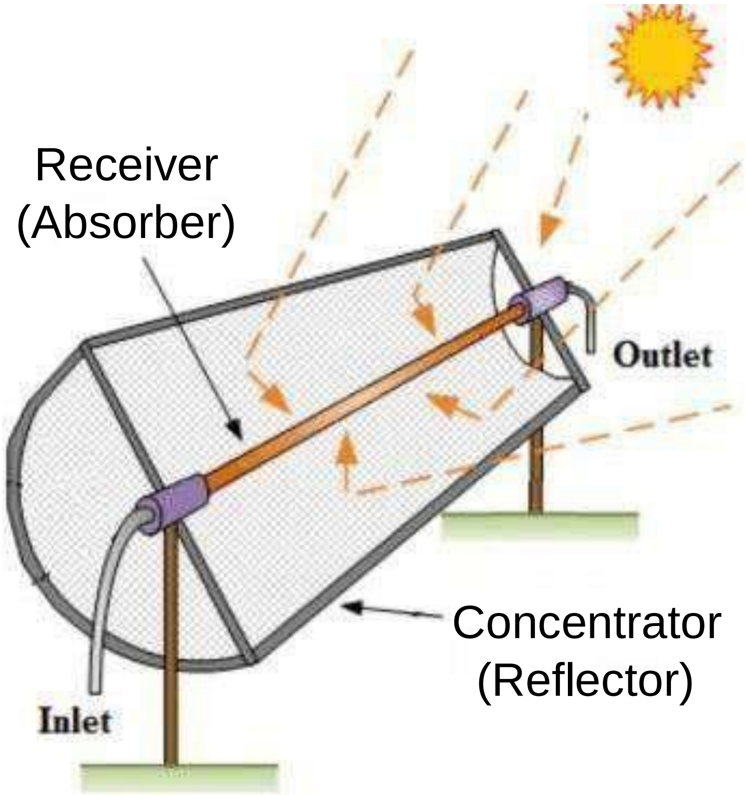
$$q_L = U_L(T_{ab} - T_a) = \frac{T_{ab} - T_a}{R_1 + R_2}$$

$$\therefore U_L = \frac{1}{R_1 + R_2}$$

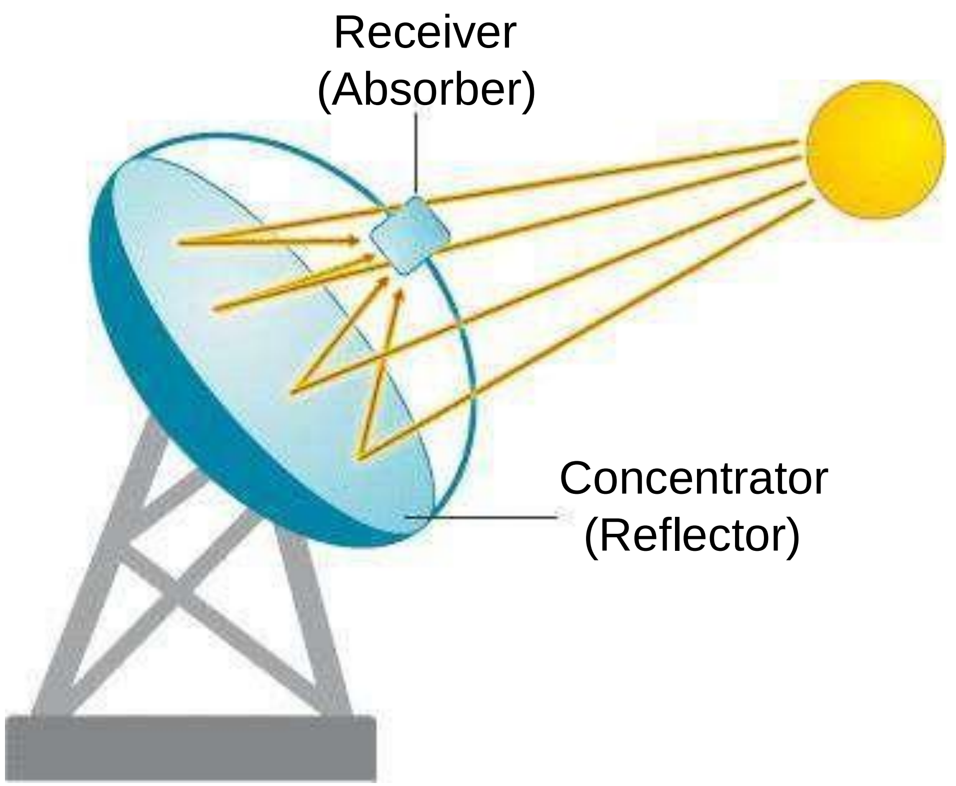


Types of Concentrating Solar Collectors

- There are broadly two types of concentrating solar collectors
  - Parabolic trough collector (PTC)
  - Parabolic dish collector (PDC)



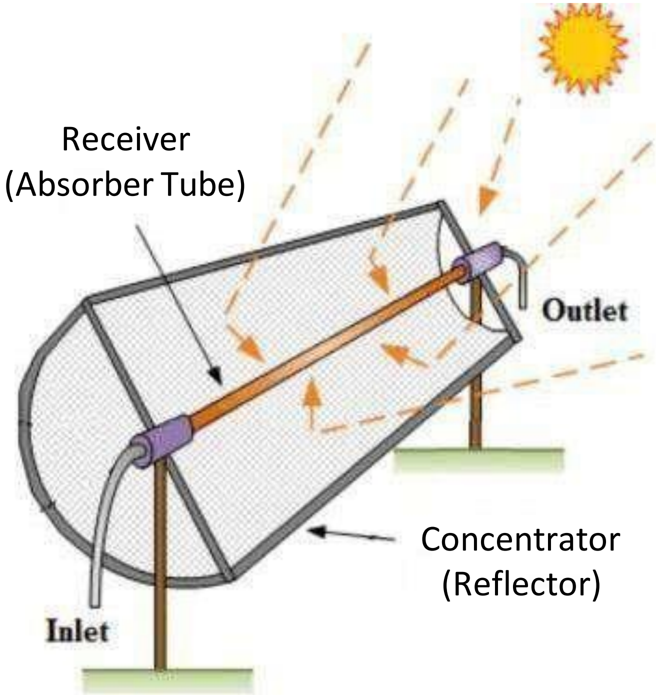
Parabolic trough collector



Parabolic dish collector

Parabolic trough collector (PTC)

- A parabolic-trough collector (PTC) is a line focusing type solar collector.
- The reflector/concentrator is manufactured in the form of a trough with the parabolic cross-section.
- It is fabricated from aluminium or SS sheet and its sun facing surface is mirror polished to increase its reflectivity.
- The parabolic-trough-shaped concentrator reflects direct solar radiation towards the focal line (focal axis) of the parabola.



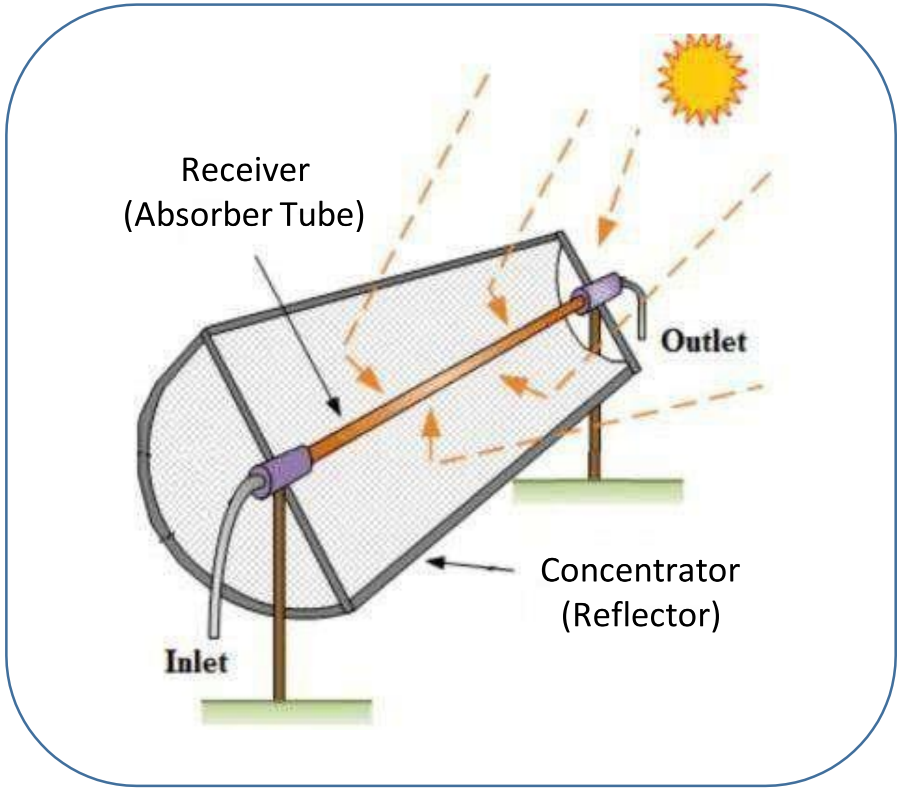
Parabolic trough collector (PTC)

- An absorber tube is placed along the focal line of parabolic trough collector and a working fluid (usually synthetic oil or water) flows through it. When the reflected solar radiations fall on the absorber tube, it heats the fluid to a high temperature. The solar radiation is thus transformed into thermal energy in the form of sensible or latent heat of the fluid.

- The working fluid also transfers the absorbed solar energy from solar collector to some other location for subsequent use, hence working fluid is also called **heat transfer fluid (HTF)**.

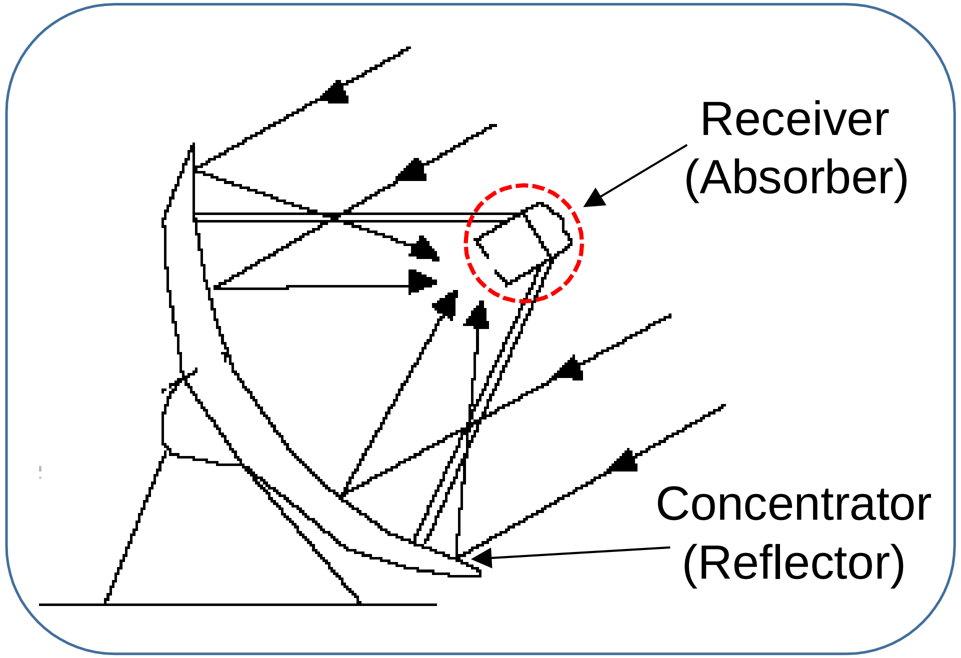
- The thermal energy of HTF can be used to supply heat to various industrial energy demanding processes (e.g., curing, drying, dyeing, washing, boiling, pasteurisation and sterilization) in industries such as food industry, petro-chemical industry, textile industry etc.

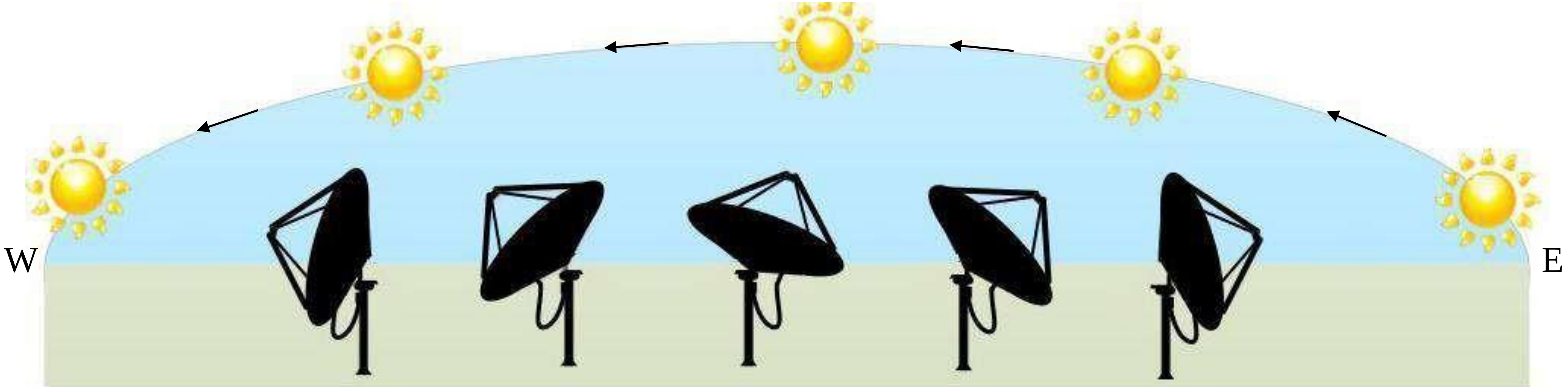
- The thermal energy of HTF can also be used for converting water into steam in the generator/boiler in a solar energy based thermal power plant to produce electricity with a steam turbine.



Parabolic dish collector (PDC)

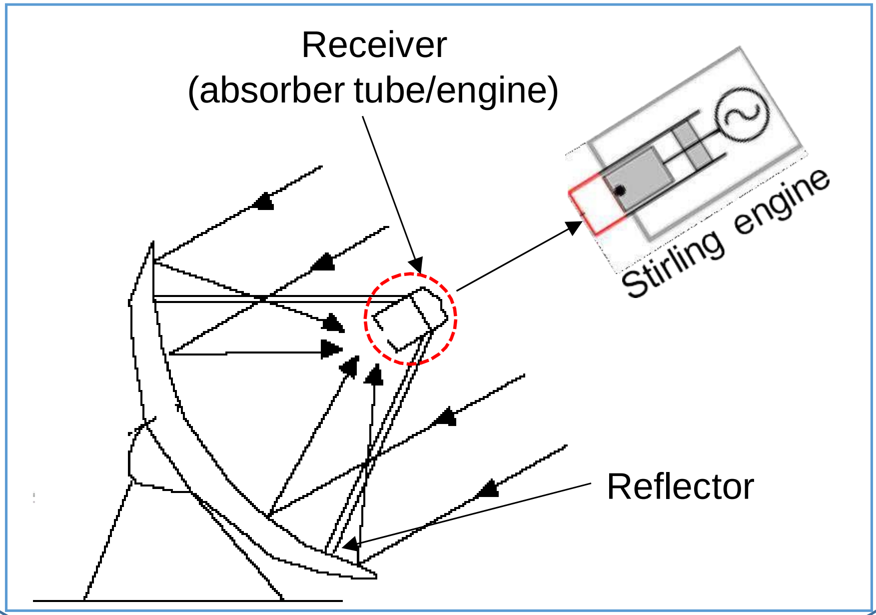
- A parabolic dish collector is a point focusing type solar collector.
- The parabolic-dish-shaped reflector reflects direct solar radiation towards a small focal point area in front of the dish.
- A parabolic dish collector system uses a dual-axis tracking to follow the Sun across the sky and concentrate the Sun's rays towards the focal point of parabolic dish.
- The reflector dish is formed into a paraboloidal shape by stamping them out from thin sheet metal.





Parabolic dish collector (PDC)

- The parabolic solar dish is covered with several mirror reflectors all around its shape to help concentrate the solar energy into a single focal point. The reasons for using several mirror reflectors instead of a single highly polished dish are:
  - They are relatively inexpensive.
  - They can be easily cleaned.
  - The individual mirrors can be easily replaced if damaged.
  - They can last a long time in an extreme outdoor environment conditions.
- Parabolic dish collector focuses the Sun's rays onto the receiver located at the focal point in front of the dish. The receiver can be as simple as a small absorber tube or a more complex solar heat engine, such as a **Stirling Engine**.
- Due to the very high temperatures at the focal point, a synthetic thermal oil type fluid is generally used instead of water inside the receiver, which transfers the intense heat created by focusing the sunlight on the receiver.



Thermal analysis of concentrating collector

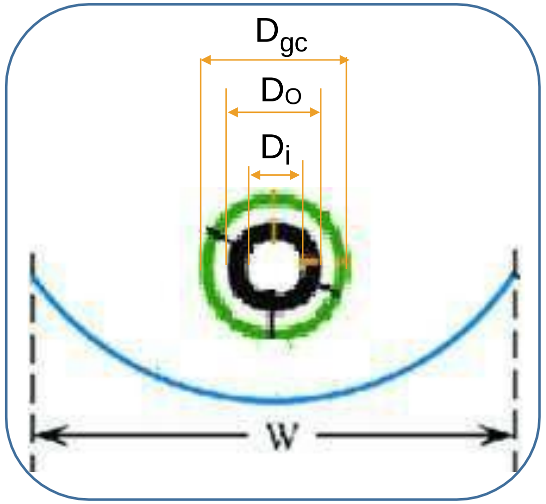
- The procedure for thermal analysis of concentrating collector is same as that for flat plate collector. Following the same procedure, the mathematical expressions of collector efficiency factor, collector heat removal factor and useful energy gain for concentrating collector are as follows:

Parameters	Concentrating collector	Flat plate collector
Collector Efficiency Factor (F_1)	$\dfrac{1/U_L}{\dfrac{1}{U_L} + \dfrac{D}{h_{fi}D_i} + \dfrac{D}{2k}\ln\left(\dfrac{D}{D_i}\right)}$ where, h_{fi} is heat transfer coeff. on inside tube wall surface, D is tube outside diameter, D_i is tube inside diameter and k is thermal conductivity of tube material	$\dfrac{1/U_L}{W\left[\dfrac{1}{U_L[D + (W - D)F]} + R_b + \dfrac{\ln(D/D_i)}{2\pi k} + \dfrac{1}{h_{fi}\pi D_i}\right]}$
Collector heat removal factor (F_R)	$zF_1\left[1 - \exp\left(-\frac{1}{z}\right)\right]$, where $z = \dfrac{\dot{m}c_p}{A_{ab}F_1U_L}$	$zF_1\left[1 - \exp\left(-\frac{1}{z}\right)\right]$, where $z = \dfrac{\dot{m}c_p}{A_cF_1U_L}$
Useful energy gain (Q_u)	$Q_u = F_R \times Q_{max} = F_R\left[A_{ap}S - A_{ab}U_L(T_{fi} - T_a)\right]$ where, S is absorbed solar radiation flux per unit aperture area	$Q_u = F_R \times Q_{max} = F_R \times A_c\left[S - U_L(T_{fi} - T_a)\right]$ where, S is absorbed solar radiation flux per unit absorber plate area

Question

A parabolic trough collector is 10 m long and 2.5 m wide. The ambient temperature is 10°C and absorbed radiation flux per unit aperture area is 430 W/m^2. The absorber is a cylindrical tube surrounded by an evacuated cylindrical glass cover. The absorber tube has an outside diameter of 60 mm and the cylindrical glass cover has a diameter of 90 mm. The tube is made of stainless steel (k = 16 W/m-°C) with a wall thickness of 5 mm. The collector is designed to heat a fluid entering the absorber at 200°C at a flow rate of 0.0537 kg/s. The fluid has specific heat of 3.26 kJ/kg-°C. The heat transfer coefficient inside the tube is 300 W/m^2-°C and the overall loss coefficient is 10.6 W/m^2-°C. **Estimate the useful gain and exit fluid temperature**.

Solution



Given data

$L = 10$ m

$W = 2.5$ m

$T_a = 10$°C

$S = 430$ W/m^2

$T_{fi} = 200$°C

$\dot{m} = 0.0537$ kg/s

$c_p = 3.26$ kJ/kg-°C

$h_{fi} = 300$ W/m^2-°C

$U_L = 10.6$ W/m^2-°C

$D_o = 60$ mm $= 0.06$ m

$D_i = 60 - 10 = 50$ mm $= 0.05$ m

$D_{gc} = 90$ mm $= 0.09$ m

$k = 16$ W/m-°C

Surface area of absorber tube = $A_{ab} = \pi D_o L = 1.88$ m^2

Aperture area = $A_{ap} = (W - D_{gc}) \times L = 24.1$ m^2

Collector efficiency factor = $F_1 = \dfrac{\frac{1}{U_L}}{\frac{1}{U_L} + \frac{D_o}{h_{fi} D_i} + \frac{D_o}{2k}\ln\left(\frac{D_o}{D_i}\right)} = 0.96$

Collector heat removal factor = $F_R = zF_1\left[1 - exp\left(-\frac{1}{z}\right)\right]$

where $z = \dfrac{\dot{m} c_p}{A_{ab} F_1 U_L} = 9.15$ $\quad \therefore F_R = 0.91$

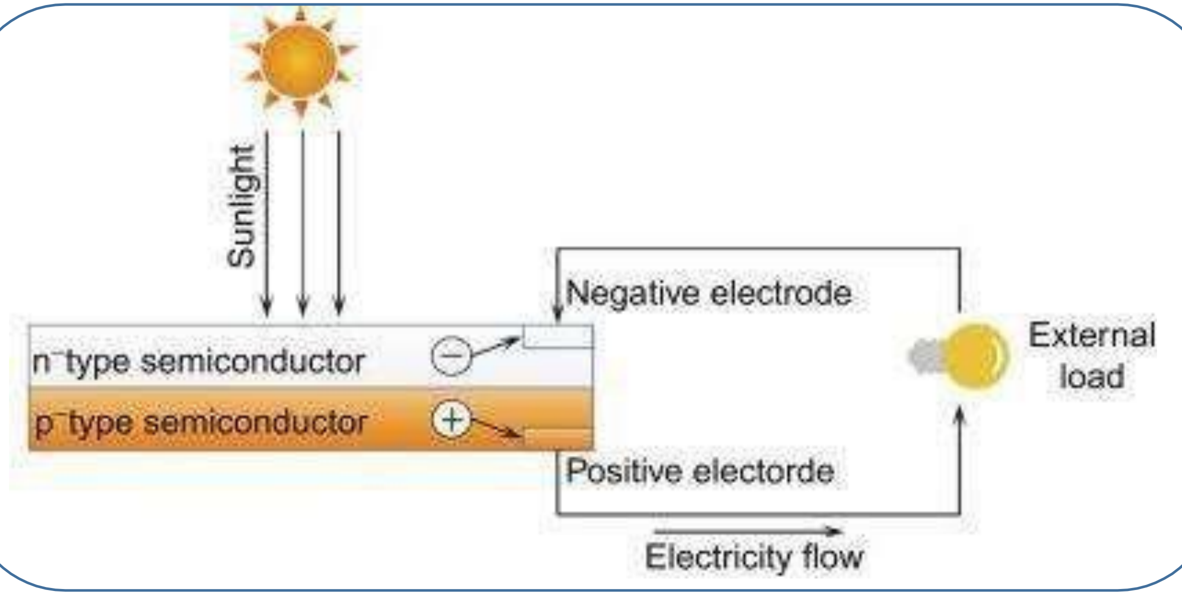
Useful energy gain = $Q_u = F_R\left[A_{ap} S - A_{ab} U_L \left(T_{fi} - T_a\right)\right] = 5980$ W **(Ans)**

Since useful energy gain is also given by: $Q_u = \dot{m} c_p \left(T_{fo} - T_{fi}\right)$

$\therefore T_{fo} = T_{fi} + \dfrac{Q_u}{\dot{m} c_p} = 234$ °C **(Ans)**

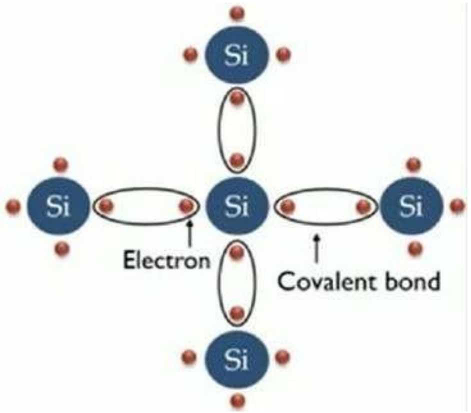
Photovoltaic cell – An Introduction

- A photovoltaic cell (PV cell) can be defined as an electrical device that converts light energy into electrical energy through the **photovoltaic effect**.
- The **photovoltaic effect** is a phenomenon in which two dissimilar materials in close contact produce an electrical voltage and current when exposed to light or other radiant energy.
- The photovoltaic effect is used for direct transformation of solar radiation into electrical energy by using photovoltaic cells. That is why photovoltaic cells are also called **solar cells**.
- Solar cell is a semiconductor device made from two different types of semiconductors, i.e., P-type and N-type semiconductors.

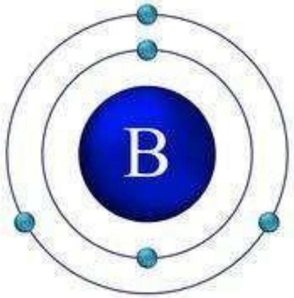


P-type and N-type Semiconductors

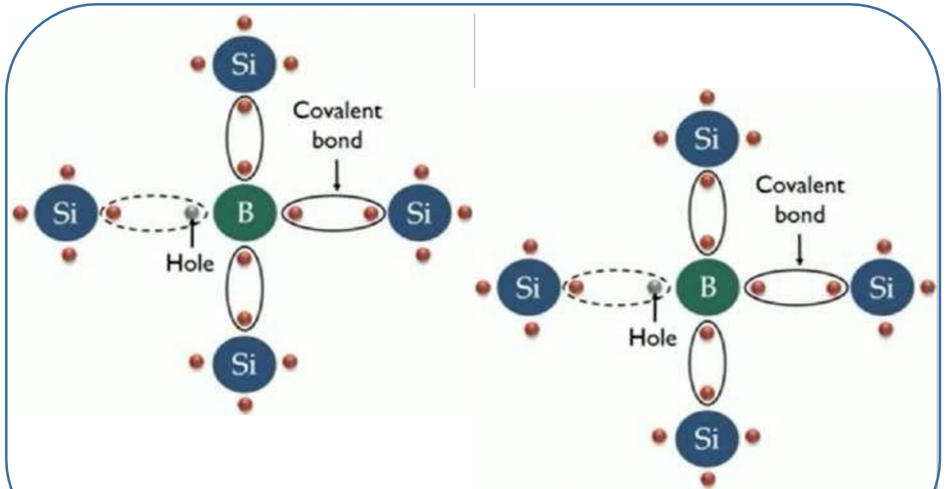
P-type Semiconductor: P-type semiconductor is made by doping pure semiconductor material (*e.g.* silicon and germanium) with Boron.



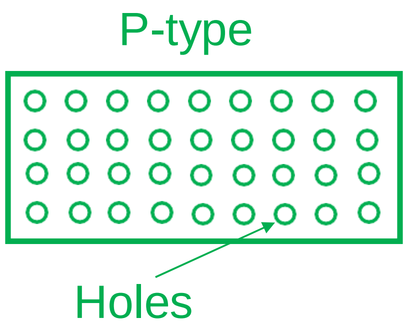
Lattice structure of Si (atomic number = 14)



Atomic structure of Boron (atomic number = 5)

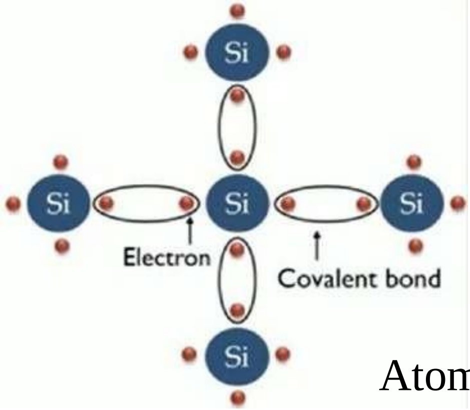


Lattice structure of Si with doped B

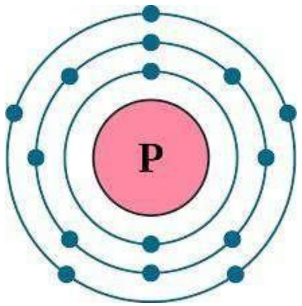


Representation of P-type semiconductor

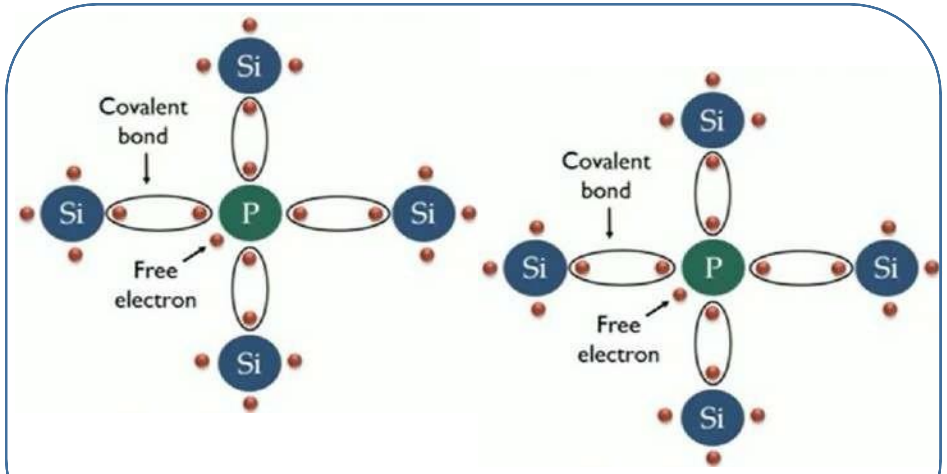
N-type Semiconductor: N-type semiconductor is made by doping pure semiconductor material (*e.g.* silicon and germanium) with Phosphorous.



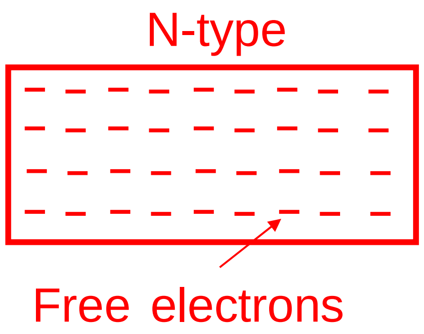
Lattice structure of Si



Atomic structure of Phosphorous (atomic number = 15)



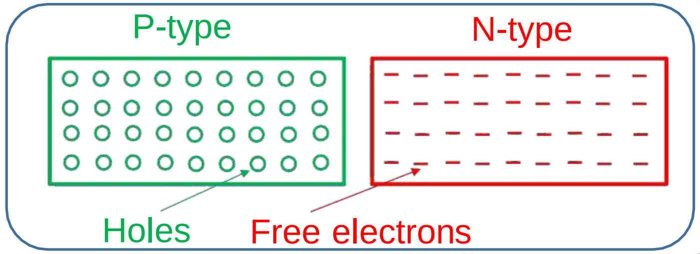
Lattice structure of Si with doped P



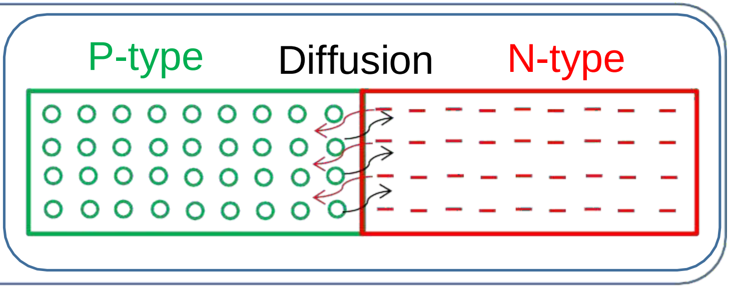
Representation of N-type semiconductor

Working Principle of Solar Cell

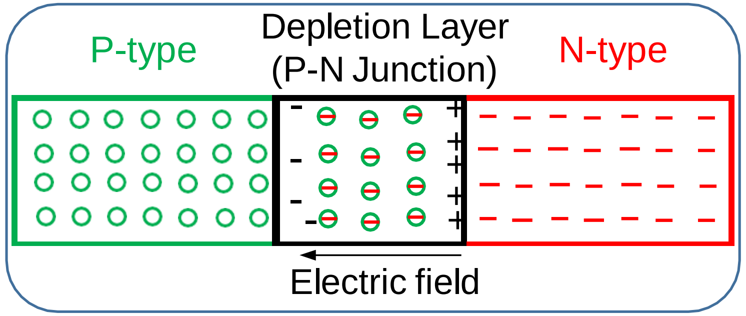
- Solar cell is, in fact, a p-n junction diode formed by joining p-type and n-type semiconductors.



- When these two types of semiconductor materials are joined together, some electrons from ‘n’ side diffuse to the ‘p’ region and fill the holes available there.
- Likewise some holes from the ‘p’ side diffuse to the ‘n’ region and combine with the free electrons available there.

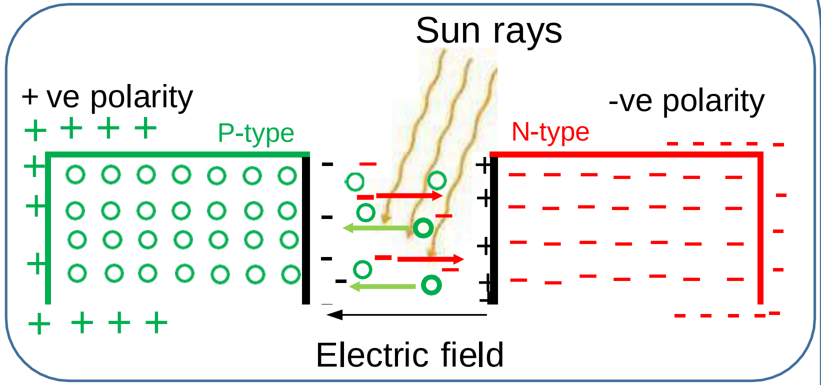


- Diffusion of mobile charges and electron-hole combination result in the formation of a depletion region (depletion layer) wherein there are no mobile charges, i.e., there are no free electrons and holes.
- Due to the outflow of electrons from n-side and inflow of holes into n-side, the n-side boundary of depletion layer becomes slightly positively charged. Likewise p-side boundary of depletion layer becomes slightly negatively charged.
- Thus an electric field is formed between these charges, which acts as a barrier for further diffusion of free charge carriers from ‘p to n’ region or ‘n to p’ region.



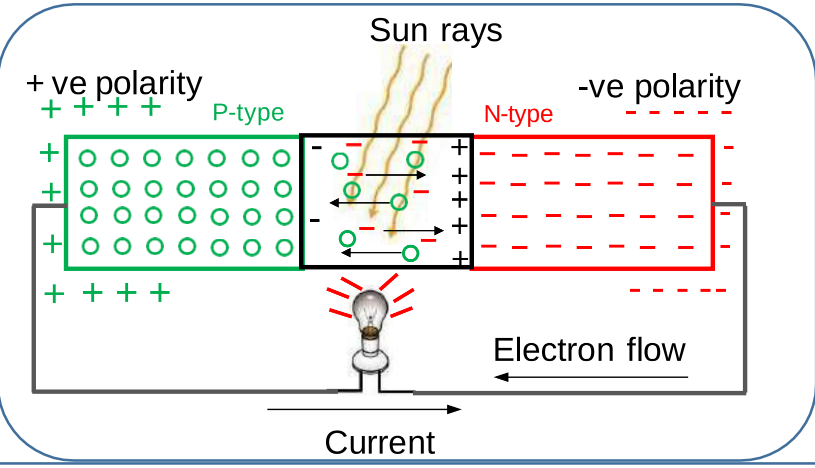
Working Principle of Solar Cell

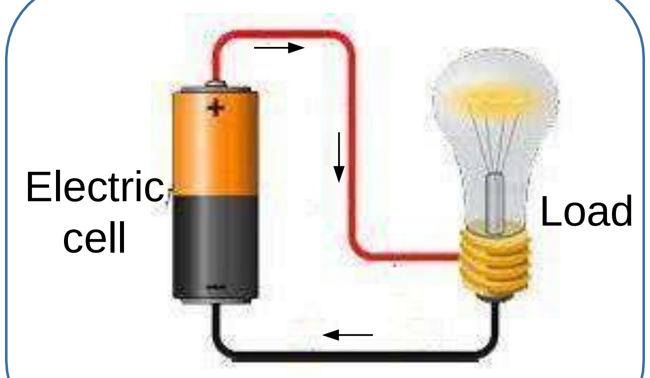
- When the light strikes the p-n junction (depletion layer), the photon energy of light is sufficient to generate electron-hole pairs in the depletion region.
- The electric field in the depletion region drives the electrons and holes out of the depletion region. The holes (+ve charge carriers) move along the direction of electric field and electrons (-ve charge carriers) move opposite to the direction of electric field.



- Thus the concentration of electrons in the 'n' region becomes so high that this side acquires '-ve polarity'. Likewise 'p' region acquires '+ve polarity'.
- Thus, a p-n junction diode behave like a small battery cell when its p-n junction is exposed to light. A voltage is set up across the p-side and n-side region, which is known as **photo voltage**.

- On connecting any electric load between 'p' and 'n' end surfaces, the electrons will start flowing through the load.
- In this way, a solar cell continuously gives direct current so long as the depletion layer receives the light.

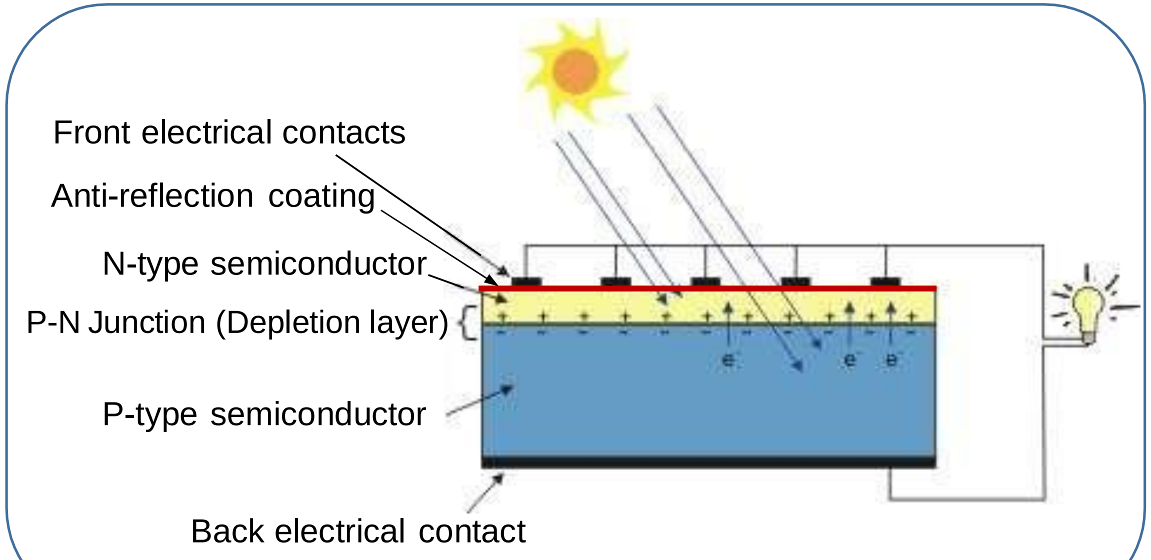




Construction of Solar cell

- A solar cell consists of a p-n junction diode formed by joining p-type and n-type semiconductors.
- The upper layer (top layer) of p-n junction diode is made extremely thin so that incident light photons may easily reach the p-n junction. Overall typical thickness of solar cells is in range of **200 to 500 μm**.
- The semiconductor materials like silicon (Si), germanium (Ge) and gallium arsenide (GaAs) are used for making the solar cells. Mostly silicon is used for making the solar cells.
- The main components of solar cell are as follows:

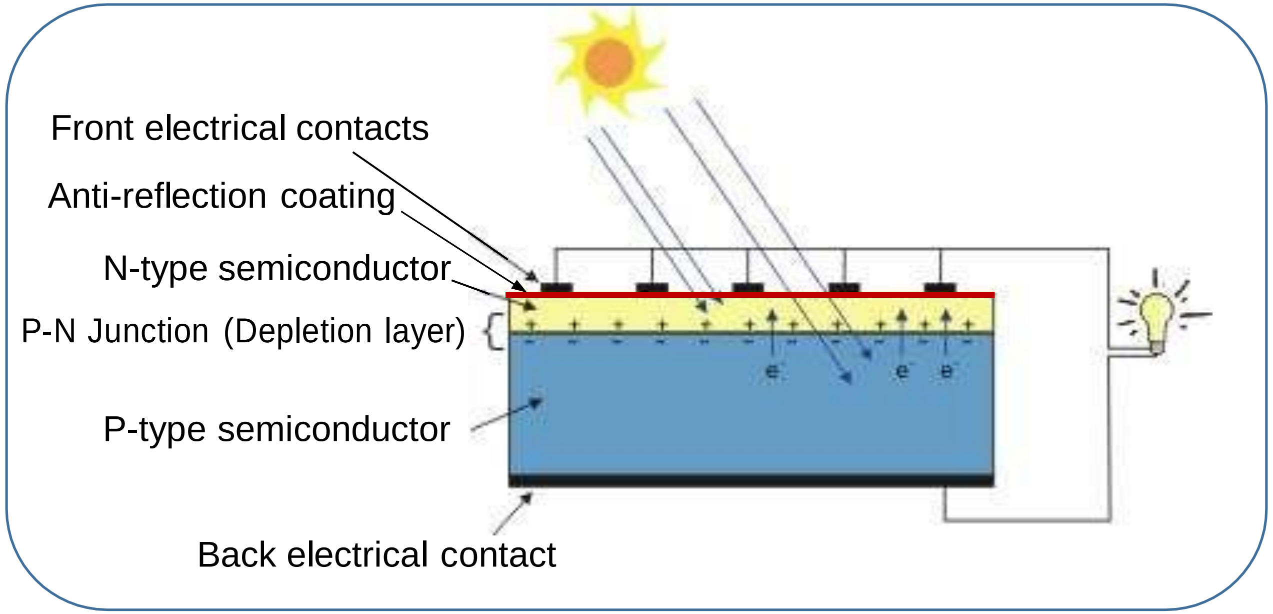
1. Top layer of solar cell
2. Bottom layer of solar cell
3. Anti-Reflection Coating
4. Front electrical contacts
5. Back electrical contact
6. Fingers



Construction of Solar cell

1. Top layer of solar cell

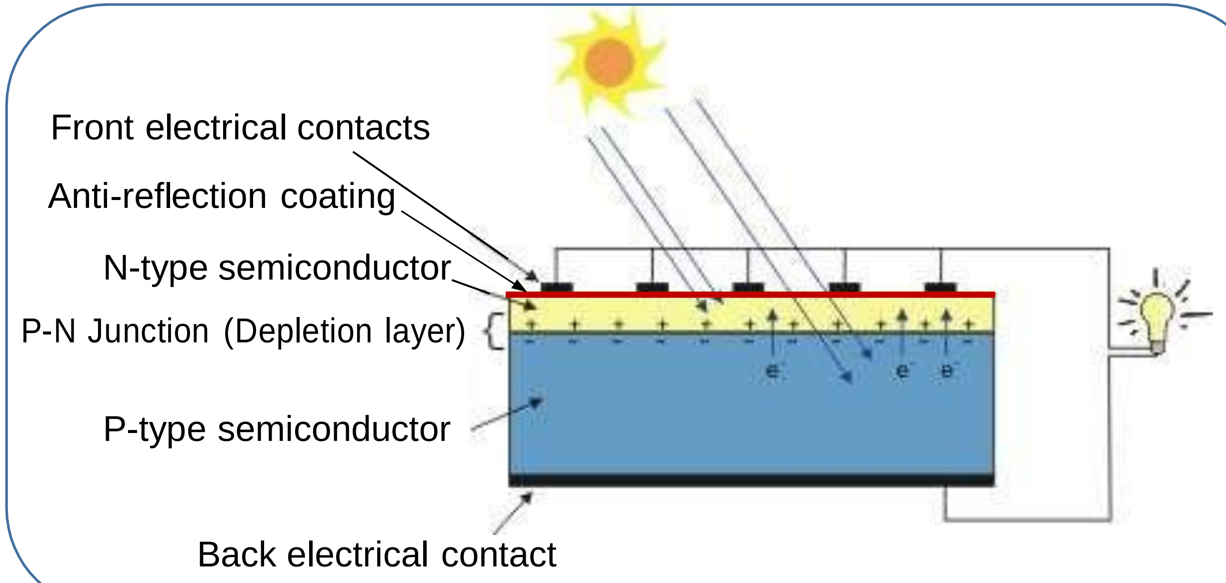
- The top layer of solar cell consists of N-type semiconductor. N-type semiconductor is made by doping pure semiconductor with Phosphorous. The most common N-type semiconductor for solar cell construction is silicon doped with phosphorous (known as N-type silicon).
- N-type silicon has a higher surface quality than P-type silicon so it is placed at the top of the cell. Thus the top of the cell is the **negative terminal**.
- The thickness of top layer is ultra-thin, i.e., **less than 1 µm**, so that incident light photons can easily reach the p-n junction to generate mobile charge carriers.



Construction of Solar cell

2. Bottom layer of solar cell: The bottom layer of solar cell consists of P-type silicon. The most common P-type semiconductor for solar cell construction is silicon doped with boron (known as P-type silicon).

3. Anti-Reflection Coating (ARC): Silicon has a high surface reflection of over **30%**. Therefore top surface of N-type silicon is coated with thin layer of anti-reflection coating to reduce reflection of incident light. Anti-reflection coating consists of a thin layer of **dielectric material** such as **silicon oxide, titanium oxide, silicon nitride and boron nitride.**



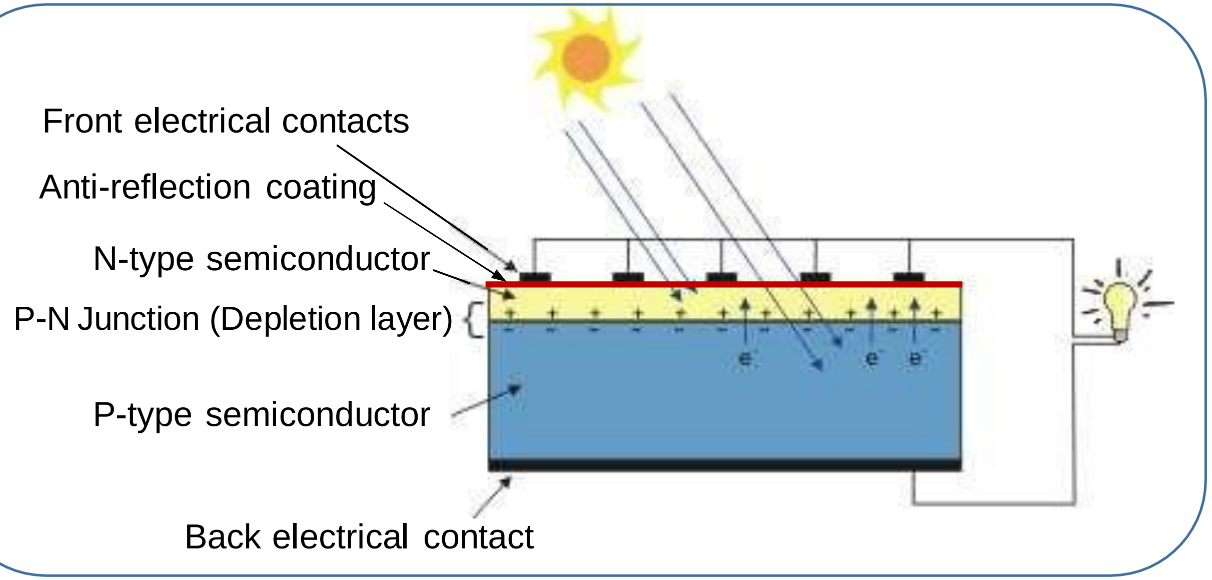
Construction of Solar cell

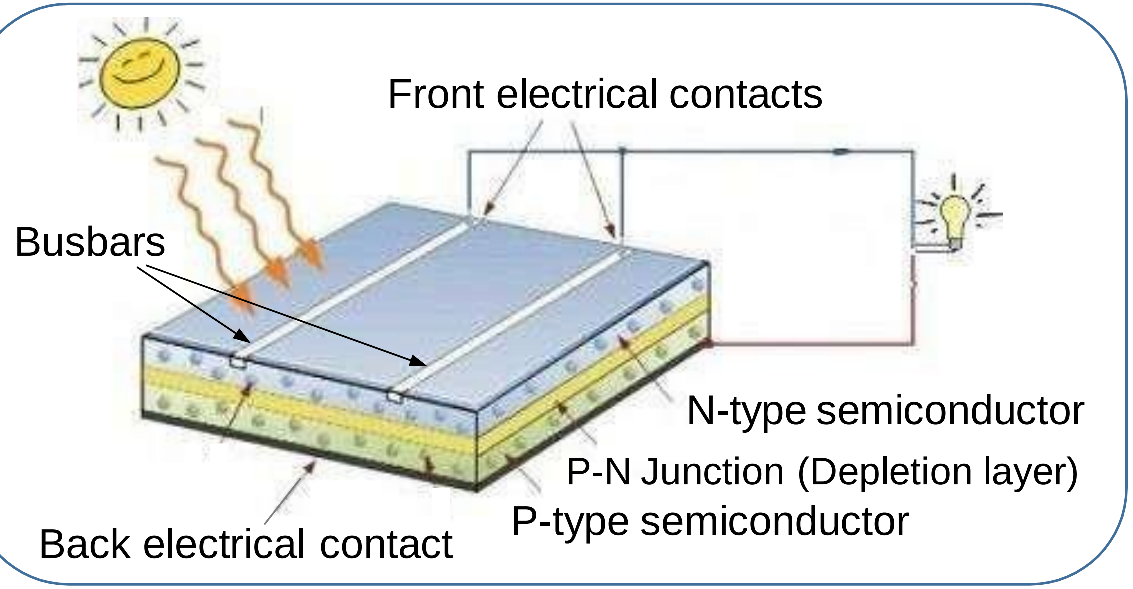
4. Front electrical contacts

- Metallic thin strips are attached on the top surface of the cell. These metallic strips are also referred as busbars. These busbars are used as front electrical contacts of cell to carry the electric current out to an external load.
- In other words, front electrical contacts are used as one of the output terminal of cell.
- Usually, solar cell busbars are made of a **silver paste** or similar high conductivity materials.
- Typically **3-5 basbars** are used in a single cell.

5. Back electrical contact

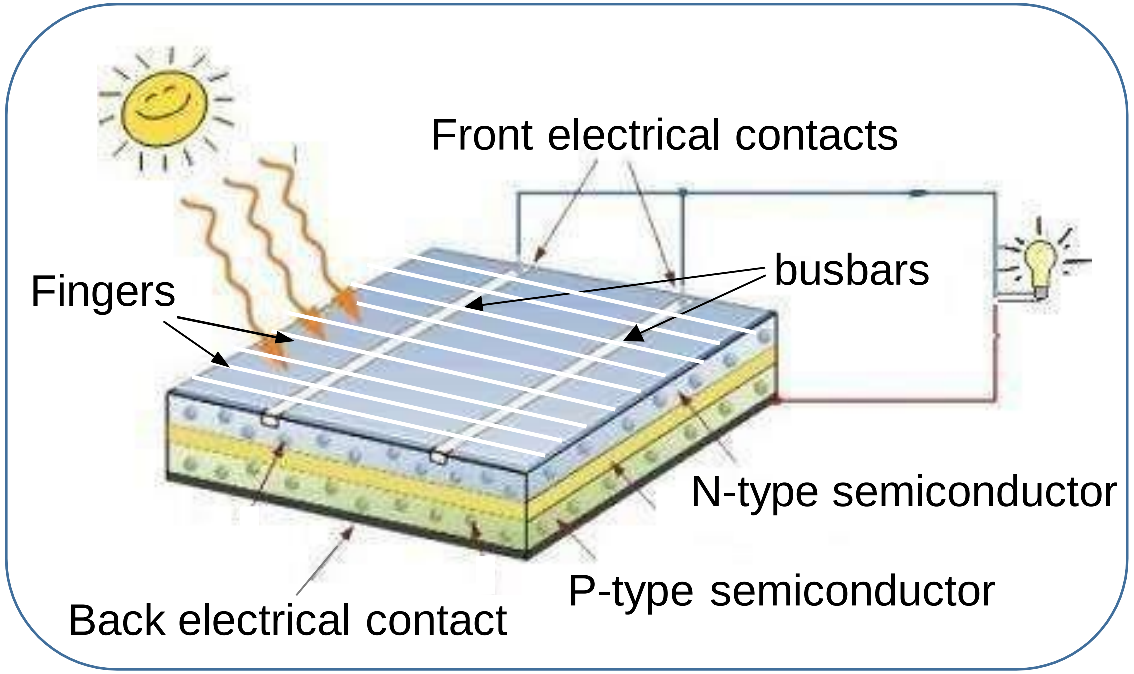
- A thin metallic sheet is attached on the beneath surface of the P-type semiconductor and it is connected with the front electrical contacts (busbars) to complete the electric circuit for the flow of an electric current.

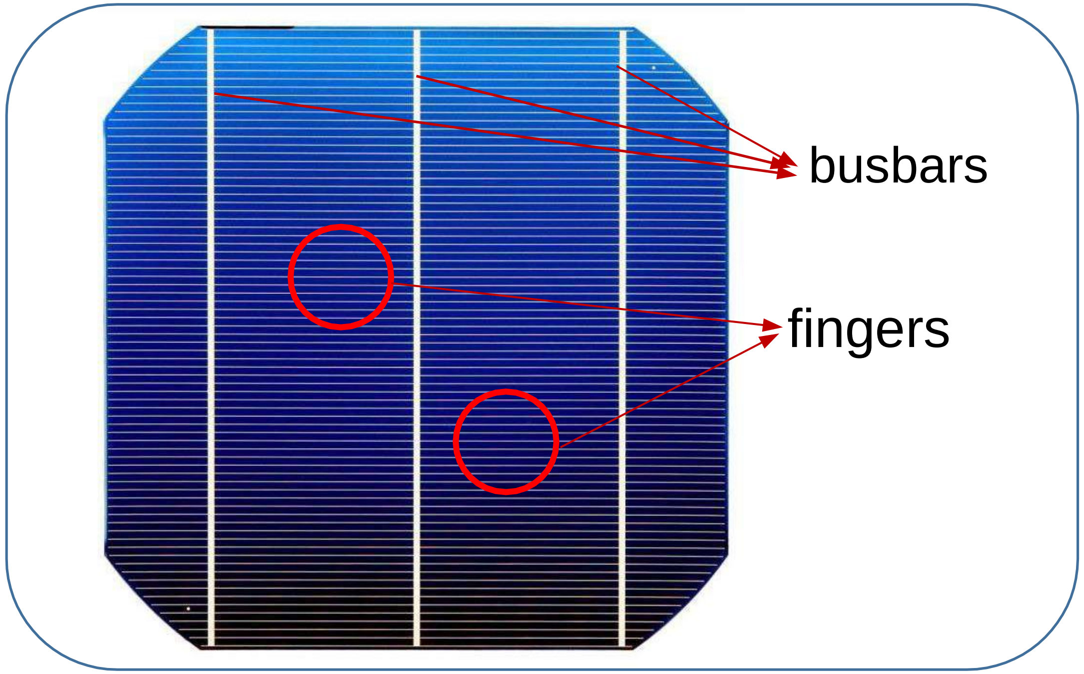




6. Fingers

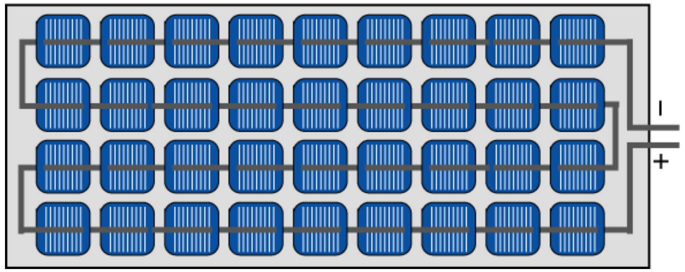
- Perpendicular to the busbars are the super-thin metallic strips which are connected by the busbar. These super-thin metallic strips are called fingers.
- Fingers are used to collect the generated charges (i.e., current) from the top surface of N-type semiconductor and deliver it to the busbars.
- Typical width of fingers is **20 to 200 µm** and they are placed **1-5 mm** apart.





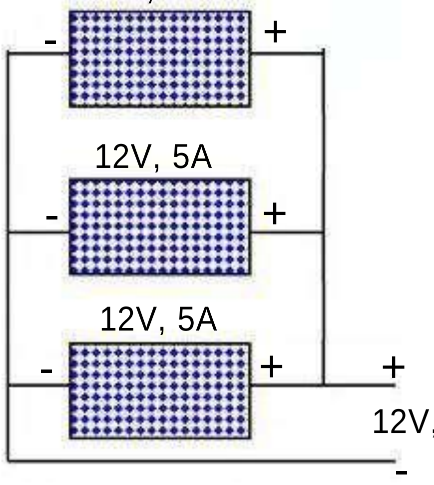
Solar panel and its construction

- The voltage and current generated by a single cell is very small. Hence, in order to generate high voltage several solar cells are connected in **series** combination. This series combination of solar cells is called **solar panel or solar module**.
- The voltage and current generated by solar panel depends on the number of cells connected in series and size of front area of each cell, exposed to sunlight.



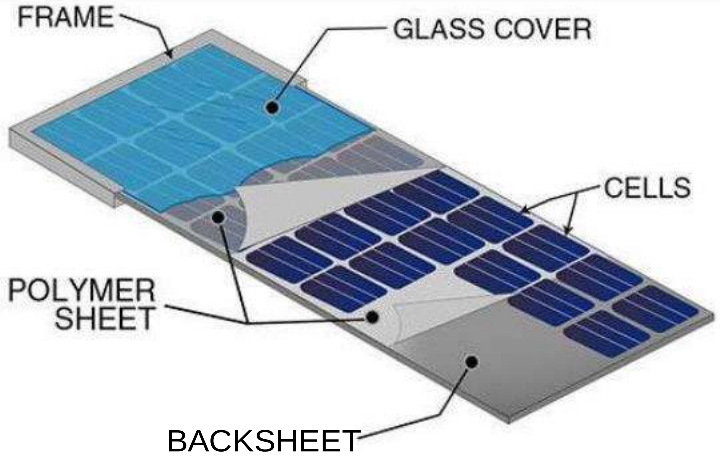
12V, 5A solar panel

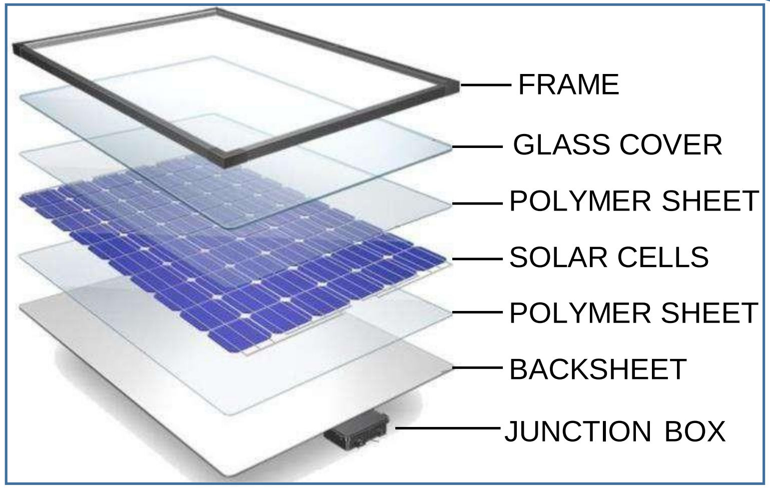
- In order to generate high current, several such solar panels are then connected in **parallel** combination.



- A solar panel consist of following main components:

1. Solar cells
2. Glass cover
3. Polymer sheet
4. Backsheet
5. Frame
6. Junction Box

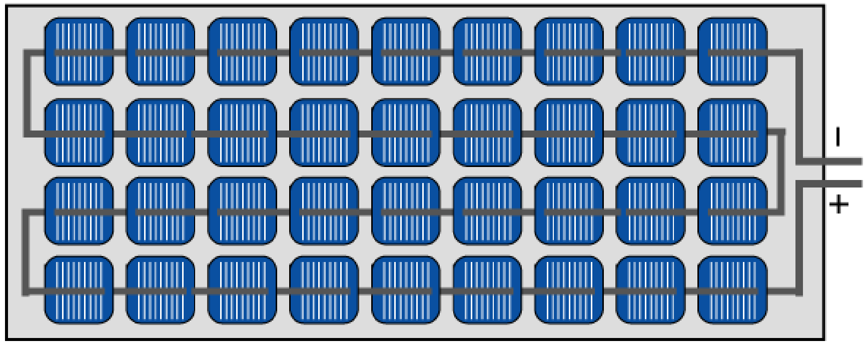


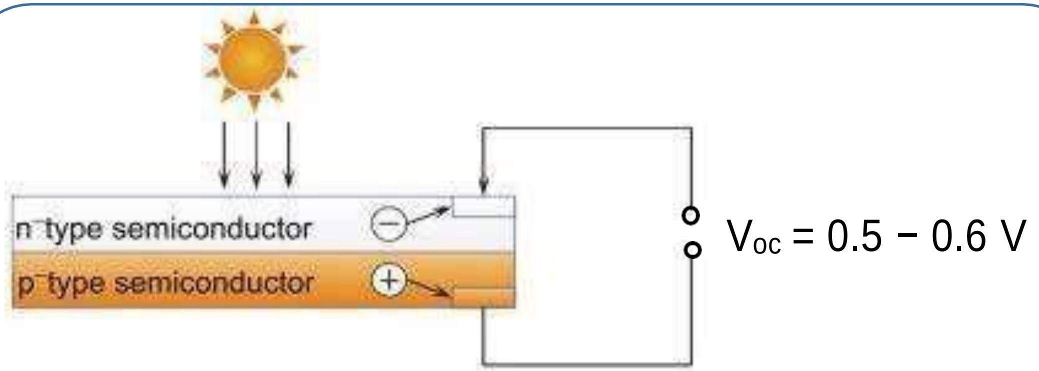


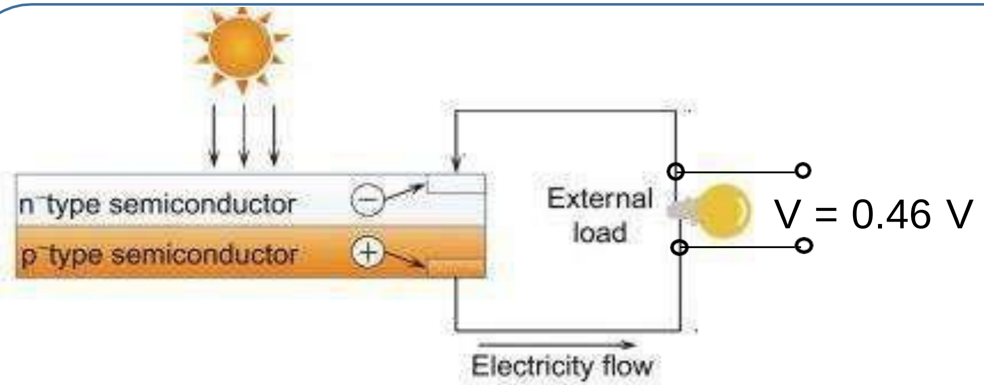
Solar panel and its construction

1. Solar cells

- A solar panel is made of solar photovoltaic cells arranged in a configuration that can contain 32, 36, 48, 60, 72 and 96 cells.
- A typical single silicon solar cell generates **open circuit voltage (V_{oc})** of about **0.5 – 0.6 volts**.
- The output current generated by solar cell depends on the size of the front cell area exposed to sunlight and the intensity of sunlight incident on it. In general, a typical commercially available silicon cell produces a current between **28 and 35 milliamps per square centimetre**.
- A solar panel comprising 32 cells typically can produce 14.72 volts output (each cell producing about 0.46 volt of electricity). Thus a solar panel of 32 cells is capable of charging a 12 VDC battery.



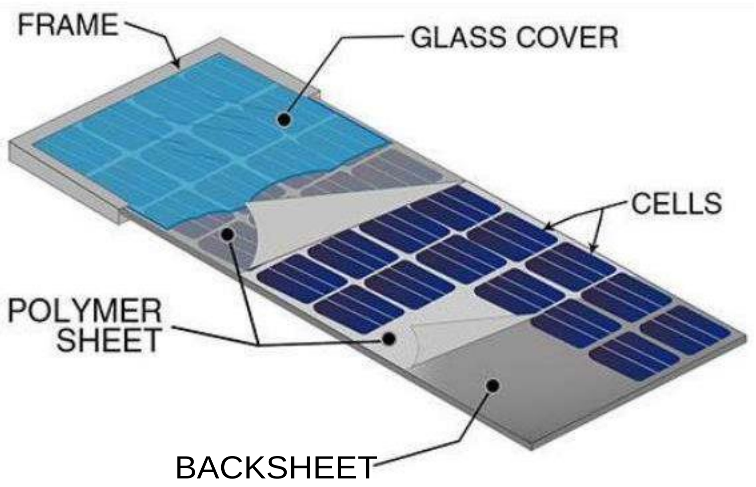


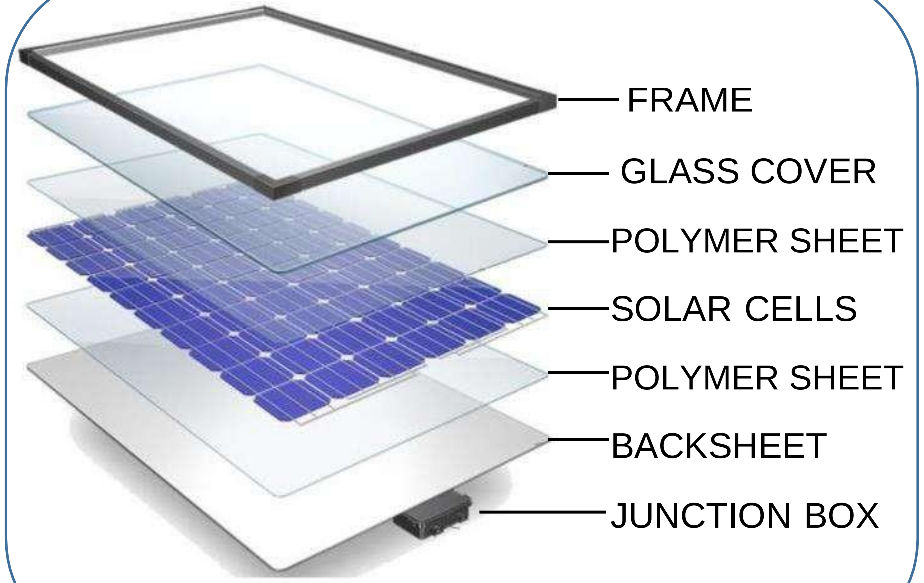


Solar panel and its construction

2. Glass cover

- The glass cover protects the PV cells from the weather and impact from hail or airborne debris.
- The glass used for glass cover is typically a high strength **toughened/tempered** glass which is 3 to 4 mm thick and is designed to resist mechanical loads and extreme temperature changes. The IEC (International Electrotechnical Commission) minimum standard impact test requires solar panels to withstand an impact of hail stones of 1 inch (25 mm) diameter traveling up to 60 mph (27 m/s).
- In the event of an accident or severe impact tempered glass is also much safer than standard glass as it shatters into tiny fragments rather than sharp jagged sections.
- To improve the efficiency and performance of solar cell, most of the manufacturers use **high transmittance** glass which has a very **low iron oxide** content. Low-iron glass is a type of high-clarity glass that is made from silica with very low amounts of ferric oxide.





Solar panel and its construction

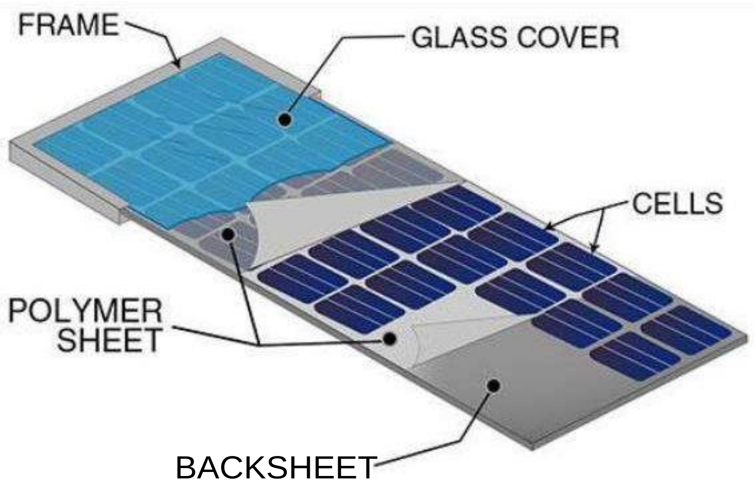
3. Polymer sheet

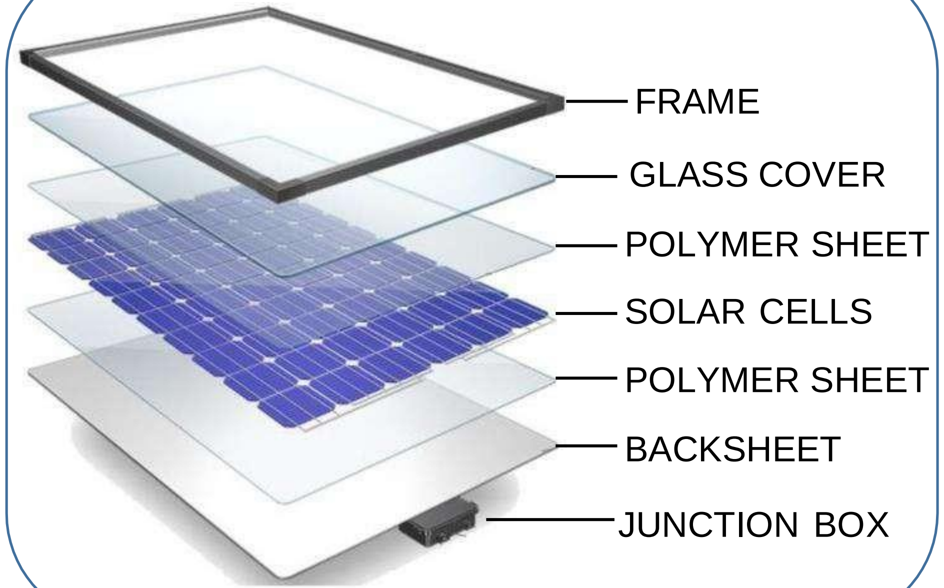
- A very thin and highly transparent sheet, fabricated from specially designed polymer known as ethylene vinyl acetate (EVA), is used to encapsulate the cells and hold them in position during manufacture.

- The EVA material is extremely durable and tolerant of extreme temperature and humidity, it plays an important part in the long term performance by preventing moisture and dirt ingress.

- The lamination either side of the PV cells provides some shock absorption and helps protect the cells and interconnecting wires from vibrations and sudden impact from hail stones and other objects.

- A high quality EVA film provides long life to panel and prevent panel failure due to water ingress.

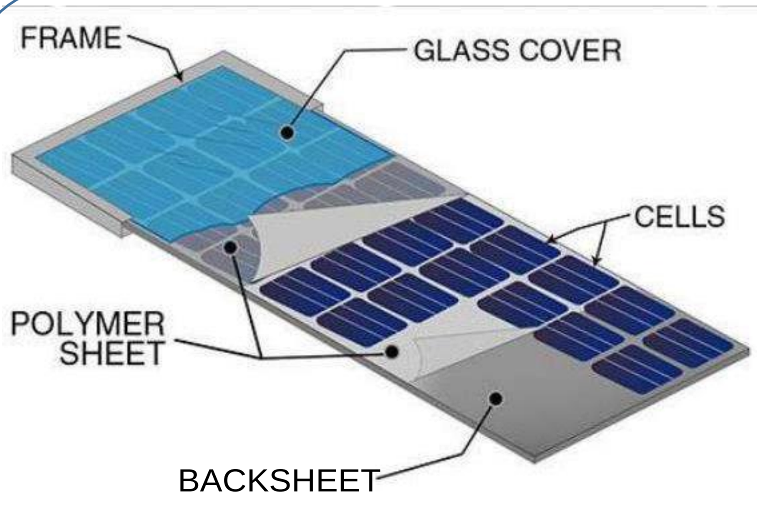


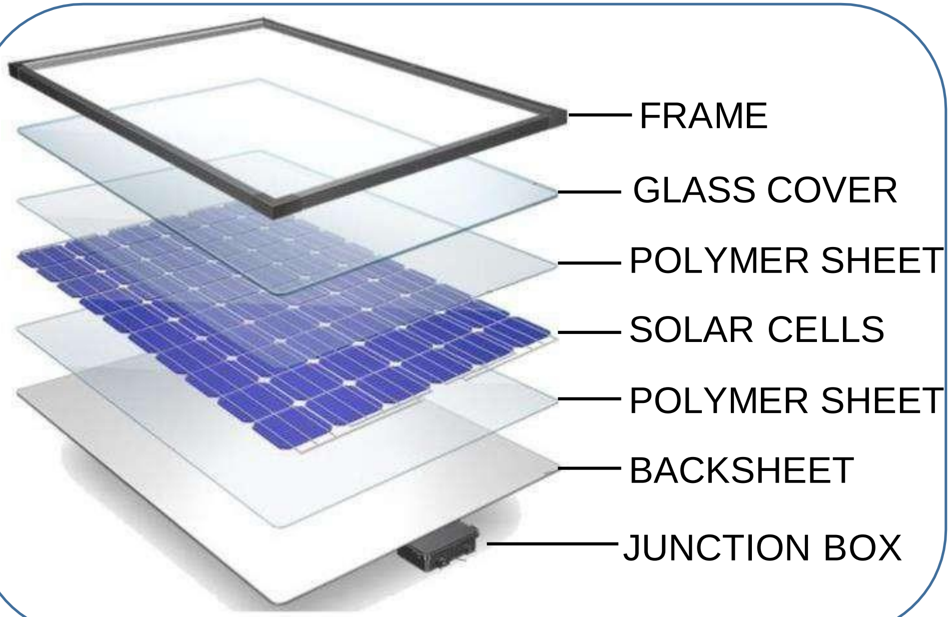


Solar panel and its construction

4. Backsheet

- The backsheet is the rear most layer of common solar panels which as acts as a moisture barrier and final external skin to provide both mechanical protection and electrical insulation.
- The backsheet material is made of various polymers or plastics including PP (Polypropylene), PET (Polyethylene Terephthalate) and PVF (Polyvinyl Fluoride) which offer different levels of protection, thermal stability and long term UV resistance.
- The backsheet layer is typically white in color but is also available as clear or black depending on the manufacturer and module.





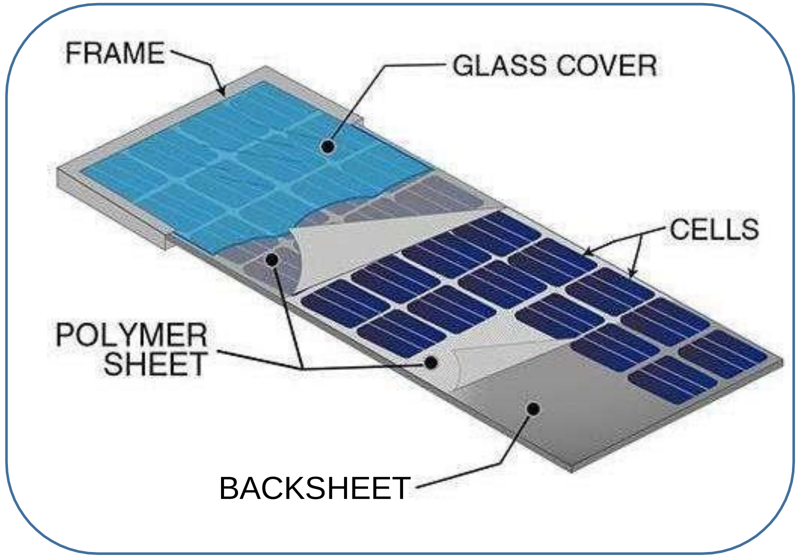
Solar panel and its construction

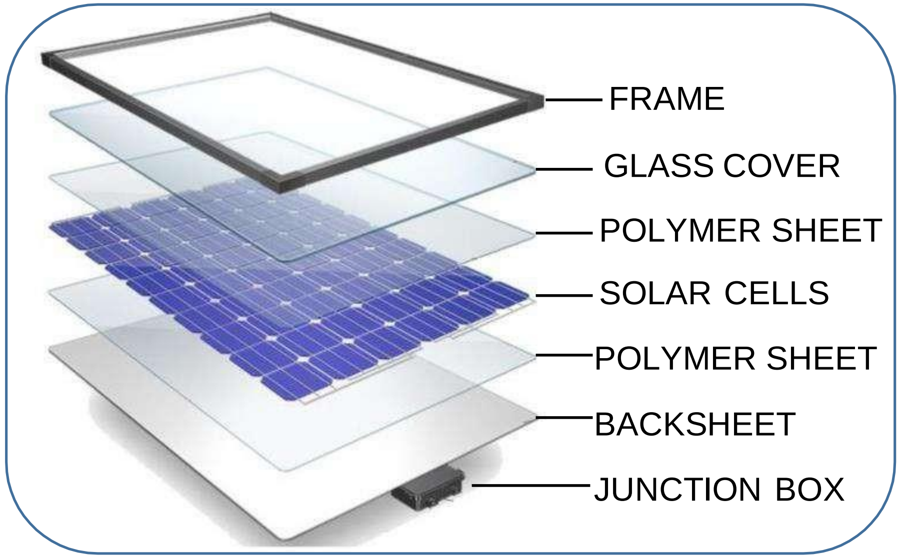
5. Frame

- The aluminium frame plays a critical role by both protecting the edge of the laminate section housing the cells and providing a solid structure to mount the solar panel in position.
- The extruded aluminium sections are designed to be extremely lightweight, stiff and able to withstand extreme stress and loading from high wind and external forces.
- The aluminium frame can be silver or anodised black and depending on the panel manufacturer the corner sections can either be screwed, pressed or clamped together providing different levels of strength and stiffness.

6. Junction Box

- The junction box is a small weather proof enclosure located on the rear side of the panel.
- It is needed to securely attach the cables required to interconnect the panels.





END

$T = 5791.40$ K

Example 4.4. Calculate the declination angle (δ) for March 31 in a leap year.

Solution. Declination angle (δ) is given by

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + n)\right]$$

n = No. of days in January + No. of days in Feb. + No. of days in March

$n = 31 + 29 + 31 = 91$ days

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + 91)\right]$$

$\delta = 4.016°$ **Ans.**

Example 4.5. Calculate the hour angle (ω) at 2 : 30 p.m.

Solution.

$$\omega = 15\,(\text{ST} - 12 \text{ hours})$$

$$= 15(1430 \text{ hours} - 12 \text{ hours})$$

$$\omega = 37.5° \quad \textbf{Ans.}$$

Example 4.6. Calculate the number of daylight hours at Delhi on December 21 and June 21 in a leap year.

Solution.

$$\phi = 28°35'$$

For Dec. 21.

$$n = 356$$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + 356)\right]$$

$$\delta = -23.44° \quad \textbf{Ans.}$$

$$N = \frac{2}{15}\cos^{-1}\left[-\tan(-23.44°)\tan 28° 35'\right]$$

$$= 10.18 \text{ hours} \quad \textbf{Ans.}$$

Similarly, for June 21

$$n = 173$$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + 173)\right]$$

$$\delta = 23.45° \quad \textbf{Ans.}$$

$$N = \frac{2}{15}\cos^{-1}[-\tan 28° 35' . \tan 23.45]$$

$$N = 13.82 \text{ hours} \quad \textbf{Ans.}$$

Example 4.7. Determine the local apparent time corresponding to 1430 hrs. (IST) on July 1, at Mumbai (latitude 19°07′ *N*, longitude 72°51′ E). Equation of time = –4′.

Solution. We know that

LAT = Standard time – 4(standard time longitude – longitude of location) + Equation of time correction

$= 1430 - 4' - 4(82.5 - 72.85)$ mint

LAT = $13h\ 47'\ 24''$ **Ans.**

Example 4.8. Determine LAT and declination at Ahmedabad (longitude 72°40′ E, latitude 23°00′ *N*) corresponding to 1430 hrs IST on December 15. (Given *E* = 5′13″)

Solution.

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + n)\right]$$

$$n = \text{no. of days} = 349$$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + 349)\right]$$

$$= -23.33°$$

$$\therefore \quad \delta = -23°20'\ 6.79''$$

$$\text{Declination} \quad \delta = -23°20'\ 6.79'' \quad \textbf{Ans.}$$

$$\text{LAT} = 1430 - 5'13'' - 4(82.5 - 72.67)$$

$$= 13\text{h}\ 45'27'' \quad \textbf{Ans.}$$

Example 4.9. Calculate the sunset hour angle and day-length at a location latitude of 35°N, on Feb. 14.

Solution.

$$n = \text{no. of days} = 45$$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284+45)\right]$$

$$\delta = -13.62°$$

$$N = \frac{2}{15}\cos^{-1}\left[-\tan 35° \times (\tan(-13.62°))\right]$$

$$N = 10\text{h } 41' \, 51.5'' \quad \textbf{Ans.}$$

Sunset hour angle can be calculated by using the equation (4.9)

$$\omega_s = \cos^{-1}(-\tan\phi \tan\delta)$$

$$= \cos^{-1}[-\tan 35° \, . \, \tan(-13.62)]$$

$$\omega_s = 80°14' \, 6.21'' \quad \textbf{Ans.}$$

Example 4.10. Calculate the sun's altitude and azimuth angles at 9 a.m., solar time on Sept. 1 at a latitude of 23°N.

Solution.

$$\phi = 23°, \quad n = 244 \text{ days}$$

$$\omega = 15 \times 3 = 45°$$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284+244)\right]$$

$$= 7.724$$

$$\delta = 7°43'28.66''.$$

$$\cos\theta_z = \sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega \quad \text{(from eq. 4.8)}$$

$$= \sin 23° \, . \, \sin 7.724 + \cos 23 \, . \, \cos 7.724 \cos 45°$$

$$= 0.39 \, . \, 0.134 + 0.92 \, . \, 0.99 \, . \, 0.707$$

$$\theta_z = 45.87°$$

Solar azimuth angle $\cos\gamma_s = \dfrac{\cos\theta_z \sin\phi - \sin\delta}{\sin\theta_z \, . \cos\phi}$

$$\cos\gamma_s = \frac{\cos 45.87° \, . \sin 23° - \sin 7.724}{\sin 45.87° \, . \cos 23°}$$

$$= \frac{0.696 \, . \, 0.39 - 0.1344}{0.7177 \, . \, 0.92}$$

$$= 0.207$$

$$\gamma_s = 78.01° \quad \textbf{Ans.}$$

Example 4.11. Determine the sunset hour angle and day length for Allahabad (longitude 81°58′E, latitude 24°25′ N) for January 1.

Solution.

$$n = 1$$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284+1)\right]$$

$$\delta = -23^\circ$$

$$N = \frac{2}{15}\cos^{-1}\left[\tan 24^\circ 51' . \tan(-23^\circ)\right]$$

$$N = 10.53 \text{ h}$$

$$\omega_s = \cos^{-1}[\tan 24^\circ 25' . \tan(-23^\circ)]$$

$$\omega_s = 79^\circ$$

Sunset hour angle $= 79^\circ$

Day length $= 10.53$ h **Ans.**

Example 4.12. Calculate the angle made by beam radiation with the normal to a flat plate collector, pointing due south location in New Delhi (28°38′ N, 77°17′ E) at 9:00 hour, solar time on Dec. 1. The collector is tilted at an angle of 36° with the horizontal. Also calculate the day length.

Solution.

$$\gamma = 0^\circ$$

$$n = 335$$

$\therefore$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + 335)\right] = -22.11^\circ$$

At 0900h : $\omega = 45^\circ$

$$\cos\theta = \sin\delta\sin(\phi - \beta) + \cos\delta\cos\omega\cos(\phi - \beta)$$

$$= \sin(-22.11^\circ)\sin(28.58^\circ - 36^\circ) + \cos(-22.11^\circ)\cos 45^\circ\cos(28.58^\circ - 36^\circ)$$

$$\cos\theta = 0.6982$$

$\theta = 45.7^\circ$ **Ans.**

$$N = \frac{2}{15}\cos^{-1}(-\tan 28.58^\circ . \tan(-22.11^\circ))$$

$N = 10.28$ h **Ans.**

Example 4.13. Calculate the zenith angle, solar azimuth angle for a place with a latitude of 43° at 9:00 am solar time on Feb. 11.

Solution. On Feb. 11, $n = 42$

$$\text{Declination } \delta = 23.45 \sin\left[\frac{360}{365}(284 + 42)\right]$$

$$= -14.58^\circ$$

Hour angle, $\omega = 15 \times 3 = 45^\circ$

Zenith angle :

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta$$

$$\cos\theta_z = \cos 43^\circ\cos(-14.58^\circ)\cos 45^\circ + \sin 43^\circ \sin(-14.58^\circ)$$

$$= (0.731)(0.968)(0.707) + (0.682)(-0.252)$$

$$= 0.5 - 0.172 = 0.328$$

$\therefore$

$$\theta_z = 70.85^\circ$$

Solar azimuth angle

$$\cos\gamma_s = \frac{\cos\theta_z\sin\phi - \sin\delta}{\sin\theta_z . \cos\phi}$$

$$\therefore \quad \cos \gamma_s = \frac{\cos 70.85^\circ \sin 43^\circ - \sin(-14.58^\circ)}{\sin(70.85^\circ) . \cos 43^\circ}$$

$$= \frac{(0.328)(0.682) - (-0.252)}{0.944 . (0.731)}$$

$$= \frac{0.224 + 0.252}{0.69} = 0.689$$

$$\gamma_s = 46.38^\circ$$

Example 4.14. For example 4.5, calculate the angle of incidence of beam radiation on a plane surface, tilted by 45° from horizontal plane and pointing 30° west of south on 15 November.

Solution.

$$n = 319$$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + 319)\right]$$

$$\delta = -19.147^\circ$$

$$\text{LAT} = 13\text{h}47'24'' = \text{ST}$$

$$\omega = 15(\text{ST} - 12)$$

$$\omega = 15(13\text{h } 47'24'' - 12) = 15(1\text{h } 47'24'')$$

$$\omega = 26.85^\circ$$

$$\gamma = 30^\circ, \beta = 45^\circ, \phi = 19^\circ07'$$

Angle of incidence can be calculated by using Eq. (4.6)

$$\cos \phi = \sin(19.12^\circ)(\sin(-19.147^\circ)\cos 45^\circ + \cos(-19.147)\cos 30^\circ \cos(26.85^\circ)\sin 45^\circ) + \cos 19.12^\circ (\cos(-19.147^\circ)\cos 26.85^\circ \cos 45^\circ - \sin(-19.147^\circ)\cos 30^\circ \sin 45^\circ) + \cos(-19.147)\sin 30^\circ \sin 26.85^\circ \sin 45^\circ$$

$$\cos \theta = 0.996$$

$$\theta = 5.11^\circ$$

Example 9.1. A propeller type, horizontal shaft wind turbine having following wind characteristics.

Speed of wind 10 m/s at 1 atm and 15 °C.

The turbine has diameter of 120 m and its operating speed is 40 rpm at maximum efficiency. Calculate

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

(*ii*) the maximum obtainable power density assuming $\eta = 40\%$

(*iii*) total power produced (in kW) and

(*iv*) the torque and axial thrust.

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

where,
P = Pressure of air, Pa
T = Temperature of air, K
R = Gas constant

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

$$1 \text{ atm} = 1.01325 \times 10^5 \text{ Pa}$$

$$T = 15 + 273 = 288 \text{ K}$$

$$\rho = \frac{1.01325 \times 10^5}{0.287 \times 288} = 1.226 \text{ kg/m}^3$$

∴

(i)
$$\text{Total Power } (P_t) = \frac{\rho A V_i^3}{2} = \frac{1}{2} \times 1.226 \times A \times (10)^3$$

$$\text{Power density} = \frac{P_t}{A} = 613 \text{ W/m}^2$$

(ii)
$$\text{Maximum Power} = \frac{8}{27} \rho A V_i^3$$

$$\text{Maximum Power Density} = \frac{8 \text{ Maximum Power}}{A}$$

$$= \frac{8}{27} \rho V_i^3$$

$$= \frac{8}{27} \times 1.226 \times 10^3 = 363 \text{ W/m}^2.$$

(iii)
$$\eta = 0.4 \text{ (given)}$$

$$\frac{\rho}{A} = 0.4 \times 613 = 245.2 \text{ W/m}^2$$

$$\text{Total Power } P_{\text{total}} = \text{Power density} \times \text{Area}$$

$$= 245.2 \times \frac{\pi D^2}{4}$$

$$= 245.2 \times \frac{\pi (120)^2}{4} = 2771740.8 \text{ W}$$

$$= 2771.74 \text{ kW}.$$

(iv) Torque at maximum efficiency

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

$$= \frac{2}{27} \frac{1.226 \times 120 \times 10^3}{40/60}$$

$$= 16346.67 \text{ N}.$$

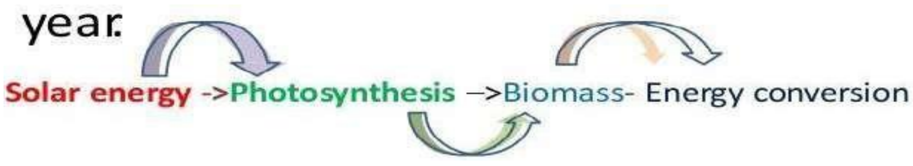
Maximum Axial Thrust $F_x = \dfrac{\pi}{9} \rho D^2 V_i^2$

$$F_x = \frac{\pi}{9} \times 1.226 \times (120)^2 \, (10)^2$$

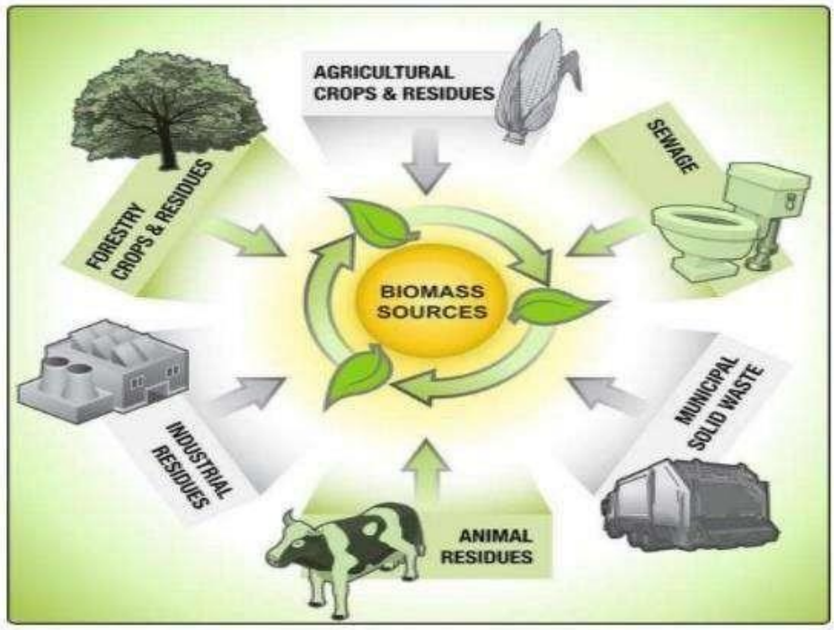
$$F_x = 615942.4 \text{ N}.$$

UNIT-IV: BIOMASS & BIOGAS

- The energy obtained from organic matter,derived from biological organisms (Plants and animals) is known as biomass energy.
- Animalsfeedonplants,andplantsgrowthroughthephotosynthesisprocessusing solar energy. Thus, photosynthesis process is primarily responsibleforthegenerationofbiomassenergy.
- Asmallportionofthesolarradiation is captured and stored in the plants during photosynthesisprocess.
- Therefore, it is an indirect form of solar into biomass energy isestimated to be0.5 – 1.0%. To use biomass energy, the initial biomassmaybetransformedbychemicalorbiologicalprocessestoproduceintermediatebiofuelssuchasmethane,producergas,ethanolandcharcoaletc.
- Oncombustionitreactswithoxygentoreleaseheat,butthe elements of the material remain available for recycling in naturalecological or agricultural processes.
- Thus, the use of industrial bio-fuels,when linked carefully to natural ecological cycle, may be non-pollutingand sustainable. It is estimated that the biomass, which is 90% in trees,is equivalent to the proven current extractable fossil fuels reserves in theworld.
- The dry matter mass of biological material cycling in biosphere isabout 250 x 10^9tons/y. The associated energy bound in photosynthesisis2x 10^{21}J/y (0.7 x10^{14}W ofpower).
  - Biomass mainly in the form of wood, is mankind‘s oldest form ofenergy.Ithastraditionallybeenusedbothindomesticaswellasindustrialactivities,basicallybydirectcombustion.Asindustrialactivities increased, the growing demand for energy depleted the biomassnatural reserves.
  - The development of new, more concentrated and moreconvenient sources of energy has led to its replacement to a large extentbyothersources.Thoughbiomassenergyshareinprimaryenergysupply for the industrialized countries is not more than 3%, a number ofdeveloping countries still use a substantial amount of it, mostly in theformof non-commercial energy.



BIOMASS SOURCES



What is Photosynthesis?

- The preparation of food by the leaves of green plant and micro-organism in the presence of sunlight, water and CO_2 is called Photosynthesis .

Bio mass Resources

1. Field and plantation biomass

- Agricultural crop residues- Cobs, stalks, Straw, Cane thrashes and etc
- Edible matters from crops-Environmentally spoiled grains, pulses, fruits, nuts, spices, seeds and lint etc
- Dedicated energy crops- Bamboo
- Plantation debris-Leaves, barks and trunks
- Livestock wastes from fields

2. Urban waste biomass

- Municipal solid wastes
- Sewage sludges
- Kitchen and canteen wastes

3. Industrial biomass

- Agro-industrial processed biomass and their wastes - Husk
- Oil cake
- Sugar molasses
- Hides and skin wastes
- Fruit and pulp debris Saw dust
- Wood pulp and paper shavings
- Fermented microbial mass etc

4. Forest biomass

- Log residues
- Timber
- Forest floor debris
- Animal carcass

5. Aquatic biomass

- Sea weeds (E.g. Kelp)
- Fresh water weeds (E.g. Water Hyacinth)
- Dead fishes
- Microalgae blooms

Biomass Conversion Processes/ Technologies

I. Densification

II. Diect Combustion & Incineration

III. Thermo-Chemical Conversion

- 1. Gasification
- 2.Liquification /Pyrolysis

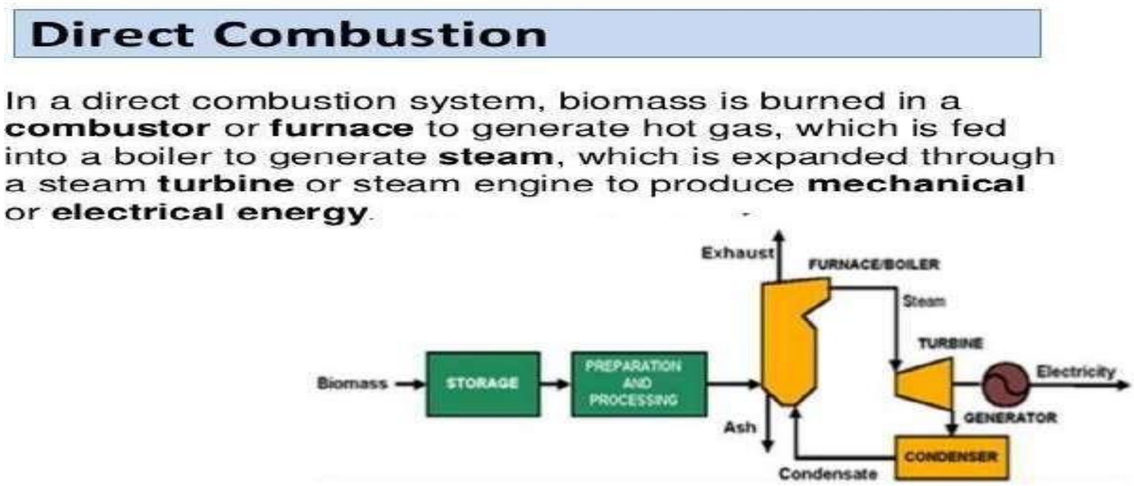
IV. Bio-Chemical Conversion

- 1. Aneraboic Conversion
- 2.Aerobic Conversion

I. Densification

- In this process bulky biomass is reduced to a smaller size by compressing in a die at a high temperature and pressure. The biomass is pressed into pellets or briquettes.
- Due to this transportation and storage will become easy

II. Direct Combustion



Direct Combustion

- The direct combustion of biomass in **presence** of **oxygen/air** to produce heat and by products is called direct combustion.
- The complete combustion of biomass into ash is called incineration.
- This heat energy in the product gases or in the form of steam can be used for various applications like space heating or cooling, power generation process heating in industries or any other application.
- However, if biomass energy by combustion is used as co generation with conventional fuels, the utilization of biomass energy makes it an attractive proposition.

III. Thermo Chemical Conversion

The thermo chemical reaction can convert the organic biomass into more valuable and convenient form of products as gaseous and liquid fuels,residue and by-products etc.

These processes can be carried out in following ways:

1) Gasification
2) Pyrolysis

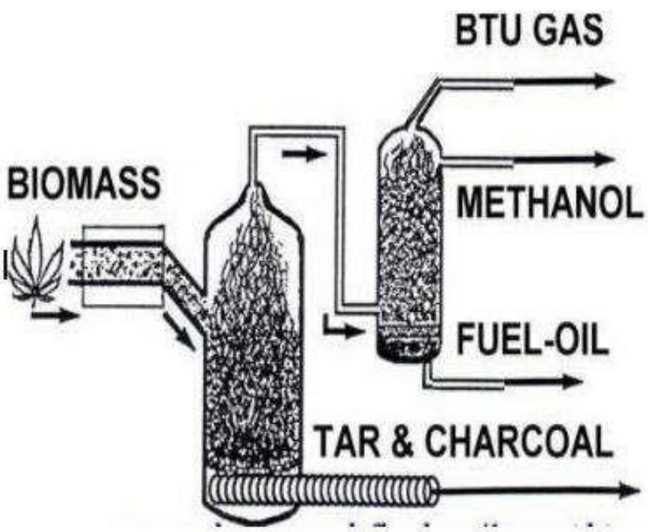
Gasification- takes place by heating the biomass with **limited oxygen / Air** (deficient O2 and Air) to produce low heating value gas or by reacting it with **steam** & **oxygen** at **high pressure** & **temperature** to produce medium heating value gas like H_2,CO,CH_4,N_2

Pyrolysis

It is the heating of biomass in a closed vessel at temperatures in the range 500°C-900°C in **absence** of **O_2/air** or with steam. It produces solid, liquid and gases.

The pyrolysis process can use all type of organic materials including plastic and rubeers.

Pyrolysis is the decomposing of biomass (fresh or fossil) by the heat of **anaerobic** (reduced air) combustion which converts organic material into gases and/or fuel oils.



Liquification

- Biomass can be liquefied through flash pyrolysis.
- The purified gas from biomass is converted into a liquid fuel like Methanol.

IV. Bio- Chemical Conversion

In biochemical processes the **bacteria and micro organisms** are used to transform the raw biomass into useful energy like methane and ethane gas. Following organic treatments are given to the biomass:

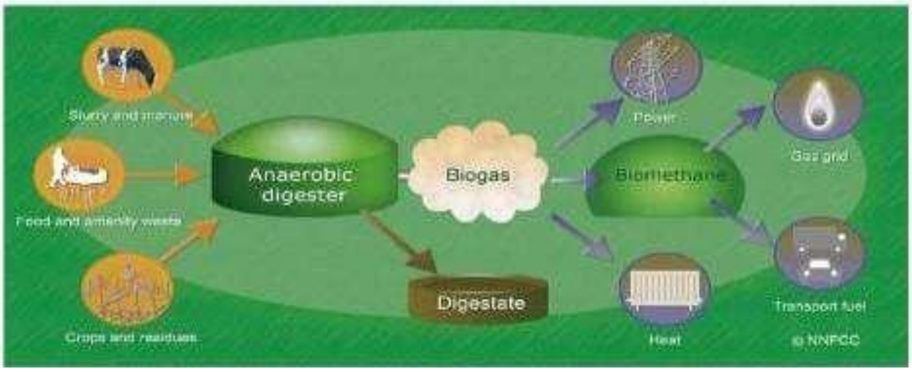
- **1. Anerobic Digestion**

  – In the absence of Oxygen

- **2. Aerobic digestion/Fermentation**

  –In the presence of Oxygen

Anaerobic Digestion



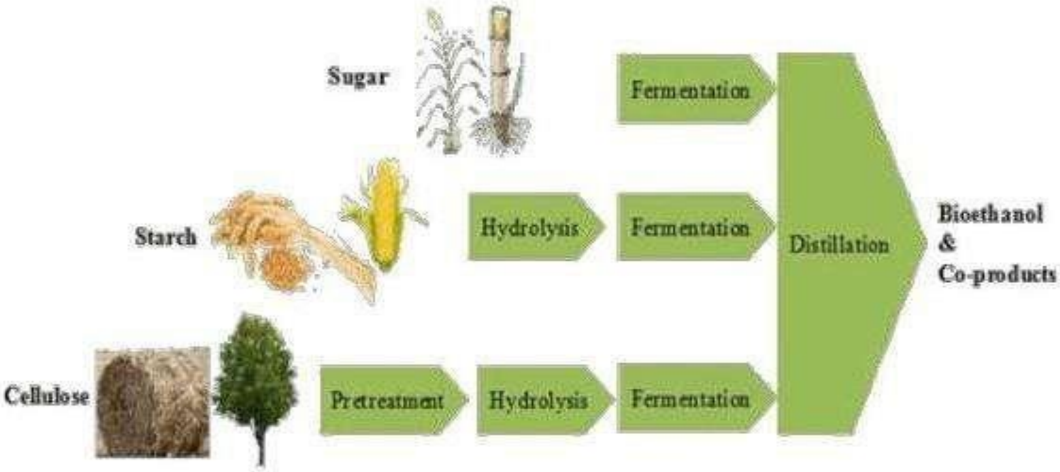
The anaerobic digestion or anaerobic fermentation process involves the conversion of decaying wet biomass and animal waste into biogas through decomposition process by the action of anaerobic bacteria.

The most useful biomass for production of biogas are animal and human waste, plant residue and other organic waste material with high moisture content.

Fermentation is a process of decomposition of complex molecules of organic compound under the influence of micro-organism(**ferment**) such as **yeast**, bacteria, enzymes etc.

The example of fermentation process is the conversion of grains and sugar crops into ethanol and CO_2 in presence of yeast.

Fermentation



In other Words……

1. *Anaerobic* digestion involves the microbial digestion of biomass. The process takes place at **low** temperature up to **60ºC** & requires a moisture content of at least **80%,** and generates a gas consisting of CO_2 & methane (CH_4)
2. *Fermentation* is the breakdown of complex molecules in organic compound under influence of a ferment such as *Yeast*, bacteria, *enzymes* etc.

Main advantages of biomass energy are:

i. It is a renewable source.
ii. Theenergystorageisan in-builtfeatureofit.
iii. Itisanindigenous sourcerequiringlittleor noforeignexchange.
Thepollutantemissionsfromcombustionofbiomassareusuallylower than those from fossil fuels.

iv. Commercial use of biomass may avoid or reduce the problems ofwastedisposalinotherindustries,particularlymunicipalsolidwastein urbancenters.
v. The nitrogen rich bio-digested slurry and sludge from biogas plantserves as a very good soil conditioner and improves the fertility ofthe soil.

Maindisadvantagesare:

i. Itisadispersedandlandintensivesource.
ii. Itisoftenoflowenergydensity.
iii. Itisalsolabourintensive,andthecostofcollectinglargequantitiesforcommercial applicationissignificant.

Most current commercial applications of biomass energy use materialthathasbeencollectedforotherreasons,suchastimberandfoodprocessingresidues and urbanwaste.

Biomass: It is the organic matter consisting of plant animal matter. Anymatter which is biodegradable is known as biomass or organic matter.Generationofenergyfrombiomassisreferredtoas‗Photochemical‘harnessing of solar radiation since to generate biomass; solar radiation is amustas seen from the following equation

Solarradiation $\longrightarrow$ Photosynthesis $\longrightarrow$ Biomass $\longrightarrow$ EnergyEnergyfromthebiomassisgeneratedinthreedifferentformsnamely) Directburning,ii)Liquefaction,iii)Gas generation.

Directburning: Whenbiomassisdirectlyburnt,energyisgeneratedasgivenbythe following expression,

$$CO_2 + O_2 \xrightarrow{\text{sun's radiation (photosynthesis)}}$$

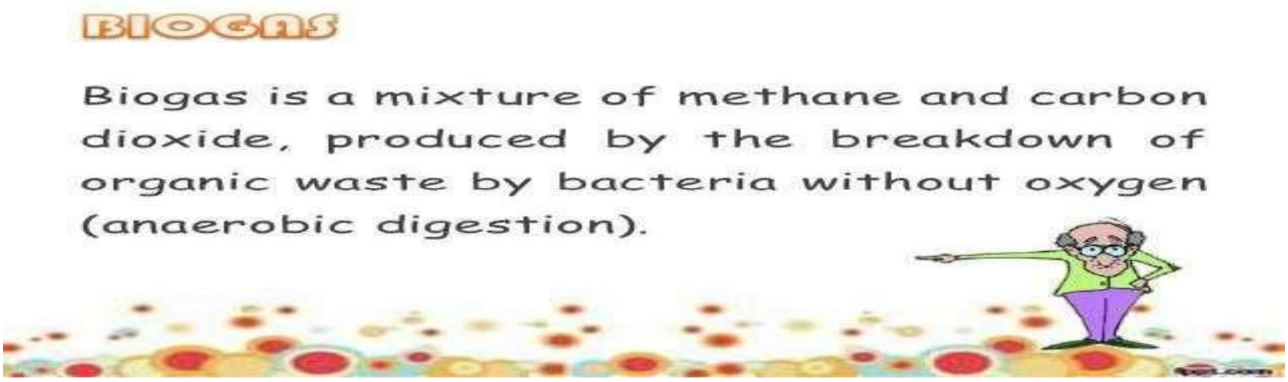
$$\cancel{CH_2O + O_2 CH_2O + O_2} \longrightarrow$$

$$CO_2 + H_2O + \text{Energy}$$

Thus when photosynthesis reaction is reversed energy is liberated.

BIOGAS

- Biomass is converted to biogas by the process of digestion orfermentationinthepresenceofmicromorganisms.Thisbiogasmainlycontainsmethane which is a good combustible gas.



- Biogas consists of 50-55% of methane, 30-35% of CO_2 and remaining wastegases like H_2, N_2, H_2S etc. since it contains a hydrocarbon gas it is a verygoodfuelandhencecanbeusedin ICengines.
- It isaslowburninggaswith calorific value of 5000-5500 Kcal/kg. the raw material used to generate thisare algae, crop residue, garbage, kitchen waste, paper waste,wastefromsugarcanerefinery,waterhyacinthetc.apartfromtheabovementionedraw materials excreta of cattle, piggery waste and poultry droppings are also used as raw materials.

- Biogas is generated by fermentation or digestion of organic matter in thepresence of aerobic and anaerobic micro-organisms.
- Fermentation is theprocess of breaking down the complex organic structure of the biomass tosimple structures by the action of micro-organisms either in the presence ofO_2 or in the absence of O_2.
- The container in which the digestion takes place is knownas the digester.

FuelProperties:

- **Calorific Value :**

  60% Methane - 22.35 to 24.22 MJ/m^3

  Without CO_2 - 33.52 to 35.39 MJ/m^3
- **Octane Number - 110 to 130**
- **Ignition Temperature- 650^0 C**
- **Air Fuel Ratio - 10:1**

Advantages

- The initial investment is low fort heconstructionofbiogasplant.
- Thetechnologyisverysuitableforruralareas.
- Biogasislocallygeneratedandcanbeeasilydistributedfordomesticuse.
- Biogasreducestheruralpoorfromdependenceontraditionalfuelsources,which lead to deforestation.
- Theuseofbiogasinvillagehelpsinimprovingthesanitaryconditionandchecksenvironmental pollution.
- Theby-productslikenitrogenrichmanurecanbeusedwithadvantage.
- Biogasreducesthedrudgeryofwomenandlowersincidenceofeyeandlungdiseases

The digestion takes place in the following steps

i)Enzymatichydrolysisii)Acidformationiii)Methaneformation.

i) **Enzymatic hydrolysis:**In this step the complex organic matter like starch,protein, fat, carbohydrates etc are broken down to simple structures usinganaerobicmicro-organisms.

ii) **Acid formation:**In this step the simple structures formed in the enzymatichydrolysissteparefurtherreactedbyanaerobicandfacultativemicro-organisms (which thrive in both the presence and absence of oxygen) togenerateacids.

iii) **Methaneformation:**Inthissteptheorganicacidsformedarefurtherconvertedto methaneandCO_2byanaerobicmicro-organisms(anaerobes).

Selection of Site for a Biogas Plant

1. Distance –For 2 m^3 plant distance is 10m

2. Minimum Gradient – For gas conveying, minimum 1% gradient must be available for the line

3. Open space – Sunlight should fall on the plant – temperature 15-30^{0}C is essential for gas generation at higher rate

4. Water Table – prevent seepage of water – plant should not be constructed if the water table is above/more than 10ft (3m)

5. Seasonal run off - proper care has to be taken to prevent the interference of rain water during the monsoon.

6. Distance from wells - the seepage of fermented slurry may pollute the well water. Minimum 15m from the well

7. Space requirements - 10-12 m^2 area is needed per one m^3 of the gas

8. Availability of water - plenty of water must be available as the cow dung slurry with a solid concentration of 7 to 9%

9. Source of materials(cow dung/Biomass) - to economise the transportation cost

FactorsaffectingBiogasgeneration:

1) PHvalue
2) Temperature
3) Totalsolidcontent
4) Loadrating
5) Seeding
6) Uniform feeding
7) Diatodepthratio
8) Carbontonitrogenratio
9) Nutrient
10) Mixing
11) Retentiontime
12) Typeoffeedstock
13) Toxicity
14) Pressure

1) **PH value:** It is an index of hydrogen ion concentration in the mixture whichalso predicts acidity or alkalinity of the mixture. For effective gas generationtherequiredPHvalueis6.5to7.6.Ifthisvaluedecreasesto4-6,themixture becomes acidic and if the value becomes 9-10 then it becomesalkaline.Bothforacidicandalkalineconditionsthemethaneformingbacteriabecomesinactiveandthegasgenerationisreduced.Thusforeffectivegas generationthe requiredPHvalueis 6.5-7.5.
2) **Temperature:** The effect of temp ongas generation is as shown in graph.Thetwocurvesrepresenttwotypesof bacteria which are sensitive to twodifferent temp levels. Mesophilic typeofbacteriawilleffectivelygenerategasatatempofabout35ºC.Thermophilic typeofbacteriawillgenerate gas effectively at a temp ofabout55ºC.Asthetemperature

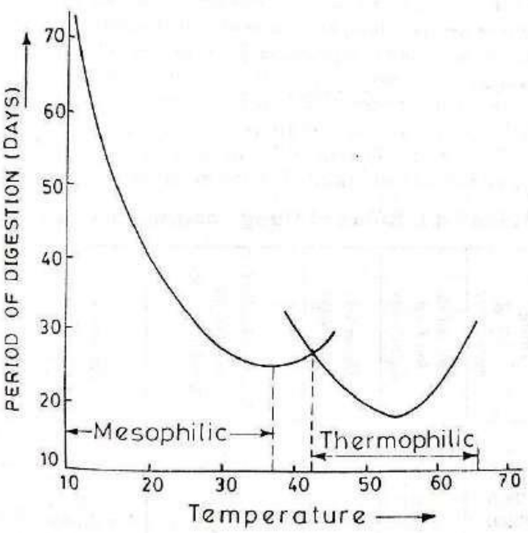


Fig. 7.5.1. Effect of temperature on digestion.

decreases or increases from the above values the period of gas generationwill be increased. Since it is easy to maintain a temp of 35º C, it is advisabletoselect mesophilictype of bacteriafor digestion.

3) **Total solid content:**The raw material added to the digester contains bothsolid and liquid in the ratio of 20:80 by weight. From the experience it isfound that the gas generation is improved by maintaining the solid contentof the mixture at about 8 to 10% by weight. This is done by adding water tothe mixture.
4) **Loading rate:** It is the addition of the raw material to the digester/day/unitvolume.Theeffectiveloadratingisfoundtobe0.5to1.6kgofsolid material/day/m^3.
5) **Seeding:** Duringdigestionthemethaneformingbacteriaareconsumedrapidly and their number will decrease affecting the gas generation. In orderto maintain the quantity of methane forming bacteria, digested slurry fromthe previous batch is added to the digestor. The digested slurry is rich inmethaneformingbacteriaand theprocessis knownasseeding.
6) **Uniform feeding:** this is one of the prerequisites of good digestion. Thedigester must be fed at the same time every day with a balanced feed of thesamequality and quantity.
7) **Dia to depth ratio:** from the experiments it is seen that the gas generationis improved by maintaining a dia to depth ratio of 0.66 to 1. This providesuniformtempdistributionthroughoutthedigesterresultinginincreased gasgeneration.
8) **Carbon to nitrogen ratio:**The bacteria in the digester utilize carbon forenergy generation (as food) while nitrogen is used for cell building. Hence acarbon to nitrogen ratio of 30:1 is maintained for effective gas generation. Ifthe ratio is not maintained the availability of carbon and nitrogen will varyresultingin reduced gas generation.
9) **Nutrients:** The nutrients required by the bacteria for food digestion arehydrogen, nitrogen, oxygen, carbon, phosphorous and sulphur. Of thesenitrogen and phosphorous have to be provided externally while the othersarecontainedintherawmaterialitself.Nitrogenisprovidedbyadding ‗leguminous plants'(plantswithseedsenclosed incasings,eg:Maize)which

are rich in nitrogen content. Phosphorous is provided by adding ‗night soil'(soilmixedwithexcretaofanimals andhumans)tothedigester.

10) **Mixing:**Since bacteria in the digester have very limited reach to theirfood it is necessary that the slurry is properly mixed and the bacteria gettheir food supply. It is found that the slight mixing improves the digestionanda violent mixing retardsthe digestion.

11) **Retention time:**It is the time period required for the gas generation. Itcompletely depends on the type of the raw materials used. Eg: Night soilrequires30days,pigdumpandpoultrydroppingsrequire20dayswhilecowdungandotherkitchenwasterequires50daysof retentiontime.

12) **Type of feed stock:**The usual feed stock used are cow dung, humanexcreta,poultrydropping,pigdump,kitchenwasteetc.Toobtainanefficientdigestionthesefeedstocksareinsomeproportions,Predigestedandfinallychopping willbehelpfulforfibroustypeof rawmaterials.

13) **Toxicity:**If the digester is left with the digested slurry it results intoxicity which in turn reduces the gas generation. Hence the digested slurryshouldberemoved after the gas is generated.

14) **Pressure:**Itisfoundthatthegasgenerationisincreasedwiththedecreasein thepressureof thedigester.

PhotosynthesisProcess:

Solarradiationincidentongreenplantsandotherphotosyntheticorganismsperformstwobasicfunctions:(i)temperaturecontrolforchemicalreactionstoproceed,and(ii)Photosynthesisprocess.Thefundamental conversion process in green plants is photosynthesis, whichis the process of combining $CO_2$from the atmosphere with water pluslightenergytoproduceoxygenandcarbohydrates(sugars,starches,celluloses and hemicelluloses). They are the ultimate source of most ofour foods and other necessities of daily life such as clothes (in the form ofcotton),furniture (in the form of wood), etc.

$$xCO_2 + y\,H_2O + \text{light energy} \longrightarrow x\,O_2 + C_x(H_2O)_y \quad (i)$$

Thegeneralizedsymbol$C_x(H_2O)_y$isusedtoindicatethecarbohydrates. The products of this reaction are about 5ev per C atomhigher in energy than the initial material. Photosynthesis is a complexprocess.Itinvolvesseveralsuccessivestages,buttheoverallbasic reactionistheformationofhexose(glucose,fructose,etc.)asrepresentedby:

$$6CO_2+6H_2O + \text{light energy} \longrightarrow 6O_2+C_6H_{12}O_6 \qquad \text{(ii)}$$

More complex hydrocarbons (sucrose, starch, cellulose, etc.) areformed by a chain of these simple structures. The reverse of this processis called respiration, in which CO_2, H_2O and energy are produced usingcarbohydrateandoxygen.Ingreenplants,bothphotosynthesisandrespiration occur during the day and only respiration at night. This isshowninfigurebelow.Thereisanetoverallgainofenergyintheprocess,astherateofenergylossinrespirationismuchlessascomparedtorateofenergygainduringphotosynthesisprocess.Theprocess also results in net gain of oxygen and fixation of carbon in theform of biomass. The net energy absorbed from solar radiation duringphotosynthesiscan bemeasured from itscombustion.

$$x\,CO_2+ yH_2O + \Delta Q \rightleftharpoons x\,O_2+ C_x(H_2O)_y \qquad \text{(iii)}$$

ΔQ is enthalpy change of the combustion process, equal to theenergyabsorbedfromphotonsofsolarradiation,lesstheenergyofrespiration during growth. The value of ΔQ is 4.8eV per carbon atom,470kJ per mole of carbon or 16 MJ/kg of dry carbohydrate material. It istobenotedthatthecombustionrequiresthetemperatureofapproximately400^{0}C,whereasrespirationoccursat20^{0}Cthroughcatalytic enzyme reactions.

The uptake of $CO_2$by a plant leaf is a function of many factors,especiallytemperature,CO_2concentrationandtheintensityandwavelength distribution of light. Solar radiation incident on a leaf isreflected, transmitted and absorbed. Part of the absorbed radiation (<5%)provides the energy stored in the photosynthesis and produces oxygenandcarbohydrate;theremainderisabsorbedintheplantassensibleheat raising its temperature, or as latent heat for water evaporation.Absorptionisusuallymostmarked intheblueand redregions.

Biochemicalreactionsinanaerobicdigestion:

There are four key biological and chemical stages of anaerobic

digestion:Hydrolysis

Acido

genesisAceto

genesisMethanoge

nesis.

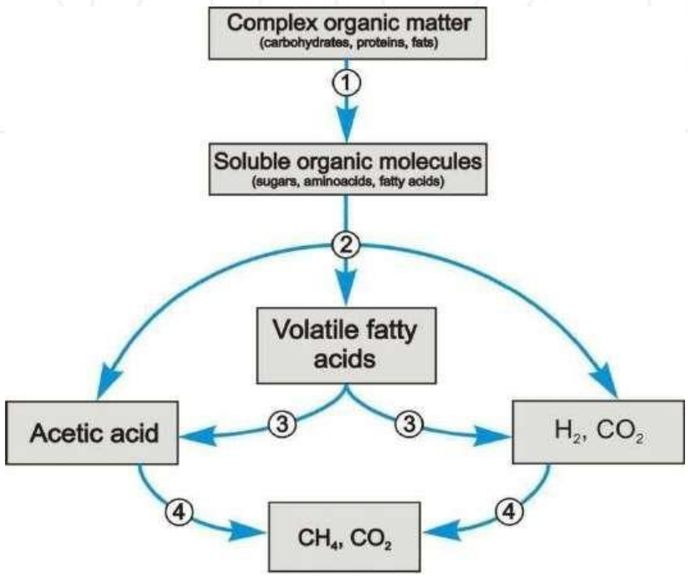


Fig.7.2.Anaerobicpathwayofcomplexorganicmatterdegradation

In most cases biomass is made up of large organic compounds. In orderfor the microorganisms in anaerobic digesters to access the chemicalenergypotentialoftheorganicmaterial,theorganicmattermacromolecular chains must first be broken down in to their smallerconstituent parts. These constituent parts or monomers such as sugarsarereadilyavailabletomicroorganismsforfurtherprocessing.Theprocess of breaking these chain sand dissolving the smaller molecules into solution is called hydrolysis. Therefore hydrolysis of high molecularweightmoleculesisthenecessaryfirststepinanaerobicdigestion.It maybeenhancedbymechanical,thermalorchemicalpretreatmentofthe waste. Hydrolysis step can be merely biological (using hydrolyticmicroorganisms)orcombined:bio-chemical(usingextracellularenzymes), chemical (using catalytic reactions) as well as physical (usingthermalenergy and pressure)in nature.

Acetates and hydrogen produced in the first stages can be used directlybymethanogens.Othermoleculessuchasvolatilefattyacids(VFA's)with a chain length that is greater than acetate must first be catabolisedintocompoundsthatcanbedirectlyutilizedbymethanogens.Thebiological process of acidogenesis is where there is further break down ofthe remaining components by acidogenic (fermentative) bacteria. HereVFA'saregeneratedalongwithammonia,carbondioxideandhydrogensulphideaswell asotherby-products.

Thethirdstageanaerobicdigestionisacetogenesis.Heresimplemoleculescreatedthroughtheacidogenesisphasearefurtherdigested byacetogenstoproducelargelyaceticacid(oritssalts)aswellascarbondioxidea nd hydrogen.

Thefinalstageofanaerobicdigestionisthebiologicalprocessofmethanogenesis .Heremethanogenicarchaeautilizetheintermediateproductsoftheprecedings tagesandconvertthemintomethane,carbondioxide and water. It is these components that makes up themajorityofthebiogasreleasedfromthesystem.Methanogenesisis–besideotherfactors-sensitivetobothhighandlowpHvaluesandperforms well between pH 6.5 and pH 8. The remaining, non-digestibleorganicandmineralmaterial,whichthemicrobescannotfeedupon,a longwithanydeadbacterialresiduesconstitutesthesoliddigestate.

<u>Classificationofthebiogasplants:</u>

1) Continuous and Batchtype
   - Singlestage
   - Doublestage

2) Dome anddrumtype
   - FloatinggasholderorKVICmodel
   - Fixed dome type or Chainese model or Janathamodel

3) **<u>Variation in the above type Single stage continuousplant:</u>**

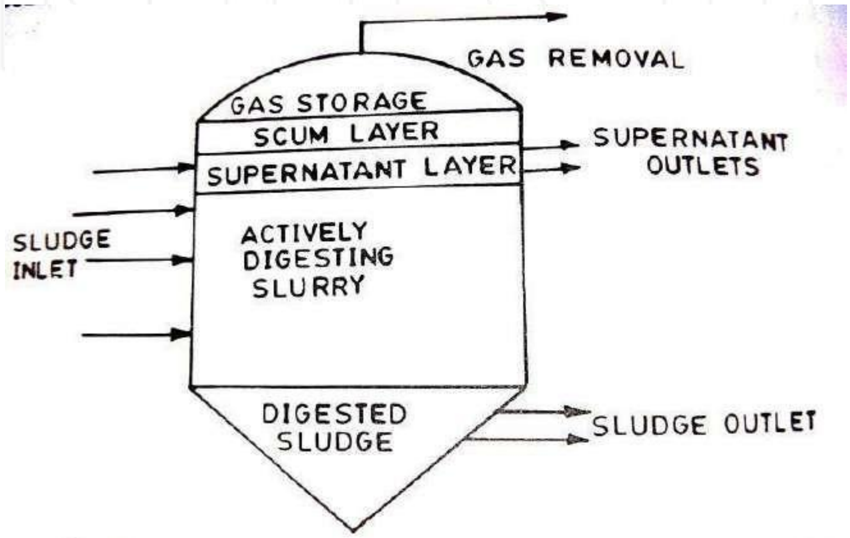


Fig. 7.6.1. Schematic of single process conventional digester.

The entire process of conversion of complex organic compounds into biogasincompletedinasinglechamber.Thischamberisregularlyfedwiththerawm aterialswhilethespentresiduekeepsmovingout.Seriousproblems are encountered with agricultural residues when fermented in a single stagecontinuousprocess.

<u>Twostagecontinuousplant:(i)Acid&ii)Methaneforming:</u>

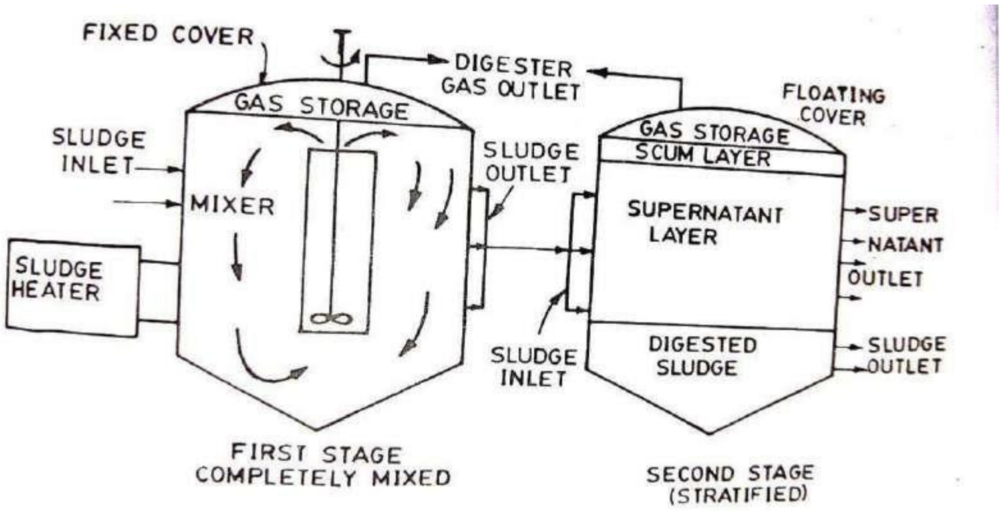


Fig. 7.6.2. Schematic of two-stage digestion process.

The acidogenic stage and methanogenic stage are physically separated intotwo chambers. Thus the first stage of acid production is carried out in aseparatechamberandonlythedilutedacidsarefedintothesecondchamber where bio-methanation takes place and the biogas can be collectedfromthesecondchamber.Consideringtheproblemsencounteredinferm enting fibrous plant waste materials the two stage process may offerhigher potential of success. However, appropriate technology suiting to rural India is needed to be developed based on the bauble stage process.

Themainfeaturesofcontinuousplantarethat:

1) Itwillproducegascontinuously;
2) Itrequires small digestion chambers;
3) Itneedslesserperiodfordigestion;
4) Ithasfewerproblemscomparedtobatchtypeanditiseasierinoperation.

a) IndianDigester(Floatingdrumtype/KhadiVillegeIndustriesCommissionPlant(KVIC)):

This mainly consists of a digester or pit for fermentation and a floating drumfor the collection of gas. Digester is 3.5-6.5 m in depth and 1.2 to 1.6 m indiameter. There is a partition wall in the center, which divides the digesterverticallyandsubmergesintheslurrywhenitisfull.Thedigesterisconnectedtotheinletandoutletbytwopipes.Throughtheinlet,thedungismixedwithwater(4:5)andloadedintothedigester.Thefermentedmaterial will flow out through outlet pipe. The outlet is generally connectedto a compost pit. The gas generation takes place slowly and in two stages. Inthe first stage, the complex, organic substances contained in the waste areacteduponbyacertainkindof bacteria,calledacidformersandbrokenupintosmall-chainsimpleacids.Inthesecondstage,theseacidsareacteduponbyanotherkindofbacteria,calledmethaneformers and produce methane andcarbondioxide.

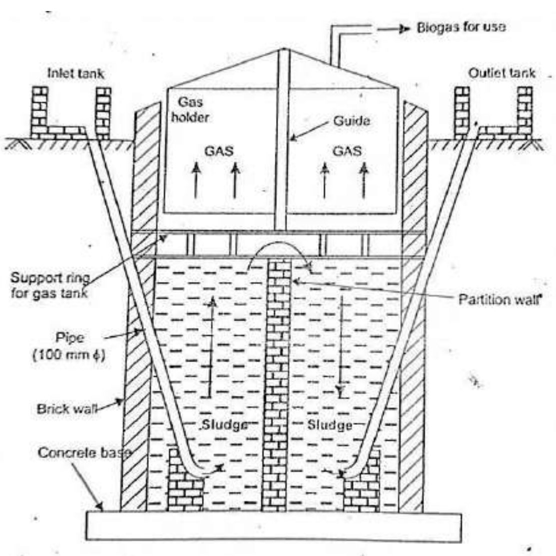
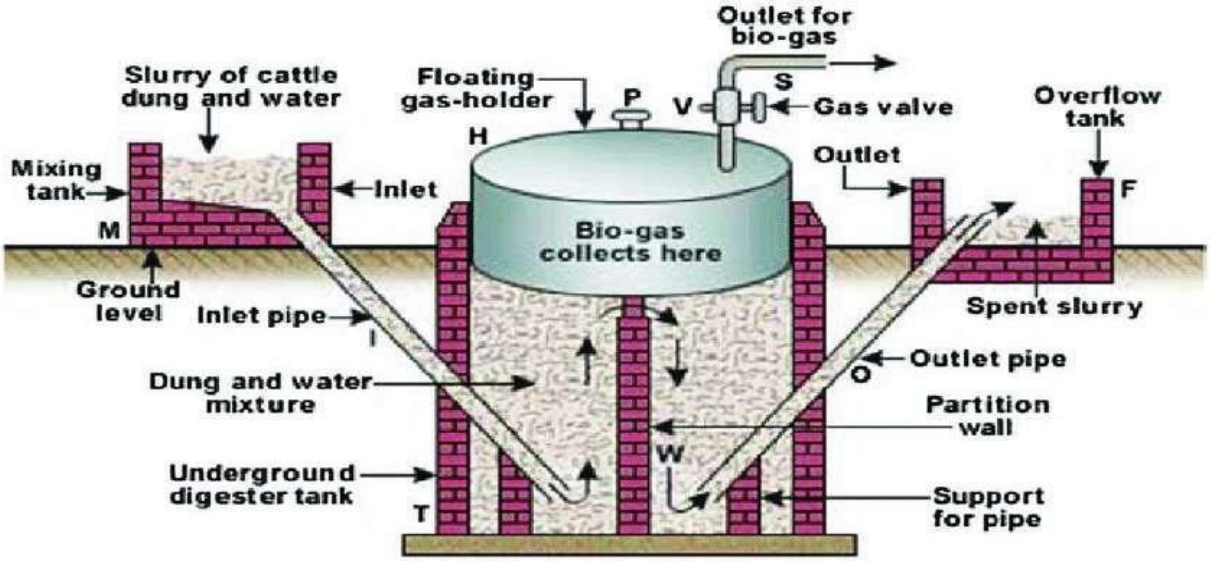


Fig. 8-6. Indian Design Digestor

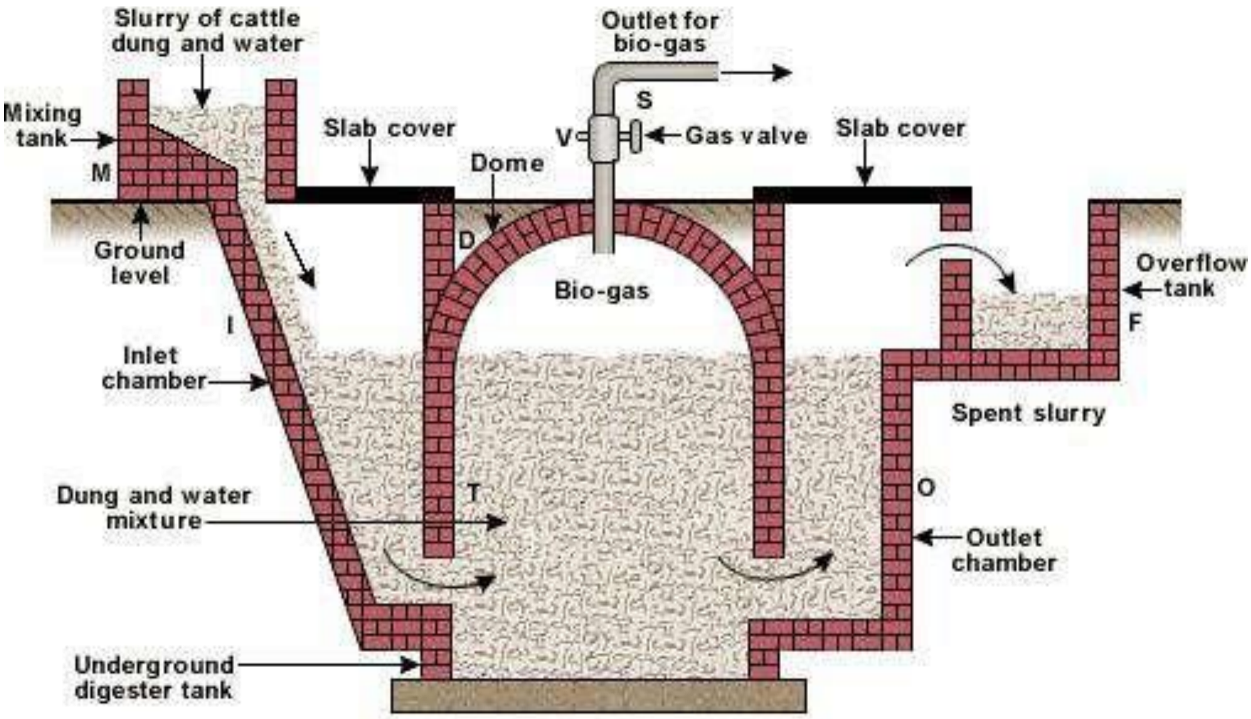
Gasholder:

The gas holder is a drum constructed of mild steel sheets. This is cylindrical in shape with concavetop. The top is supported radially with angular iron stripes. The holder fitsinto the digester like a stopper. It sinks into the slurry due to its own weightand rests upon the ring constructed for this purpose. When gas is generatedthe holder rises and floats freely on the surface of slurry. A central guidepipe is provided to prevent the holder from tilting. The holder also acts as aseal for the gas. The gas pressure varies between 7 and 9 cm of watercolumn.Undershallowwatertableconditions,theadopteddiameterofdigesterismoreanddepthisreduced.Thecostofdrumisabout40%oftotal cost of plant. It requires periodical maintenance. The unit cost of KVICmodelwithacapacity of2m3/day costsapproximatelyRs.14,000/.

IndianDigester(Floatingdrumtype/KhadiVillegeIndustriesCommissionPlant(KVIC)):



Fixed Dome type Biogas Plant/ Janata Model /Chinese Model



Fixed-dome type bio-gas plant.

FixedDomtypeBiogasPlant/JanataModel/ChineseModel

ThedesignofthisplantisofChineseoriginbutithasbeenintroducedunder the name ―Janata biogas plant‖ by Gobar Gas Research Station,Ajitmal in view of its reduced cost. This is a plant where no steel is used,there is no moving part in it and maintenance cost is low. The plant can beconstructed by village mason taking some pre-explained precautions andusingalltheindigenouslyavailablebuildingmaterials.Goodqualityofbricksandcementshouldbeusedtoavoidtheafterwardstructuralproblems like cracking of the dome and leakage of gas. This model have ahigher capacity when compared with KVIC model, hence it can be used as acommunity biogas plant. This design has longer life than KVIC models.Substratesotherthancattledungsuchasmunicipalwasteandplantresidues can also be used in janata type plants. The plant consists of anunderground well sort of digester made of bricks and cement having a domeshaped roof which remains below the ground level is shown in figure. Atalmostmiddleofthedigester,therearetworectangularopeningsfacingeach other and coming up to a little above the ground level, act as an inletand outlet of the plant. Dome shaped roof is fitted with a pipe at its topwhichisthegasoutletoftheplant.

The principle of gas production issame as that of KVIC model. Thebiogas is collected in the restrictedspace of the fixed dome; hence thepressureofgasismuchhigher,whichisaround90cmofwatercolumn.

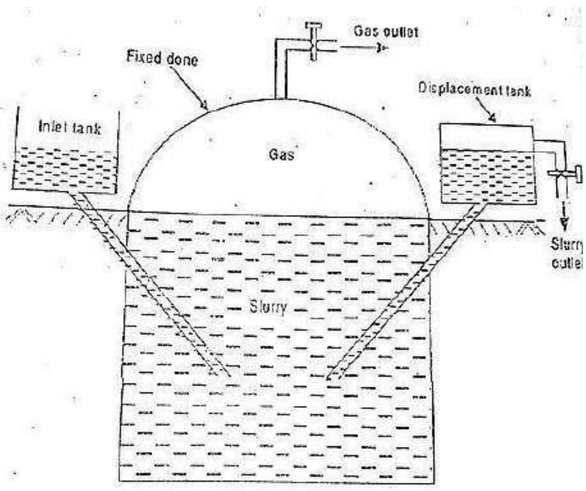
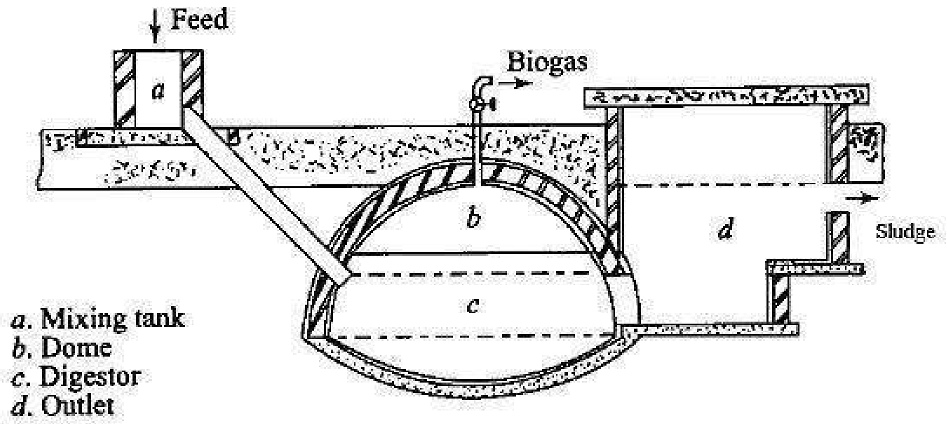


Fig. 8-7. Chinese design biogas plant

Deenbandhubiogasplant:



Deenbandhu model was developed in 1984, by Action for Food Production(AFPRO),avoluntaryorganizationbasedinNewDelhi.Schematicd iagramof a Deenabandhu biogas plant entire biogas programme of India as itreduced the cost of the plant half of that of KVIC model and brought biogastechnology within the reach of even the poorer sections of the population.Thecostreductionhasbeenachievedbyminimizingthesurfacear eathrough joining the segments of two spheres of different diameters at theirbases. The cost of a Deenbandhu plant having a capacity of 2 m3/day isabout Rs.8000/. The Deenbandhu biogas plant has a hemispherical fixed-dome type of gas holder, unlike the floating dome of the KVIC-design isshown. The dome is made from pre-fabricated Ferro cement or reinforcedconcreteandattachedtothedigester,whichhasacurvedbottom.Th eslurry is fed from a mixing tank through an inlet pipe connected to thedigester.Afterfermentation,thebiogascollectsinthe spaceunderthedome. It is taken out for use through a pipe connected to the top of thedome,whilethesludge,whichisaby-product,comesoutthroughanopening in the side of the digester. About 90% of the biogas plants in Indiaareof the Deenbandhu type.

Differences between Floating drum & Fixed dome Biogas Plants

S.NO.	FEATURE	FLOATING DRUM	FIXED DOME
1.	Cost	More(due to steel drum)	Less
2.	Corrosion	Yes (likely in steel drum)	No
3.	Maintenance	More • Drum requires painting • Flexible gas pipe requires replacement	Less • No steel part is used • Gas pipe is fixed type
4.	Thermal Insulation	Bad	Good(due to underground construction)
5.	Scum Troubles	Less likely	More likely
6.	Gas Production Per Unit Volume Of Digester	High	Low
7	Scum Braking	By rotation of drum	External stirrer is required
8	Leakage	Less Likely	More Likely
9	Danger Of Mixing With Oxygen Due To Leakage,Cracks	No	More likely
10	Gas Pressure	constant	Variable
11	Masonry Workmanship	Average skill	Specialized, skilled masonry work required

ProblemsRelatedtoBio-gasPlants:

Some problems are natural and some are created by the persons biogasplantsowners butall arecontrollable.

1. Handling of effluent slurry is major problem if the person is not havingsufficient open space or compost pits to get the slurry dry. Use of pressfiltersandtransportationisexpensiveandoutofreachofpoorfarmers.For

b) a domestic plant, 200 litres capacity oil drums can be used to carry thiseffluent to the fields but this will require some human-animal labour orconsumptionof dieselif aauto vehicle is used.

c) The gas forming-methanogenic bacteria are very sensitive towards thetemperature compared to those of non-methanogenic. During winter as thetemperature falls, there is decrease in the activity of methanogenic bacteriaand subsequently fall in gas production rate. Many methods have beensuggestedtoovercomethistemperatureproblemasdescribedearlier,e.g.,

a) Use of solar heated hot water to make a slurry of influent but thetemperatureofwatershouldnotexceed60^{o}Cotherwisethemesophilicbacteriawill die.

b) Circulation of hot water obtained either from solar heater or I.C.engineheatexchanger,through pipesinside thedigester.

c) Green house effect also give good results but it is costlier and afterfewyearsthepolythene sheetusedinit becomesopaque.

d) Additionofvariousnutrientsforbacteria.

e) Convertingthebiogasplantbystrawbagsduringnighthours.

2. Duetolackofpropertrainingtothebio-gasplantownersfortheoperation of plant, a lot of problems arises. It has been noticed that manypersons increase the loading rate and some also do not try to mix the cattledung with water, keeping in mind more gas production. Due to this, the flowofslurryfrominlettowardsoutletisveryslowerevenstops.Thismaycause accumulation of volatile fatty acids and drop in Ph and then failure ofdigester. Also it is not possible to stir the digester content of high solidconcentration.

3. Some persons add urea-fertilizer in large quantities due to which toxicityofammonianitrogenmaycauseadecreaseingasproduction.

4. pH and volatile fatty acids play an important role in anaerobic digestionandshouldremainunderoptimumrangeotherwisethismaycauseupset ting of digester and even its failure. pH can be checked from time totimebytheuseofcheepandeasilyavailablepHpaperbutvolatilefattyacids can only be determined in a laboratory having its testing facilities. ForcontrollingpHinoptimumrange,ittendstofallbelow7.0,limehasbeen suggested,asitiseasilyavailablecheapmaterialanddoesnotharmtheactivityof bacteria.

5.LeakageofgasfromgasholderespeciallyincaseofJantatypebiogasplantsisamajor andverycommonproblem.Whenthereisquiteenoughgasinagasholder,theleakages houldbecheckedbyusingwaterandthepointsmarkedandthengetrepaired.Duringr epairingthereshouldbenogas inside the gas holder and the stop cock remains open till repaired pointsget dry. Quality of constructing material such as cement is important.

AdvantagesofBiogas:

1. Biogas is an energy carrier which can be used for several energyapplications(eg.electricitygeneration,heatproduction,combineheatandpowerproduction,transportfuel,injectiontothenaturalgasgrid).

2. Biogas can contribute to several sectors:

i) Environment
(eg.FightagainstClimatechange)
ii) Energy
(eg.Energysecurity,localsource)
iii) Agriculture
(eg.Sustainablecultivationandanimalbreeding)
iv) Society
(eg.Employmentenhancement,ruraldevelopment)

3. SomeEnvironmentalbenefitsofbiogas:

i) Reduced emissions of greenhouse gases, direct and indirect (eg. CO_2,$CH_4$and nitrousoxide–N_2O).
ii) Water and Waste management (Reduced consumption of resourcesandincreasedrecycling,reducedwaterenvironmentpollutionfromleachingof nutrients, environmental friendly solutionto the wastedisposalproblem).
iii) Reducedodourandfliesnuisances.
iv) Soilandlandscape

4. Emissions reduction of greenhouse gases (eg. CO_2, CH_4 and nitrousoxide–N_2O).

Direct:

ThecombustionofbiogasalsoreleasesCO2.Comparedtofossilfuels,the carbon in biogas was recently up taken from the atmosphere, byphotosyntheticactivityoftheplants(closedcarboncycle).

- Biogas production by AD reduces also emissions of methane (CH4) andnitrous oxide (N2O) from storage and utilization of animal manure asfertilizer.Itisworthmentioningthatalthoughbiogasisapotentiallow

- carbon energy source, this depends on the way biogas is produced. Inthe case that biogas comes from residues, waste or from energy cropsgrownonabandonedagriculturalandthisofferssustainedGHGadvantages.

- Emissionsreductionofgreenhousegases(eg.CO2,CH4andnitrousoxide–N2O). Indirect:
- Utilisationofbiogassubstitutefossilfuel(suchaslignite,hardcoal,crudeoil andnaturalgas)andthusreducesemissions(externalities).

5. Waterand Wastemanagement

- Compared to other biofuels, biogas needs the lowest amount of processwater. This aspect is very important since many regions of the world facehugewater problems
- One of themain advantagesof biogas productionis the abilitytotransformwastematerialintoavaluableresource,byusingitasfeedstockfor AD.
- Biogas technologies contribute to reduce the volume of wastes and thecostsfor wastedisposal (transportation,disposal).

6. Healthissues,odourandflies

Utilisationofdigestateasfertilizerimprovesveterinarysafety,whencomparedto untreatedmanure and slurries.

AD reduces odours(positive change in the compositionof odours aswell). Digestate is almost odourless and the remaining disappear shortlyafterapplicationasfertilizeron thefields(ammoniaodours).

7. Employment
8. Ruraldevelopment
9. LocaleconomyandEnergyMarketdevelopment

Applicationof bio-gas in engines:

BiogasinDieselEngineapplications:

Biogas generally has a high self-ignition temperature hence; it cannot bedirectly used in a CI engine. So it is useful in dual fuel engines. The dualfuel engine is a modified diesel engine in which usually a gaseous fuelcalled the primary fuel is inducted with air into the engine cylinder. Thisfuel and air mixture does not auto ignite due to high octane number. Asmall amount of diesel, usually called pilot fuel is injected for promotingcombustion. The primary fuel in dual fuelling system is homogeneouslymixed with air that leads to very low level of smoke. Dual fuel engine canuse a wide variety of primary and pilot fuels. The pilot fuels are generallyofhighcetanefuel.Biogascanalsobeusedindualfuelmodewith vegetable oils as pilot fuels indieselengines. Introduction of biogasnormallyleadstodeteriorationinperformanceandemissioncharacteristics. The performance of engine depends on the amount ofbiogas and the pilot fuel used. Measures like addition of hydrogen, LPG,removalofCO_2etc.haveshownsignificantimprovementsintheperformance of biogas dual fuel engines. The ignition delay of the pilotfuel generally increases with the introduction of biogas and this will leadto advance theinjection timing. Injectors opening pressure and rate ofinjectionalsoarefoundtoplayimportantroleinthecaseofbiogasfuelledengine,wherevegetablesoilisusedasapilotfuel.TheCO_2percentage in biogas acts as diluents to slow down the combustionprocess in Homogenous charged compression ignition (HCCI) engines.However,italsoaffectsignition.Thusafuelwithlowself-ignitiontemperature could be used along with biogas to help its ignition. Thiskind of engine has shown a superior performance as compared to a dualfuelmode of operation.

BiogasinDualFuelEngineapplications:

Inthiscase,thenormaldieselfuelinjectionsystemstillsuppliesacertain amount of diesel fuel. The engine however sucks and compressesa mixture of air and biogas fuel which has been prepared in externalmixing device. The mixture is then ignited by and together with the dieselfuel sprayed in. The amount of diesel fuel needed for sufficient ignition isbetween 10% and 20% of the amount needed for operation on diesel fuelalone. Operation of the engine at partial load requires reduction of thebiogas supply by means of a gas control valve. A simultaneous reductionof airflow would reduce power and efficiency because of reduction ofcompression pressure and main effective pressure. So, the air/fuel ratiois changed by different amounts of injected biogas. All other parametersandelements ofdieselengineremain unchanged.

BiogasAsAlternateFuelInDieselEngines:ALiteratureReviewModification of diesel engine into dual fuel engine Advantages-Operationondieselfuelaloneispossiblewhenbiogasisnotavailable.-Anycontribution of biogas from 0% to 85% can substitute a correspondingpart of diesel fuel while performance remains as in 100% diesel fueloperation.-Because of existence of a governor atmost diesel enginesautomatic control of speed/power can be done by changingthe amountof diesel fuel injection while the biogas flow remains uncontrolled. Dieselfuelsubstitutions bybiogasare less substantial inthis case.

Limitations:

-
Thedualfuelenginecannotoperatewithoutthesupplyofdieselfuelforignition.

-
The fuel injection jets may overheat when the diesel fuel flow is reducedto10%or15%ofits normalflow.Largerdualfuelenginescirculateextradieselfuel through the injector for cooling.

-

To what extent the fuel injection nozzle can be affected is however aquestion of its_ specific design, material and the thermal load of theengine,and hencedifersfromcase to case.
-
Acheckoftheinjectornozzleafter500hoursofoperationindualfuelisrecommended.

<u>BiogasinHCCIEngineapplications:</u>
TheHomogeneousChargeCompressionIgnition(HCCI)conceptisapotential for achieving a high thermal efficiency and low Nitrogen Oxide(NO) emission. The HCCI engine with 50 % biogas as a primary fuel and50% diesel as pilot fuel gives a maximum NO of 20 ppm is a majoradvantage over biogas diesel dual fuel mode. In biogas diesel dual fuelmodethepresenceofCO_2inbiogaslowersthethermalefficiencyhowever, in biogas diesel HCCI (BDHCCI) mode CO_2reduces high heatrelease rate. The break mean effective pressure (BMEP) in BDHCCI modeis in the range of 2.5 bar to 4 bar. The smoke and Hydro Carbon (HC)level were also low when the biogas is used as a primary fuel for BDHCCImode.ForHCCIoperationtheinductedchargetemperatureisrequiredto be maintained at 80-135°C, which can be obtained from the exhaustheat.ThusbiogaswithHCCIenginegiveshighefficiencyandlowemission.

ECONOMIC AND OPERATIONAL CONSIDERATIONS

- There are different basic situations out of which the use of biogas for the generation of mechanical or electric energy may be considered.

a) Biogas availability or potential

- A biogas plant already exists and the gas yield is larger than what is already consumed in other equipment or the yield could be increased.
- Organic matter is available and otherwise wasted; the boundary allow for anaerobic digestion.
- Environmental laws enforce anaerobic treatment of organic waste conditions from municipalities, food industries, distilleries, etc.
- b) Demand for mechanical power
- Other fuels are practically not available.
- Other sources of energy or fuels are more expensive or their
- supply is unreliable.
- Having a fuel at one's own disposal is of specific advantage.

- c) Possible revenue through selling mechanical power, electric power or
- related services to other customers (e.g. the public electricity supply company).

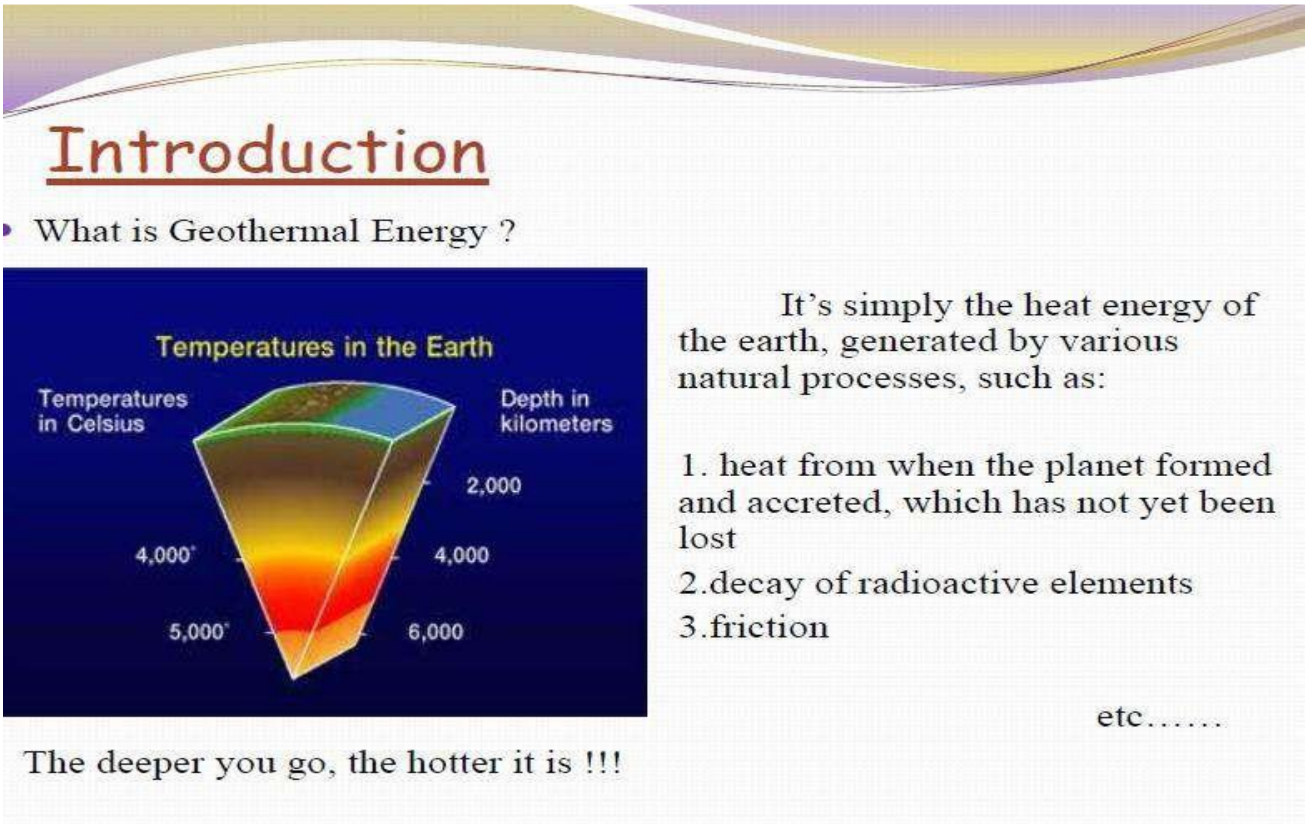
INVESTMENT AND OPERATIONAL COST

- Investment for the biogas engine system will differ from case to case,
- depending on what is actually required for completion of the system:
- biogas plant, gas storage,
- -biogas piping and instrumentation,
- engine cum modification,
- driven machine cum transmission,
- -civil works, i.e. foundations, sheds, fences, etc.,
- -wiring, piping, switchgear.

GEOTHERMAL ENERGY

Syllabus: Resources, types of wells, methods of harnessing the energy, potential in India.

- ✓ Geothermal comes from Greek words
- ✓ Geo means Earth &Therme means Heat
- ✓ Geothermal energy is the heat from the Earth
- ✓ Its sources lies 6500 km beneath the Earth's surface, Core containing hot Magma



Geothermal Reservoirs

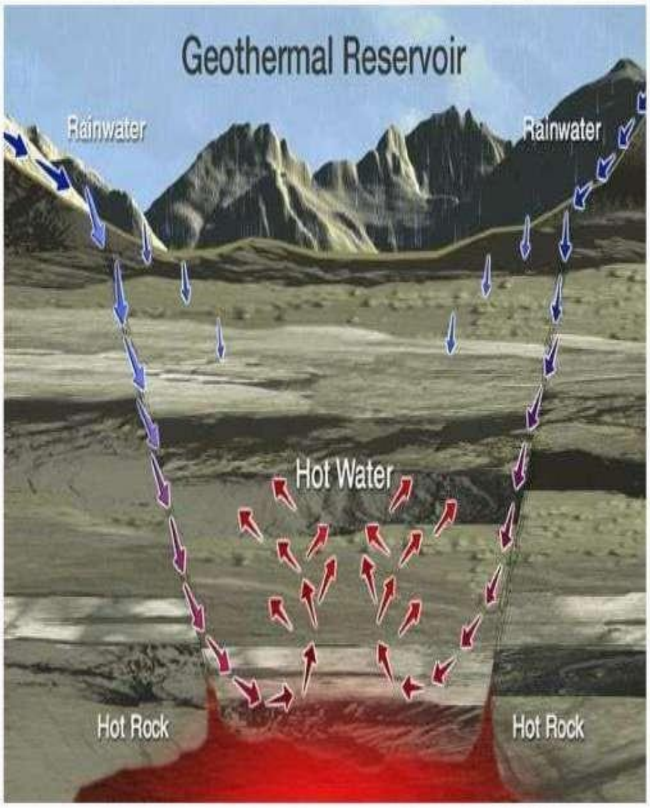
- Reservoirs can be suspected in the areas where we find :-

→Geyser

→Boiling mud pot

→Volcano

→Hot springs



- The rising hot water & steam is trapped in permeable & porous rocks to form a geothermal reservoir.
- Reservoirs can be discovered by

  → testing the soil

  → analyzing underground temperature

ORIGIN AND DISTRIBUTION OF GEOTHERMAL ENERGY

- Geothermal energy is the heat that originates from the core of the earth, where temperatures are about 4000 °C.
- The heat occurs from a combination of two sources:
  - (i) the original heat produced from the formation of the earth by gravitational collapse and
  - (ii) the heat produced by the radioactive decay of various isotopes. As the thermal conductivity of the rock is very low, it is taking many billions of years for the earth to cool.
- Average geothermal heat dissipation from land and ocean surface is about 0.06 W/m2 , which is negligible as compared to power dissipation due to other sources e.g. solar energy (~ 1 kW/m2).
- The core is surrounded by a region, known as mantle, which consists of semi-fluid material called the magma. The mantle is finally covered by the outermost layer known as crust, which has average thickness of about 30 km.
- The temperature in the crust increases with depth at a rate of 30 °C/km.
- The temperature at the base of crust is about 1000 °C and then increases slowly into the core of the earth.
- A section through the earth is shown in Fig. 9.1. Though the general distribution of layers is as shown in the Fig. 9.1, at certain locations anomalies exist in composition and structure of these layers.
- There are regions in which hot molten rock (magma) of the mantle has pushed up through faults and cracks towards the surface.
- In an active volcano, the magma actually reaches the surface, but more often "hot spots" occur at moderate depths (within 2 to 3 km), where the heat of the magma is being conducted upward through an overlaying rock layer.
- In fact, the zone of likely geothermal sites corresponds roughly to the regions of seismic and volcanic activities. High enthalpy geothermal fields occur within welldefined belts of geologic activity

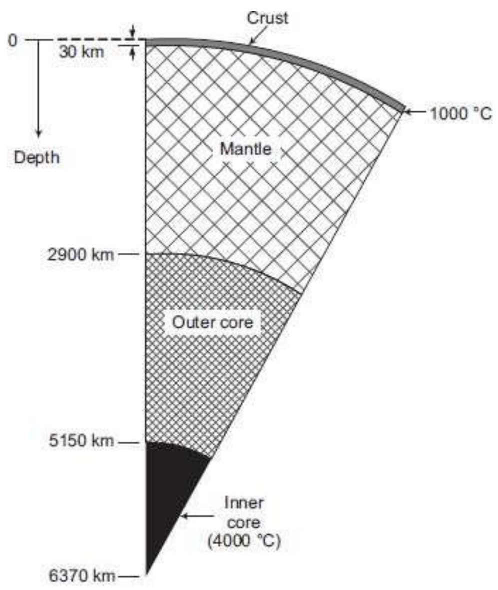
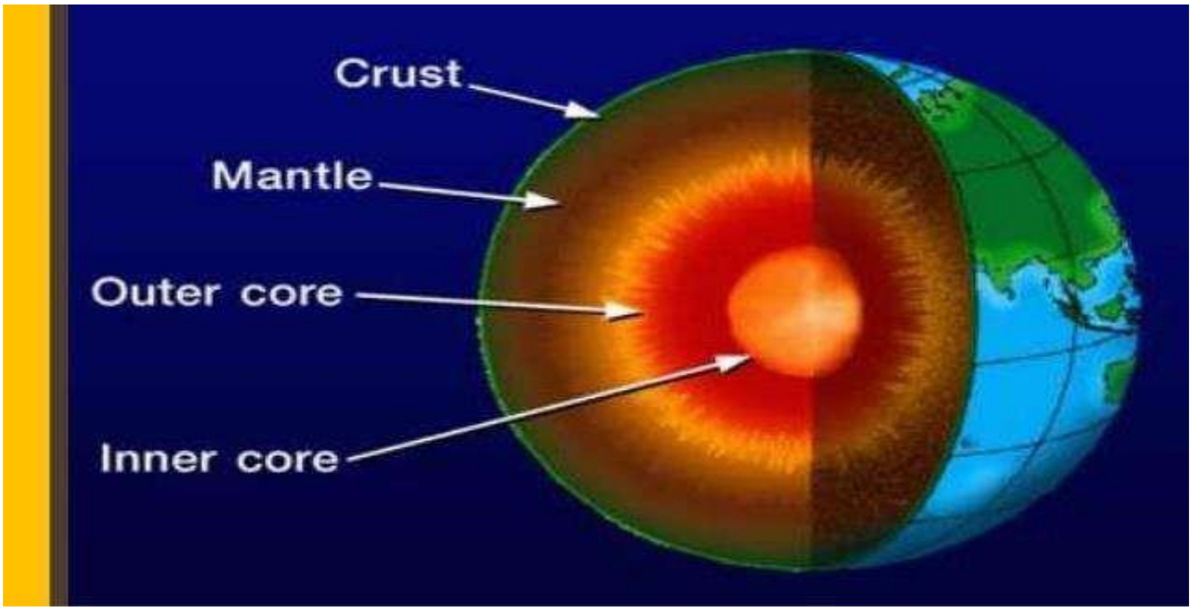


Figure 9.1 Cross section of the earth

Internal structure of the Earth



CRUST

- It is the outermost solid part of the earth, normally about 8-40 kms thick.
- It is brittle in nature.
- Nearly 1% of the earth's volume and 0.5% of earth's mass are made of the crust.
- The thickness of the crust under the oceanic and continental areas are different. Oceanic crust is
- thinner (about 5kms) as compared to the continental crust (about 30kms).
- Major constituent elements of crust are Silica (Si) and Aluminium (Al) and thus, it is often termed as SIAL(Sometimes SIAL is used to refer Lithosphere, which is the region comprising the crust and uppermost solid mantle, also).
- The mean density of the materials in the crust is 3g/cm3.
- The discontinuity between the hydrosphere and crust is termed as the Conrad Discontinuity.

MANTLE

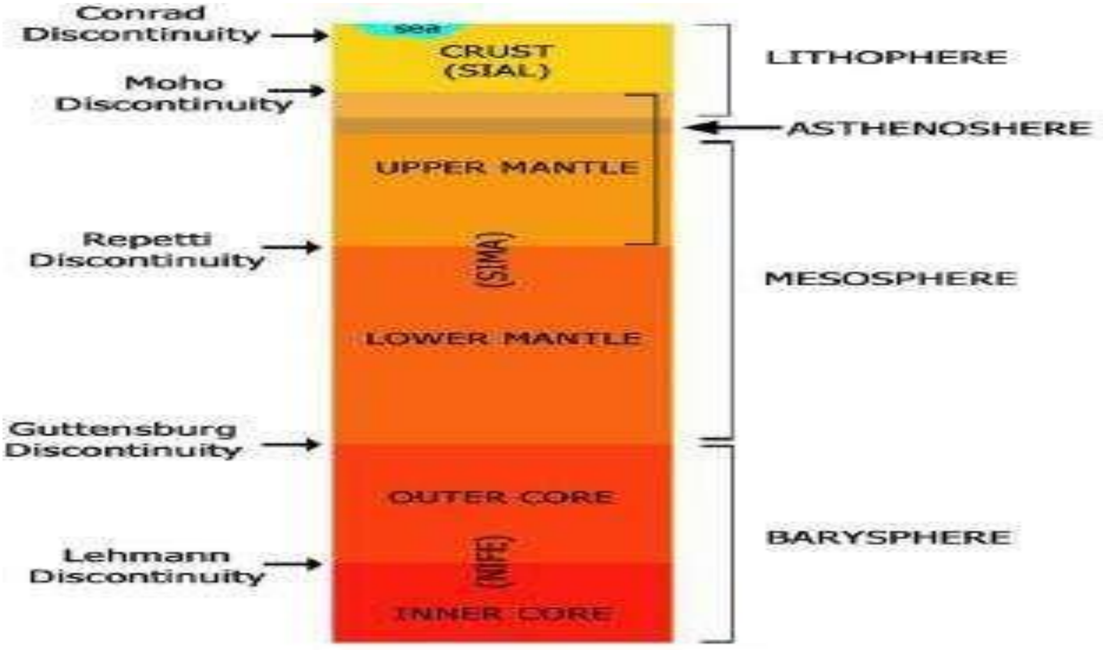
- The portion of the interior beyond the crust is called as the mantle.
- The discontinuity between the crust and mantle is called as the Mohorovich Discontinuity or Moho discontinuity.

- The mantle is about 2900kms in thickness.
- Nearly 84% of the earth's volume and 67% of the earth's mass is occupied by the mantle.
- The major constituent elements of the mantle are Silicon and Magnesium and hence it is also termed as SIMA.
- The density of the layer is higher than the crust and varies from 3.3 – 5.4g/cm3.
- The uppermost solid part of the mantle and the entire crust constitute theLithosphere.
- The asthenosphere (in between 80-200km) is a highly viscous, mechanically weak and ductile, deforming region of the upper mantle which lies just below the lithosphere.
- The asthenosphere is the main source of magma and it is the layer over which the lithospheric plates/ continental plates move (plate tectonics).

CORE

- It is the innermost layer surrounding the earth's centre.
- The core is separated from the mantle by Guttenberg's Discontinuity.
- It is composed mainly of iron (Fe) and nickel (Ni) and hence it is also called as NIFE.
- The core constitutes nearly 15% of earth's volume and 32.5% of earth's mass.
- The core is the densest layer of the earth with its density ranges between 9.5- 14.5g/cm3
- .The Core consists of two sub-layers: the inner core and the outer core.
- The inner core is in solid state and the outer core is in the liquid state (or semiliquid).
- The discontinuity between the upper core and the lower core is called as Lehmann Discontinuity.

Barysphere is sometimes used to refer the core of the earth or sometimes the wholeinterior



STRUCTURE OF THE EARTH'S INTERIOR

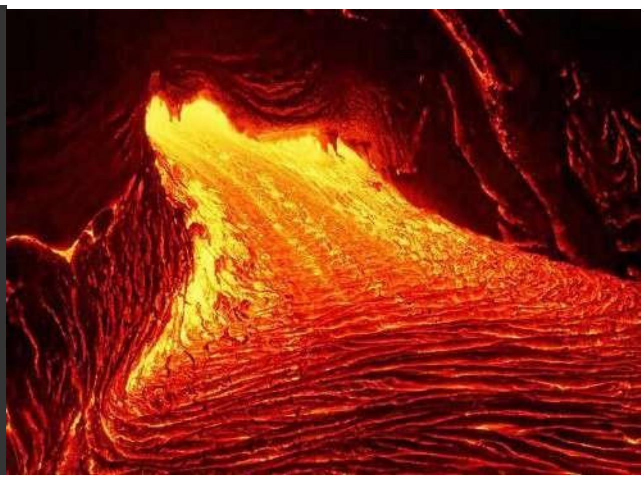
Types/Nature of Geothermal Fields

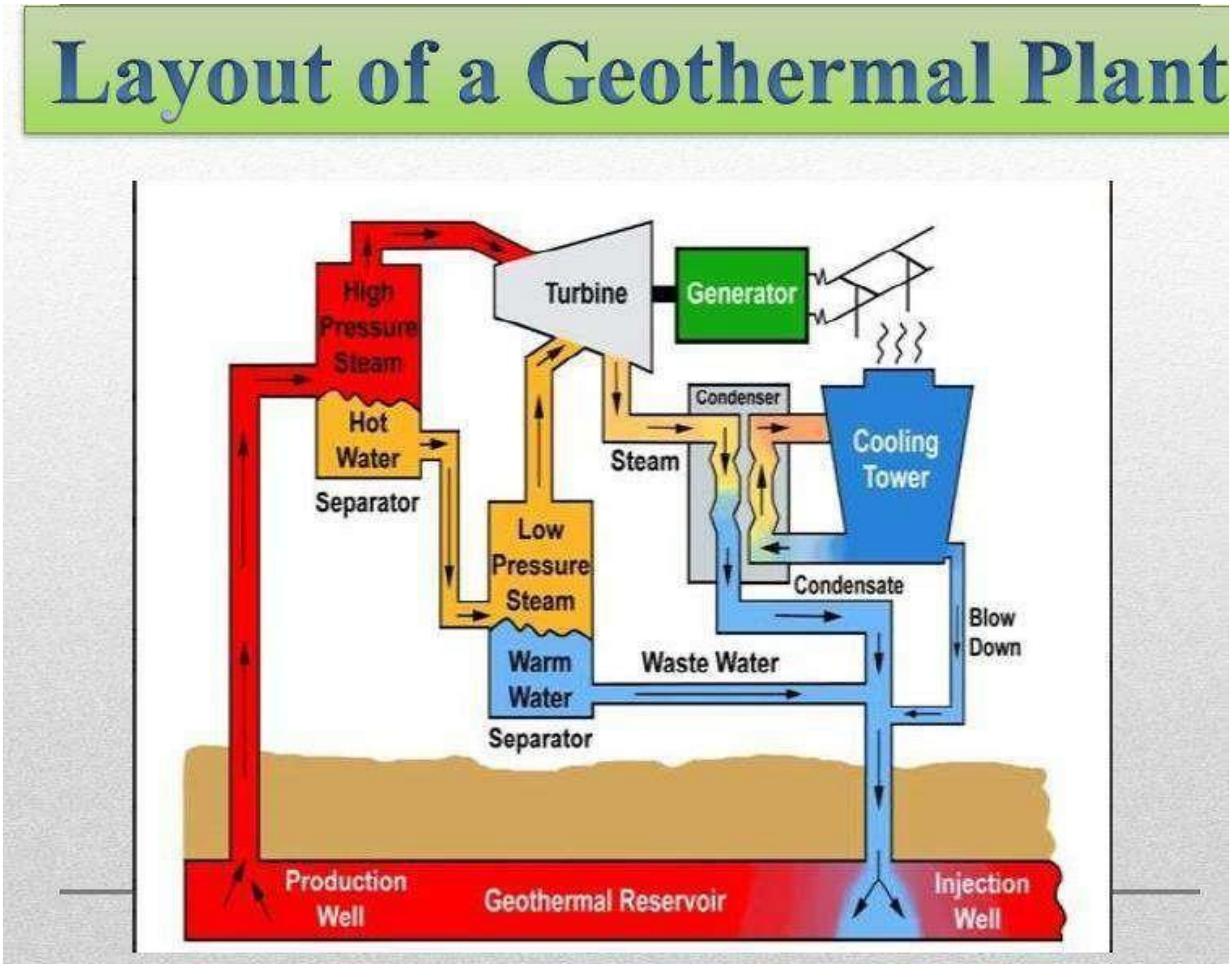
- **1.Non Thermal fields - Temperature gradient of 10-40^{0}C per km depth**
- **2.Semi Thermal fields – 70^{0}C per km depth**
- **3.Hyper Thermal fields –**
- **a) Wet fields – steam is above 100^{0}C**
- **b) Dry fields – produce dry steam**

Geothermal Sources

1) **Hydro thermal convective systems**
    1) **Vapour dominated or dry steam fields**
    2) **Liquid dominated of wet steam fields**
    3) **Hot water fields**
2) **Geo pressure resources**
3) **Hot Dry Rock (HDR) or Petro thermal**
4) **Magma Resources**

5) Volcanoes





Process Flow:

- To harness energy, large holes have to be dug into the earth until a geothermal hotspot is found.
- Pipes are inserted inside these holes through which water is sent¬ and steam output is obtained.
- The production involves two process¬ 1) Converting Geothermal energy into Mechanical energy 2) Converting Mechanical Energy into Electrical Energy
- The success of the energy production depends on the temperature¬ of the plant which depends on the temperature of the rocks in earth.
- The water is sent through the injection well and reaches the rocks¬ and then hot water comes from the production well.
- The steam that comes out of the mixture might have dissolved¬ brine and some dust particles.
- Due to the high pressure when it reaches the topmost of the earth¬ surface it is converted into steam.
- The separator is the place where steam that comes from the earth¬ is made clean by removing the brine and dirt so that they do not damage the turbine blades.
- The high pressure and low pressure steam runs the turbine.¬ The generator is coupled with turbine to produce electricity.
- The condenser is a phase changer where the steam output of the¬ turbine is given

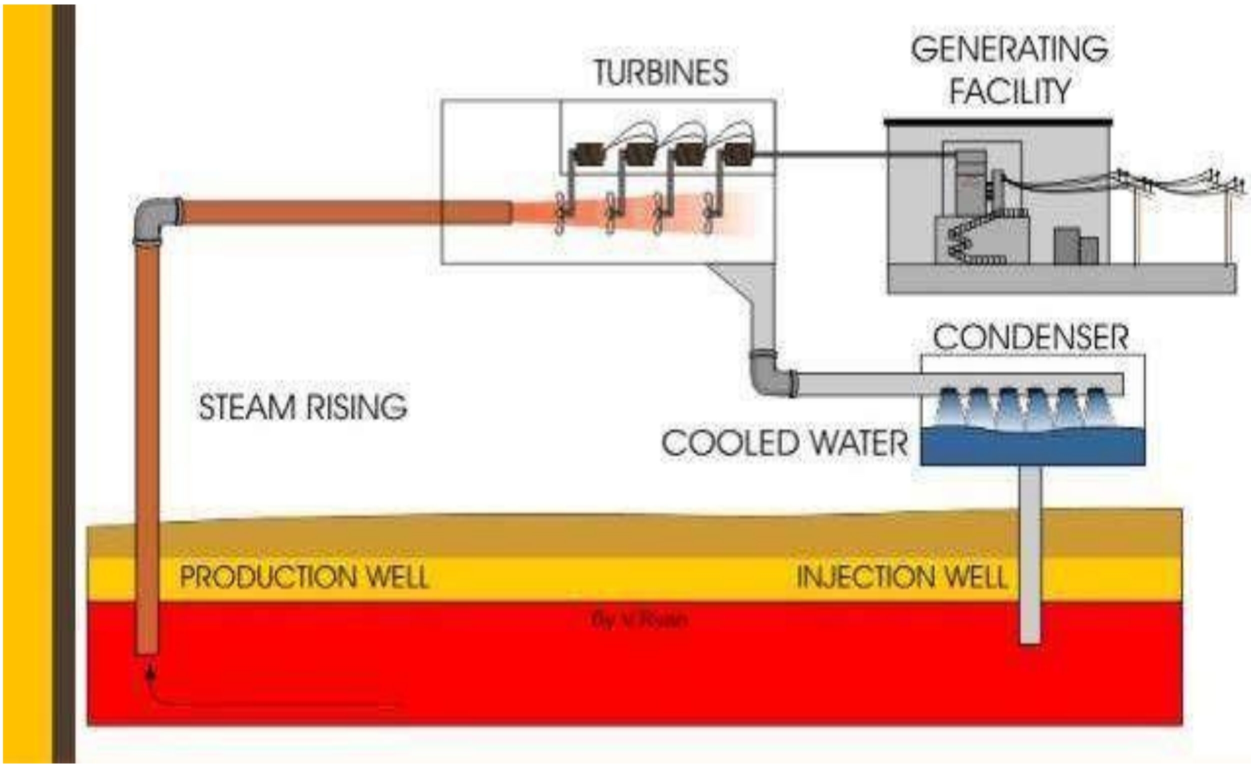
to the condenser and gets converted to hot water.

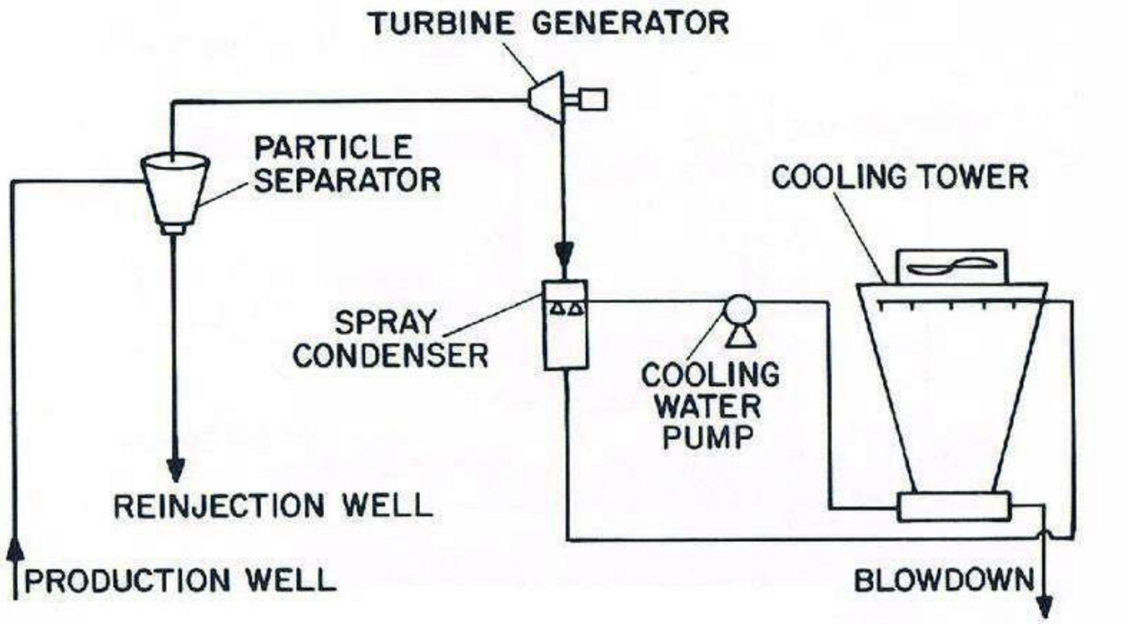
- This hot water is then sent to the cooling tower where it loses it¬ heat and then sent to the geothermal reservoir for further production of steam.

Types of Geothermal Power plants

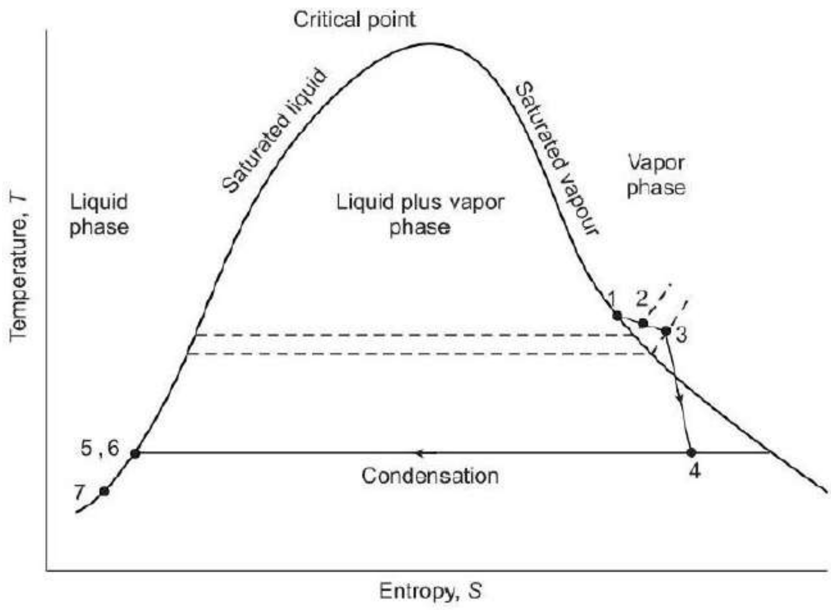
- **1.Dry steam or Vapour dominated plant – working fluid is dry steam**
- **2.Wet steam or Flash or Liquiddominated plant – working fluid is wet steam**
- **3.Binary cycle plant – working fluid is Iso Butane or Iso Pentane**

1. Dry steam or Vapour dominated plant – working fluid is dry steam



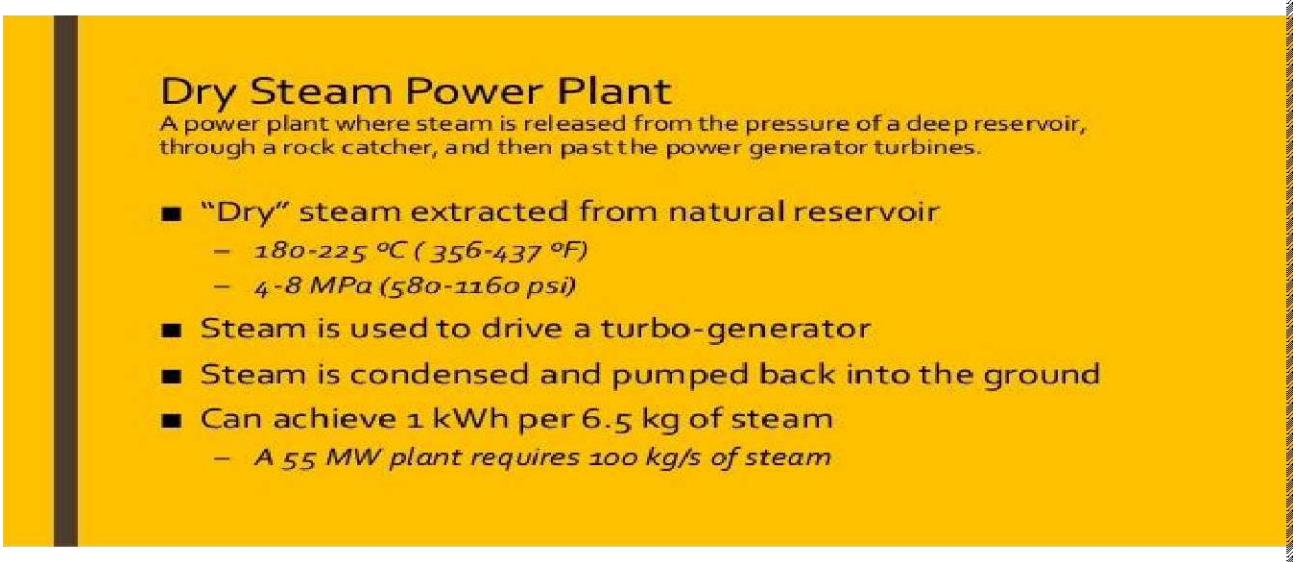


DIRECT STEAM CYCLE FOR VAPOR DOMINATED SYSTEMS



(b) T–S diagram of vapor dominated system

- Dry steam field is the most desirable form of geothermal energy .
- The geothermal fluid for those plants is dry steam at temperatures between 180º C to 240º C.
- Steam from the production well is collected ,filtered to remove abrasive particles and passed through the steam turbine coupled to electric generators.
- Steam plants use hydrothermal fluids that are primarily steam.
- Steam goes directly to a turbine, which drives a generator that produces electricity.
- Steam eliminates the need to burn fossil fuels to run the turbine.
- These plants emit only excess steam and very minor amounts of gases.

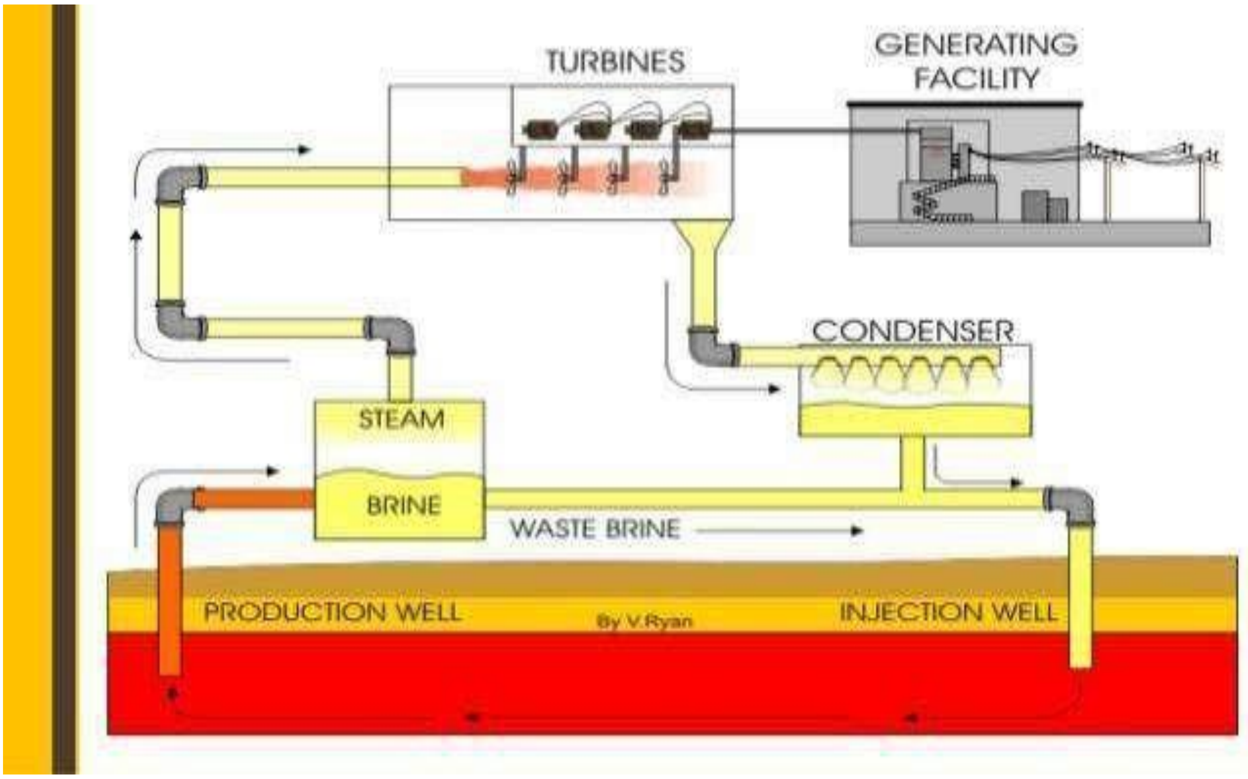


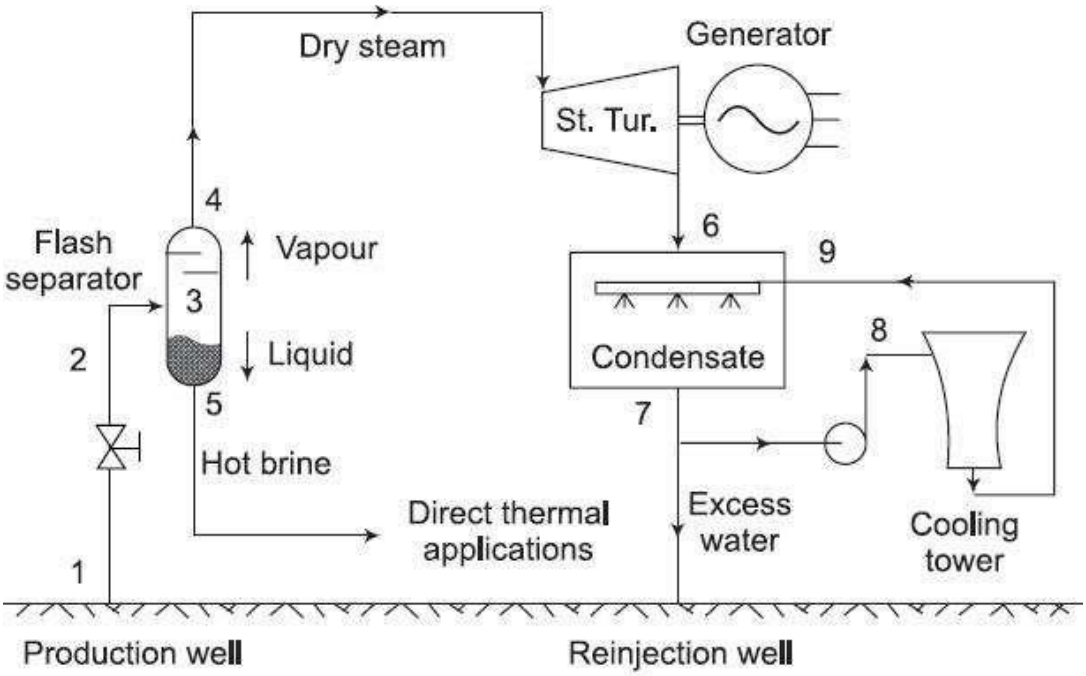
Major differences as compared to conventional thermal (steam) plants are as follows:

- The temperature and pressure in such plants are much less (about 165 °C and about 7.8 atm) compared to that in conventional thermal plants (where these are about 540 °C and about 160 atm). As a result, the efficiency of this plant is much less; about 15 per cent, compared to 35–40 per cent in case of conventional thermal plants.
- In conventional thermal plants, surface-cooling condenser is used as the condensed steam is to be used as boiler feed water and therefore condensate and cooling water are not allowed to mix. Whereas, in hydrothermal systems, steam is continuously supplied by the resource, which allows more simple and efficient direct contact condensing.
- Hydrothermal systems produce their own cooling water whereas in conventional thermal plants, make up cooling water is required from an external source.
- In case of conventional thermal plants, the steam is not mixed with Noncondensable gases. Whereas in hydrothermal system non-condensable gases are also present in the steam. These non-condensable gases need to be removed from the condenser.

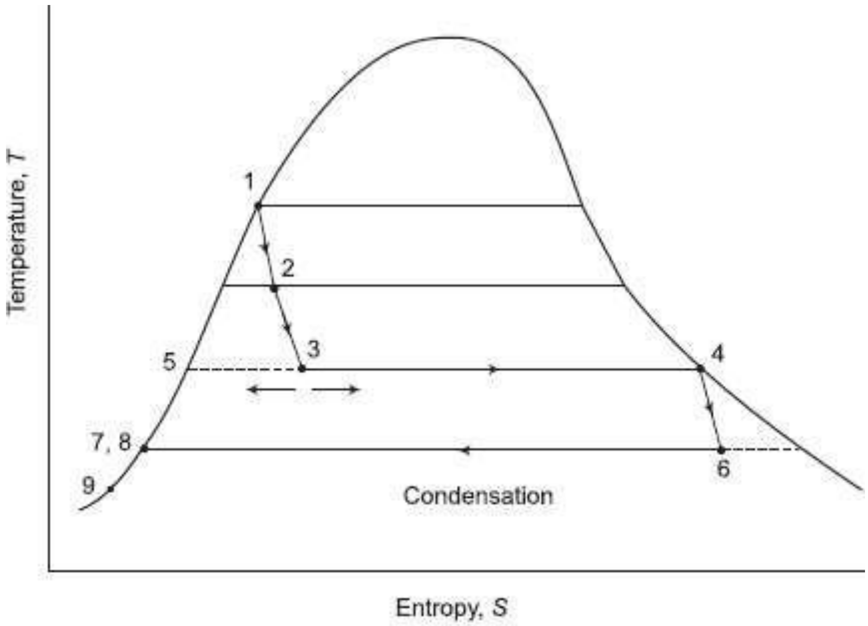
2. Wet steam/Liquid dominated/Flash type

Steam plants are the most cost effective technology, when the resource temperature is above about 175 °C. Therefore, liquid dominated or wet steam fields may further be subdivided into (a) high temperature (above 175 °C), where steam plants can be used and (b) low temperature (below 175 °C) fields where other technologies are used.





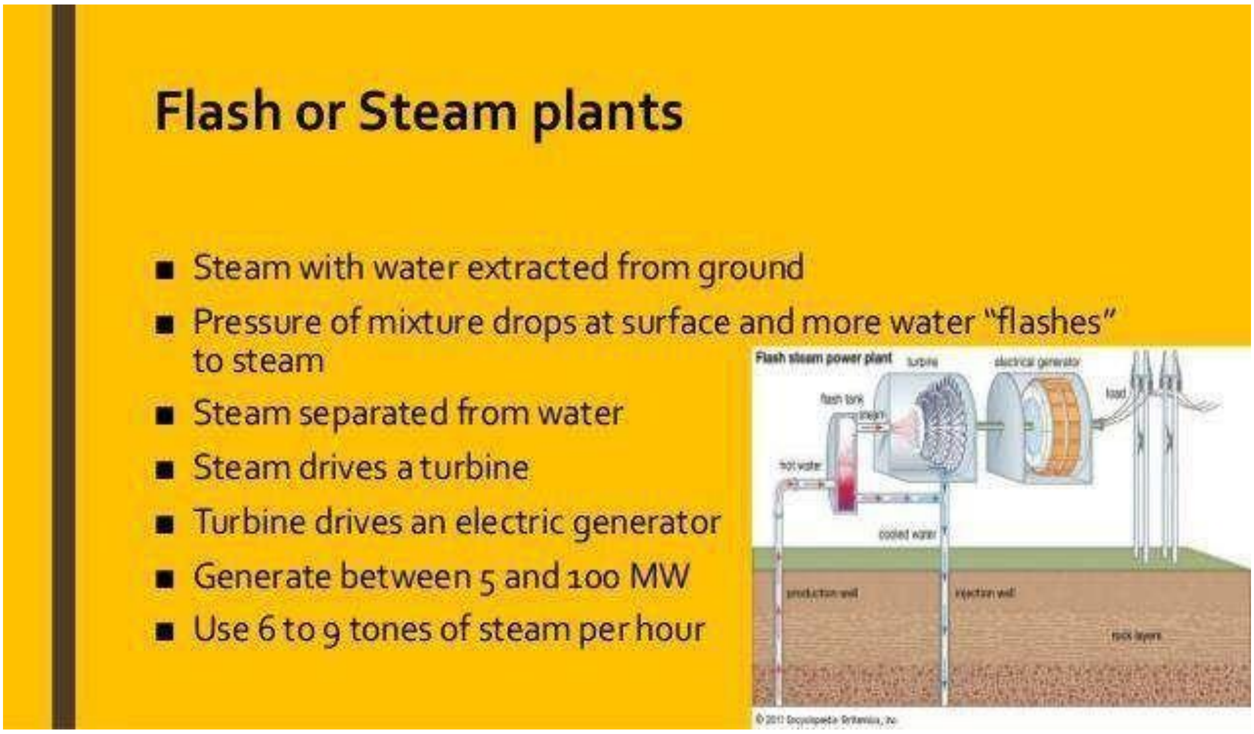
(a) Layout diagram



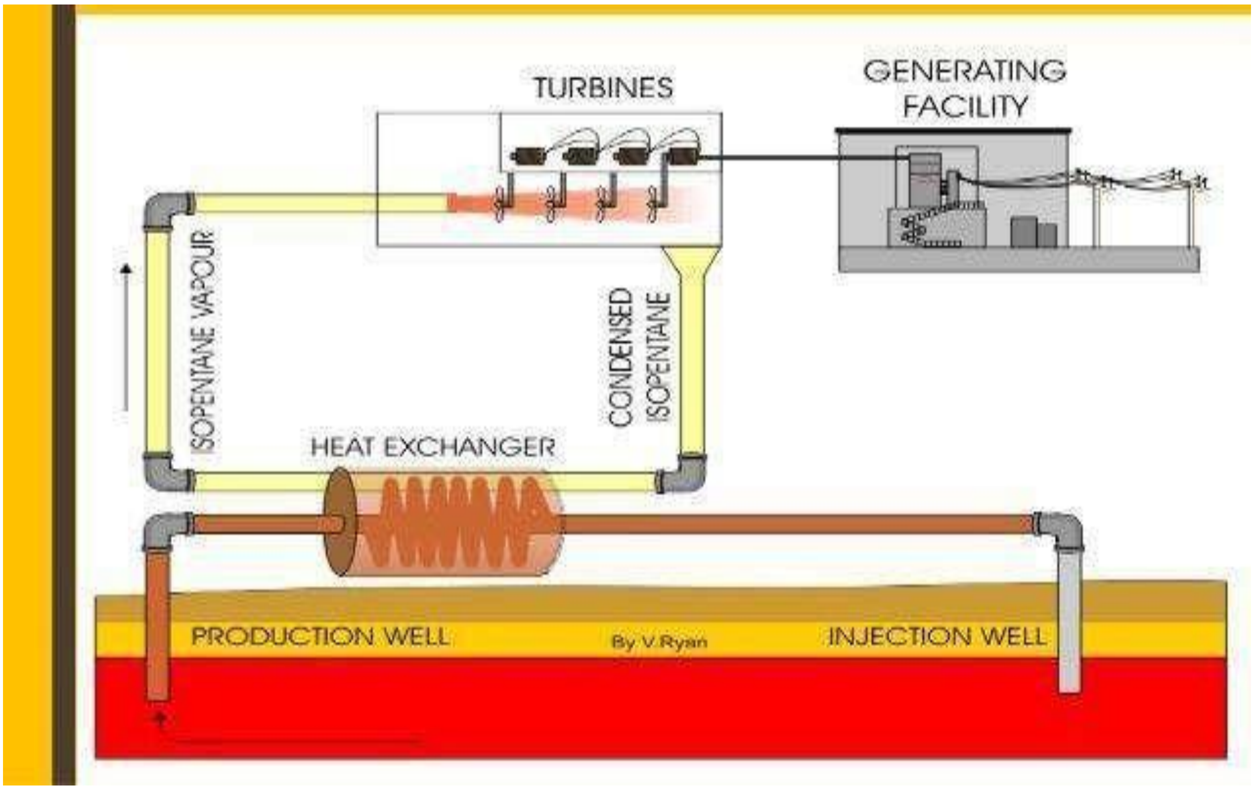
(b) T–S diagram

Flash steam power plant (cont.)

- Commonly used geothermal power plant.
- Geothermal reservoirs containing both hot water & steam is required.
- Pressure changing system is required.
- Operating at Hawaii, Nevada, Utah & some other places



3. Binary cycle plant - working fluid is Iso Butane or Iso Pentane



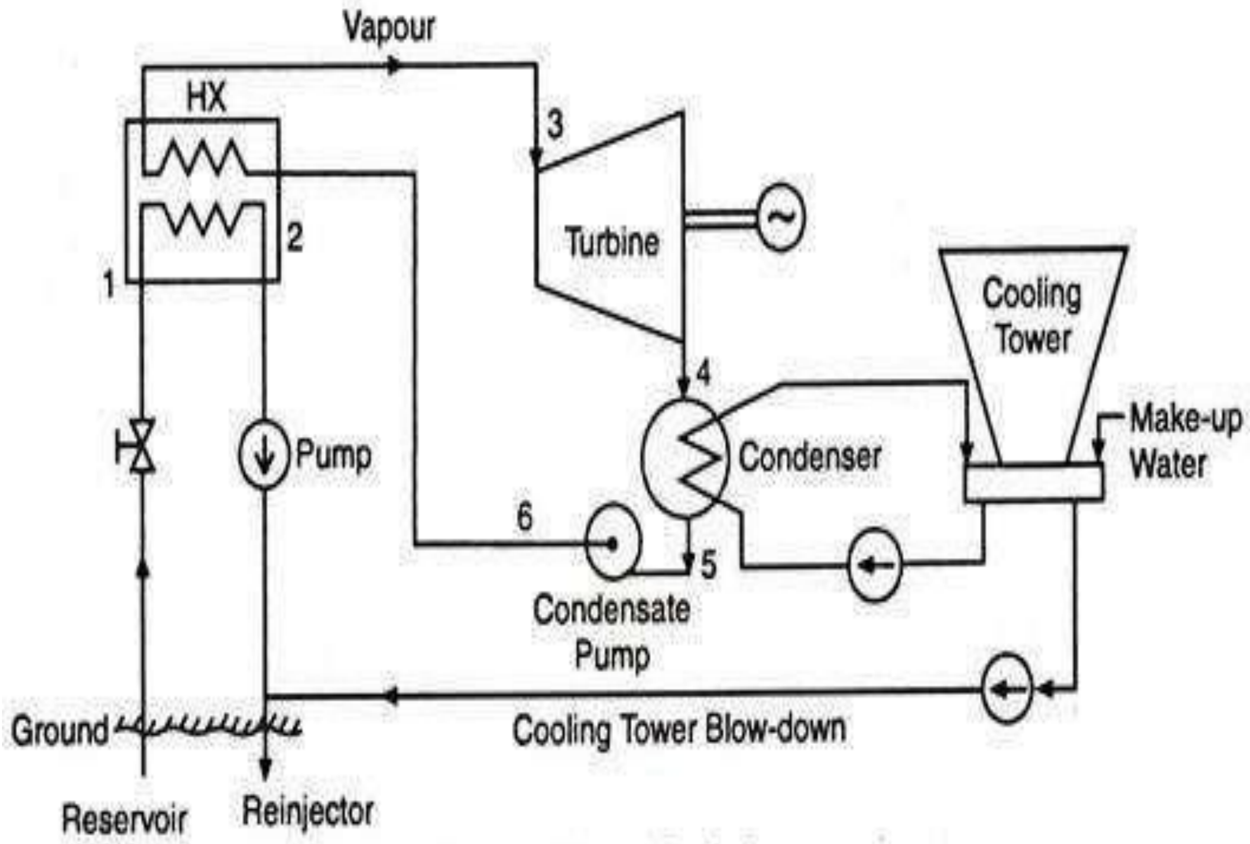


Fig. 7.7. Binary Cycle System

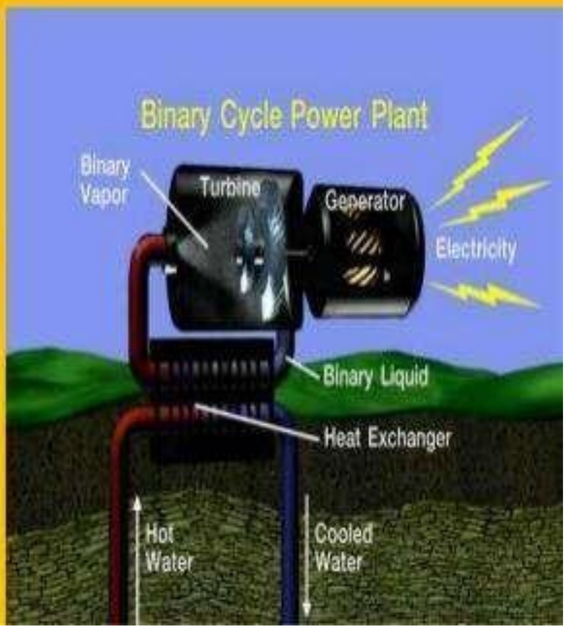
- Moderate-temperature water is used in it.
- Hot geothermal fluid and a secondary fluid with a much lower boiling point than water pass through a heat exchanger.
- Heat from the geothermal fluid causes the secondary fluid to flash to vapour, which
  then drives the turbines.
- Because this is a closed-loop system, nothing is emitted to the atmosphere.
- Most efficient for future.

Binary cycle power plant (cont.)

- Does not use steam directly to spin turbines.
- Only the heat of the underground water is used.
- Vapourized hydrocarbons are used to spin the turbine.
- Hydrocarbons having lower boiling point such as isopentane, isobutane and propane can be used.
- No harmful gas is emitted to the atmosphere because the underground water is never disclosed to outside.
- This's the worldwide accepted power plant.

Binary Cycle Power Plant

- Low temps – 100° and 150°C
- Use heat to vaporize organic liquid
  - *E.g., iso-butane, iso-pentane*
- Use vapor to drive turbine
  - *Causes vapor to condense*
  - *Recycle continuously*
- Typically 7 to 12 % efficient
- 0.1 – 40 MW units common



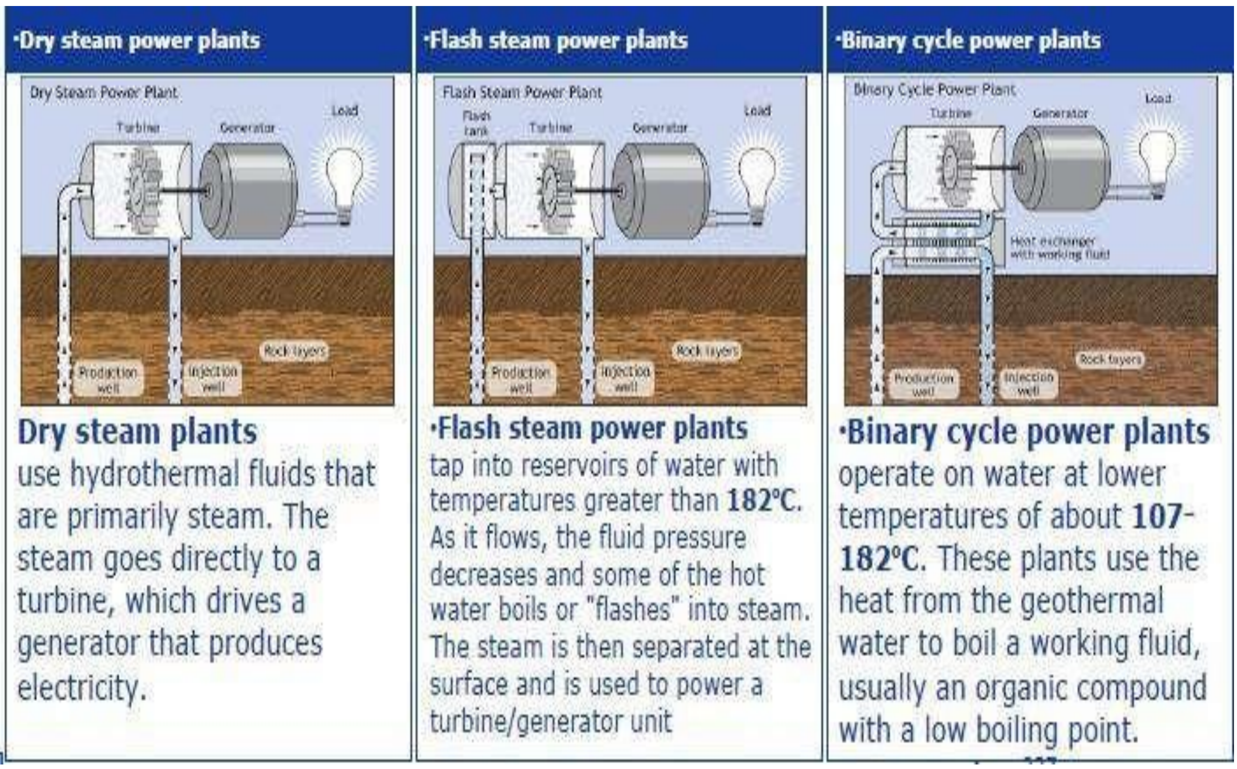
Advanatages of Binary cycle power plant

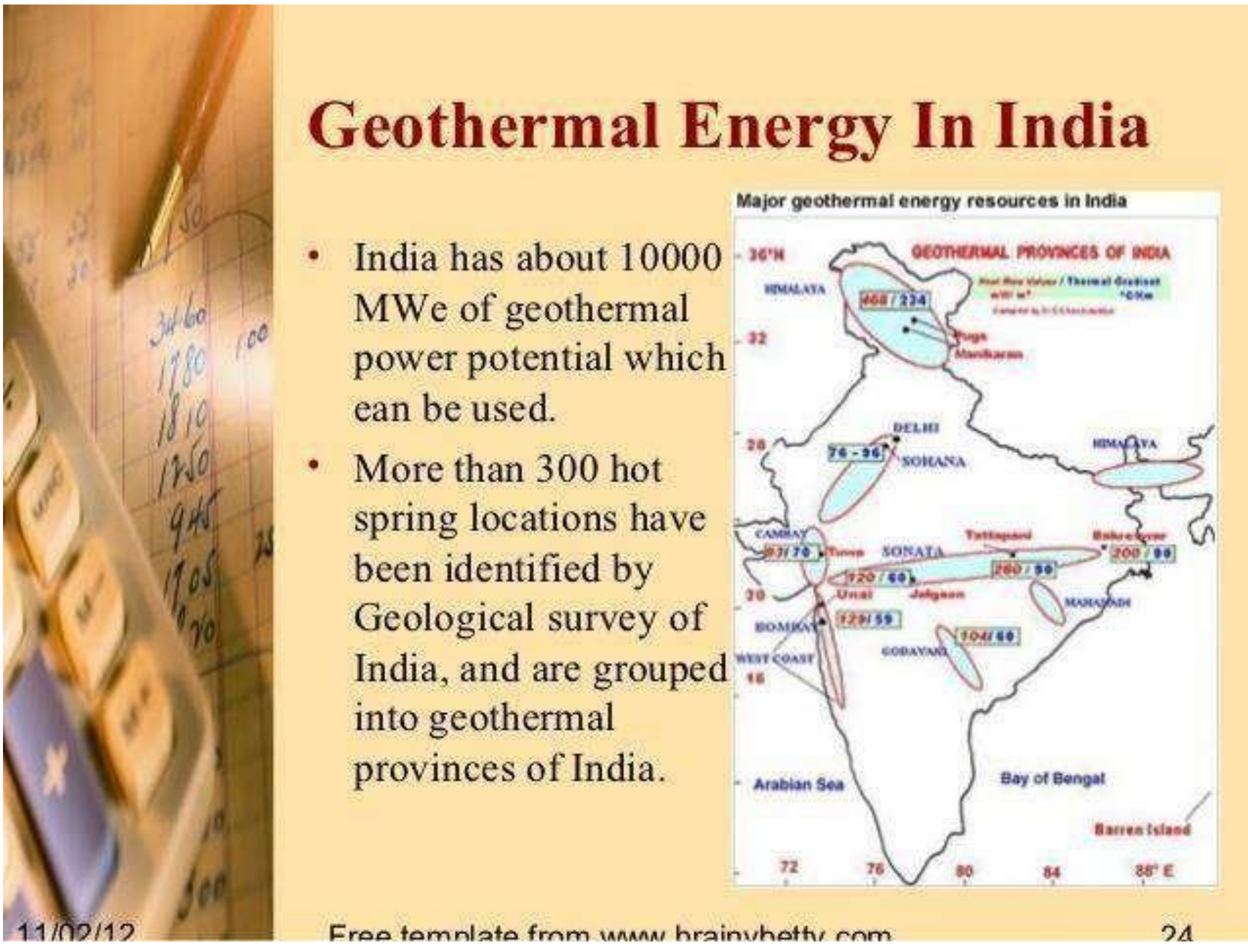
- Reliable sources
- No harmful emissions
- High efficiency
- Low maintenance
- No external source required to keep plant running
- Power stations are smaller.

Disadvanatages of Binary cycle power plant

- Possibility of depletion of geothermal sources.
- High Investment cost ,difficult in transportation
- Source is close to volcanic activity ,may stop working suddenly.

Difference between various Geothermal Plants



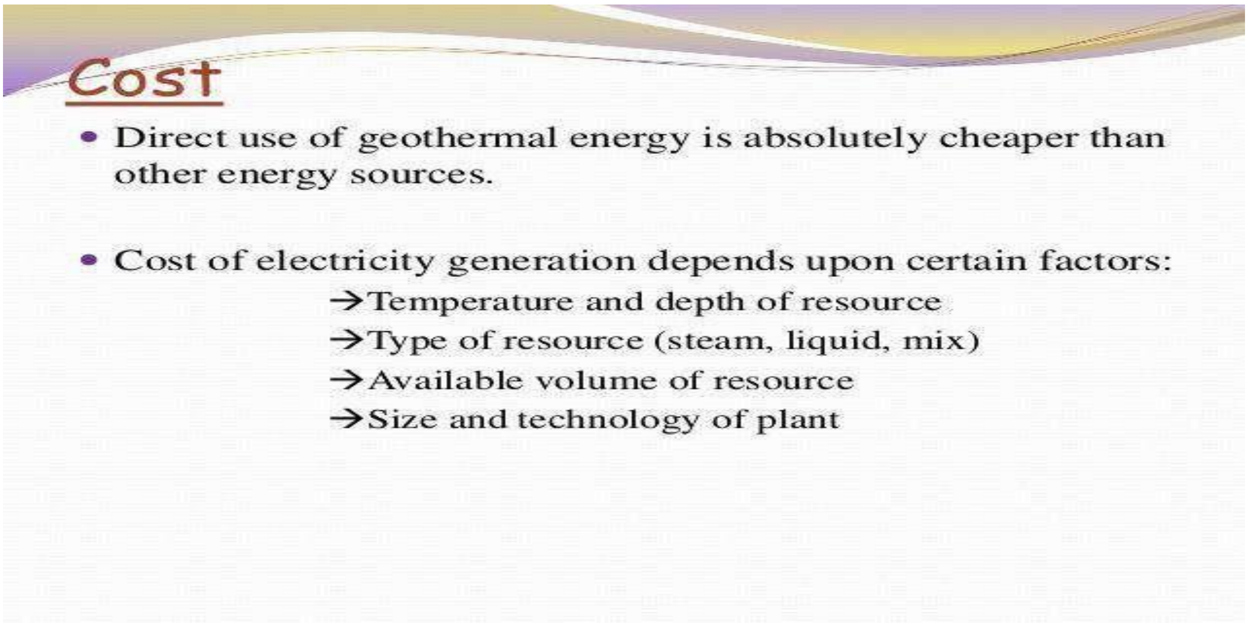


- Geothermal provinces are estimated to produce 10,600 MW of power (experts are confident only to the extent of 100 MW)
- Geothermal provinces in India: the Himalayas, Sohana, West coast, Cambay, Son-Narmada-Tapi , Godavari, and Mahanadi
- Reykjavík Geothermal will assist Thermax to set up a pilot project in Puga Valley, Ladakh (Jammu & Kashmir)
- First operational commercial geothermal power plant is likely to come up in AP with a capacity of 25 MW by Geosyndicate Pvt Ltd.

Geothermal potential in India

- Puga Valley (Jammu & Kashmir)

- Tatapani(Chhattisgarh)
- Godavari Basin Manikaran(Himachal Pradesh)
- Bakreshwar(West Bengal)
- Tuwa (Gujarat)
- Unai(Maharashtra)
- Jagaon(Maharashrta)



MERITS OF GEOTHERMALPOWER PLANT

- It is a renewable source of energy.
- By far, it is non-polluting and environment friendly.
- There is no wastage or generation of byproducts.
- Geothermal energy can be used directly. In ancient times, people used this source of
  energy for heating homes, cooking, etc.
- Maintenance cost of geothermal power plants is very less.
- Geothermal power plants don't occupy too much space and thus help in protecting natural environment.
- Unlike solar energy, it is not dependent on the weather conditions.

DEMERITS OF GEOTHERMAL POWER PLANT

- Only few sites have the potential of Geothermal Energy.
- Most of the sites, where geothermal energy is produced, are far from markets or

cities, where it needs to be consumed.

- Total generation potential of this source is too small.
- There is always a danger of eruption of volcano.
- Installation cost of steam power plant is very high.
- There is no guarantee that the amount of energy which is produced will justify thecapital expenditure and operations costs.
- It may release some harmful, poisonous gases that can escape through the holesdrilled during con struction.

Applications of Geothermal Power Plant

1. Generation of electric power
2. Space heating for building
3. Industrial process heat
4. Crop drying
5. Plastic manufacture
6. Paper manufacture
7. Mushroom culture
8. Timber seasoning – moisture in the timber is reduced

Syllabus

OCEAN ENERGY: OTEC, Principles utilization, setting of OTEC plants, thermodynamic cycles. Tidaland wave energy: Potential and conversion techniques, mini-hydel power plants, and their economics.
DIRECT ENERGY CONVERSION: Need for DEC, Carnot cycle, limitations, and principles of DEC.
Thermo-electric generators, Seebeck, Peltier and Joule Thomson effects, Figure of merit, materials, applications,
MHD generators, principles, dissociation and ionization, hall effect, magnetic flux, MHDaccelerator,MHD Engine, power generation systems, electron gas dynamic conversion, economic aspects. Fuel cells, principles, faraday‟s law‟s, thermodynamic aspects, selection of fuels and operating conditions.

OCEAN ENERGY

- ✓ Ocean energy refers to all forms of renewable energy derived from the sea. There are three main types of ocean technology:
  - ❖ **Ocean Thermal Energy Conversion (OTEC)**
  - ❖ **Tidal Energy**
  - ❖ **Wave Energy**

- ✓ All forms of energy from the ocean are still at an early stage of commercialization.
- ✓ Ocean thermal energy is generated by converting the temperature difference between the ocean's surface water and deeper water into energy.
- ✓ Ocean thermal energy conversion (OTEC) plants may be land-based as well as floating or grazing.

Tidal energy comes in two forms, both of which generate electricity:

- ✓ Tidal range technologies harvest the potential energy created by the height difference between high and low tides. Barrages (dams) harvest tidal energy from different ranges.
- ✓ Tidal stream (or current) technologies capture the kinetic energy of currents flowing in and out of tidal areas (such as seashores). Tidal stream devices operate in arrays, similar to wind turbines.

- ✓ Wave energy remains more costly than the other ocean technologies.
- ✓ Tidal range (see explanation below) has been deployed in locations globally where there is a strong tidal resource (for example La Rance in France, Sihwa in South Korea), while tidal stream (see below) has been demonstrated at pilot scale.

How does it work?

- ✓ Wave energy is generated by converting the energy within ocean waves (swells) into electricity.
- ✓ There are many different wave energy technologies being developed and trialled to convert wave energy into electricity.

Ocean Thermal Energy Conversion (OTEC)

- ✓ Ocean Thermal Energy Conversion (OTEC) is a process that can produce electricity by using the temperature difference between deep cold ocean water and warm tropical surface water.
- ✓ OTEC is an energy technology that converts solar radiation to electric power .
- ✓ OTEC utilizes the world's largest solar radiation collector.
- ✓ The ocean contains enough energy power all of the world's electrical needs.
- ✓ Oceans cover more than 70% of Earth's surface, making them the world's largest solar collectors.
- ✓ OTECis a renewable energy technology that converts solar radiation into electric power by use of world oceans.
- ✓ OTEC process uses temperature difference between cold deep water (5 °C) & warm surface water (27 °C) to power a turbine to generate electricity.
- ✓ If a heat source is high temperature and a heat sink at lower temperature, this temperature difference can be utilized in a machine to convert it into mechanical energy and there by into electrical energy.
- ✓ In the OTEC system, the warm ocean surface is the heat source and the deep colder water provides the sink.

Surface water of Ocean

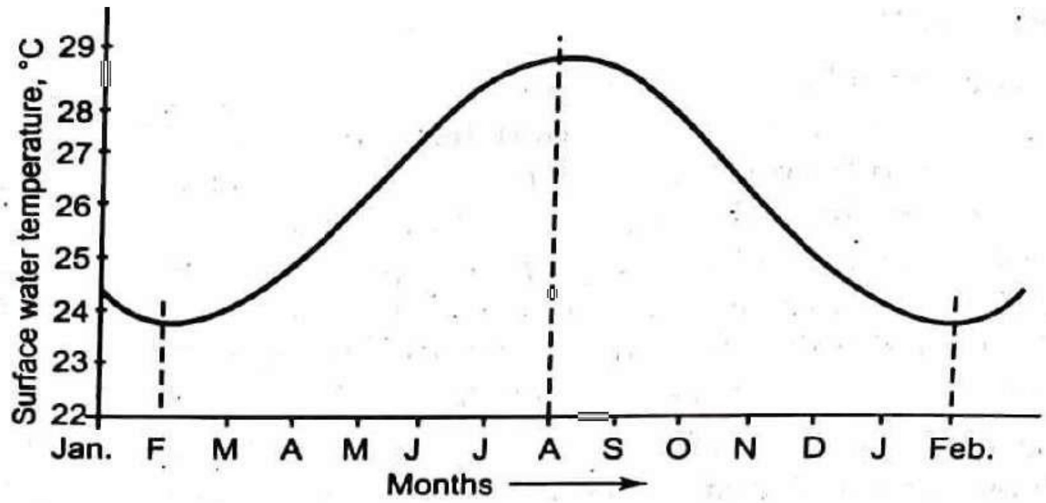
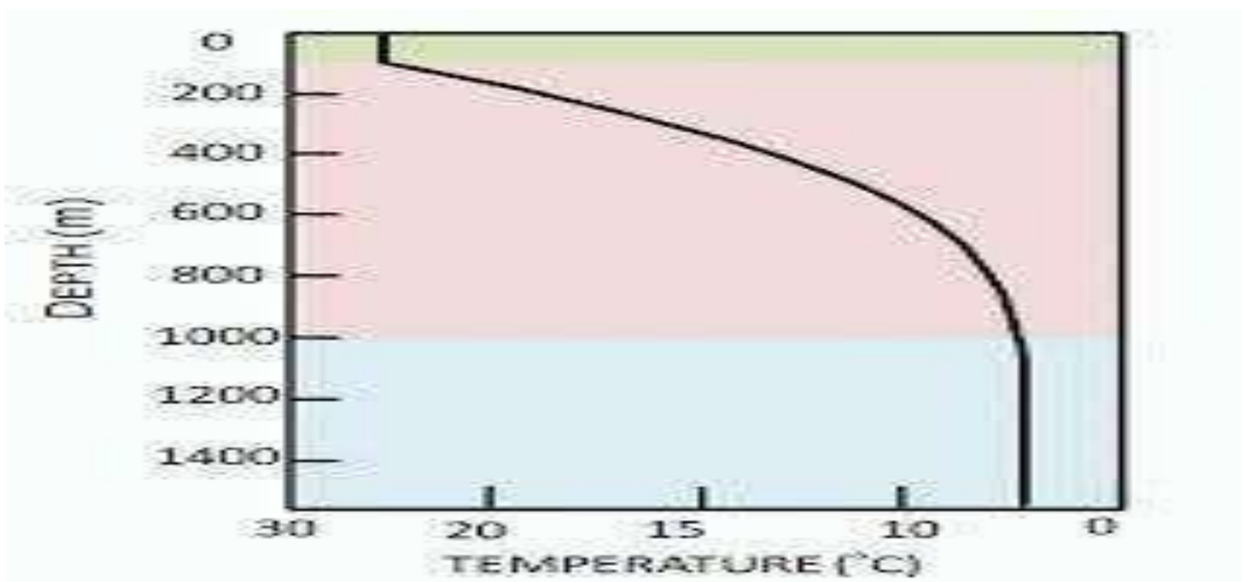


Fig. 8.22: Monthly variation of surface temperature of tropical ocean water.

Deep Cold water of Ocean

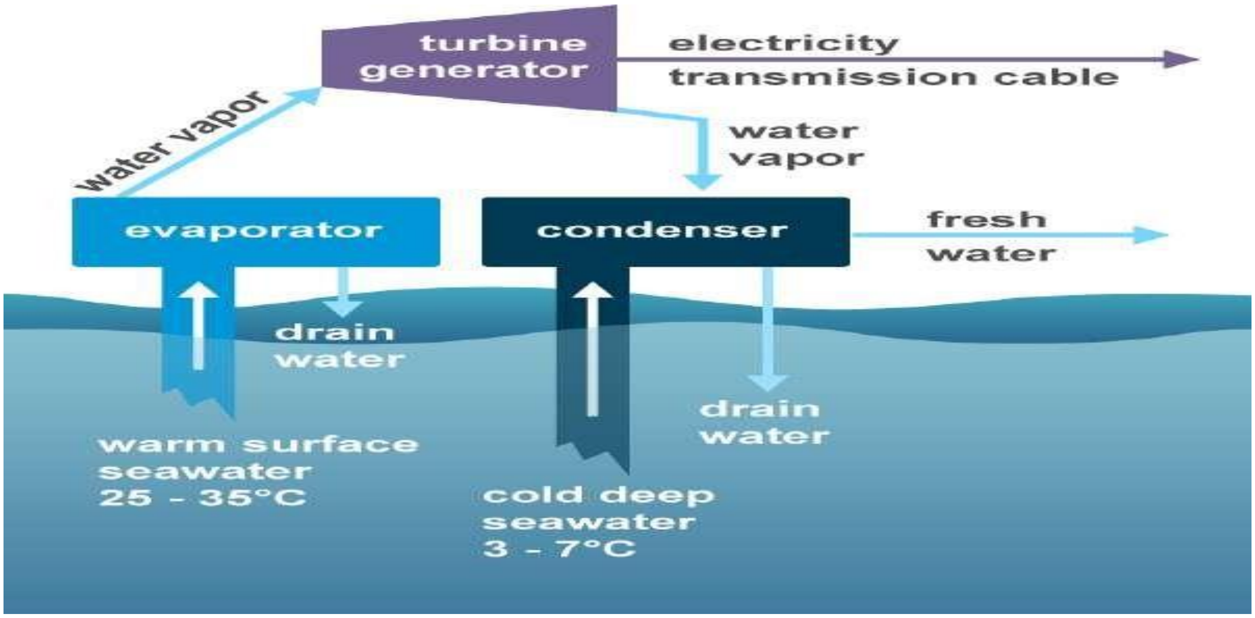


Working Principle of OTEC

- ✓ OTEC plant works on the principle of a closed Rankine Cycle.
- ✓ Warm Water is used in Evaporator to produce steam or to evaporate working fluid like Ammonia or halocarbon Refrigerant.
- ✓ Evaporated Fluid expands in a low pressure turbine, which is coupled with a turbo alternator to produce electricity.

✓ Cold water is used in CONDENSER for condensation process.

WORKING PRINCIPLE OF OTEC



Efficiency of OTEC

Carnot cycle efficiency $\eta = 1 - \frac{T_2}{T_1}$

Where T_1 = Temperature of warm water in the upper surface layer

T_2 =Cold water in the depth of the tropical ocean

If $T_1 = 27^0 C$ or $T_1 = 27 + 273 = 300K$

$T_2 = 5^0 C$ or $T_2 = 5 + 273 = 278K$

Then Carnot efficiency is

$$\eta = 1 - \frac{T_2}{T_1} = 1 - \frac{278}{300}$$

$$\eta = 7.33\%$$

- The actual efficiency of an OTEC power plant is less than the carnot cycle and it is given by

$\eta_{OTEC} = EF \times \eta_C$

Where EF=Relative efficiency factor (0.4 to 0.6)

η_C=Carnot cycle efficiency

Facts about OTEC Renewable Energy

- ✓ Oceans are the largest solar collectors on earth
- ✓ Oceans are already built and paid for
- ✓ Man-made solar collectors only work when the sun shines
- ✓ OTE's base load power operates 24 hours per day
- ✓ Stored solar energy throughout the equatorial zone could provide 300 times the world's consumption of electricity

Environmental Impacts

A number of potential environmental impacts due to use of OTEC have been identified as follows:

(i) It is feared that biota including eggs, larvae and fish could be entrained and destroyed due to intake and expulsion of large volumes of water. Appropriate siting of intake may reduce the problem.

(ii) Changes in local temperature and salinity might also effects the local ecosystem, impact coral and influence ocean currents and climate.

In open cycle OTEC system, CO_2 dissolved in warm water is released to atmosphere. However, the quantity of CO_2 released is very small and under worst conditions would be only 1/15 that of oil or 1/25 that of coal based generation of same power. It could be reinjected into warm water discharge.

(iv) Release of large quantities of cold water into warmer surface environment will also have biological effects, which are yet to be known. Actual environmental impacts will have to be estimated from small-scale trials.

TYPES OF ELECTRICITY CONVERSION SYSTEMS

- **There are three types of electricity conversion systems:**

1. Closed or Anderson or Vapour OTEC Cycle Power Plant
    - **Working fluid – Organic fluid like NH_3**
2. Open or Claude or Steam OTEC Cycle Power Plant
    - **Working fluid – Steam**

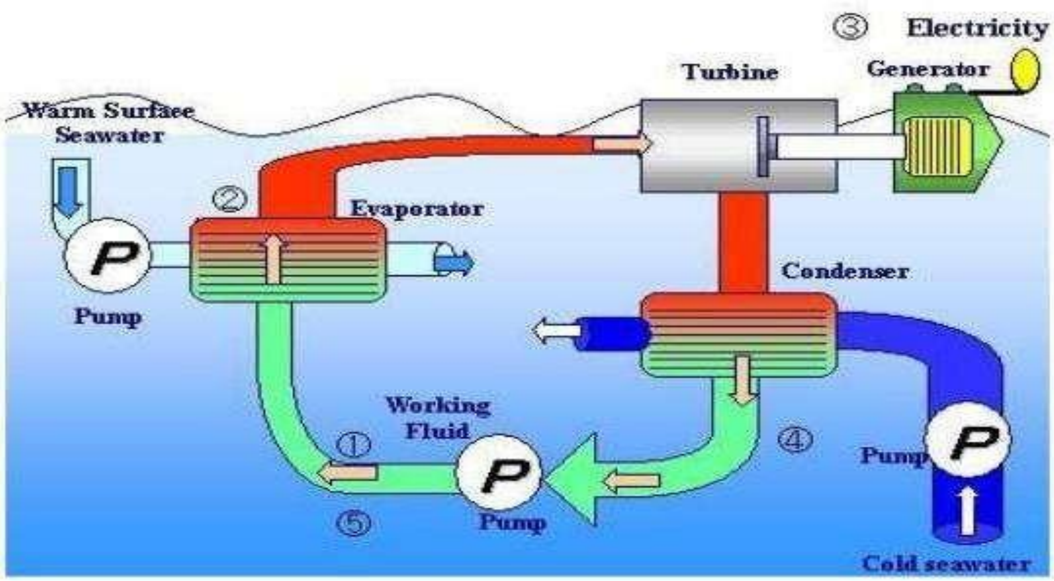
3.Mixed/Hybrid Cycle OTEC Power plant

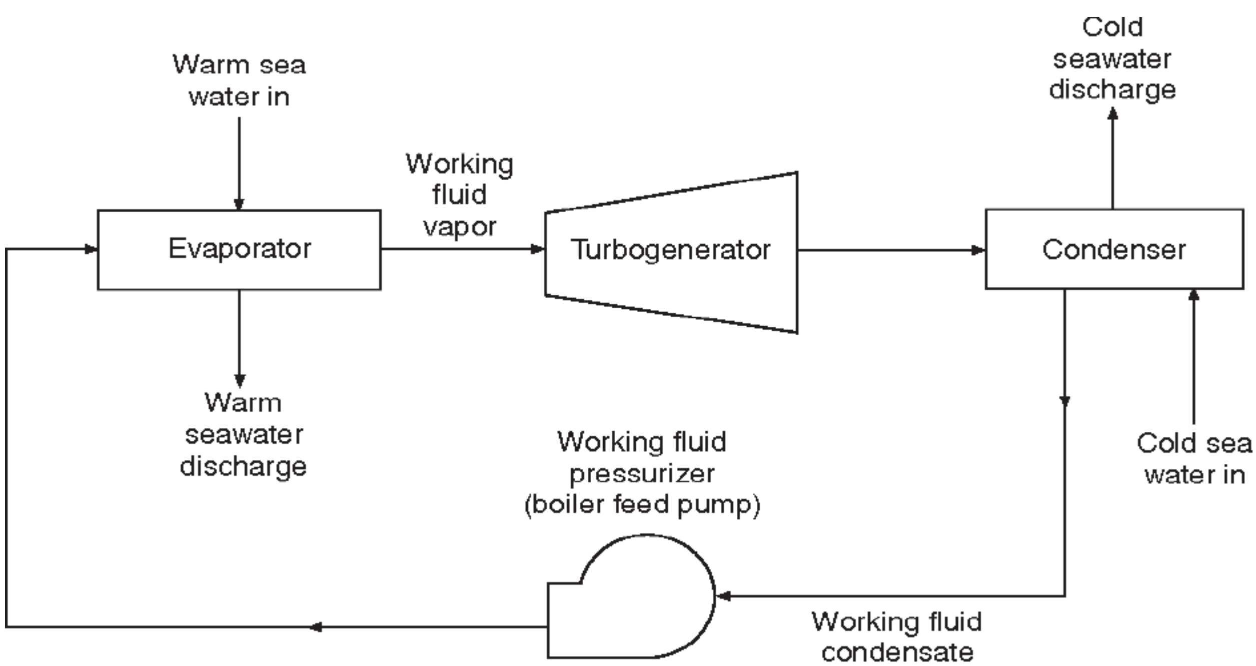
- **Working fluid – Both steam & NH_3**

1.Closed or Anderson or Vapour OTEC Cycle Power Plant:

- ✓ In the closed-cycle OTEC system, warm sea water vaporizes a working fluid, such as ammonia, flowing through a heat exchanger (evaporator).
- ✓ The vapor expands at moderate pressures and turns a turbine coupled to a generator that produces electricity.
- ✓ The vapor is then condensed in heat exchanger (condenser) using cold seawater pumped from the ocean's depths through a cold- water pipe.
- ✓ The condensed working fluid is pumped back to the evaporator to repeat the cycle.
- ✓ The working fluid remains in a closed system and circulates continuously.
- ✓ The heat exchangers (evaporator and condenser) are a large and crucial component of the closed-cycle power plant, both in terms of actual size and capital cost.

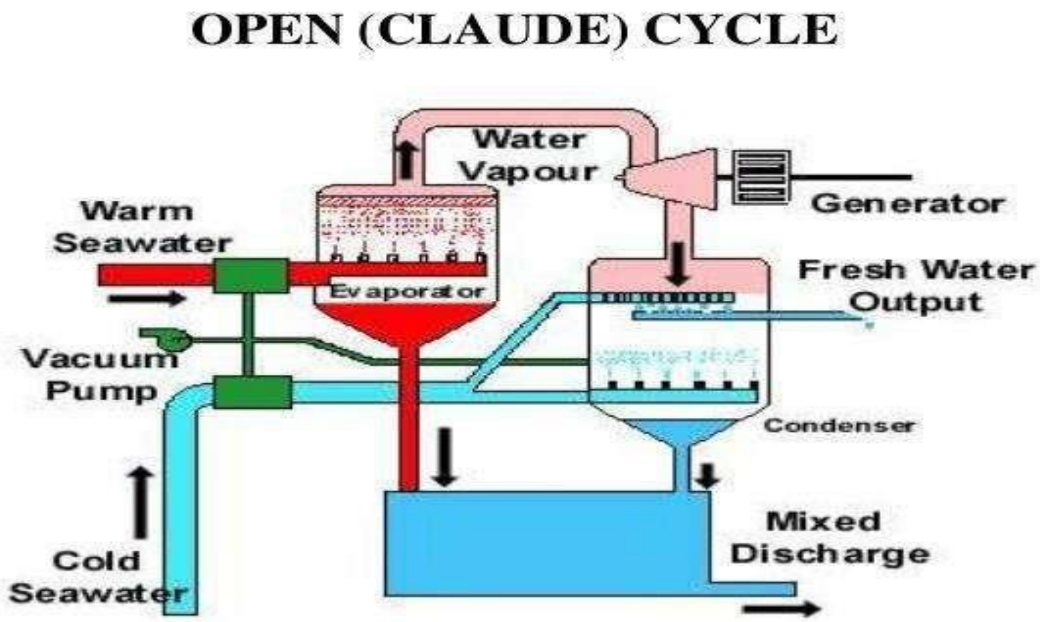
CLOSED (ANDERSON) CYCLE





2.Open or Claude or Steam OTEC Cycle Power Plant

- ✓ In an open-cycle OTEC, the sea water is *itself* used to generate heat without any kind of intermediate fluid.
- ✓ Open-cycle OTEC uses the tropical oceans' warm surface water to make electricity.
- ✓ **The open cycle consists of the following steps:**
  - ❖ Flash evaporation of a fraction of the warm seawater by reduction of pressure below the saturation value corresponding to its temperature
  - ❖ Expansion of the vapor through a turbine to generate power;
  - ❖ Heat transfer to the cold seawater thermal sink resulting in condensation of the working fluid.
  - ❖ Compression of the non-condensable gases (air released from the seawater streams at the low operating pressure) to pressures required to discharge them from the system.
- ❖ **Deaerator –** Removes oxygen from water.
- ❖ **Air Pump –**Removes other non-condensable gases from water
- ❖ **Flash Evaporator –** Produces vapour at low pressure.



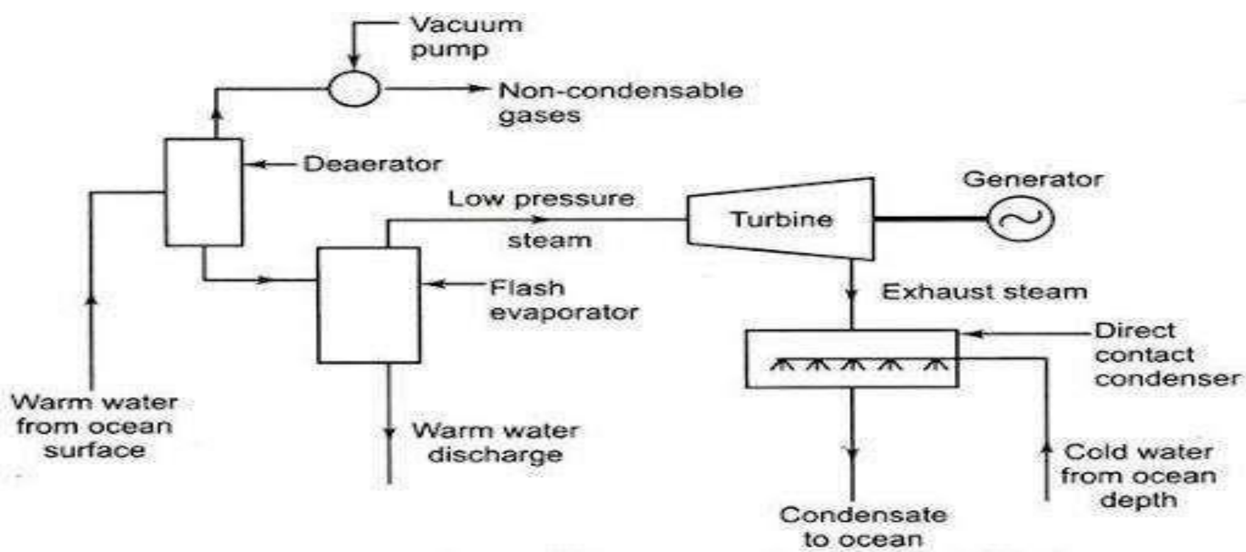


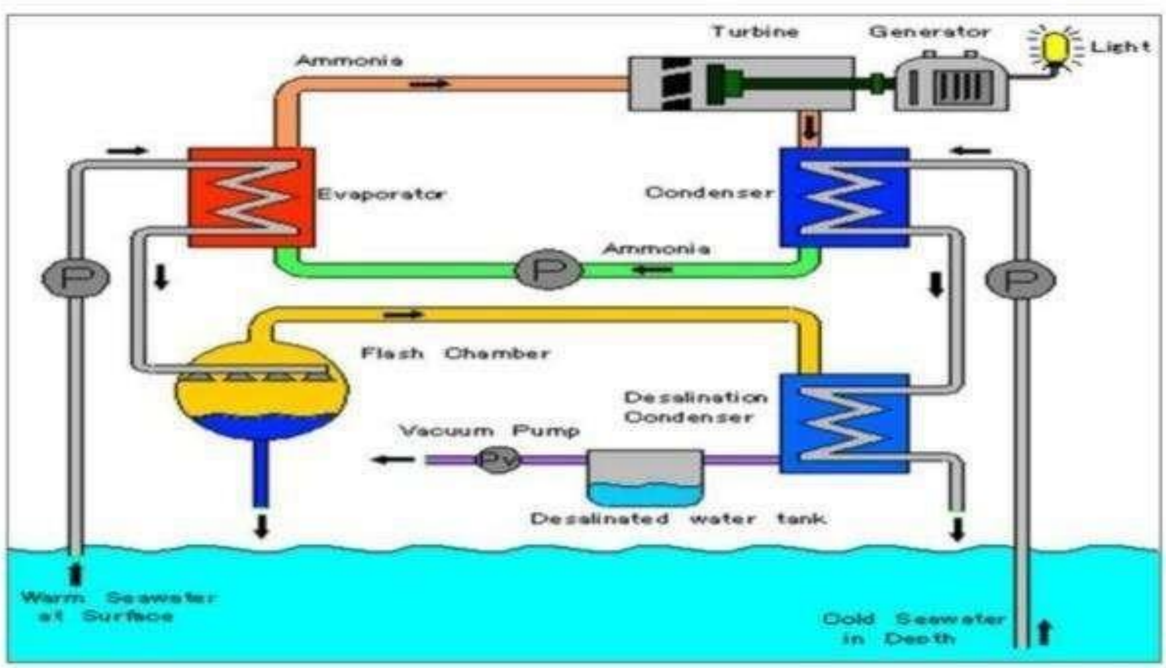
Fig. 8.25: Schematic layout of the open or claude cycle OTEC plant.

3.Mixed/Hybrid Cycle OTEC Power plant

- ✓ A hybrid cycle combines the features of both the closed- cycle and open-cycle systems.
- ✓ In a hybrid OTEC system, warm seawater enters a vacuum chamber where it is flash-evaporated into steam, which is similar to the open-cycle evaporation process.

- ✓ The steam vaporizes the working fluid of a closed-cycle loop on the other side of an ammonia vaporizer.
- ✓ The vaporized fluid then drives a turbine that produces electricity. The steam condenses within the heat exchanger and provides desalinated water

HYBRID CYCLE



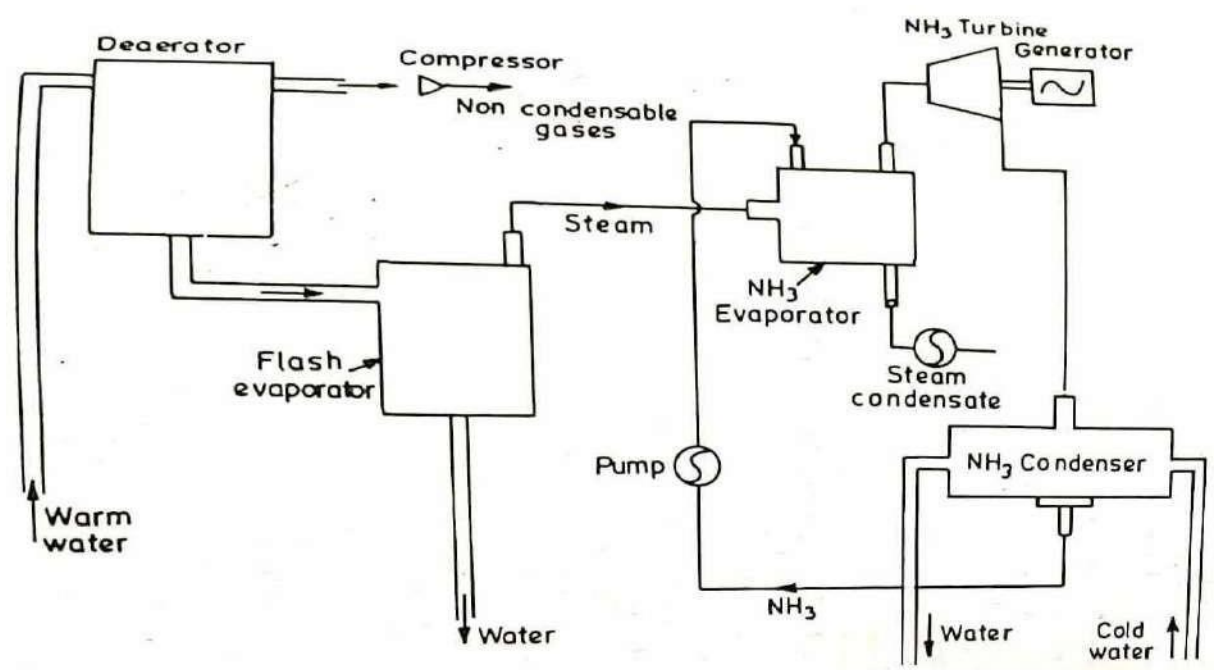


Fig. 9.2.5.1. Hybrid Cycle.

OTEC System Applications

- ✓ Ocean thermal energy conversion (OTEC) systems have many applications or uses.
- ✓ OTEC can be used to generate electricity, desalinate water, support deep-water mariculture, and provide refrigeration and air- conditioning as well as aid in crop growth and mineral extraction.

1. Electricity Production

- ✓ Two basic OTEC system designs have been demonstrated to generate electricity: closed cycle and open cycle.
- ✓ The details are discussed in the above slide.

2. Desalinated Water

- ✓ Desalinated water can be produced in open- or hybrid-cycle plants using surface condensers.
- ✓ A surface condenser can be used to recover part of the steam in the cycle and to reduce the overall size of the heat exchangers.

- ✓ One way to produce large quantities of desalinated water without incurring the cost of an open-cycle turbine is to use a hybrid system.
- ✓ In a hybrid system, desalinated water is produced by vacuum flash distillation and power is produced by a closed cycle loop.

3. <u>Refrigeration and Air-Conditioning</u>

- ✓ The cold [5°C (41ºF)] seawater made available by an OTEC system creates an opportunity to provide large amounts of cooling to operations that are related to or close to the plant.
- ✓ The low-cost refrigeration provided by the cold seawater can be used to upgrade or maintain the quality of indigenous fish, which tend to deteriorate quickly in warm tropical regions.
- ✓ The cold seawater delivered to an OTEC plant can be used in chilled-water coils to provide airconditioning for buildings

4. <u>Mineral Extraction</u>

- ✓ The ocean contains 57 trace elements in salt dissolved in solution.
- ✓ The Japanese recently began investigating the concept of combining the extraction of uranium dissolved in sea water with wave-energy technology.
- ✓ They found that developments in other technologies were improving the viability of mineral extraction processes that employ ocean energy.

Advantages of OTEC

- ✓ Helps in producing fuels such as hydrogen, ammonia, and methanol .
- ✓ Produces base load electrical energy .
- ✓ Produces desalinated water for industrial, agricultural, and residential uses .
- ✓ Is a resource for on-shore and near-shore Mari culture operations .
- ✓ Provides air-conditioning for buildings .
- ✓ Provides moderate-temperature refrigeration
- ✓ Has significant potential to provide clean, cost-effective electricity for the future.
- ✓ Food Aquaculture products can be cultivated in discharge water.
- ✓ Eco- friendly .

- ✓ Minimal maintenance costs compared to other power production plants.
- ✓ OTEC helps in mining .
- ✓ Specially beneficial for small islands as they can become self- sufficient .

Disadvantages of OTEC

- ✓ OTEC produced electricity at present would cost more than electricity generated from fossils fuels at their current costs.
- ✓ No energy company put money in this project because it only had been tested in a very small scale.
- ✓ Construction of OTEC plants and lying of pipes in coastal waters may cause localized damage to reefs and near-shore marine ecosystem.
- ✓ OTEC plant construction and operation may affect commercial and recreational fishing.
- ✓ Other risks associated with the OTEC power system are the safety issues associated with steam electric power generation plants are : -
  - ❖ Electrical hazards,
  - ❖ Rotating machinery,
  - ❖ Use of compressed gases,
  - ❖ Heavy material-handling equipment, and
  - ❖ Shop and maintenance hazards.

Development of OTEC Plants

- ➢ In 1979 First OTEC power plant(40kW) at Hawai, USA
- ➢ In 1981 another plant (100kW) at Nauru,Japan
- ➢ In India 1MW plant at Tamilnadu
- ➢ India has a potential of 50,000 MW

Design Parameters

- ✓ In a 50kW OTEC plant nearly 35kW is wasted for pumping water from Ocean.
- ✓ In a 100kW OTEC plant we will get only 30 kW of net power output.

- ✓ 1km long cold water pipe line is required with proper supports
- ✓ Axial flow turbine with 3000 rpm.

OTEC Scenario

- ✓ Oceans cover about 70% of the global surface
- ✓ Most of the Sun's radiation is absorbed by Sea water.
- ✓ Power from OTEC is Renewable
- ✓ OTEC technology is in infant stage

CONCLUSION

- ✓ Ocean thermal energy conversion is a potential source of
- ✓ renewable energy that creates no emissions. It is fuel free.
- ✓ It has a low environmental impact, can supply pure water for both drinking and agriculture purposes.
- ✓ Can supply refrigeration and cooling and can provide a coastal community with reliable energy.
- ✓ It is predicted that in the year 2040, the world will consume 820 quadrillion Btu of energy.
- ✓ Amount of solar energy absorbed by oceans is 4000 times presently consumed by humans. We would need less than 1% of that renewable energy to satisfy our desires.

TIDAL ENERGY

- ✓ Tidal range technologies harvest the potential energy created by the height difference between high and low tides. Barrages (dams) harvest tidal energy from different ranges.
- ✓ Tidal stream (or current) technologies capture the kinetic energy of currents flowing in and out of tidal areas (such as seashores). Tidal stream devices operate in arrays, similar to wind turbines.
- ✓ Wave energy remains more costly than the other ocean technologies.
- ✓ Tidal range (see explanation below) has been deployed in locations globally where there is a strong tidal resource (for example La Rance in France, Sihwa in South Korea), while tidal stream (see below) has been demonstrated at pilot scale.
- ✓ Tide is a periodic rise and fall of water level of sea.
- ✓ Tide is created due to gravitational force between earth sun and moon.
- ✓ Tidal Energy is a form of Hydro Power, Which converts energy of tides into the electricity.

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.

8.3.2. Tidal Range (R)

The tidal range is the difference between consecutive high tide and low tide water level. It is denoted by R and is measured in metres.

*Tidal **energy** refers to the potential energy in the tidal range.*

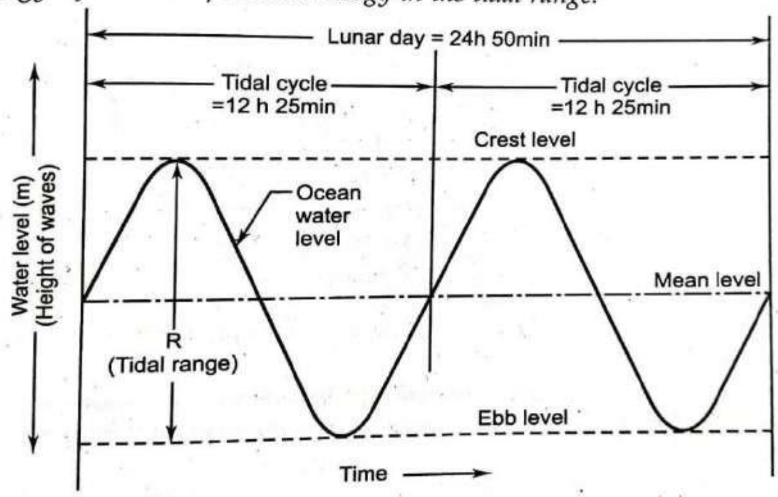


Fig. 8.1. Tidal range [Daily (diurnal) tides].

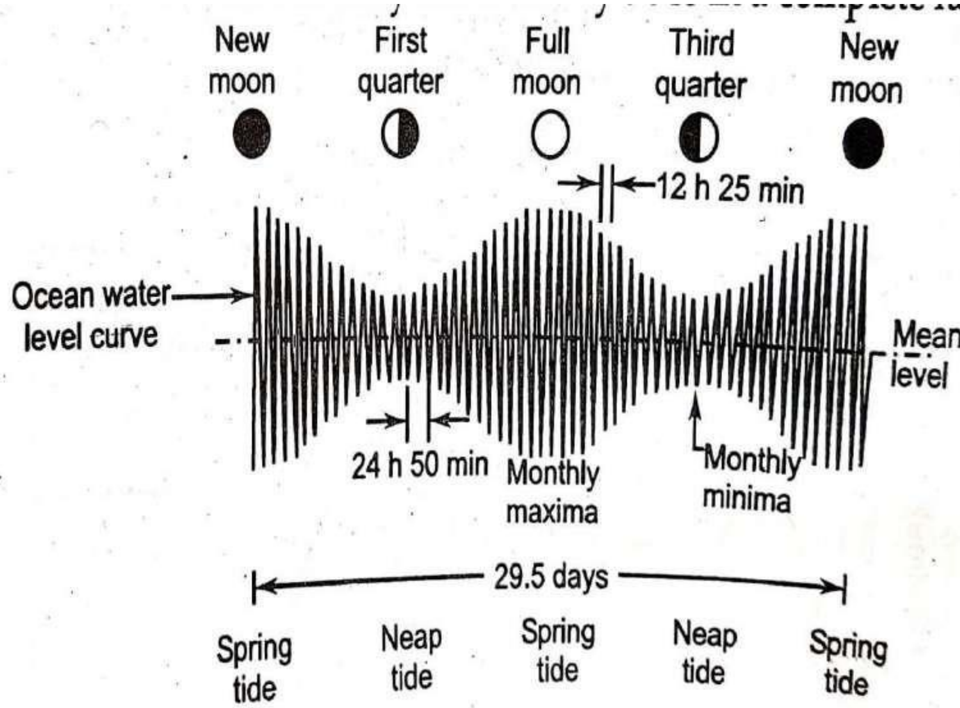
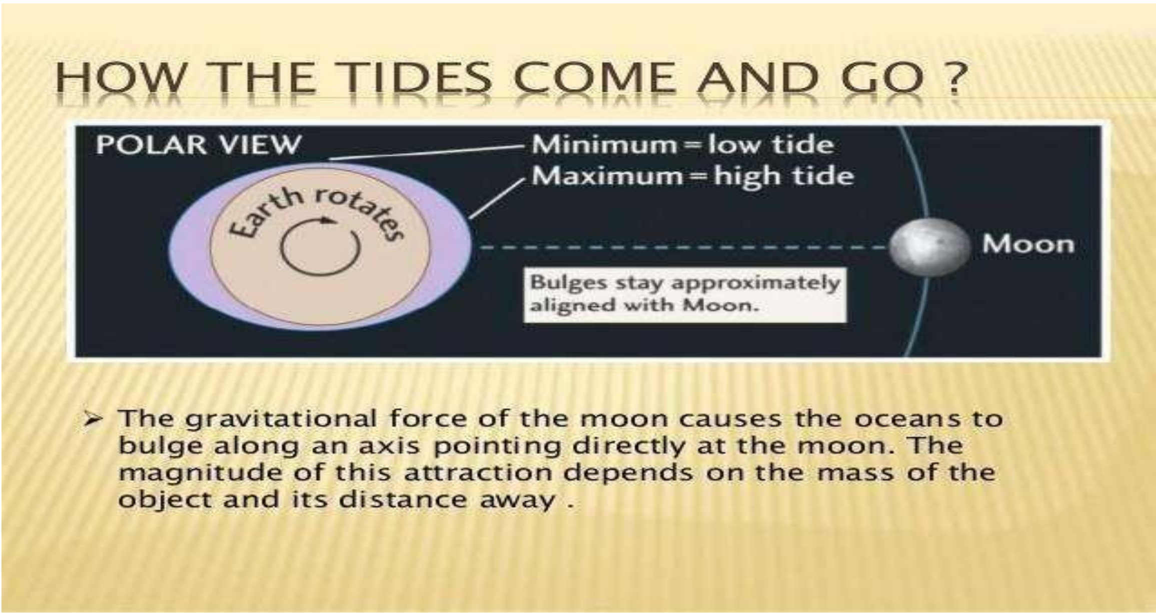
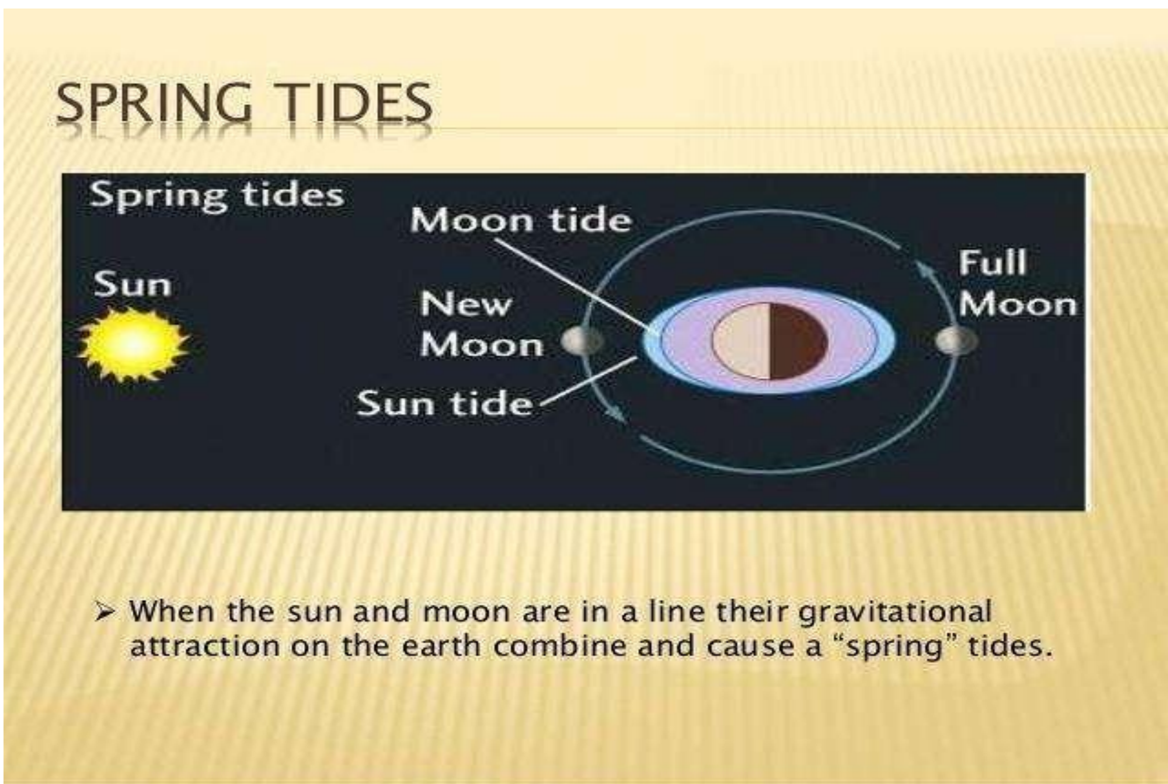


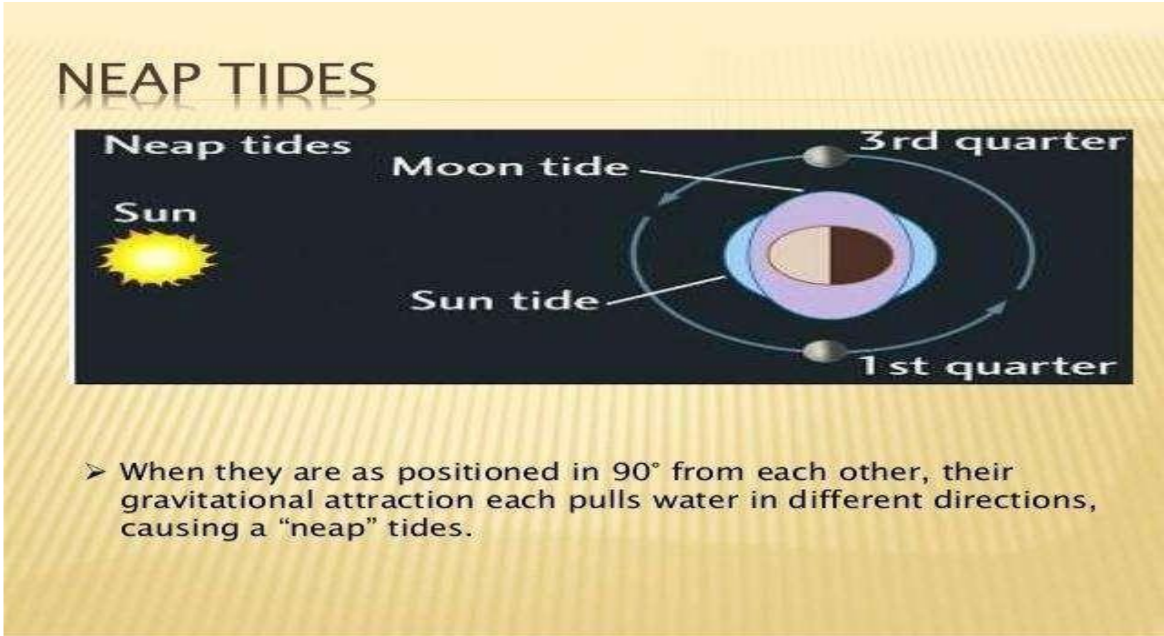
Fig. 8.3. Record of daily and monthly tides.

Note:

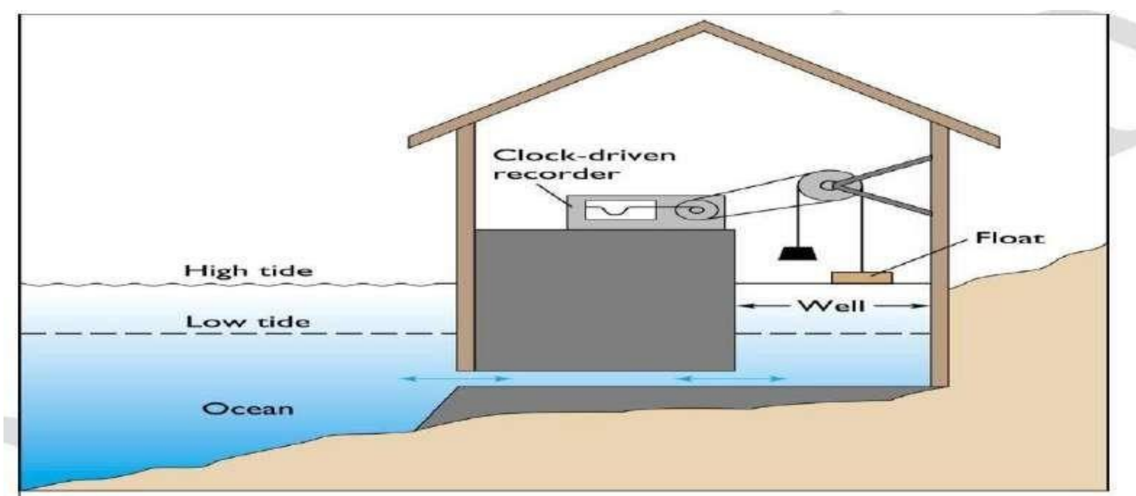
1. Over a month the daily tidal ranges vary systematically with the cycle of the Moon.
2. Tidal range is also altered by the shape of a basin and sea floor configuration.







Following figure shows a tide gauging station



(a) TIDE-GAUGE STATION

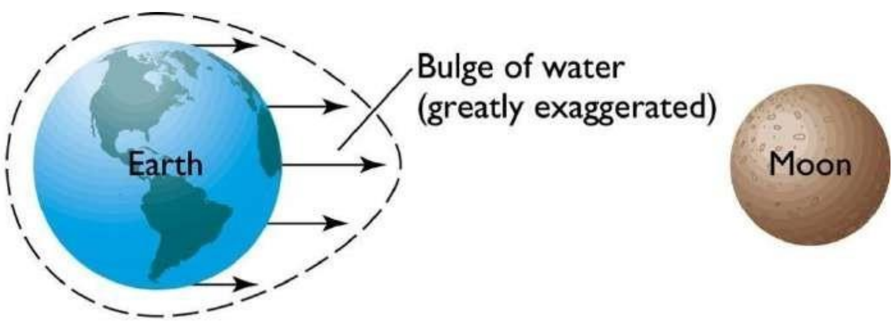
Tides result from gravitational attraction and centrifugal effect.

- 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

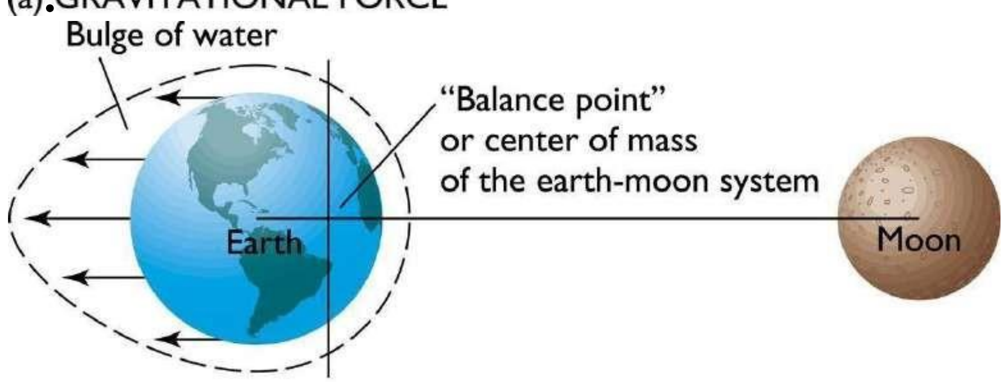
because the Moonis closer.

- 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



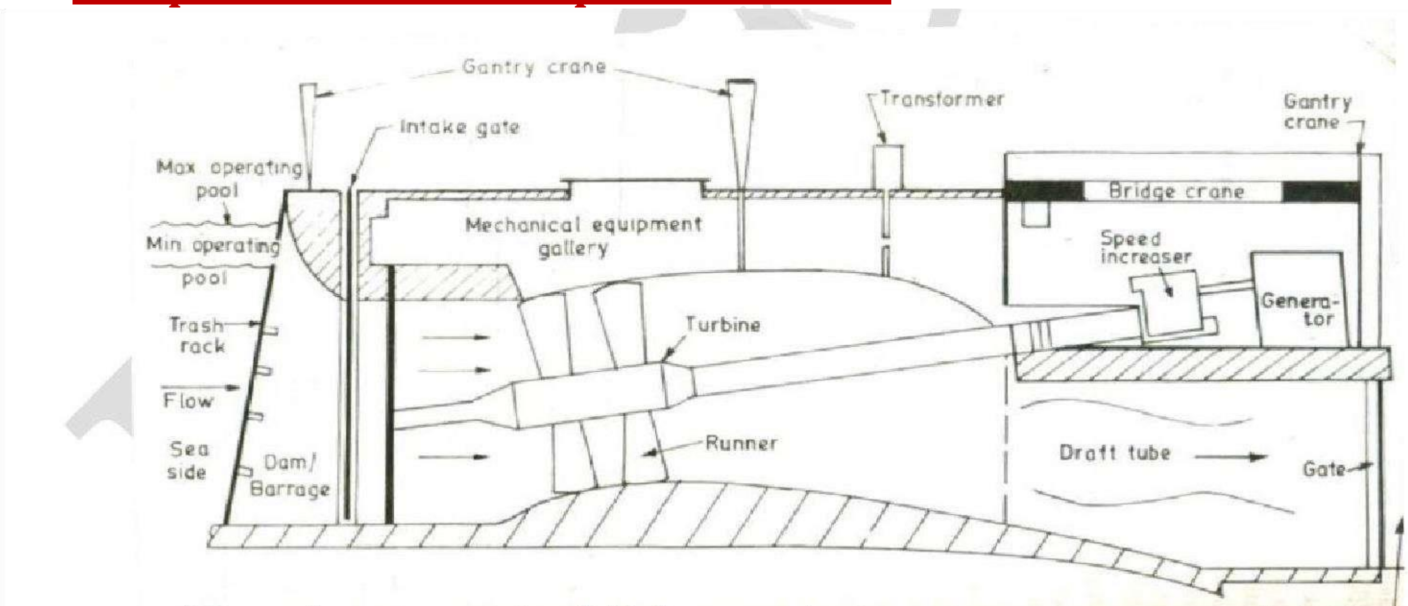
(b) CENTRIFUGAL FORCE

- ✓ 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 andthese causes the tides to occur 50 minutes later each day.

Components of a tidal power station:



The main components of tidal power plant are

Components of a 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.

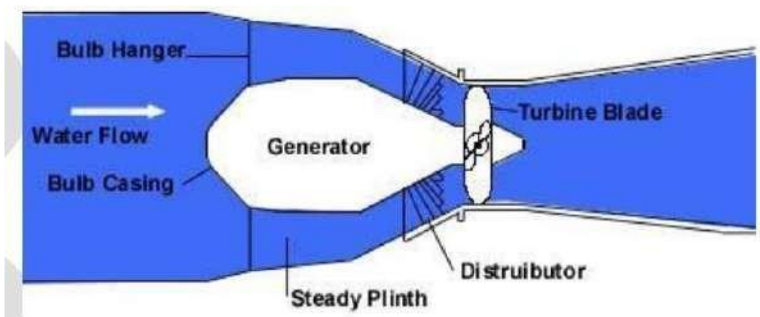
(ii) Rim type:

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.

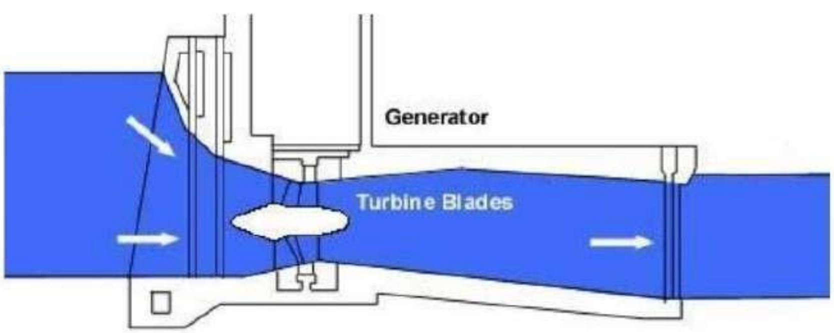
(iii) Tubular type:

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.

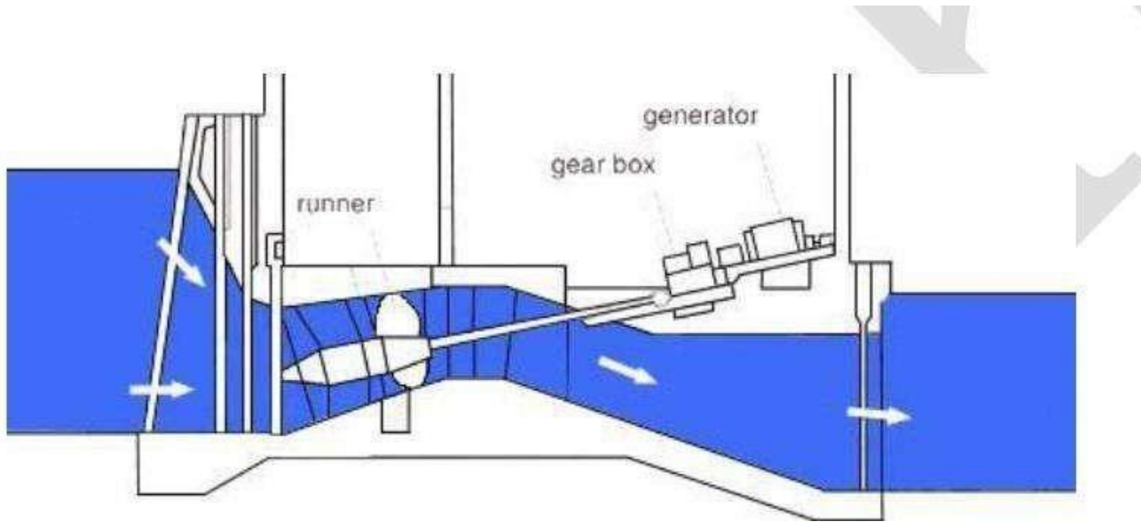
Following are the figures.



BULB TYPE TURBINE



RIM TYPE TURBINE



TUBULAR TYPE TURBINE

Types of Tidal Power plants

1. Single basin Tidal Plants

- Single cycle/effect plant
- Double cycle/effect plant

2. Double basin Tidal Plants

Double basin, linked basin plant

Double basin, paired basin plant

Single Basin Tidal System:

- ✓ The simplest generating system for tidal plants, known as an ebb generating system involves a dam, known as a barrage across an estuary.
- ✓ Sluice gates on the barrage allow the tidal basin to fill on the incoming high tides and to exit through the turbine system on the outgoing tide (known as the ebb tide).

- ✓ Alternatively, flood-generating systems, which generate power from the incoming tide are possible, but are less favored than ebb generating systems.

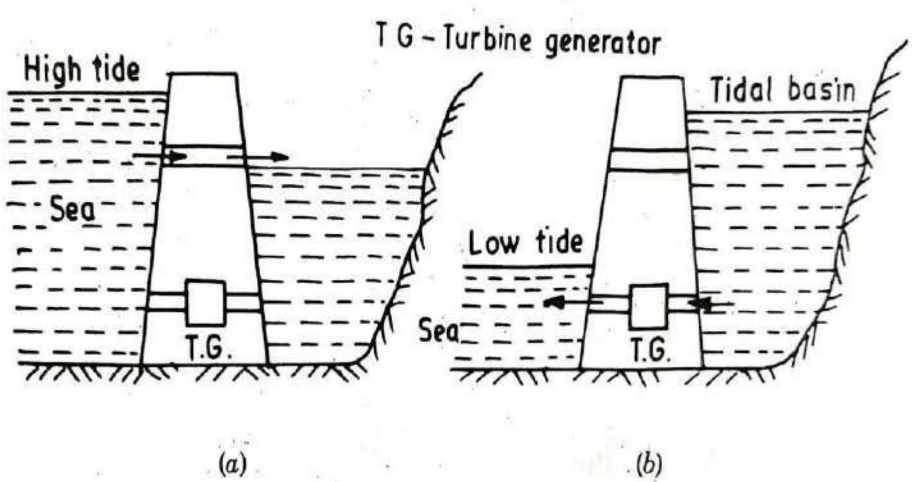


Fig. 9.3.1. Principle of Tidal power generation.

Single basin double cycle plant

- ✓ 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.

(a) High tide (b) Low tide

Fig. 9.3.4.2. Double cycle system.

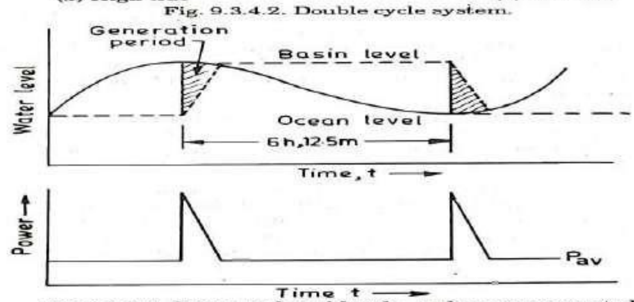


Fig. 9.3.4.3. Ocean and pool levels and power generated in a single-basin tidal system.

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 favorable geographies, however, which are well suited to this type of scheme.

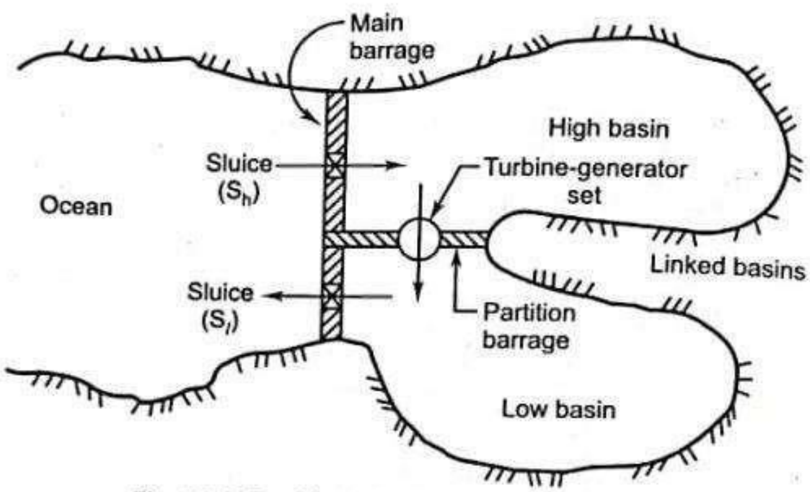


Fig. 8.10. Double-basin, linked-basin scheme.

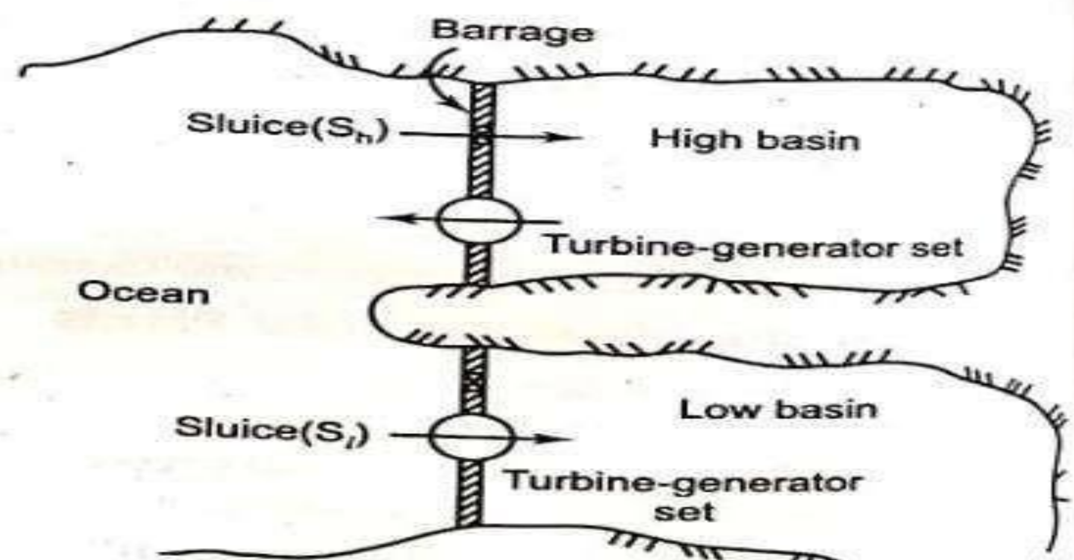


Fig. 8.11. Double-basin paired-basin scheme.

Estimation of tidal power:Single basin system:

Energy and Power in Single Basin System :

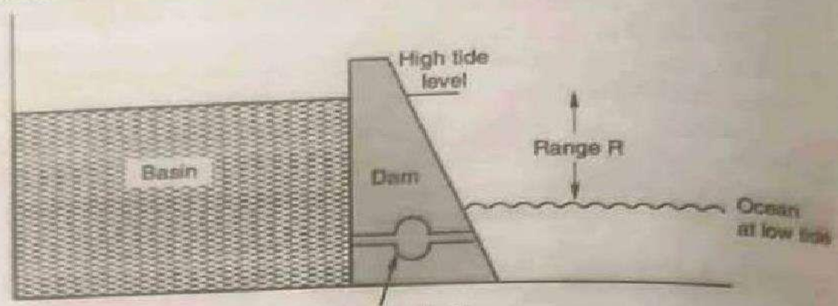


Fig. 12.5.

Let
R = Tidal range
dh = Small head
h = Intermediate head
g = Gravitational constant
m = Mass flowing through turbine
ρ = Density of water
ω = Workdone by water
A = Surface area of basin

$$\therefore \quad d\omega = dm \cdot g \cdot h \qquad \text{...(12.14)}$$

But
$$dm = -\rho A dh \qquad \left(\because \text{ Density} = \frac{\text{Mass}}{\text{Volume}}\right)$$

$$\therefore \quad d\omega = -\rho Agh\, dh \qquad \text{...(12.15)}$$

Total work during emptying of filling

$$W = \int_R^0 d\omega = \int_R^0 -\rho Agh\, dh$$

$$W = \frac{1}{2} g\rho AR^2 \qquad \text{...(12.16)}$$

$$W \propto R^2 \qquad \text{...(12.17)}$$

Therefore, the work is proportional to square of the tidal range.

$$\text{Average power } P_{av} = \frac{W}{t}$$

$$t = 6 \text{ hour } 12.5 \text{ min.}$$
$$= 22350 \text{ sec.}$$

$$\therefore \quad P_{av} = \frac{g\rho AR^2}{2 \times 22350}$$

$$P_{av} = \frac{1}{44700} g\rho AR^2 \qquad \text{...(12.18)}$$

Assume density of sea water = 10^{25} kg/m^3, the average power per unit basin area

$$\frac{P_{av}}{A} = \frac{1}{44700} \times 9.8 \times 1025 R^2$$

$$\frac{P_{av}}{A} = 0.225 R^2 \quad \text{W/m}^2 \qquad \text{...(12.19)}$$

Example 12.1. A tidal power plant of single basin type, has a basin area of 25×10^6 m^2. The tide has a range of 10 m. The turbine however, stops operating when the head on it falls below 2 m. Calculate the energy generated in one filling process, in KWh if the turbine generator efficiency is 75%. (Density of sea water = 1025 kg/m^2)

Solution.

$$W = \int_R^r d\omega$$

$R = 12$ m. and $r = 2$ m.

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

$$W = \frac{1}{2} \times 9.8 \times 1025 \times 25 \times 10^6 \, (12^2 - 2^2)$$

$$= 17578750 \times 106$$

$$P_{av} = \frac{W}{t} = \frac{17578750 \times 10^6}{22350} = 786.52 \times 10^6 \text{ W}$$

$$\text{Average power generated} = \frac{786.52 \times 10^6 \times 3600}{1000}$$

$$= 2831.47 \times 10^6 \text{ KWh} \quad \textbf{Ans.}$$

$$\text{Energy generated} = \eta \times \text{Average power generated}$$

$$= 0.75 \times 2831.47 \times 10^6$$

$$= 2123.6 \times 10^6 \text{ KWh.} \quad \textbf{Ans.}$$

Factors affecting the suitability of the site for tidal power plant

The feasibility and economic vulnerability of a tidal power depends upon the following factors.

- ✓ The power produced by a tidal plant depends mainly on the range of tide and the cubature of the tidal flow occurring in the estuary during a tidal cycle which can be stored and utilized for power generation. The cubature of the tidal flow not only depends on the tidal range but on the width of estuary mouth.
- ✓ The minimum average tide range required for economical power production is more.
- ✓ The site should be such that with a minimum cost of barrage it should be possible to create maximum storage volume. In addition to this, the site selected should be well protected from waves action.
- ✓ The site should not create interruption to the shipping traffic running hrough the estuary other wise the cost of the plant will increase as locks are to be provided.
- ✓ Silt index of the water of the estuary should be as small as possible to avoid the siltation troubles. The siltation leads to reduction of the range of tides and reduces the power potential of the plant.
- ✓ The fresh water prism that falls into the reservoir of the tidal plant (due to the surface flows in the streams having out fall in the estuary) eats away the valuable storage created for storing the tidal prism. Therefore, the ratio of fresh water prism to tidal water prism becomes an important index in determining the economic feasibility of a tidal scheme. The effective and cheaper will be the power production with decreasing the ratio mentioned above.

Advantages of Tidal Power

- ✓ No fuel & No Pollution
- ✓ Inexhaustible/ Renewable
- ✓ Once you built, Tidal energy is free
- ✓ Not dependent on Rain
- ✓ As 70 % of the earth is covered by water, there is a scope to generate more energy
- ✓ Large area of valuable land is not required
- ✓ Life of power plant is very long.
- ✓ Tides behavior is more predictable compared to Solar & Wind
- ✓ Efficiency is high compared to Coal , Solar & Wind plants
- ✓ Water density is 1000 times greater than air, results in very large amount of power production.

Disadvantages of Tidal Power

- ✓ Tides only happen twice a day/Tidal power is not continuous.
- ✓ Because of variable tidal range, power is variable/efficiency is not constant
- ✓ Cost of construction is high.
- ✓ Difficult to carryout the construction
- ✓ Sea water is corrosive.
- ✓ High transmission cost
- ✓ High transmission losses
- ✓ Few suitable sites are available
- ✓ Lack of Studies , Research & Development
- ✓ Sedimentation & Siltation of the basins are the main problems
    - ❖ Sedimentation –Particles settling at the bottom
    - ❖ Siltation – Blocking the system with sand/soil

WAVE ENERGY

- ✓ Wave energy is generated by converting the energy within ocean waves (swells) into electricity.
- ✓ There are many different wave energy technologies being developed and trialled to convert wave energy into electricity.

How Waves Form?

- ✓ Differential warming of the earth causes pressure differences in the atmosphere, which generate winds.
- ✓ As winds move across the surface of open bodies of water, they transfer some of their energy to the water and create waves.
- ✓ A few factors determine how strong an individual wave will be. These include:
  - ❖ Speed of wind: The faster the wind is traveling, the bigger a wave will be.
  - ❖ Time of wind: The wave will get larger the longer the length of time the wind is hitting it.
  - ❖ Distance of wind: The farther the wind travels against the wave (known as fetch), the bigger it will be.

Wave Power

- ✓ Wave power is the transport of energy by ocean surface waves, and the capture of that energy to do useful work – for example, electricity generation, water desalination, or the pumping of water (into reservoirs).

What is Wave Energy?

- ✓ Some of the kinetic (motional) energy in the wind is transformed into waves once the wind hits the ocean surface.
- ✓ Wind energy ultimately forms due to solar energy and its influence on high and low pressure.
- ✓ The density of the energy that is transported under the waves under the ocean surface is about five times higher compared to the wind energy 20 meter (about 65 feet) above.

- ✓ In other words, the amount of energy in a single wave is very high.

History

- ✓ The first known patent to use energy from ocean waves dates back to 1799 and was filed in Paris by Girard and his son.
- ✓ An early application of wave power was a device constructed around 1910 .
- ✓ From 1855 to 1973 there were already 340 patents filed in the UK alone.
- ✓ Modern scientific pursuit of wave energy was pioneered by Yoshio Masuda's experiments in the 1940s.
- ✓ A renewed interest in wave energy was motivated by the oil crisis in 1973.
- ✓ In the 1980s, a few first-generation prototypes were tested at sea.
- ✓ In 2008, the first experimental wave farm was opened in Portugal.

Advantages of wave energy

- ✓ **Renewable**: The best thing about wave energy is that it will never run out. Unlike fossil fuels, which are running out.The waves flow back from the shore, but they always return.
- ✓ **Environment Friendly**: Also unlike fossil fuels, creating power from waves creates no harmful byproducts such as gas, waste and pollution
- ✓ The energy is free - no fuel needed, no waste produced.
- ✓ Not expensive to operate and maintain.
- ✓ Can produce a great deal of energy.
- ✓ It is a reliable source
- ✓ Easily predictable

Disadvantages of Wave Energy

- ✓ Suitable to Certain Locations:The biggest disadvantage to getting your energy from the waves is location. Only power plants and towns near the ocean will benefit directly from it.

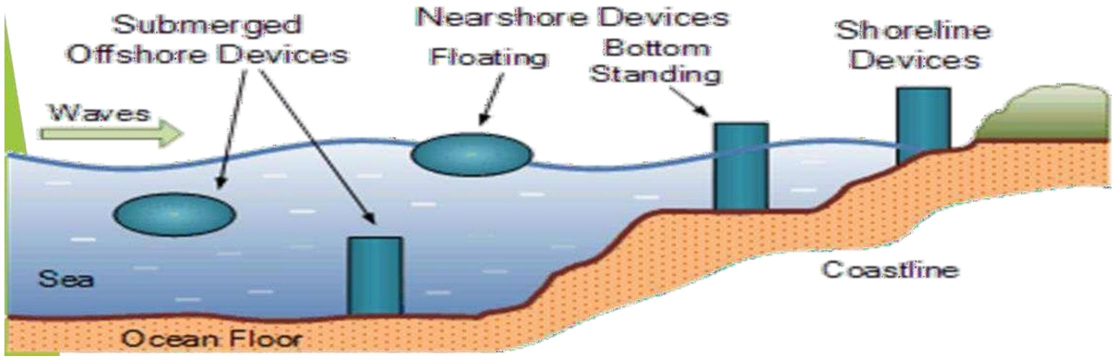
- ✓ Effect on marine Ecosystem :As clean as wave energy is, it still creates hazards for some of the animals near it
- ✓ Depends on the waves - sometimes you'll get loads of energy, sometimes almost nothing.
- ✓ Needs a suitable site, where waves are consistently strong.
- ✓ Weak performance in rough weather.
- ✓ Maintenance and weather effects
- ✓ Noisy

Harnessing Techniques

- ✓ In order to extract this energy, wave energy conversion devices must create a system of reacting forces, in which two or more bodies move relative to each other, while at least one body interacts with the waves.
- ✓ There are many ways that such a system could be configured.

Three Basic Kinds of Systems

- ✓ **Offshore** (deals with swell energy not breaking waves)
- ✓ **Near Shore** (maximum wave amplitude)
- ✓ **Embedded devices** (built into shoreline to receive breaking wave – but energy loss is occurring while the wave is breaking)



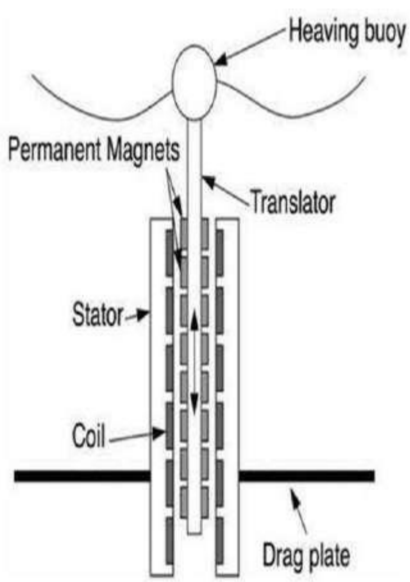
Wave Energy Devices

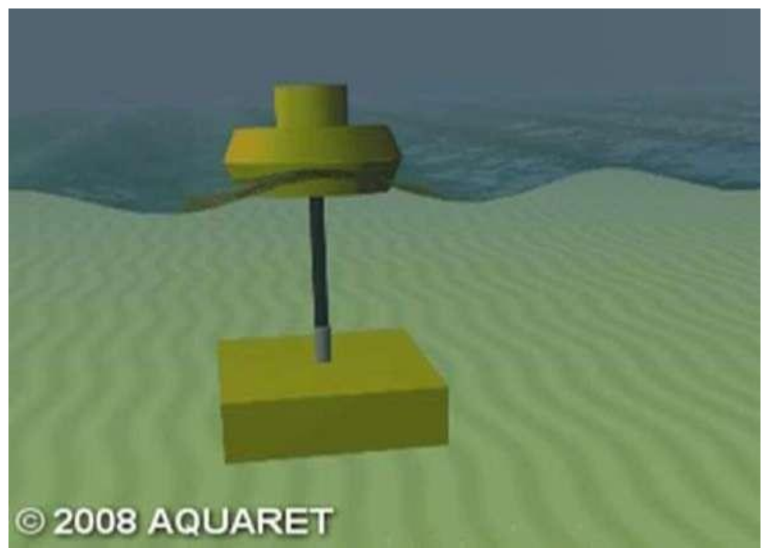
- ✓ **Wave Profile Devices:** They turn the oscillating height of the oceans surface into mechanical energy.
- ✓ **Oscillating Water Columns:** They convert the energy of the waves into air pressure.

- ✓ **Wave Capture Devices:** They convert the energy of the waves into potential energy.

Wave Profile Devices

- ✓ If the physical size of the wave profile device is very small compared to the periodic length of the wave, this type of wave energy device is called a "point absorber".
- ✓ If the size of the device is larger or longer than the typical periodic wavelength, it is called a "linear absorber“.

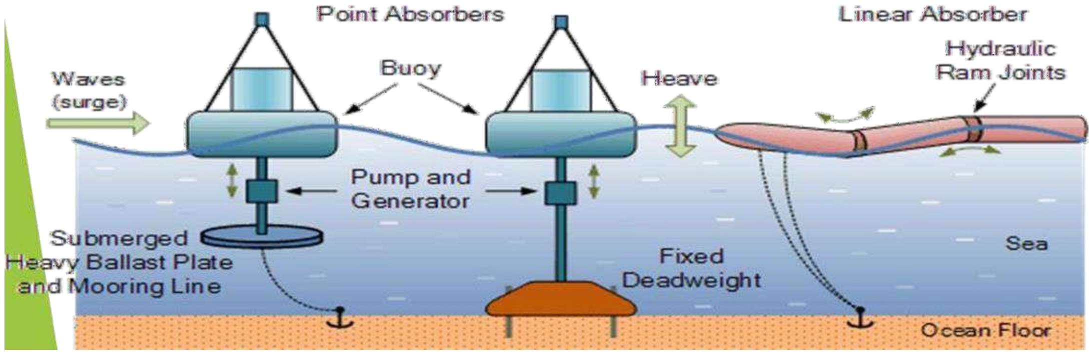




Working

The waves energy is absorbed using

- ✓ Vertical motion (heave)
- ✓ Horizontal motion in the direction of wave travel (surge)
- ✓ Angular motion about a central axis parallel to the wave crests (pitch)
- ✓ or, angular motion about a vertical axis (yaw)
- **or a combination of all four**
- ✓ The energy being generated by reacting these different movements against some kind of fixed resistance called a **reaction point**.



Wave Attenuators

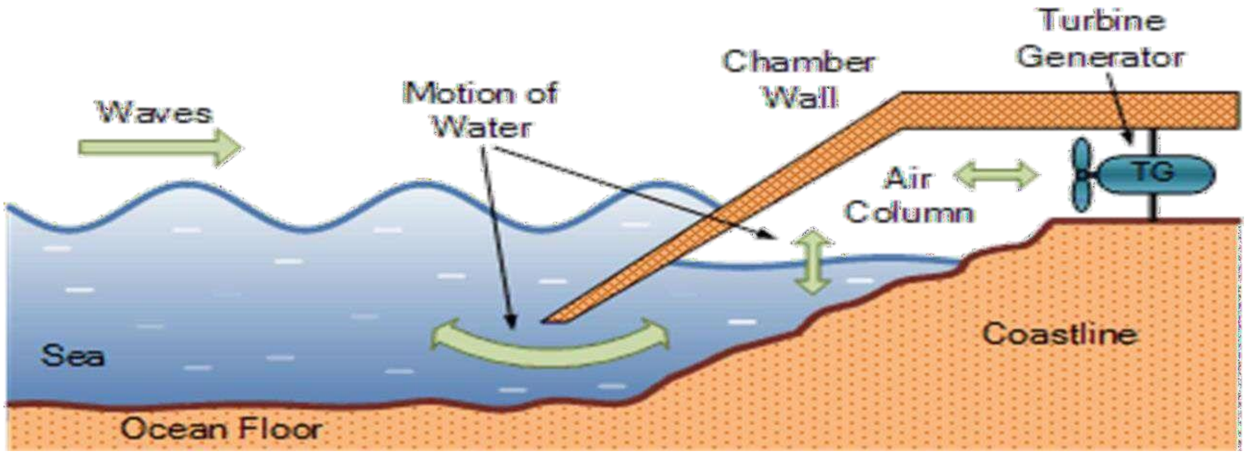
- ✓ As the waves pass along the length of the device, they cause the long cylindrical body to sag downwards into the troughs of the waves and arch upwards when the waves crest is passing.
- ✓ Connecting joints along the body of the device flex in the waves exerting a great deal of force which is used to power a hydraulic ram at each joint.
- ✓ The hydraulic ram drives oil through a hydraulic motor which drives a generator, producing the electricity.

Oscillating Water Column (OWC)

- ✓ The Oscillating Water Column, (OWC) is a popular shoreline wave energy device normally positioned onto or near to rocks or cliffs which are next to a deep sea bottom.
- ✓ They consist of a partly submerged hollow chamber fixed directly at the shoreline which converts wave energy into air pressure.

OWC- Working

- ✓ As the incident waves outside enter and exit the chamber, changes in wave movement on the opening cause the water level within the enclosure to oscillate up and down acting like a giant piston on the air above the surface of the water, pushing it back and forth.
- ✓ This air is compressed and decompressed by this movement every cycle.
- ✓ The air is channeled through a wind turbine generator to produce electricity

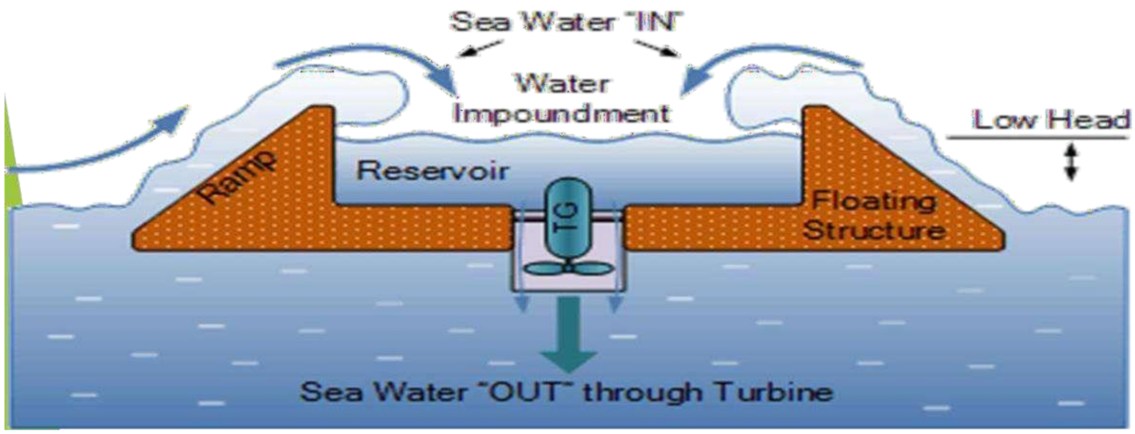


Wave Capture Device

- ✓ A Wave Capture Device also known as a Overtopping Wave Power Device, is a shoreline to nearshore wave energy device that captures the movements of the tides and waves and converts it into potential energy.
- ✓ Wave energy is converted into potential energy by lifting the water up onto a higher level.
- ✓ The wave capture device, or more commonly an overtopping device, elevates ocean waves to a holding reservoir above sea level.
- ✓ It require sufficient wave power to fill the impoundment reservoir.

Working

- ✓ As the waves hit the structure they flow up a ramp and over the top (hence the name "overtopping"), into a raised water impoundment reservoir on the device in order to fill it.
- ✓ Once captured, the potential energy of the trapped water in the reservoir is extracted using gravity as the water returns to the sea via a low-head Kaplan turbine generator located at the bottom of the wave capture device.

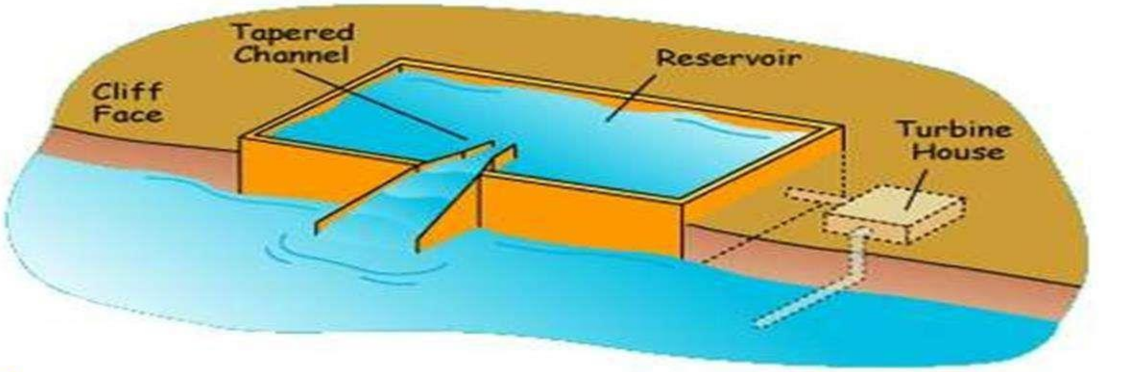


Oscillating Wave Surge Converter

- ✓ These devices typically have one end fixed to a structure or the seabed while the other end is free to move. Energy is collected from the relative motion of the body compared to the fixed point.
- ✓ These capture systems use the rise and fall motion of waves to capture energy. Once the wave energy is captured at a wave source, power must be carried to the point of use or to a connection to the electrical grid by transmission power cables.

Tapered Channel (TAPCHAN)

- ✓ The TAPCHAN is designed by a company called **Norwave**, and a 350kW prototype commenced operation in 1985 on a small Norwegian island.
- ✓ The principle behind the design is to capture waves in a raised reservoir (about 3 metres above the mean sea level) and then extracting useful work as the water is allowed to flow back to the sea.



Benefits of Ocean Wave Energy

Why better than other renewable energies

- ✓ **Available 24/7 on 365 days -** therefore power produced from them is much steadier and more predictable – waves can be accurately predicted 48 hours in advance and therefore forecast energy output (BUT irregularity in wave amplitude, and direction)
- ✓ Good data on waves from wave monitoring bouys
- ✓ Wave energy contains 1000 times the kinetic energy of wind (can produce the same amount of power in less space).

UNIT-V DIRECT ENERGY CONVERSION

- ✓ Transformation of one type of energy (such as sunlight) to another (such as electricity) without passing through an intermediate stage (such as steam to spin generator turbines).
- ✓ The fuel cell, another electrochemical producer of electricity, was developed by William Robert Grove.
- ✓ Thermoelectric generators are devices that convert heat directly into electricity.
- ✓ In a solar cell, radiant energy drives electrons across a potential difference at a semiconductor junction in which the concentrations of impurities are different on the two sides of the junction.

NEED FOR DEC

- ✓ No conversion of energy into mechanical and to electricity
- ✓ Less frictional and other losses in conversion process
- ✓ More efficient process
- ✓ Easy maintenance
- ✓ Environment friendly
- ✓ Compact and less weight
- ✓ High reliability
- ✓ No noise
- ✓ Cost is also reduced

Types of DEC System

1.Fuel Cells

2.Thermoelectric generator

3.Thermoinoic generator

4.Magneto Hydro Dynamic (MHD) generators

5.Electron Gas Dynamic (EGD) generators

6.Solar Photo Voltaic Cells

7.Nuclear Batteries

8.Electro static mechanical generators

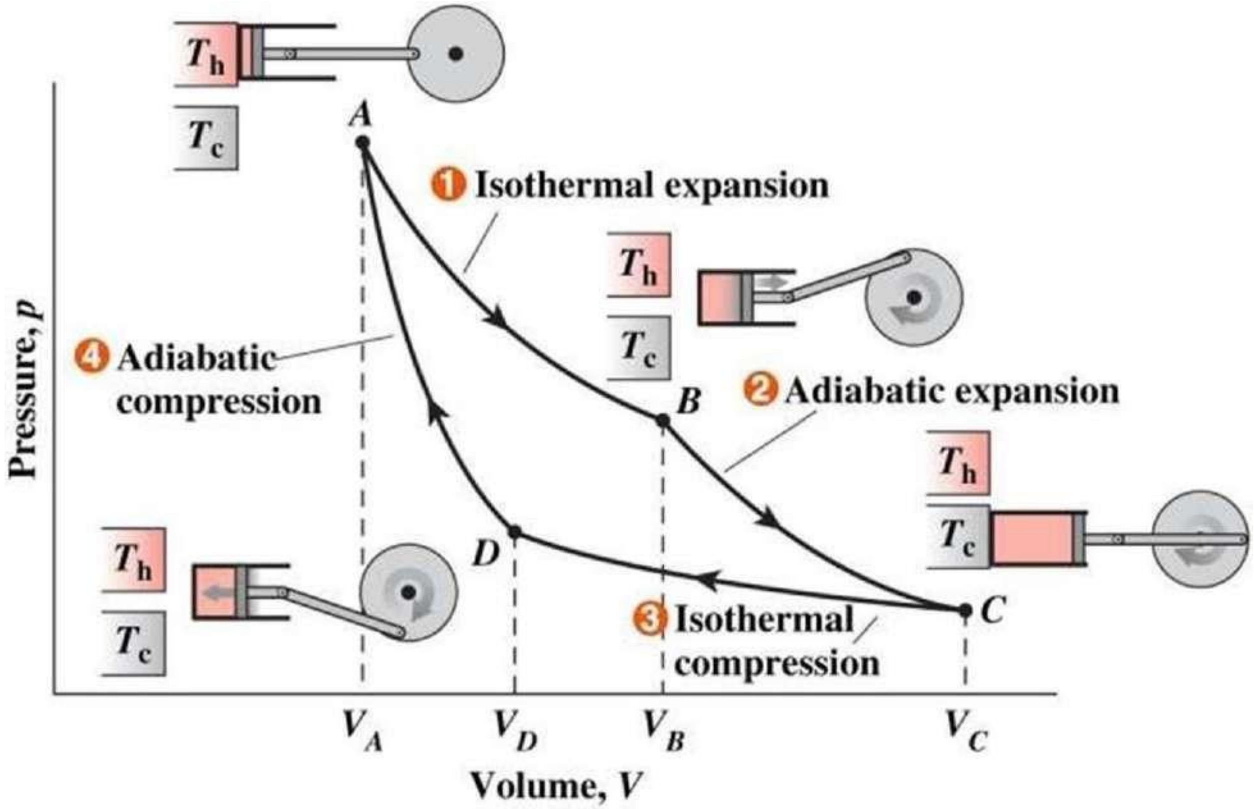
CARNOT CYCLE

- ✓ The Carnot cycle has the greatest efficiency possible of an engine (although other cycles have the same efficiency) based on the assumption of the absence of incidental wasteful processes such as friction, and the assumption of no conduction of heat between different parts of the engine at different temperatures.
- ✓ In the early 19th century, steam engines came to play an increasingly important role in industry and transportation. However, a systematic set of theories of the conversion of thermal energy to motive power by steam engines had not yet been developed. Nicolas Léonard Sadi Carnot (1796-1832), a French military engineer, published *Reflections on the Motive Power of Fire* in 1824.
- ✓ The book proposed a generalized theory of heat engines, as well as an idealized model of a thermodynamic system for a heat engine that is now known as thea Carnot cycle.

PROCESSESS OF CARNOT CYCLE

- ✓ A reversible isothermal gas expansion process. In this process, the ideal gas in the system absorbs q_{in} amount heat from a heat source at a high temperature T_h, expands and does work on surroundings.
- ✓ A reversible adiabatic gas expansion process. In this process, the system is thermally insulated. The gas continues to expand and do work on surroundings, which causes the system to cool to a lower temperature, T_l.
- ✓ A reversible isothermal gas compression process. In this process, surroundings do work to the gas at T_l, and causes a loss of heat, q_{out}.
- ✓ A reversible adiabatic gas compression process. In this process, the system is thermally insulated. Surroundings continue to do work to the gas, which causes the temperature to rise back to T_h.

P-V DIAGRM

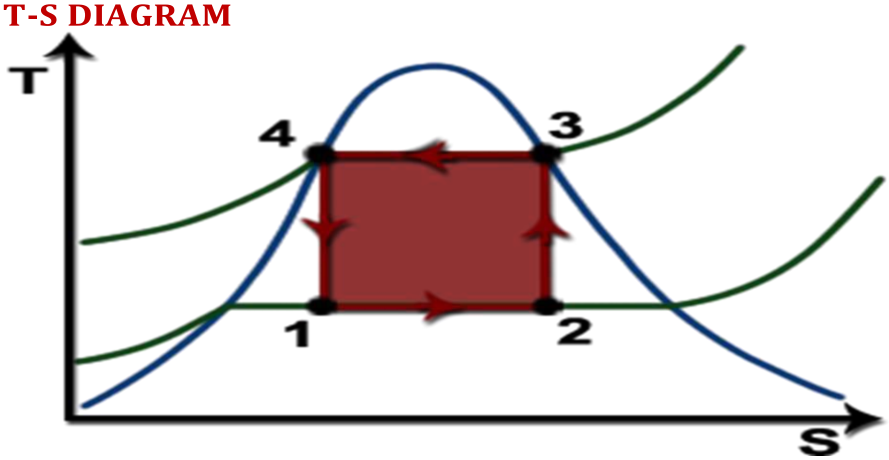


In isothermal processes I and III, ΔU=0 because

ΔT=0. In adiabatic processes II and IV,

q=0. Work, heat, ΔU, and ΔH of each process

T-S DIAGRAM



In isothermal processes I and III, ΔT=0.
In adiabatic processes II and IV, ΔS=0 because dq=0. ΔT and ΔS of each process

LIMITATION OF CARNOT CYCLE

This equation shows that the wider the temperature range, the more efficient is the cycle.(a) T3
In practice T3cannot be reduced below about 300 K (27ºC), corresponding to a condenser pressure of 0.035 bar. This is due to two tractors:

(i) Condensation of steam requires a bulk supply of cooling water and such a continuousnaturalsupply below atmospheric temperature of about 15°C is unavailable.

(ii) If condenser is to be of a reasonable size and cost, the temperature difference between thecondensing steam and the cooling water must be at least 10°C.(b) TI

(iii) The maximum cycle temperature T1 is also limited to about 900 K (627°C) by the strengthof the materials available for the highly .

Critical Point:

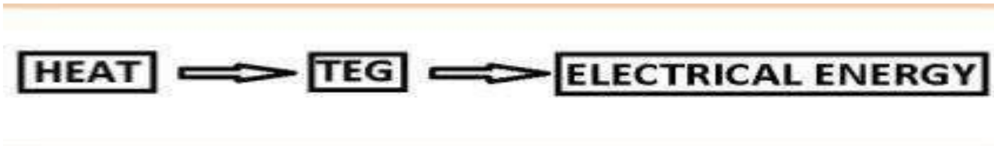
- In fact the steam Carnot cycle has a maximum cycle temperature of well below this metallurgical limit owing to the properties of steam; it is limited to the critical-pointtemperature of 374°C (647 K). Hence modern materials cannot be used to their best advantagewith this cycle when steam is the working fluid.Furthermore, because the saturated water andsteam curves converge to the critical point, a plant operating on the carnot cycle with itsmaximum temperature near the critical- point temperature would have a very large s.s.c., i.e. itwould be very large in size and very expensive.

Compression Process:

- Compressing a very wet steam mixture would require acompressor of size and cost comparable with the turbine. It Would absorb work comparable withthe developed by the turbine. It would have a short life because of blade erosion and cavitations problem. these reasons

THERMO ELECTRIC POWER GENERATION (TEG)

- ✓ TEG is a solid state device
- ✓ TEG converts heat energy directly into electrical energy based on the principles of Seebeck effect
- ✓ Electricity is produced due to temperature difference in conductor



PRINCIPLE

- ✓ In the purer metallic conductors outer electrons, less connected to others, can move freely around all the material, as if they do not belong to any atom. These electrons transmit energy one to another through temperature variation, and this energy intensity varies depending on the nature of the material.
- ✓ If two distinct materials are placed in contact, free electrons will be transferred from the more "loaded" material to the other, so they equate themselves, such transference creates a potential difference, called contact potential, since the result will be a pole negatively charged by the received electrons and another positively charged by the loss of electrons.

Why we need TEG ?

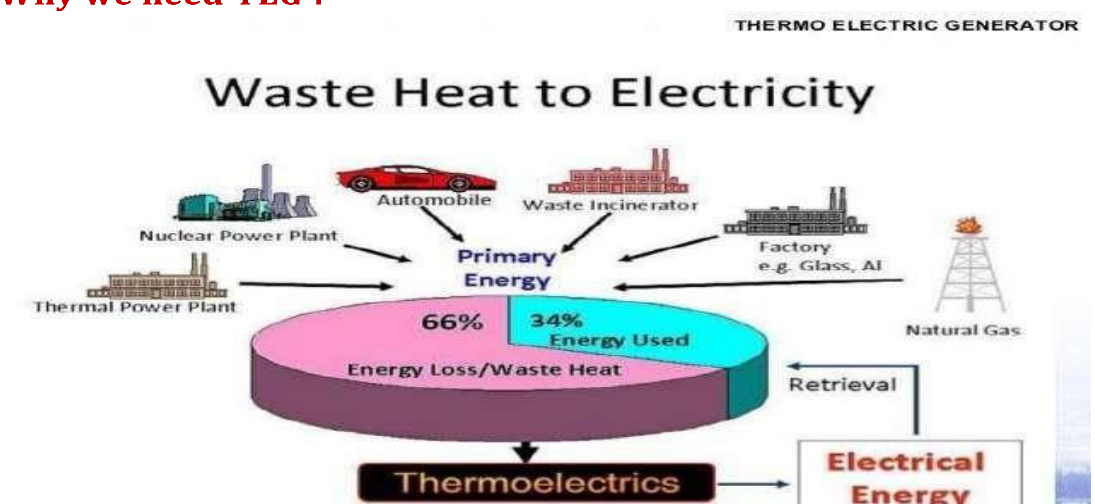
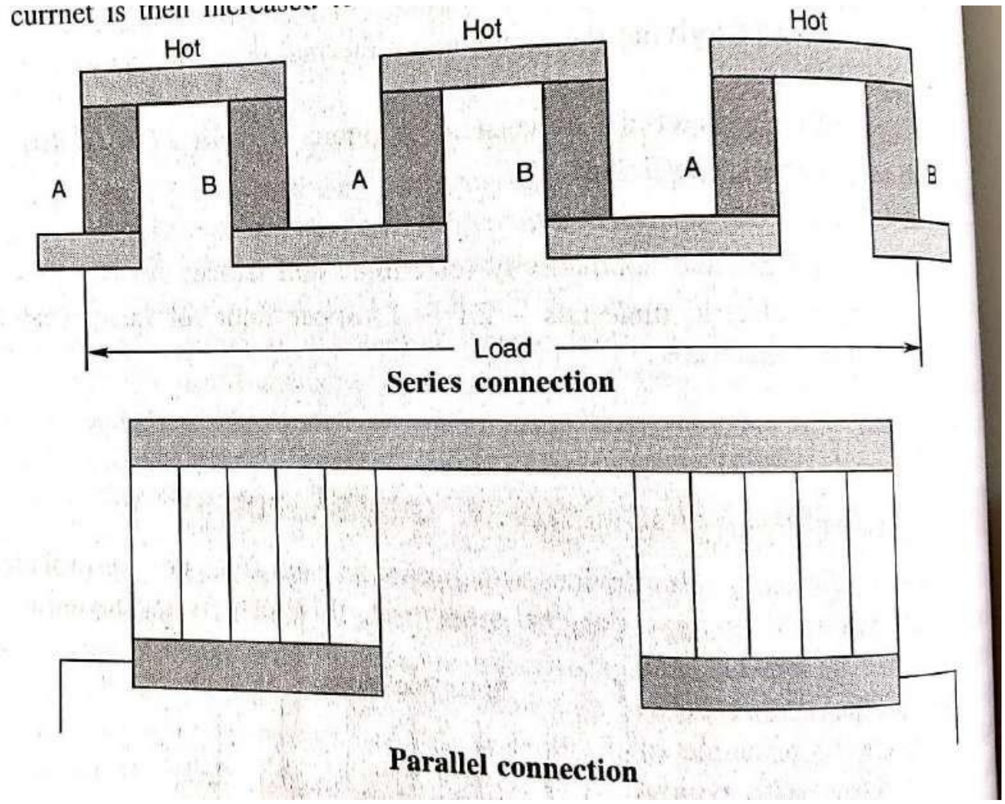


Fig.1 Energy Statistics

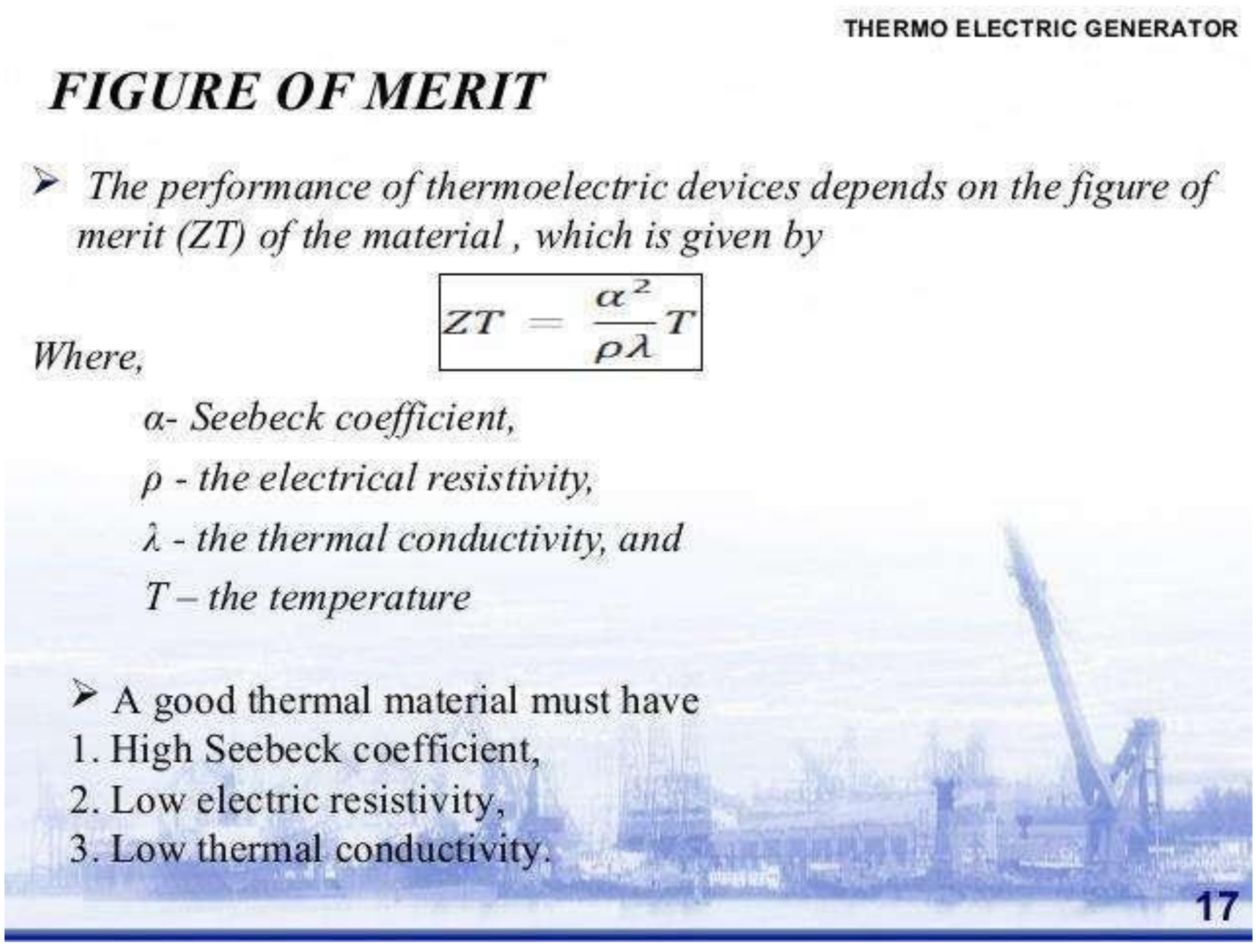
What is the specialty of TEG?

- ✓ TEG functions like a heat engine, but
  - Less bulky
  - No moving parts
  - Silent in operation

Arrangement of TEG



- ✓ Thermoelectric power generation (TEG) devices typically use special semiconductor materials, which are optimized for the Seebeck effect.
- ✓ The simplest thermoelectric power generator consists of a thermocouple, comprising a p-type and n-type material connected electrically in series and thermally in parallel.
- ✓ Heat is applied into one side of the couple and rejected from the opposite side.
- ✓ An electrical current is produced, proportional to the temperature gradient between the hot and cold junctions.



Thermoelectric Materials

- The good thermoelectric materials should possess

    1. Large Seebeck coefficients
    2. High electrical conductivity
    3. Low thermal conductivity

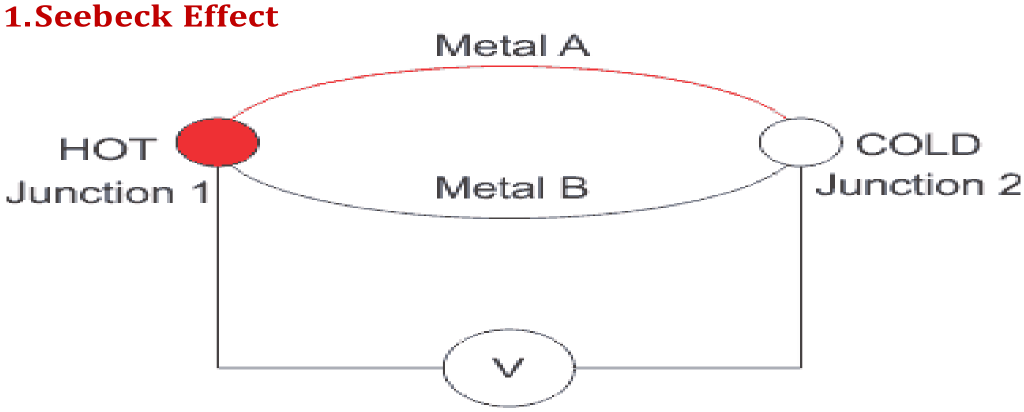
- The example for thermoelectric materials

    - BismuthTelluride (Bi_2Te_3),
    - Lead Telluride (PbTe),
    - SiliconGermanium (SiGe),
    - Bismuth-Antimony (Bi-Sb)

Thermoelectric Effects

1. Seebeck Effect
2. Peltier Effect
3. Thomson Effect
4. Joule Effect

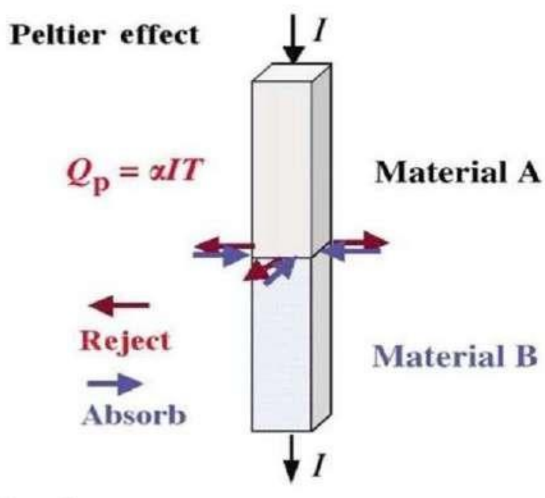
1.Seebeck Effect



- ✓ If two dissimilar materials are joined to form a loop and two junctions maintained at different temperatures, an e.m.f will be set up around the loop.
- ✓ The magnitude and current depends on the materials and the temperature difference between junctions.
- ✓ The magnitude emf (E) is given by
- ✓ $E = \alpha_s \Delta T$
  - ❖ α_{s}- Seebeck coefficient
  - ❖ ΔT – Temperature difference between hot and cold junctions

Peltier Effect

- ✓ When an electric current flows across an isothermal junction of two dissimilar materials, there is either an evolution or absorption of heat at the junction.



$$Q_p = \alpha_p I$$

- α_p- Peltier coefficient
- I – Peltier heat per unit time

Thomson Effect

- ✓ Any current carrying conductor with a temperature difference between two points will either absorb or emit heat, depending upon the material.

$$\sigma = \frac{dQt/dx}{dT/dX}$$

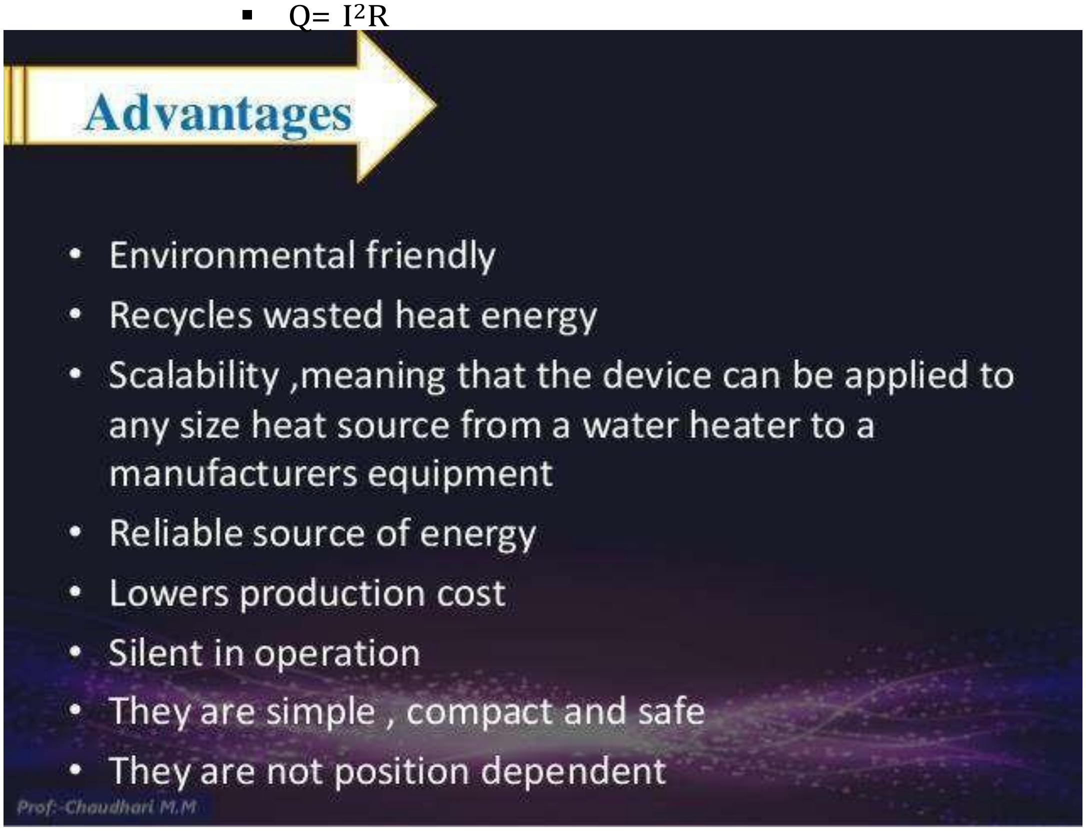
σ - Thomson coefficient

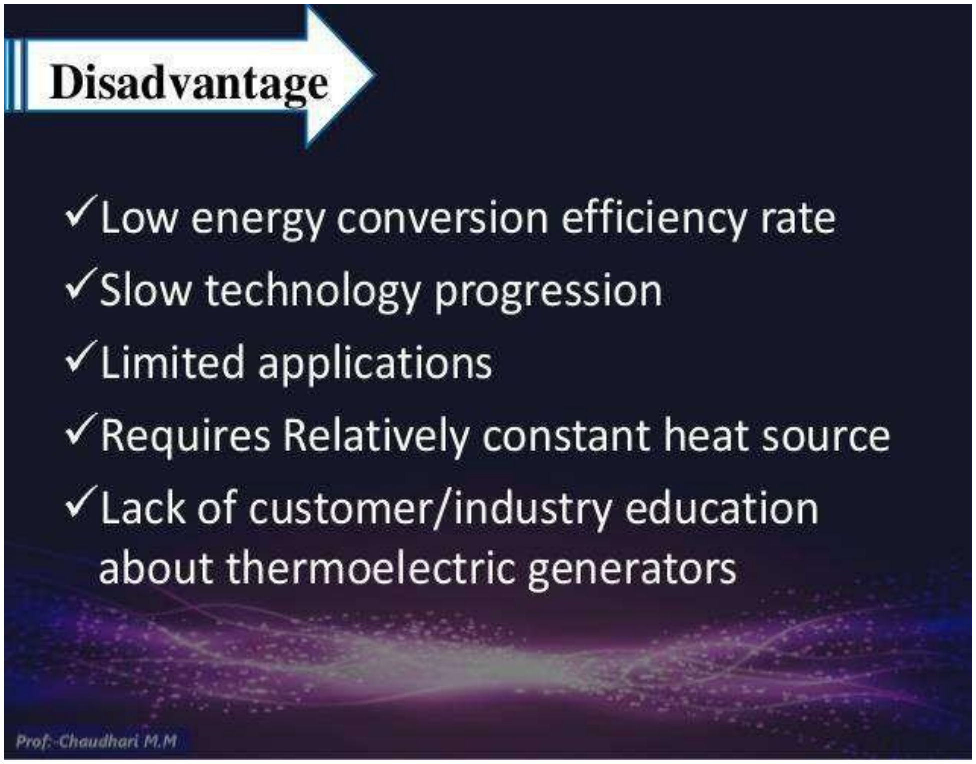
dQt/dx – Heat interchange per unit time per unit length of conductor

dT/dX – Temperature gradient

Joule Effect

- ✓ In a closed electric circuit if the current (I) flows through a resistance (R) ,the heat generated (Q) by the resistance is equal to I^2R.
- ✓ Mathematically
    - $Q = I^2R$





Thermionic Generator

- ✓ Thermionic generator converts heat energy directly to electrical energy by utilizing thermionic emission effect.
- ✓ In this , electrons act as working fluid in the place of a vapour/gas and electrons are emitted from the surface of the heated metal

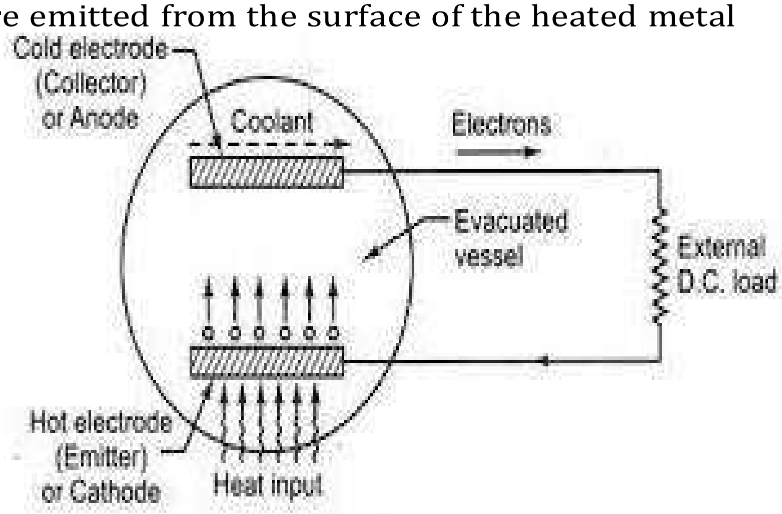


Fig. 9.7. Thermionic generator.

- **Thermionic Power Convertor** is a static device that converts heat into electricity by boiling electrons from a hot emitter surface(approx 1800 K) across a small inter electrode gap(< 0.5 mm) to a cooler collector surface(approx 1000 K)
- A **Thermionic Generator** consists of one or more of these convertors coupled to give desired power output
- Thermionic generators can be operated from any primary heat source.
- For low power level(3 kW or less) solar energy can be used
- For high power level (50 kW or more) nuclear heat source can be used

Advantages

- ✓ Compact device
- ✓ High conversion efficiency
- ✓ Silent in operation and durable.
- ✓ Low cost and less maintenance
- ✓ Absence of rotating parts
- ✓ Operates at high temperature
- ✓ Operate in remote areas
- ✓ Low power to high power generation

Disadvantages

- ✓ Metal is costly as it has to withstand high temperatures
- ✓ Needs high operating temperatures at Anode
- ✓ Needs special sea to protect the cathode from corrosive gases
- ✓ Needs Cesium vapour in the tube.
- ✓ Large number of convertors are required to produce more voltage.
- ✓ Power losses in convertors

Applications

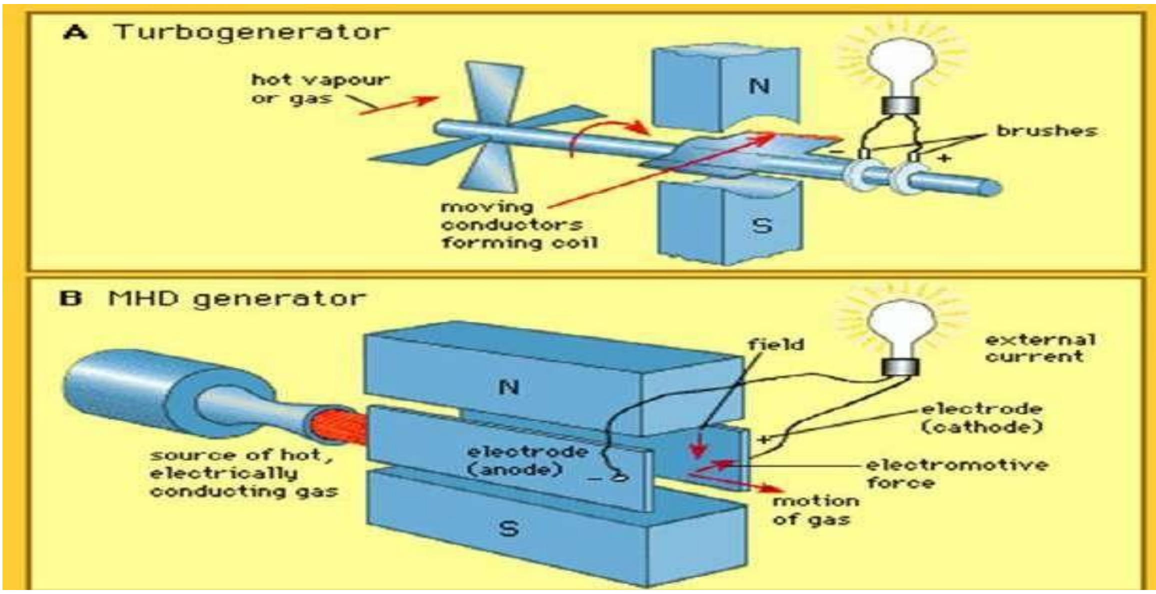
- ✓ Power generation in both centralized and distributed systems.
- ✓ Residential and commercial purpose
- ✓ Automobile , Marine applications
- ✓ Electronics and Telecommunications
- ✓ Aerospace and Military Systems

Magneto Hydro Dynamic (MHD) Generator

- Magneto -magnetic field,
- Hydro – working liquid
- Dynamics - movement.
- In MHD power generation heat is directly converted in to electrical energy.
- The basic principle of MHD generation is the same as that of conventional electrical generator i.e, the motion of a conductor through a magnetic field induces an emf in it.
- In steam power plant the heat released by the fuel is converted into mechanical energy by means of thermo –cycle and mechanical energy is then used to drive the electric generator.
- In MHD generation ,electrical energy is directly generated from hot combustion gases produced by the combustion of the fuel without moving parts.
- In this method ionized gas is produced by heating the gas to a high temperature.
- 80 % of total electricity produced in the world is Hydal.
- 20% is produced from nuclear, thermal, solar, geothermal energy ,MHD generator and other renewable energy sources.
- As its name implies, magneto hydro dynamics (MHD) is concerned with the flow of a conducting fluid in the presence of magnetic and electric field.
- The fluid may be gas at elevated temperatures or liquid metals like sodium or potassium.
- Conventional power plants

  Heat energy → Mechanical energy → Electrical energy
- MHD power plants

  Heat energy → Electrical energy
- MHD is a Direct Energy Conversion System.



- ✓ MHD generator is a device for converting heat energy of a fluid directly into electrical energy without conventional electric generator.
- ✓ MHD converter system is a heat engine in which heat is supplied at a higher temperature is partly converted into useful work and the remainder is rejected at a low temperature.
- ✓ Like all heat engines, the thermal efficiency of an MHD converter is increased by supplying the heat at the highest temperature and rejecting it at the lowest l temperature.

NEEDOF MHDS:

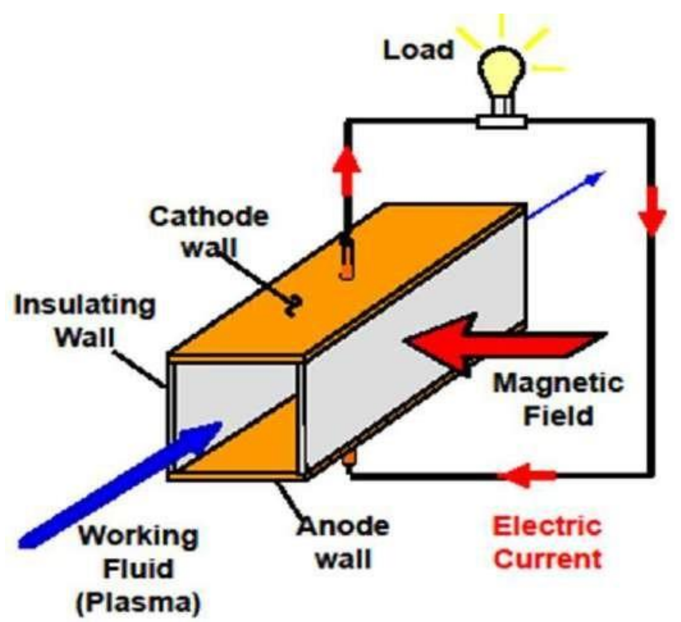
- ✓ At present a plenty of energy is needed to sustain industrial and agricultural production, and the existing **conventional energy sources** like coal, oil, uranium etc are **not adequate to meet** the ever **increasing energy demands**.
- ✓ Consequently, efforts have been made for harnessing energy from several non-conventional energy sources like **Magneto Hydro Dynamics(MHD) System.**

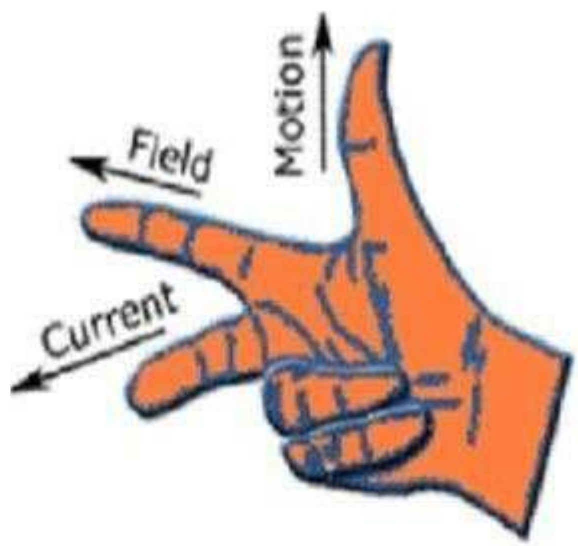
HISTORY

- ✓ In 1932 Michael Faraday, demonstrated the experiments that there is an electromagnetic induction in a current carrying conductormoving the earth magnetic field.
- ✓ In 1938, U.S scientist Bela Karlovitz is the first one developed the Magneto hydrodynamic generator.
- ✓ In India, the MHD generator program is undergoing in Thiruchirappalli in collaboration with Bharat heavy electrical limited (BHEL).

PRINCIPLE OF MHDPOWERGENERATION

1.Faraday's law of electromagnetic induction : When a conductor is placed in a magnetic field, due to relative motion between conductor and magnetic field and EMF is induced.





- This effect is a result of

  " FARADAYS LAWS OF ELECTRO MAGNETIC INDUCTION."
- The induced EMF is given by
- $E_{ind} = V \times B$
  - Where V=velocity of the conductor.

    B = magnetic field intensity.
- The induced current is given by,
- $J_{ind} = \sigma E_{ind}$
  - where σ = electric conductivity

2. Lorentz Force

- ✓ Charged particle experience a force when is moving in the electromagnetic field. This force can be explained as

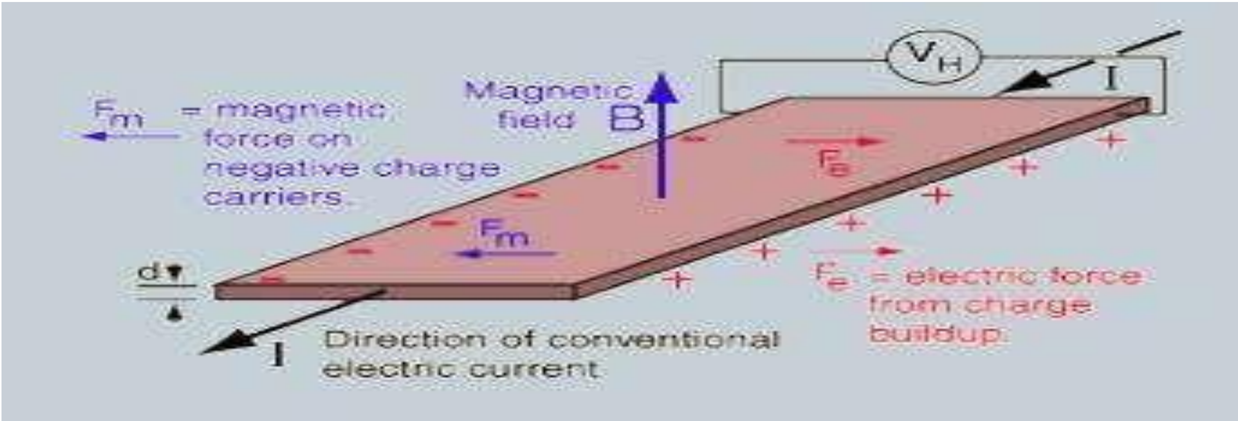
$F = q.(v \times B)$

where,

- v = velocity of the particle (vector)
- q= charge of the particle (scalar)
- B = magnetic field (vector)

What is HALL Effect?

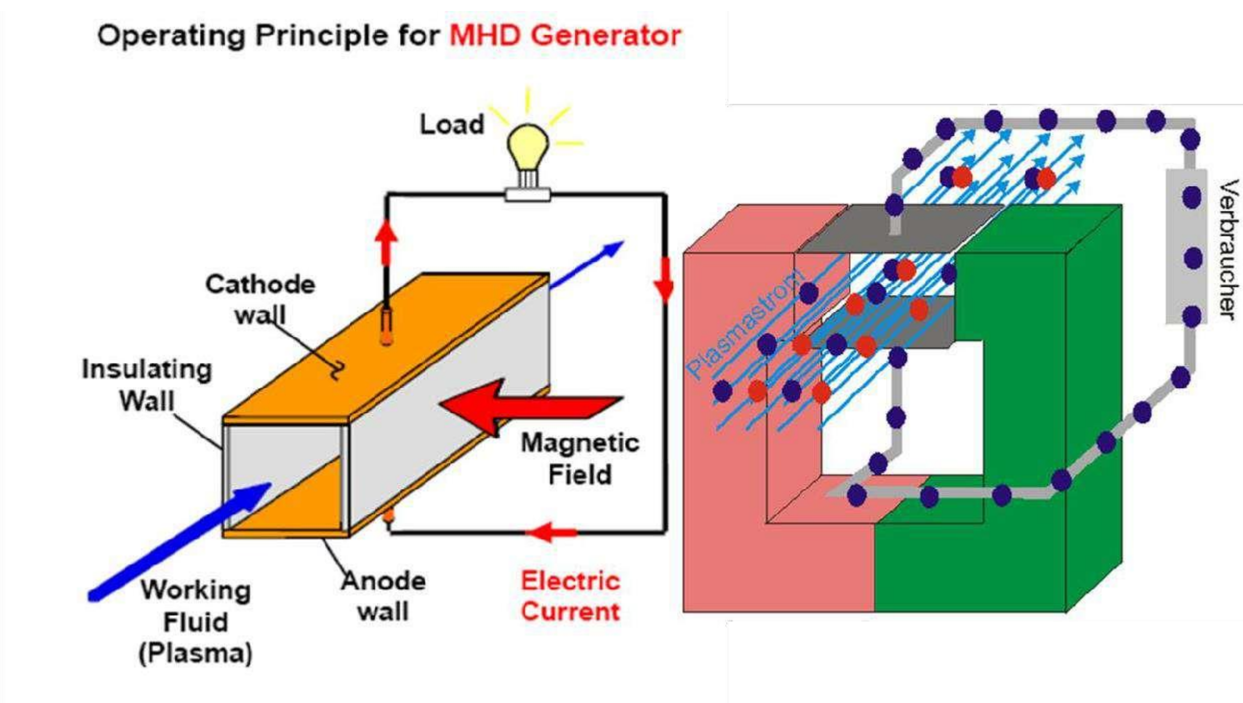
The Hall effect is the production of a voltage difference (Hall voltage) across a current carrying conductor (in the presence of magnetic field), perpendicular to both current and magnetic field.



Principle, construction and working of Magneto hydrodynamic generator (MHD)

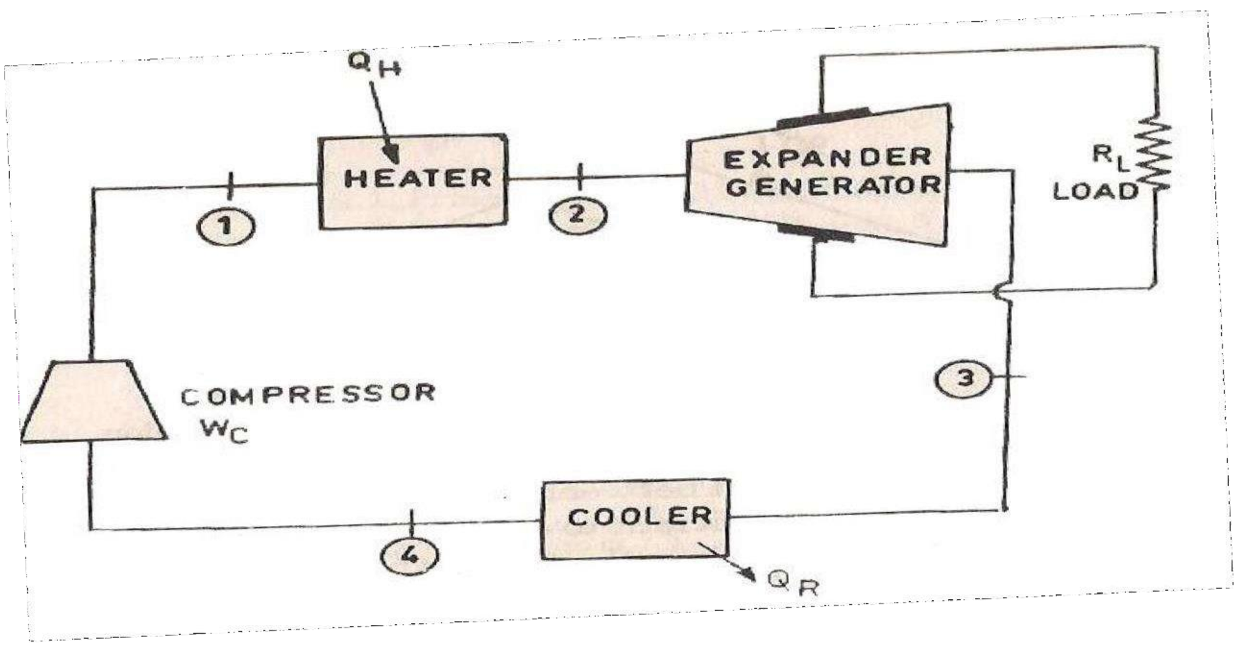
Principle :

- ✓ The principle of Magneto hydrodynamic generator is based on **Lorentz law and faraday's law**.
- ✓ v In this system, the hot ionized gaseous conductor (working fluid) is passed into the high magnetic field and thereby the current is produced. By placing suitable electrodes (Anode and cathode) inside the chamber, the output load is taken through the external circuit.

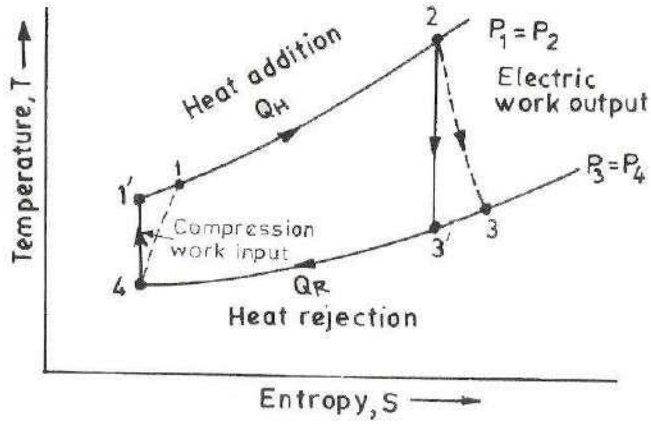


CONSTRUCTION:

Schematic of MHD power cycle and T-S diagram for cycle



JOULE/BRAYTON CYCLE



WORKING

- ✓ The gaseous (fluid) conductor is passed into the combustion chamber through inlet.
- ✓ By using a fuel like oil (or) natural gas (or) coal, the fluid conductor is heated to a plasma state and hence it is ionized.
- ✓ The temperature in the combustion chamber is around2000°K to 2400°K.
- ✓ The heat generated in the combustion chamber removes the outermost electrons in the fluid conductor.
- ✓ Therefore, the gas particle acquires the charge .
- ✓ The charged gas particles with high velocity enters into the generator chamber via nozzle.
- ✓ The positive and negative charge moves to corresponding electrodes (anode and Cathode) and constitute the current.
- ✓ In generator chamber, based principles of Faraday's law, the high velocity ionized conducting gas particles experience the magnetic filed at right angles to their motion of direction and hence the potential (current) is produced.
- ✓ The direction of current (Potential) is perpendicular to both the direction of moving gas particle and to the magnetic field.
- ✓ The electrodes are connected to an external circuit to get a load output.
- ✓ The current produced in the MHD generator are direct current (DC)

- ✓ This DC current can be converted into alternative current (AC) using an inverter attached with the external circuit.
- ✓ In MHD generator, the seeding materials such as potassium and cesium are used to reduce the ionization temperature.
- ✓ These seeds are mixed with fuel material such as natural gas and coal.
- ✓ The electrode are made generally using high temperature ceramic materials such as carbides (SiC, ZrC, MbC), bromides (ZrB_2, TiB_2, LaB_2) and silicates (WS and $MOSi_2$).

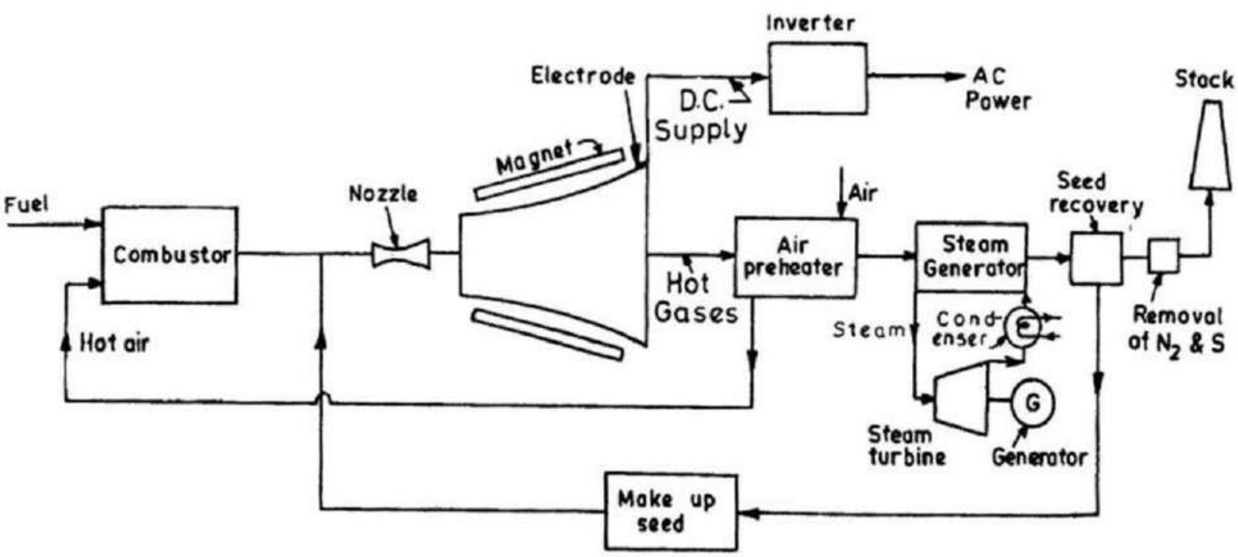
Types of MHD SYSTEMS

I. OPEN CYCLE SYSTEM :Working fluid : Gas

II. CLOSED CYCLE SYSTEM

1. **Seeded inert gas system**-Working fluid : Argon or Helium
2. **Liquid metal system**-Working fluid : Liquid Potassium

1. OPEN CYCLE MHD SYSTEM:



Hybrid MHD - Steam Part Open Cycle

- ✓ The fuel used maybe oil through an oil tank or gasified coal through a coal gasification plant
- ✓ The fuel (coal, oil or natural gas) is burnt in the combustor or combustion chamber.
- ✓ The hot gases from combustor is then seeded with a small amount of ionized alkali metal (cesium or potassium) to increase the electrical conductivity of the gas.
- ✓ The seed material, generally potassium carbonate is injected into the combustion chamber, the potassium is then ionized by the hot combustion gases at temperature of roughly 2300' c to 2700'c.
- ✓ To attain such high temperatures, the compressed air is used to burn the coal in the combustion chamber, must be adequate to at least 1100^0c.
- ✓ A lower preheat temperature would be adequate if the air is enriched in oxygen. An alternative is used to compress oxygen alone for combustion of fuel, little or no preheating is then required. The additional cost of oxygen might be balanced by saving on the preheater.
- ✓ The hot pressurized working fluid leaving the combustor flows through a convergent divergent nozzle. In passing through the nozzle, the random motion energy of the molecules in the hot gas is largely converted into directed, mass of energy. Thus , the gas emerges from the nozzle and enters the MHD generator unit at a high velocity.

For efficient practical realization an MHD system must have the following features:

1- Air super heating arrangement to heat the gas to around 2500°C, (the inlet temperature of MHD is about 2500"C), so that the electrical conductivity of the gas is increased.

2. The combustion chamber must have low heat losses.

3. Arrangement to add a low ionization potential seed material to the gas to increase its conductivity.

4. A water cooled but electrically insulating expanding duct with long life electrodes.

5. Seed recovery apparatus—necessary for both environmental and economic reasons

What is Seeding in MHD?

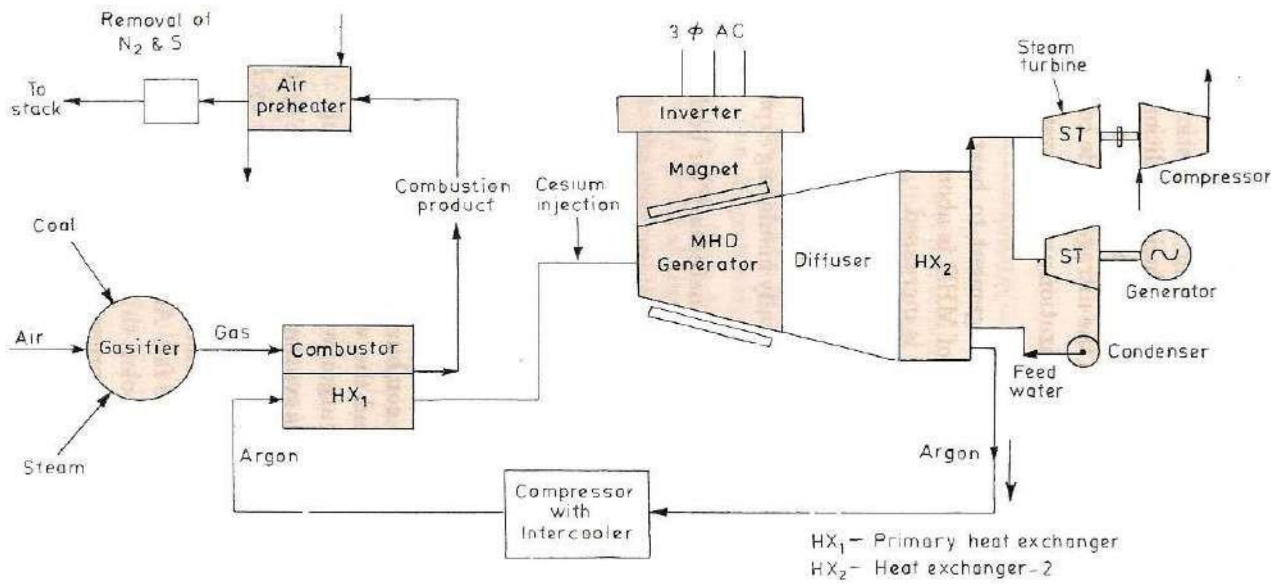
- ✓ Adding of small amount of an ionized alkali metal (Cesium of Potassium) to the gas is called as Seeding Process.

  This is done to increase Electrical conductivity of the gas.

  Seed Recovery means, removal of Cesium or Potassium from the gas. This done to save the money.

2. CLOSED CYCLE SYSTEM

(Seeded inert gas system – Working fluid is Argon or Helium)



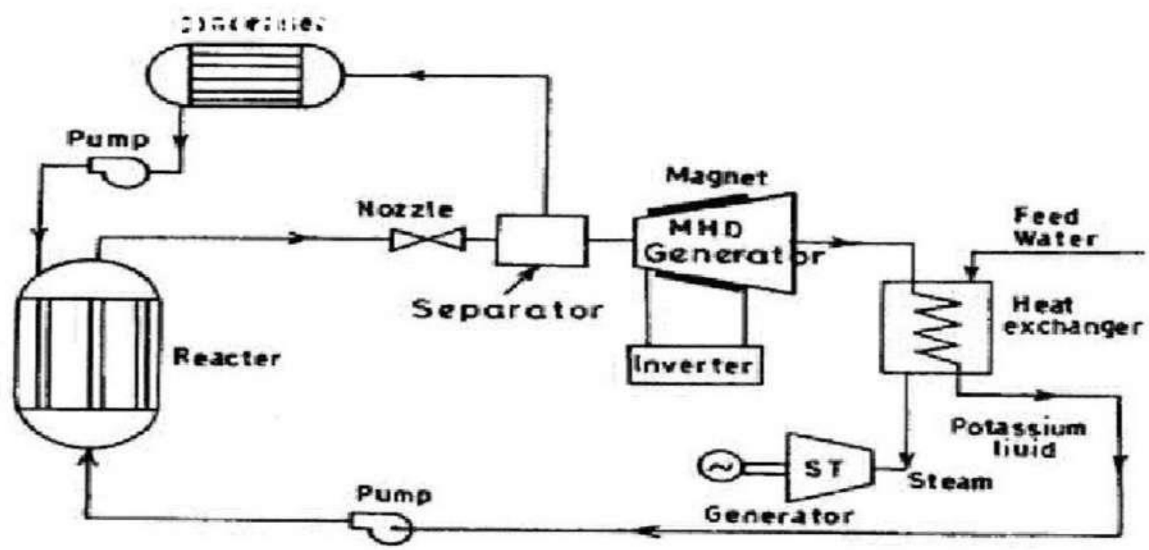
- ✓ In a closed cycle system the carrier gas operates in the form of Brayton cycle. In a closed cycle system the gas is compressed and heat is supplied by the source, at essentially constant pressure, the compressed gas then expands in the MHD generator, and its pressure and temperature fall. After leaving this generator heat is removed from the gas by a cooler, this is the heat rejection stage of the cycle. Finally the gas is recompressed and returned for reheating.
- ✓ The complete system has three distinct but interlocking loops. On the left is the external heating loop. Coal is gasified and the gas is burnt in the combustor to provide heat. In the primary heat exchanger, this heat is transferred to a carrier gas argon or helium of the MHD cycle. The combustion products after passing through the air preheater and purifier are discharged to atmosphere.
- ✓ Because the combustion system is separate from the working fluid, so also are the ash and flue gases. Hence the problem of extracting the seed material from fly ash does not arise. The flue gases are used to preheat the incoming

combustion air and then treated for fly ash and sulfur dioxide removal, if necessary prior to discharge through a stack to the atmosphere.

- ✓ The loop in the center is the MHD loop. The hot argon gas is seeded with cesium and resulting working fluid is passed through the MHD generator at high speed. The dc power out of MHD generator is converted in ac by the inverter and is then fed to the grid.

CLOSED CYCLE MHD SYSTEM LIQUID METAL SYSTEM –

Working fluid is Liquid Sodium or Potassium



Closed cycle MHD generator using liquid metal as working fluid coupled with steam genarator.

- ✓ When a liquid metal provides the electrical conductivity, it is called a liquid metal MHD system.
- ✓ An inert gas is a convenient carrier
- ✓ The carrier gas is pressurized and heated by passage through a heat exchanger within combustion chamber. The hot gas is then incorporated into the liquid metal usually hot sodium to form the working fluid. The latter then consists of gas bubbles uniformly dispersed in an approximately equal volume of liquid sodium.
- ✓ The working fluid is introduced into the MHD generator through a nozzle in the usual ways. The carrier gas then provides the required high direct velocity of the electrical conductor.

- ✓ After passage through the generator, the liquid metal is separated from the carrier gas. Part of the heat exchanger to produce steam for operating a turbine generator. Finally the carrier gas is cooled, compressed and returned to the combustion chamber for reheating and mixing with the recovered liquid metal. The working fluid temperature is usually around 800’c as the boiling point of sodium even under moderate pressure is below 900’c.
- ✓ At lower operating temp, the other MHD conversion systems may be advantageous from the material standpoint, but the maximum thermal efficiency is lower. A possible compromise might be to use liquid lithium, with a boiling point near 1300’c as the electrical conductor lithium is much more expensive than sodium, but losses in a closed system are less.

Differences between OPEN CYCLE and CLOSED CYCLE SYSTEM

Open Cycle System	**Closed Cycle System**
Working fluid after generating electrical energy is discharged to the atmosphere through a stack .	Working fluid is recycled to the heat sources and thus is used again.
Operation of MHD generator is done directly on combustion products .	Helium or argon(with cesium seeding) is used as the working fluid.
Temperature requirement: 2300°Cto 2700°C	Temperature requirement : about 530°C.
More developed.	Less developed.

MATERIALS FOR MHD GENERATORS

Important factors to be considered for selection of materials in several parts of generators like electrodes, channel or duct wall

1. Thermal shock resistance
2. Electrical conductivity
3. Corrosion resistance
4. Erosion resistance
5. Oxidation resistance
6. Melting point of the material

Advantages :

- ✓ The conversion efficiency of an MHD system can be around 50 per cent as compared to less than 40 per cent for the most efficient steam plants. Still higher thermal efficiencies (60- 65%) are expected in future, with the improvements in experience and technology.
- ✓ Large amount of power is generated.
- ✓ It has no moving parts, BO more reliable

- ✓ The closed cycle system produces power free of pollution.
- ✓ It has ability to reach the full power level as soon as started
- ✓ The size of the plant (m2/kW) is considerably smaller than conventional fossil fuel plants.
- ✓ Although the costs can not be predicted very accurately, yet it has been reported that capital costs ofMHD plants will be competitive with those of conventional steam plants.
- ✓ It has been estimated that the overall operational, costs in an MHD plant would be about 20% less than in conventional steam plants.
- ✓ Direct conversion of heat into electricity permits to eliminate the gas turbine (compared with a gas turbine power plant) or both the boiler and the turbine (compared with a steam power plant). This elimination reduces losses of energy.
- ✓ These systems permit better fuel utilization. The reduced fuel consumption would offer additional economic and special benefits and would also lead to conservation of energy resources.
- ✓ It is possible to utilize MHD for peak power generations and emergency service (upto 100 hours per year). It has bepn estimated the MHD equipment for such duties is simpler, has the capability of generating in large units and has the ability to make rapid start to full load.

Disadvantages:

- ✓ Numerous technological advancement requires prior to its commercialisation.
- ✓ It requires highly corrosive and abrasive environment.
- ✓ MHD channels operates under extream condition of temperature.
- ✓ Suffers from reverse flow (short circuits) of electrons through the conducting fluids around the ends of the magnetic field.
- ✓ Needs very large magnets and this is a major expense.
- ✓ High friction and heat transfer losses
- ✓ High operating temperature
- ✓ Coal used as fuel poses problem of molten ash which may short circuit the electrodes. Hence, oil or natural gas are much better fuels for MHDs. Restriction on use of fuel makes the operation more expensive.

APPLICATIONS

- ✓ Power generation in space craft.
- ✓ —Hypersonic wind tunnel experiments.
- ✓ — Defence applications.

MHD GENERATOR DESIGN CONSIDERATIONS

For efficient practical realization ,an MHD system must have the following design considerations.

1. Air pre heater arrangement to heat the gas to around 2500^0 C, so that the electrical conductivity of the gas is increased.
2. The combustion chamber must have the low heat losses.
3. Arrangement to add the seed material to the gas to increase it’s conductivity.

4. A water cooled but electrically insulating expanding duct with long life electrodes.
5. Seed recovery apparatus is necessary for both environmental and economic reasons.

STATUS OF MHD POWERGENERATION & FUTURE PROSPECTUS

- ✓ The first MHD - USA in 1959.
- ✓ In 1960 - USA, USSR, Japan, UK, France, Poland and other countries.
- ✓ In 1970 - A 25MW MHD plant at USSR
- ✓ The USSR has designed a 500MW power station.
- ✓ In Japan - 200MW plant near Tokyo
- ✓ Poland and China are also believed to be developing MHD systems.
- ✓ India - R&D programme on MHD started in 1977.
- ✓ In March 1985, an experimental 50 MW plant was commissioned at Tiruchurapally with BARC

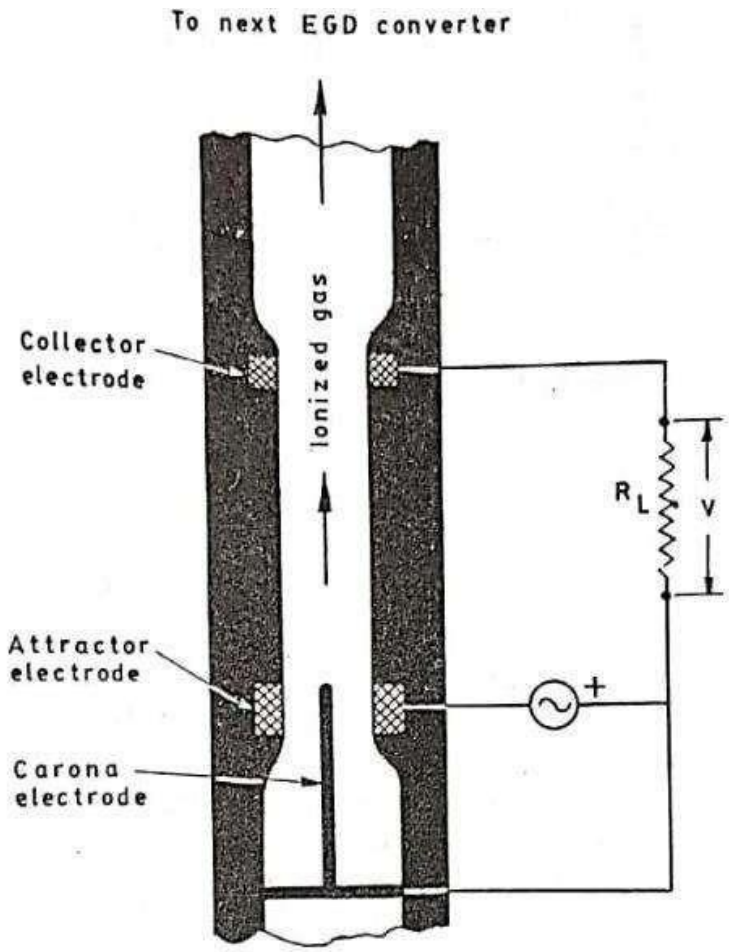
	S.No	Present Efficiency	Future Efficiency
1	Thermo Electric Generation	3%	13%
2	Thermoionic Generation	15%	40%
3	Fuel Cell	50%	60%
4	MHD Power Generation	50%	60-80%
5.	Solar PV Cell	15%	-
6	Solar Power Generation	30%	50%
7.	Wind Power Generation	30%	-
8.	Geothermal	15%	-

CONCLUSION –MHD

- ✓ MHD is a new system of electric power generation with high efficiency
- ✓ MHD generation looks the most promising of the direct conversion techniques for the larger scale production of electric power generation.

Electro Gas Dynamic (EGD) Generator

- ✓ EGD Generator uses the potential energy of high pressure gas to carry electrons from a low potential electrode to a high potential electrode , there by producing Electricity.



- ✓ Fig. 10.33. Gas duct in an EGD convertor.

Carona Discharge –

- ✓ Electrical discharge due to ionization of fluid like air surrounding a conductor that is electrically charged.

Salient Points –EGD

- ✓ Carona electrode at the entrance, generates electrons.
- ✓ Ionized Gas flow in the duct, produces electricity
- ✓ Working fluid is gas, produced by burning of fuel at high pressure.
- ✓ The max.power output is 10W- 30W per channel
- ✓ Several channels can be connected in Series/Parallel.
- ✓ The voltage produced is very high

- (1,00,000 V-2,00,000V)

- ✓ EGD efficiency is almost equal to MHD (50%)

Advantages of EGD

- ✓ It works at relatively low temperature.
- ✓ No need of injecting seed material and seed recovery
- ✓ It is a self contained system
- ✓ Max.energy can be extracted
- ✓ Does not require any cooling water

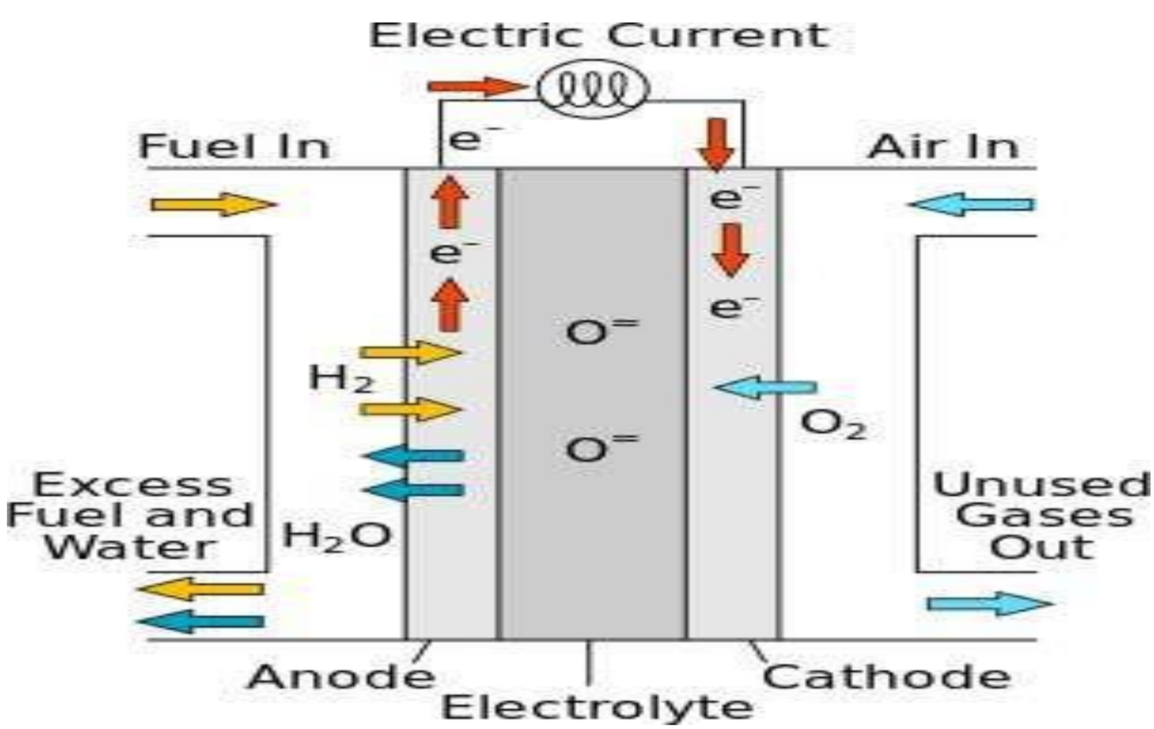
Disadvantages of EGD

- ✓ It produces less power
- ✓ More no.of channels are required
- ✓ Electrodes life is less
- ✓ Voltage reduction devices are required.
- ✓ Lack of R& D work

FUELCELLS

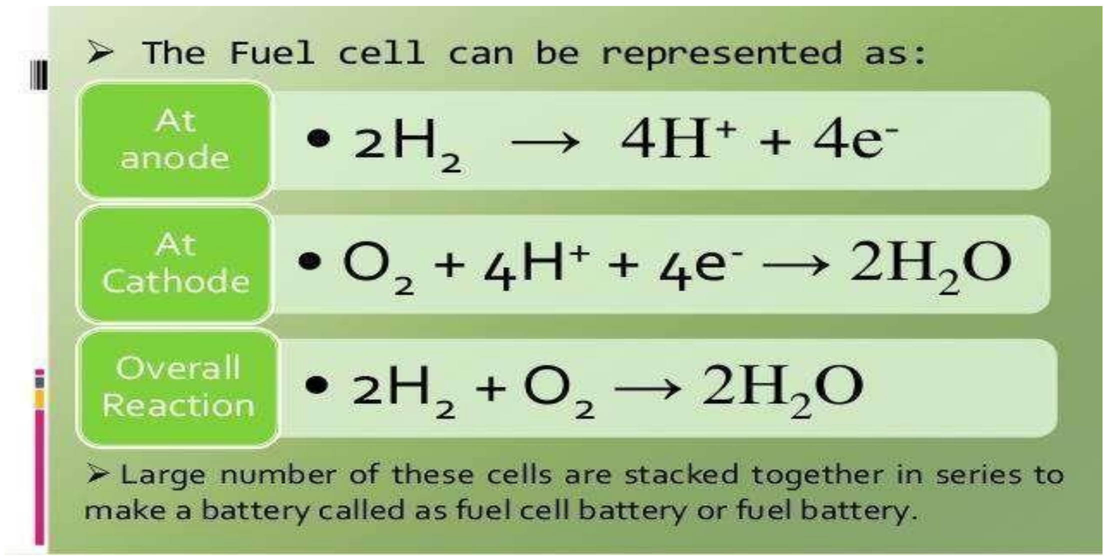
- A fuel cell is an electrochemical device that converts energy produced from a chemical reaction into electrical energy.
- Chemical Energy of fuel is converted into low voltage direct current electrical energy.
- Fuel & Oxidizer are stored external to the battery and fed to it when needed.
- Fuel gas diffused through anode, it is oxidized e- are released to external circuit oxidized fuel diffuses the cathode , combines with e- which comes from external circuit and forms water and heat.
- More specifically it is an electrochemical device that combines hydrogen and oxygen to produce electricity, with water and heat as its by- product.
  - H_2 is mostly used fuel.
  - Reaction: $2H_2+O_2 = 2H_2O$
  - Power produced in fuel cell depends on cell type, size, temperature, and pressure of gas.
  - Single fuel cell is used for small application, for larger application they are connected in series (fuel cell stacks)
  - Chemical Energy $\longrightarrow$ Electrical Energy.

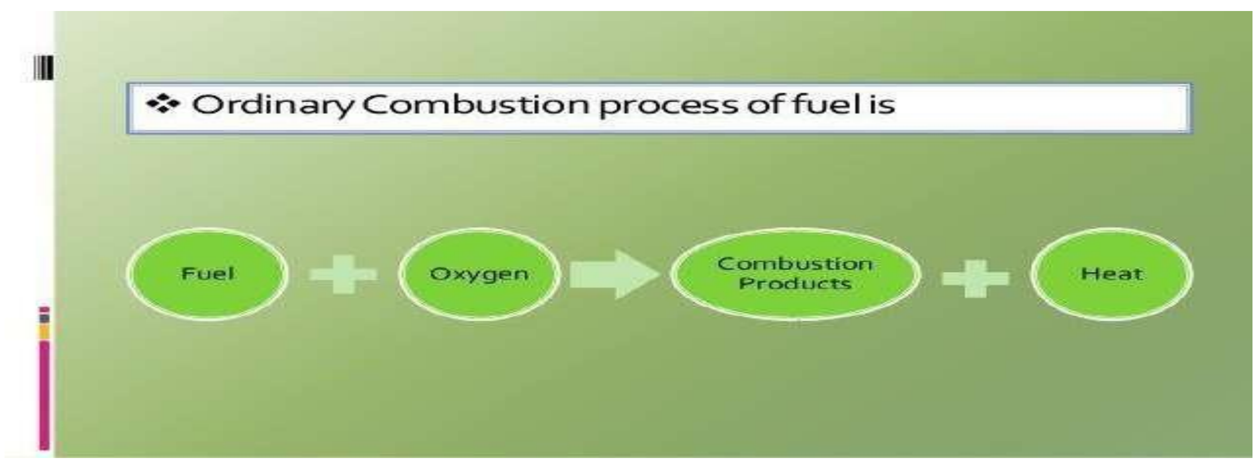
SCHEMATIC DIAGRAM of H_2-O_2 FUEL CELL

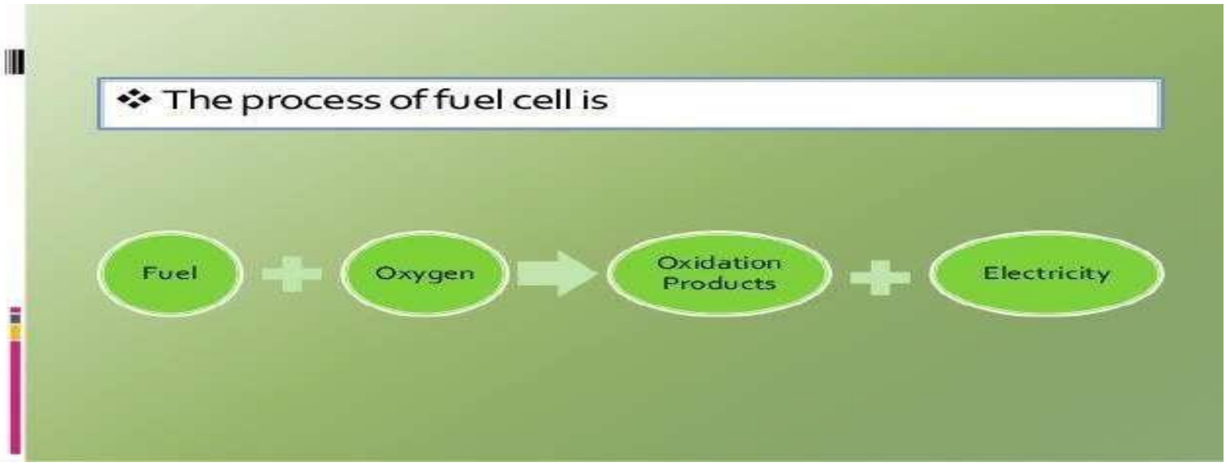


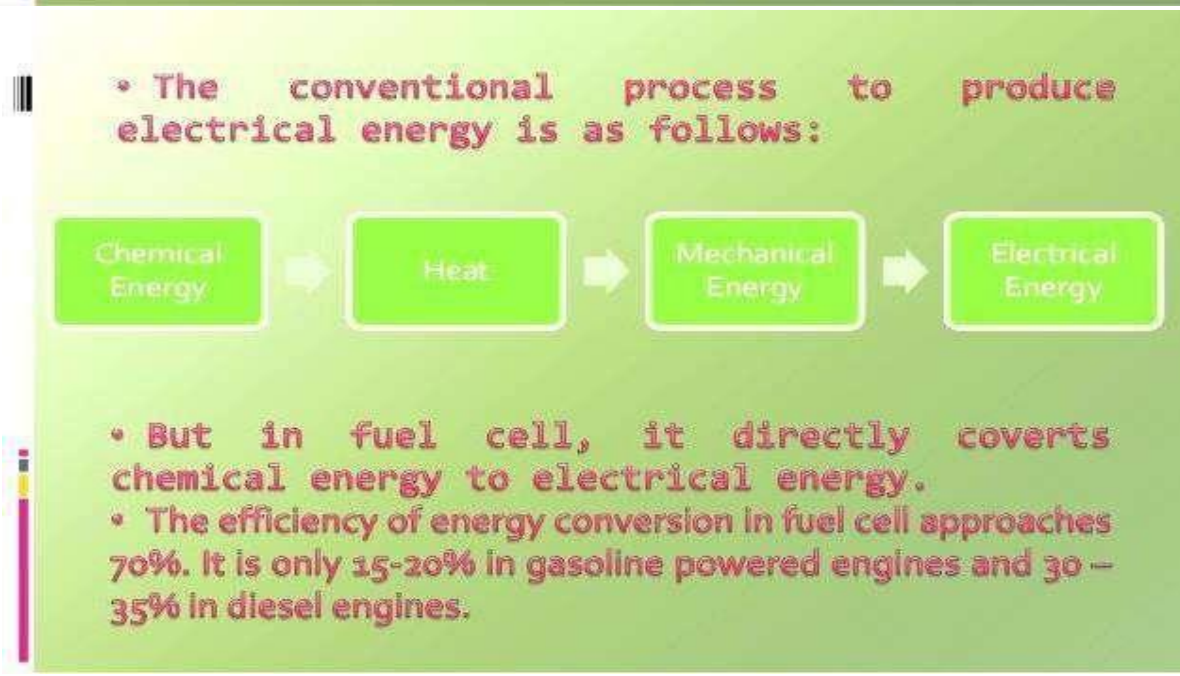
Components of Fuel Cell

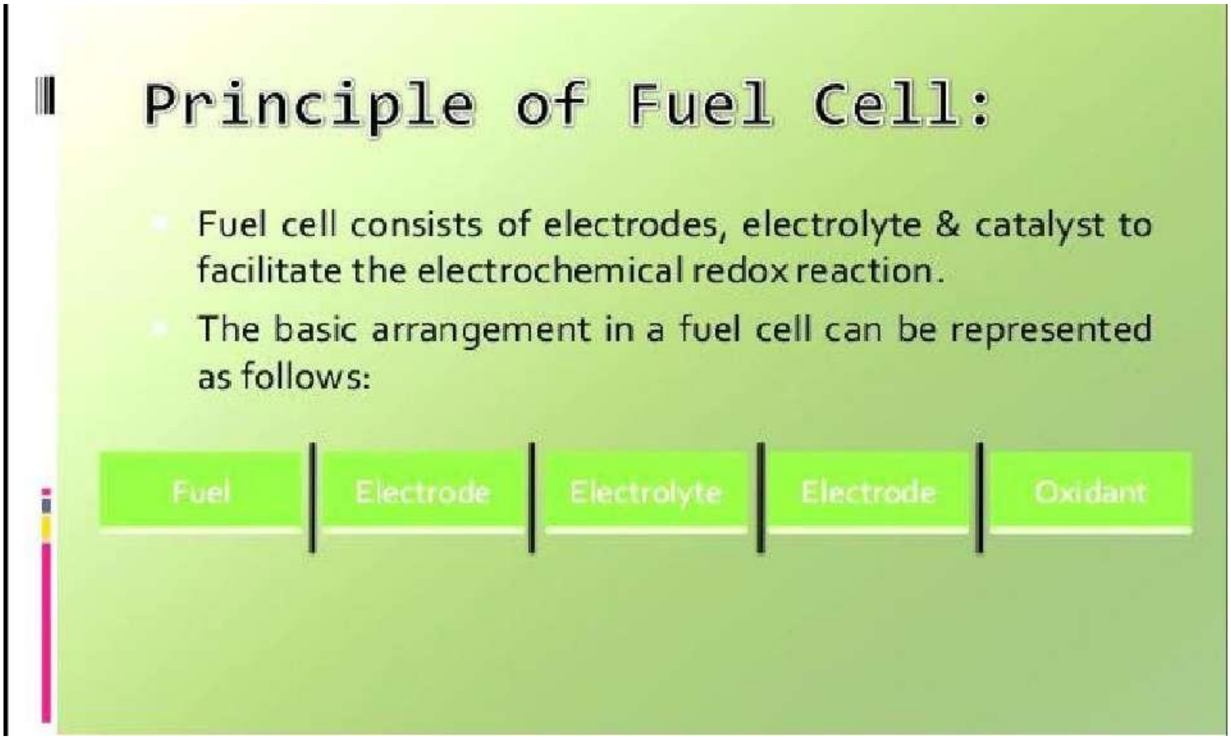
- ✓ 1.Anode (Fuel electrode)
- ✓ 2.Cathode (Oxidant electrode)
- ✓ 3.**Electrolyte Solution**
- ✓ -generally Potassium Hydroxide KOH (20-40% concentration), which has high electrical conductivity & less corrosive than acids
- ✓ 4.Container
- ✓ 5. Separators
- ✓ 6. Sealings
- ✓ 7. Fuel supply
- ✓ 8. Oxidizer

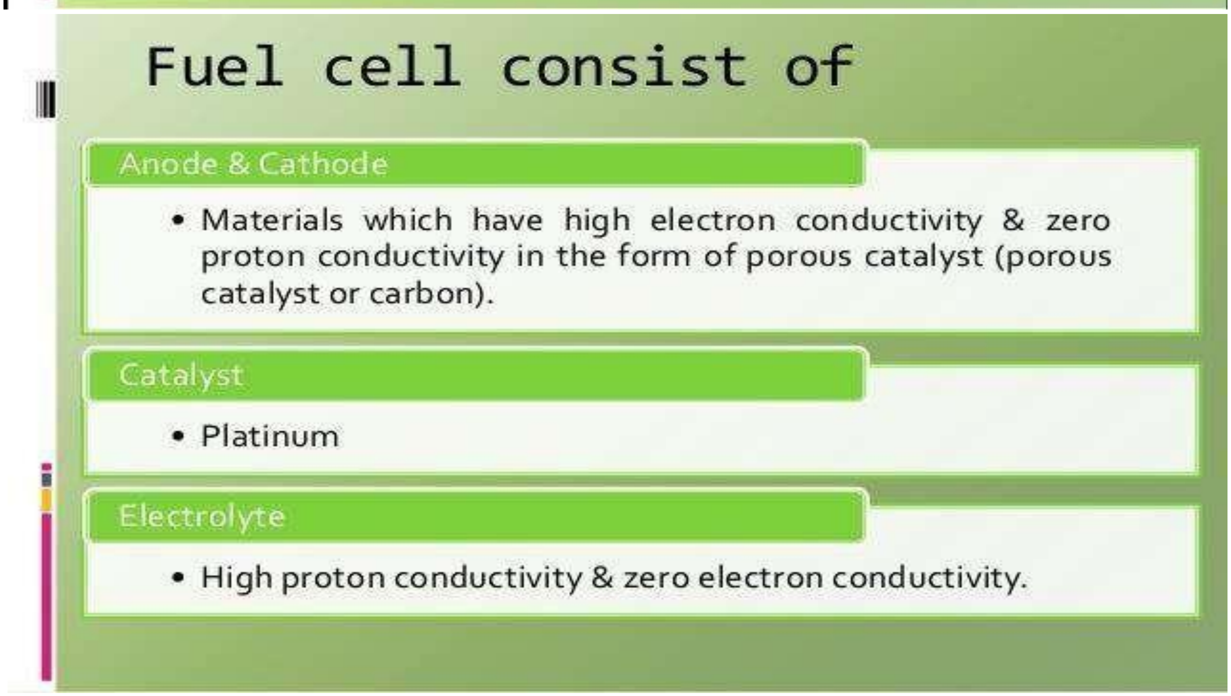





The process of fuel cell is
Fuel
Oxygen
Oxidation Products
Electricity

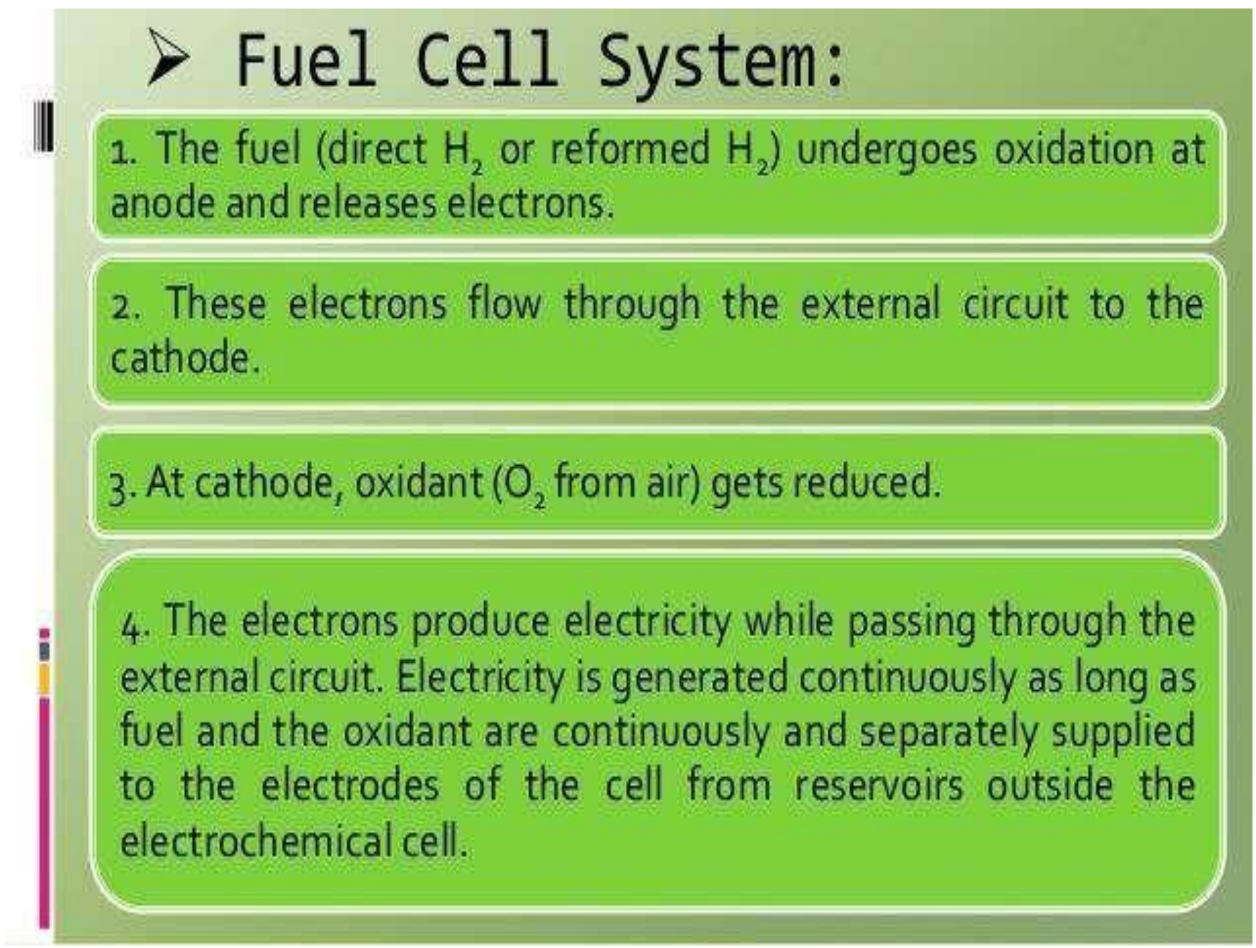

• The conventional process to produce electrical energy is as follows:
Chemical Energy
Heat
Mechanical Energy
Electrical Energy
• But in fuel cell, it directly coverts chemical energy to electrical energy.
• The efficiency of energy conversion in fuel cell approaches 70%. It is only 15-20% in gasoline powered engines and 30 – 35% in diesel engines.





Anode- Negative post of the fuel cell. Conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit. Etched channels disperse hydrogen gas over the surface of catalyst.

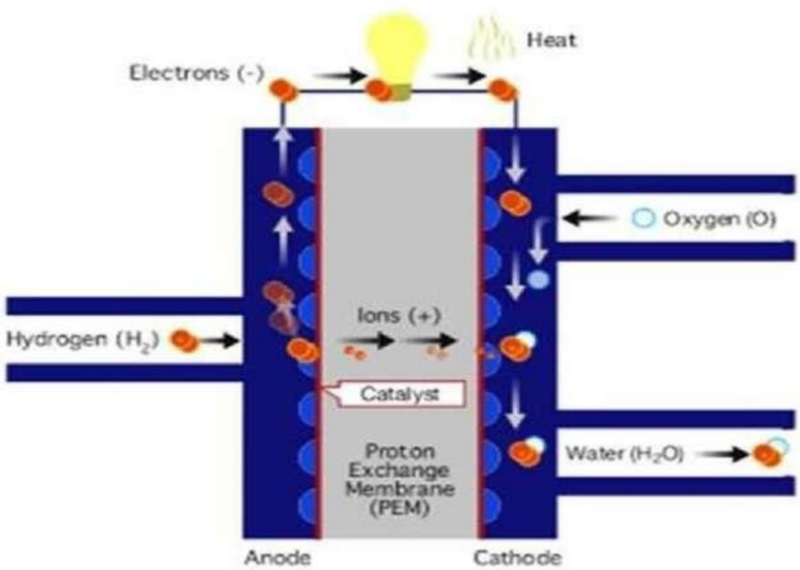
Cathode- Positive post of the fuel cell. Etched channels distribute oxygen to the surface of the catalyst. Conducts electrons back from the external circuit to the catalyst Recombine with the hydrogen ions and oxygen to form water.
Electrolyte- Proton exchange membrane. Specially treated material, only conducts positively charged ions. Membrane blocks electrons.
Catalyst- Special material that facilitates reaction of oxygen and hydrogen Usually platinum powder very thinly coated onto carbon paper or cloth. Rough & porous maximizes surface area exposed to hydrogen or oxygen The platinum-coated side of the catalyst faces the PEM.



WORKING

- ✓ A fuel cell generates electrical power by continuously converting the chemical energy of a fuel into electrical energy by way of an electrochemical reaction. The fuel cell itself has no moving parts, making it a quiet and reliable source of power. Fuel cells typically utilize hydrogen as the fuel, and oxygen (usually from air) as the oxidant in the electrochemical reaction. The reaction results in electricity, by-product water, and by-product heat.

- ✓ When hydrogen gas is introduced into the system, the catalyst surface of the membrane splits hydrogen gas molecules into protons and electrons. The protons pass through the membrane to react with oxygen in the air (forming water). The electrons, which cannot pass through the membrane, must travel around it, thus creating the source of DC electricity.



Classification of Fuel cell

I. Based on the type of electrolyte

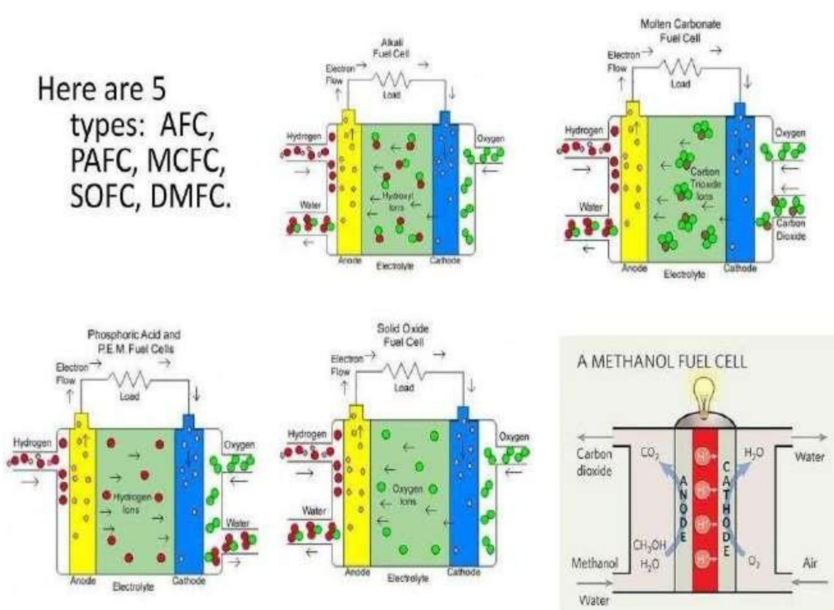
- ✓ Alkaline fuel Cell(AFC)
- ✓ Phosphoric acid Fuel Cell (PAFC)
- ✓ Polymer electrolytic membrane fuel cell (PEMFC)
- ✓ Molten Carbonate Fuel cell (MCFC)
- ✓ Solid oxide Fuel cell (SOFC)
- ✓ Direct methanol Fuel Cell (DMFC)
- ✓ Zinc-Air Fuel cell (ZAFC)
- ✓ Regenerative Fuel cell (RFC)

II. Based on operating temperature

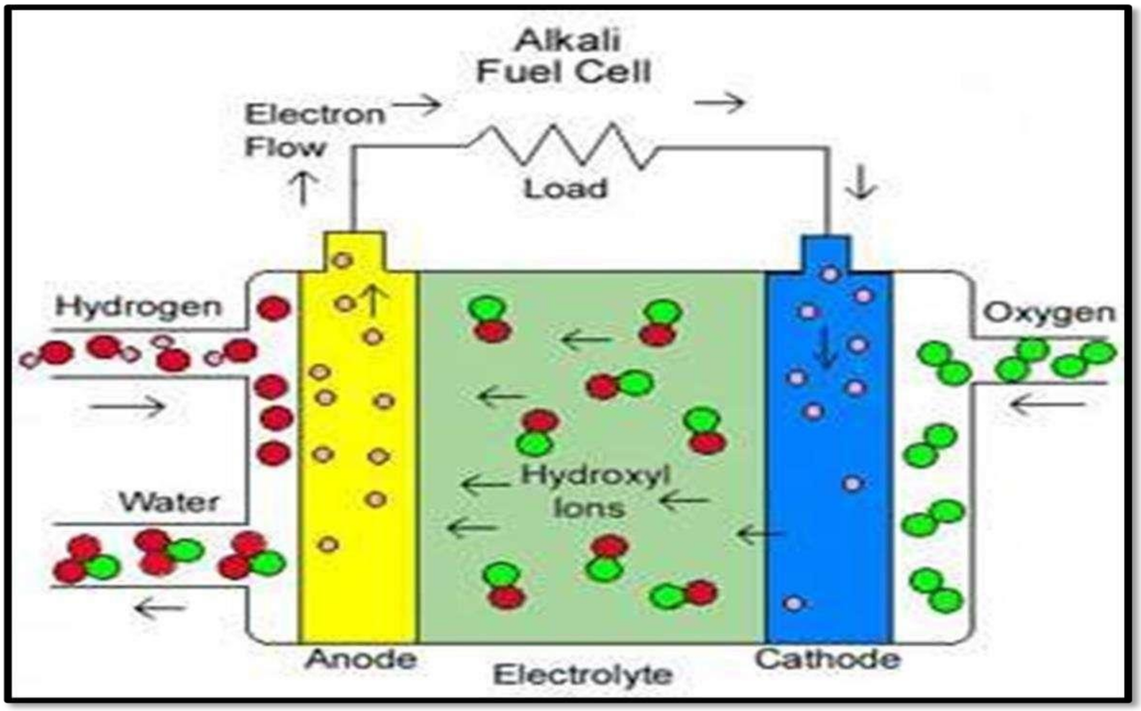
- ✓ Low temperature FC (25-100^{0}C)
- ✓ Medium temperature FC (100-500^{0}C)
- ✓ High temperature FC (500-1000^{0}C)
- ✓ Very high temperature FC (above 1000^{0}C)

III. Based on type of fuel & Oxidant

- ✓ Hydrogen –Oxygen FC
- ✓ Hydrogen – Air FC
- ✓ Hydrazine(N_2H_4)–Oxygen FC
- ✓ Ammonia- Air FC
- ✓ Synthesis gas –Air FC
- ✓ Hydrocarbon (gas)- Air FC
- ✓ Hydrocarbon (liquid) – Air FC



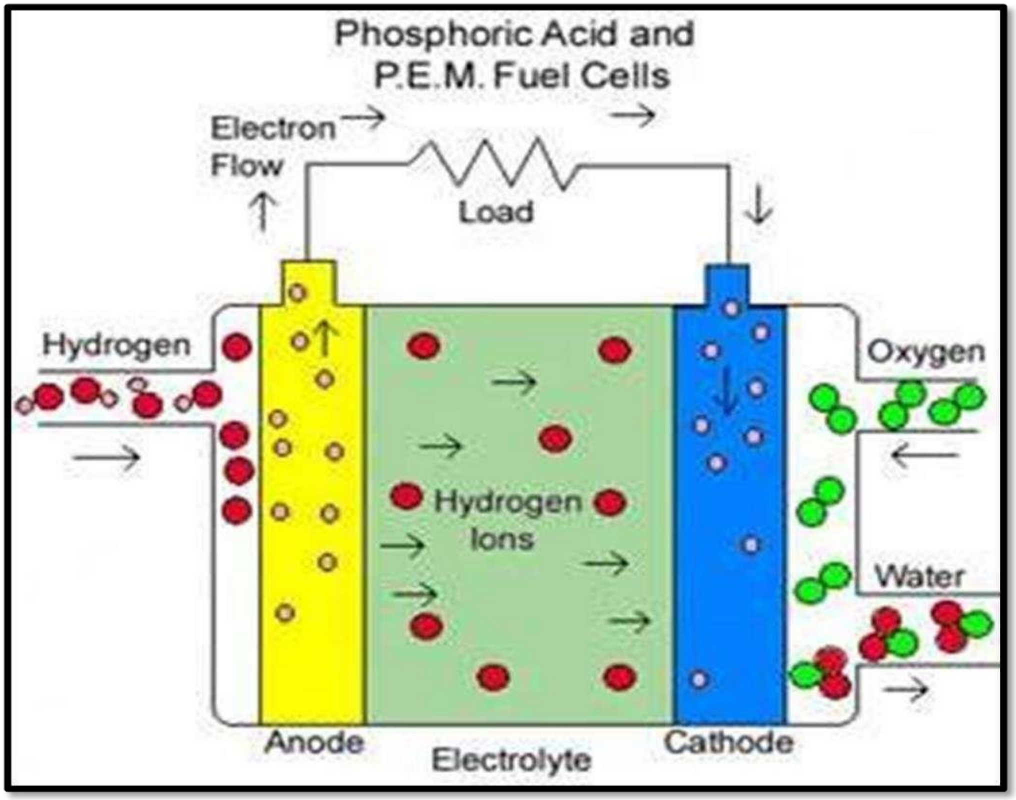
1.ALKALINE FUEL CELL



✓ This type of fuel cell was been introduced in the early 1960′s. As the electrolyte used for this device is aqueous alkaline solution like potassium hydroxide, the procedure for electricity consumption is rather expensive.

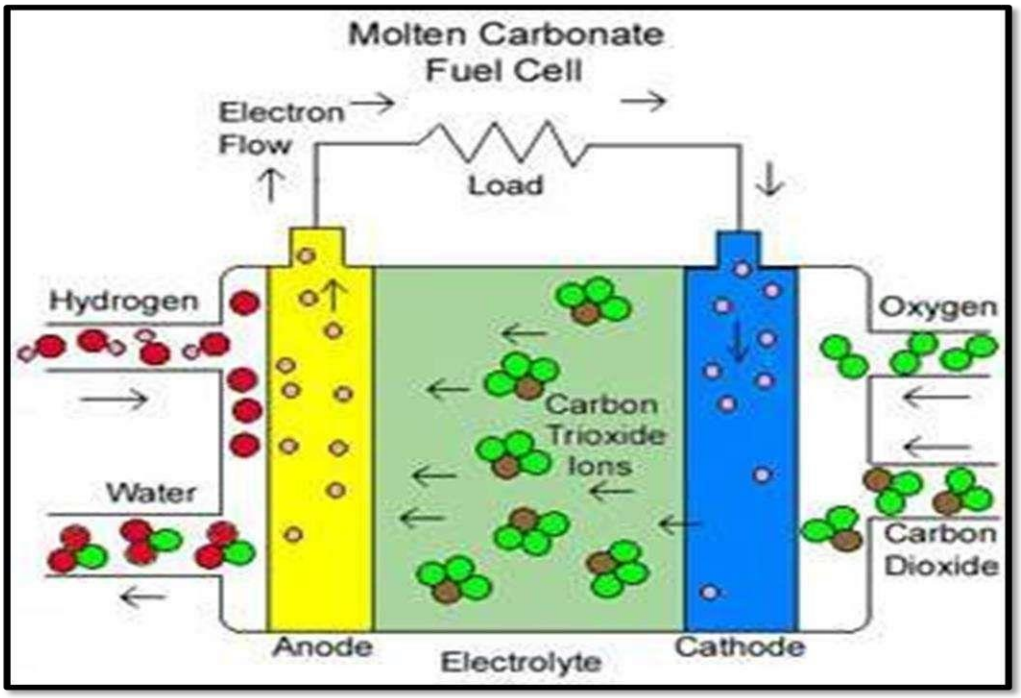
- **It has;**
  - ❖ compressed hydrogen and oxygen fuel.
  - ❖ potassium hydroxide (KOH) electrolyte.
  - ❖ ~70% efficiency.
  - ❖ 150˚C - 200˚C operating temp.
  - ❖ 300W to 5kW output requires pure hydrogen fuel and platinum catalyst.

2. PHOSPHORIC ACID FUEL CELL



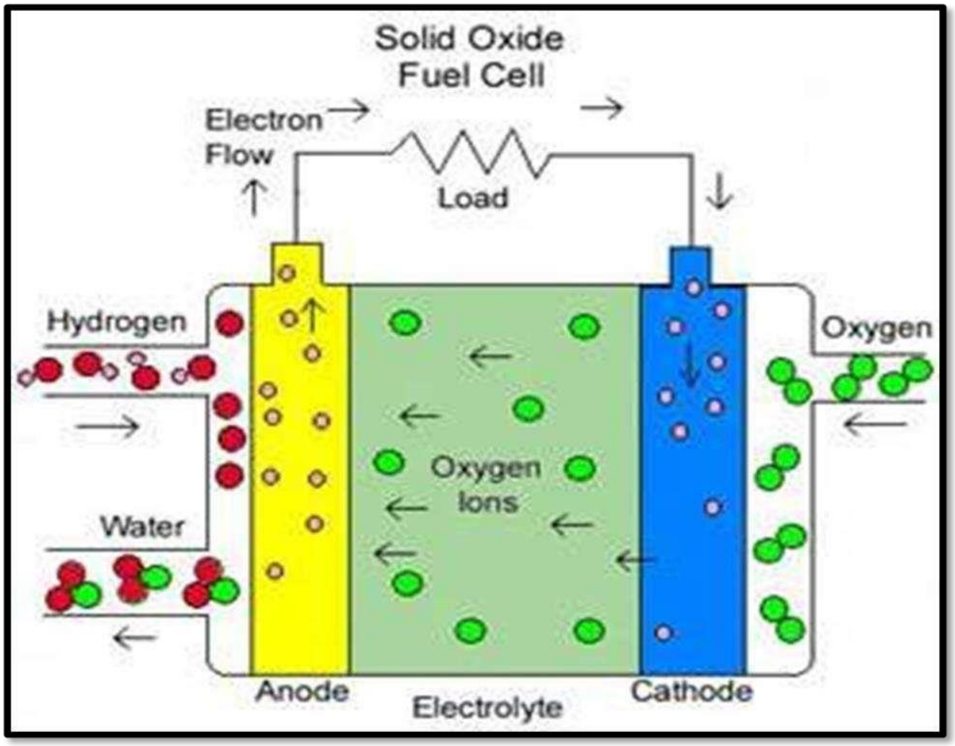
- ✓ Molten phosphoric acid is the electrolyte used in this type of fuel cell. It operates at high temperature up to 200 degree Celsius. It has an efficiency of up to 55%. This type of fuel cell is most commonly used in commercial cars.
- ✓ **It has;**
    - ❖ phosphoric acid electrolyte.
    - ❖ 40 – 80% efficiency.
    - ❖ 150˚C - 200˚C operating temp.
    - ❖ 11 MW units have been tested.
    - ❖ sulphur free gasoline can be used as a fuel.
    - ❖ The electrolyte is very corrosive.
    - ❖ Platinum catalyst is very expensive.

3.MOLTEN CARBONATE FUEL CELL



- ✓ Molten alkaline carbonate like sodium bicarbonate is used as the electrolyte.
- ✓ They can produce high powers up to 100 Mega Watts. Thus they can be used as high power generators.
- ✓ They can also be operated at high temperatures up to 650 degree Celsius.
- ✓ They are not so expensive in production and hence can be used for commercial uses.
- ✓ It has an efficiency of almost 55%.

4. SOLID OXIDE FUELCELL



- ✓ This is one of the most commercially used fuel cell as they have the highest operating life. It has a very high operating temperature of 1,000 degrees Celsius. But other parts of the fuel cell may not be able to withstand at this temperature making it highly unstable. But, when used in a continuous state they can be highly reliable. At high temperatures the device can produce water in the form of steam which can be easily transported through steam turbines to produce more electricity, thus increasing the efficiency of the system. This device is also special in the case where a wide variety of fuels can be used.
- ✓ Most of the petroleum products can be used as the fuel. The electrolyte used in the cell is called yttria stabilized zirconia (YSZ).

This electrolyte is good for large scale power generation and has the same characteristics as all the other electrolytes.

✓ As the device has a very high operating temperature, there are some disadvantages as well. There may be unwanted number of reactions taking place inside the cell due t the high temperature. As a result of these reactions carbon dust and also graphite may be built up on the anode making it insufficient from reacting with the catalyst.

Comparison of Fuel Cell Technologies

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	<1kW-100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10-100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	700-1000°C 1202-1832°F	1 kW-2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

TABLE I. COMPARISON OF FUEL CELL TYPES

Fuel Cell	Temperature (°C)	Fuel	Electrolyte	Uses	Electrical Efficiency (%)[1]
PEMFC	40-90	H_2 (~99%)	Polymer	Vehicles, small generators	40-60
AFC	40-250	H_2 (100%)	Potassium Hydroxide	Outer space	60-70
DMFC	60-130	Methanol	Polymer	Vehicles, small appliances	~ 40
PAFC	150-220	H_2 (~99%)	Phosphoric Acid	Power plants, combined heat & power	36-42
MCFC	600-700	CH_4, H_2, CO	Molten Carbonate	Power plants, combined heat & power	40-50
SOFC	600-100	CH_4, H_2, CO	Solid Oxide	Power plants, combined heat & power	50-60

Choice of Fuels for Fuel Cells

S.No.	Fuel	Voltage at $25^{0}C$
1	Hydrazine	1.61V
2	Carbon monoxide	1.29V
3	Hydrogen	1.23V
4	Methanol	1.21V
5	Ammonia	1.17V
6	Propane	1.09V

How Fuel Cell is different from Battery?

Hydrogen Fuel cell vs Battery

S No	Hydrogen Fuel Cell	Galvanic Cell (Battery)
01	Open system	Closed system
02	Anode and cathode are gases make contact with a platinum catalyst.	Anode and cathode are metals.
03	Reactants are externally supplied, no recharging required.	Reactants are internally conducted, require periodic recharging.

How Fuel cell is different from I.C Engine

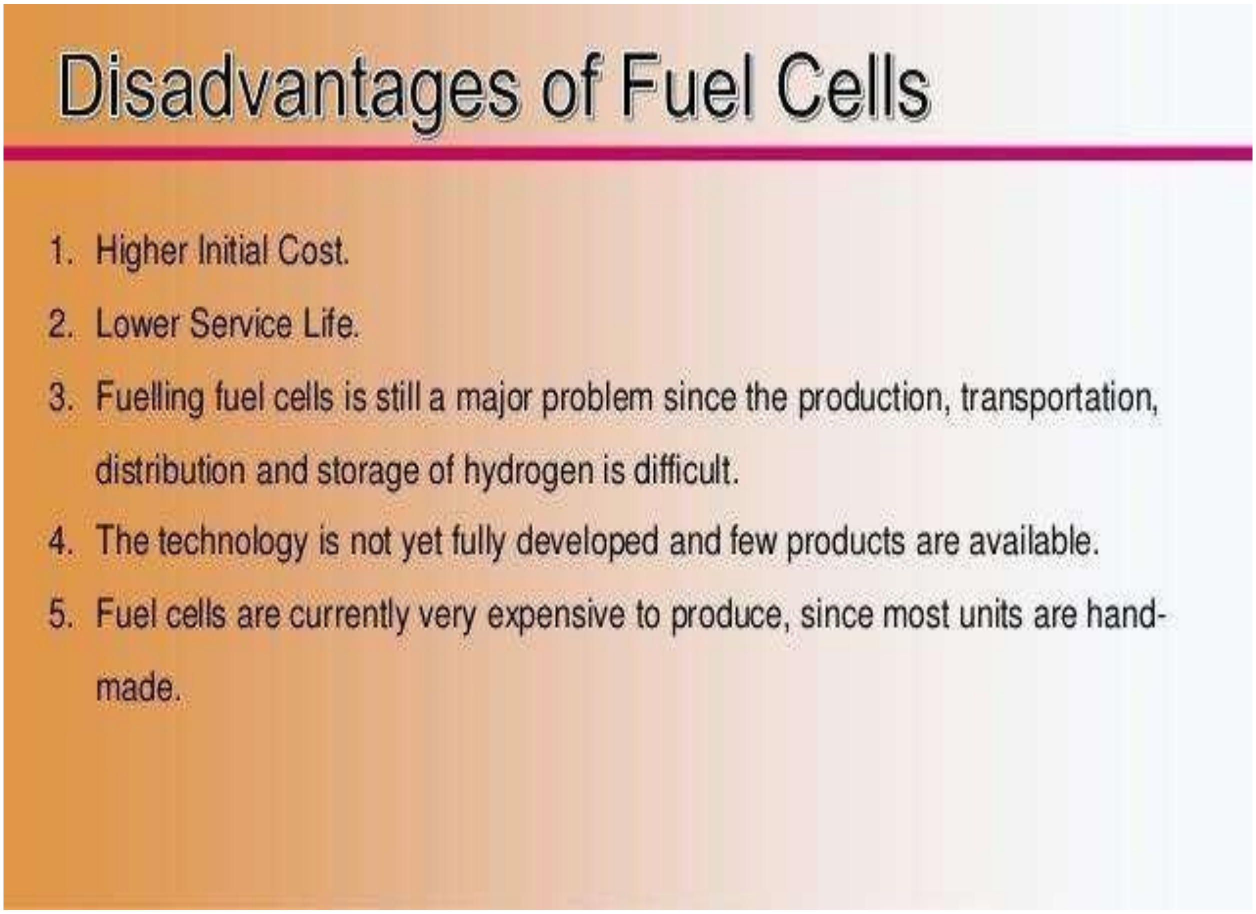
S No	Hydrogen Fuel Cell	IC Engine
01	Output is electrical work.	Output is mechanical work.
02	Fuel and oxidant respond electrochemically.	Fuel and oxidant reacts by the process of combustion.
03	Modest to nil pollution produced	Use of fossil fuels can generate considerable pollution.

Hydrogen Fuel Cell Efficiency

1. 40% efficiency generated, converting methanol to hydrogen in reformer
2. 80% of hydrogen energy content converted to electrical energy
3. 80% efficiency for inverter/motor – Converts electrical to mechanical energy
4. Overall efficiency of 24-32%

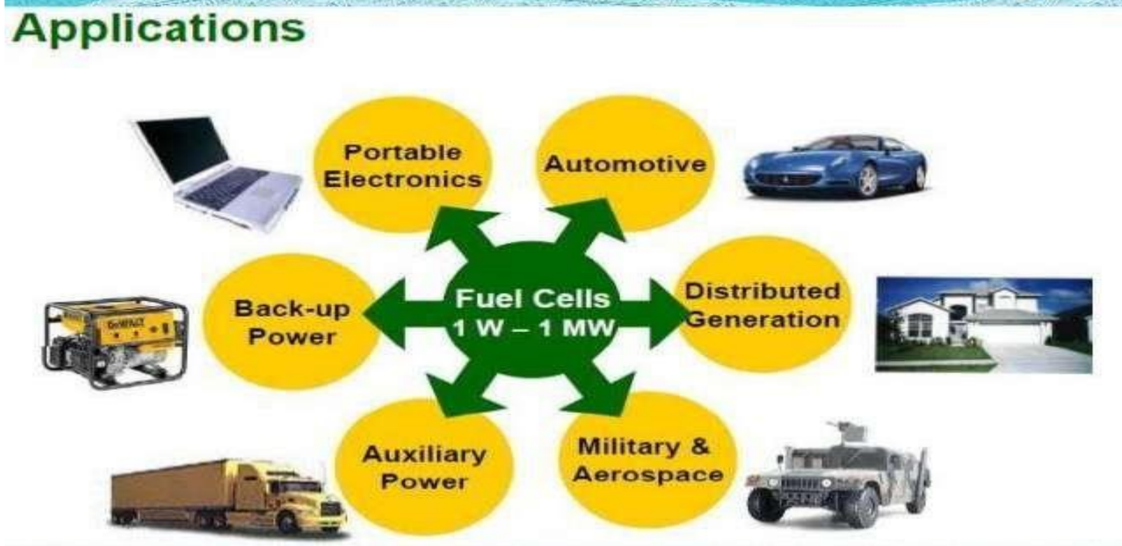
Advantages of Fuel Cells

1. Fuel cell system are ecofriendly.
2. High conversion efficiency .
3. Extremely low emission.
4. Noise less operations so readily accepted in residential areas.
5. Availability to use at any location. So less transmission & distribution losses.
6. No requirements of cooling tower as conventional plants.
7. Less space require as compared to conventional plants.



APPLICATIONS

- ✓ Can be used as power sources in remote areas.
- ✓ Can be used to provide off-grid power supplies.
- ✓ Can be applicable in both hybrid and electric vehicles.
- ✓ Waste water treatment plant and landfill.
- ✓ Cellular phone, laptop and computers.
- ✓ Hospitals, credit card centres and police stations.
- ✓ Buses, Car, Planes, Boats, Fork lift, Trains
- ✓ Vacuum cleaner.
- ✓ Telecommunication, MP3 players, etc.



Desirable Characteristics of Fuel cell

- ✓ It should have high conversion efficiency
- ✓ It should produce low chemical pollution
- ✓ It should be flexible to choose any fuel.
- ✓ It should have rapid load response
- ✓ It should be reliable

Conclusion