

Unit - 2

Solar Energy



Syllabus

- Solar Cells, Materials
- Solar Cells Power Plants
- Solar thermal energy
- Solar energy collectors
- Applications, Storage
- Solar Thermal Power Plants

Intro

- Solar Energy or Sun's energy is received in the form of radiation, that can be converted directly or indirectly into other forms of energy such as Heat or Electricity.
- Since the Sun will radiate its energy for at least a few billion years at almost constant rate, it is a **major source of energy**.
- **Major limitations** to extensive application of Solar energy are:
 1. It arrives at the Earth's surface in intermittent and variable manner.
 2. Requirement of very large area to collect the Sun's radiation.

Some Basics

- **Solar Constant:** “The rate at which solar energy arrives at the top of earth’s atmosphere is called as Solar Constant I_{sc} .”
- This is the amount of energy received in unit time at a unit area, perpendicular to the sun’s direction at the mean distance of the earth from the sun.
- Since the sun’s distance and activities varies throughout the year, the solar radiation also varies, so the solar constant is chosen as average value from which the actual values vary upto 3% in either direction.

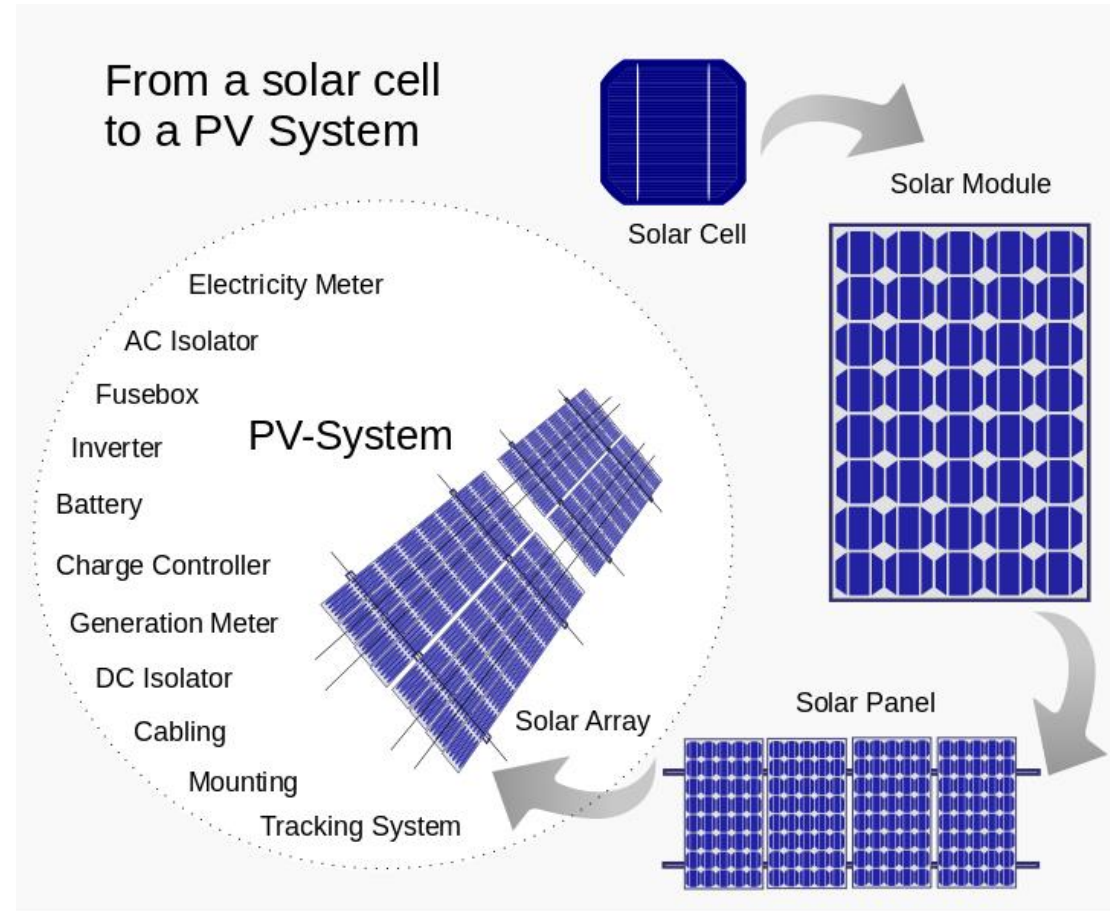
Some Basics

- The standard value of Solar constant according to NASA in different units are:
 - 1353 Watts per sq. m. or
 - 116.5 Langleys (Calories per sq. cm.) per hour or
 - 429.2 Btu per sq. feet per hour

Solar Cells

- A **Solar cell**, or **Photovoltaic cell**, is an electrical device that converts the energy of light directly into electricity by the **photovoltaic effect**, which is a physical and chemical phenomenon.
- When exposed to light, the electrical properties (e.g. resistance, current or voltage) of the PV cells are varied.
- A single junction Silicon solar cell can produce a maximum open circuit voltage of approx **0.5 – 0.6 volts**.
- To have higher ratings of voltage, current or power, many PV cells can be combined to form modules called as **Solar Panels**.

Solar Cells



Solar Cell Materials

- Solar cells are made up of **Semiconductors**, which generates free electrons when photons (light) are received. The free charges can then be collected at the contacts.
- One commonly used solar cell is **Silicon Solar Cell**, in which the crystal of Si is doped with impurity to form a semiconductor.
- The Si solar cells have efficiency of 12 – 15 %.
- Although Si is available in abundance in form of Sand (SiO_2), it is very difficult and expensive to extract Si from it. That's why Solar panels are expensive

Solar Cell Power Plant

- A **Solar Cell Power Plant** is based on the conversion of sunlight into electricity, either directly using photovoltaics (PV), or indirectly using *concentrated solar power (CSP)*.
- Concentrated solar power systems use lenses, mirrors, and tracking systems to focus a large area of sunlight into a small beam.

Solar Cell Power Plant

- Some large photovoltaic power plants in the world are:
 1. 2000 MW (52.5 km²), Shakti Sthala, Pavagada, Karnataka, India
 2. 1000 MW (23 km²), Kurnool Ultra Mega Solar Park in Andhra Pradesh
 3. 850 MW (25 km²), Longyangxia Dam Solar Park, China
 4. 648 MW (52.5 km²), Kamuthi, Tamil Nadu, India.
 5. 580 MW, Noor Complex is the world's largest concentrated solar power (CSP) plant, located in the Sahara Desert.

Solar Energy Collectors

- A **Solar Collector** is a device for collecting solar radiation and transferring the energy (heat) to a fluid (absorber) passing in contact with it.
- Types:
 1. Non-Concentrating or Flat plate type
 2. Concentrating or Focusing type

Solar Energy Collectors

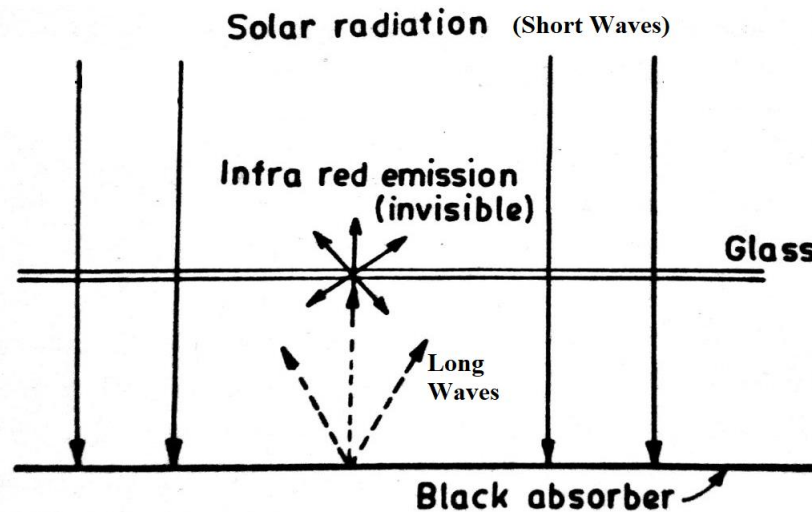
- In non-concentrating type collectors, the absorber area is same as the collector area. While in concentrating type the collector area is much bigger than the absorber area.
- By means of concentrating type collector much higher temperature can be obtained, which can be used to generate medium pressure steam.
- In concentrating type collector different types of mirrors and lenses are used to concentrate the sun's radiation.
- The concentrating type collectors have better efficiency.

Conversion of Solar energy into Heat

- The fundamental process of conversion of solar radiation into usable heat is based on the *Green House Effect*.
- Most of the Sun's energy comes to earth in form light of **short waves**, and not all of which are visible to human eye.
- When this radiation strikes any material (solid or liquid), the energy is absorbed by the material and it becomes warm.
- The material again re-radiates the energy as **long wave** radiation.
- **Glass** has a very useful property that, it can easily pass short waves but cannot pass long waves.

Conversion of Solar energy into Heat

- In a green house the sun light (short waves) enters through the glass and is absorbed by material inside it, which reradiates it as long waves, which are trapped inside by the glass. This is called as **Green House Effect**.



Conversion of Solar energy into Heat

- A **Black surface** has highest absorption rate and also highest emission coefficient for all wavelengths of light.
- The emission increases with temperature as T^4 .
- By **Wien's law**:
$$\lambda_{max} T = \text{Constant} = 2989 \mu m \text{ Kelvin}$$
- Here T = temperature of black surface
 λ_{max} = wavelength at which emission reaches maximum
- The Glass absorbs the infrared emission of black surface and re-emits it in all directions.

Conversion of Solar energy into Heat

- Half part of the infrared is emitted outside the glass and half is emitted towards black surface, which is again absorbed, accumulating more heat.
- Equilibrium is reached when energy gain by absorption of visible light is balanced by loss of energy by infrared emission.
- With rising temperature the wavelength of infrared emission becomes shorter, e.g. $6\mu\text{m}$ at 200°C , $4\mu\text{m}$ at 500°C etc.
- Hence the Green house effect is efficient only below 500°C .

Flat Plate Collectors

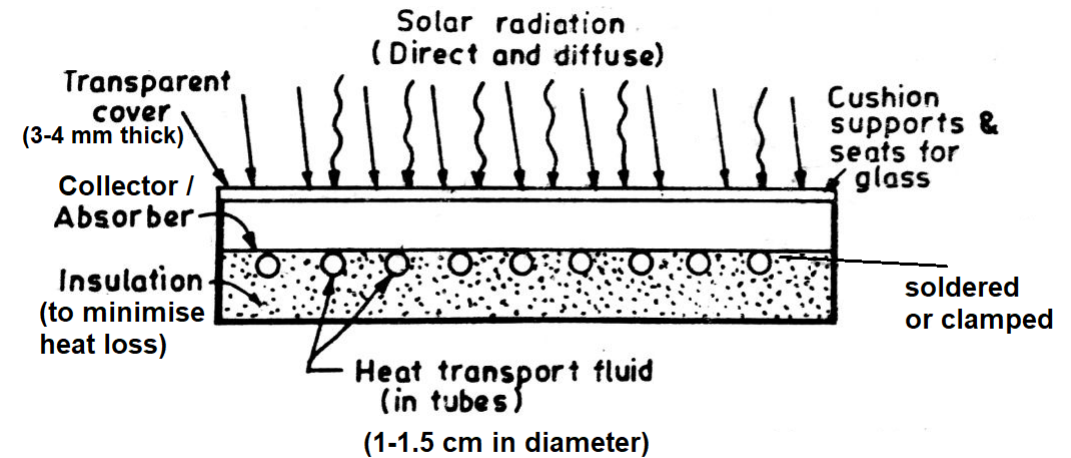
- When temperature below 90°C is sufficient, flat plate collectors are used.
- They are made up of flat rectangular panels of 1.7 – 2.9 sq.m. area, are easy to construct and erect. But they become less effective in absence of sufficient light such as in a cloudy day.
- Types:
 1. Liquid Heating Collectors
 2. Air or Gas Heating Collectors aka Solar Air Heaters

Flat Plate Collectors

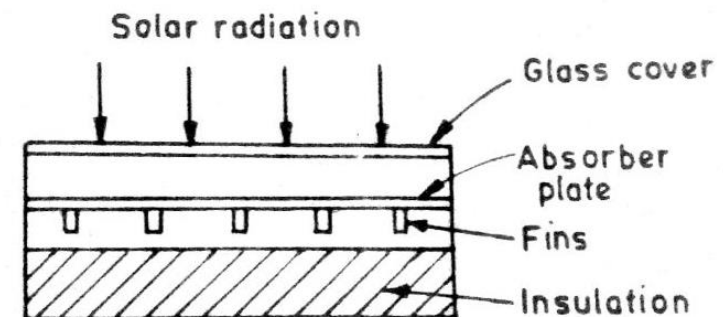
- There are five main components of any flat plate collector
 1. A transparent cover
 2. tubes or channels or fins for liquid or air flow
 3. The Absorber Plate
 4. Insulation
 5. The casing or container

Flat Plate Collectors

- Liquid Heating Collector



- Air Heating Collector



Flat Plate Collectors

- Advantages of Flat plate collectors:
 1. They have advantage of using both direct beam and diffused solar radiation.
 2. They do not require orientation towards sun.
 3. Requires less maintenance.
 4. Mechanically simpler in build as compared to the concentrating collectors.

Transmissivity of Cover System

- It is denoted by τ and the range is $0 < \tau \leq 1$.
- The transmissivity is a function of the wavelength and angle of incidence of the incoming solar radiation (like reflectivity ρ & absorptivity α).
- An opaque surface has $\tau = 0$ and a completely transparent surface has $\tau = 1$.
- The transmissivity in partially transparent (translucent) surface depends on both reflection and absorption, which makes its measurement difficult.

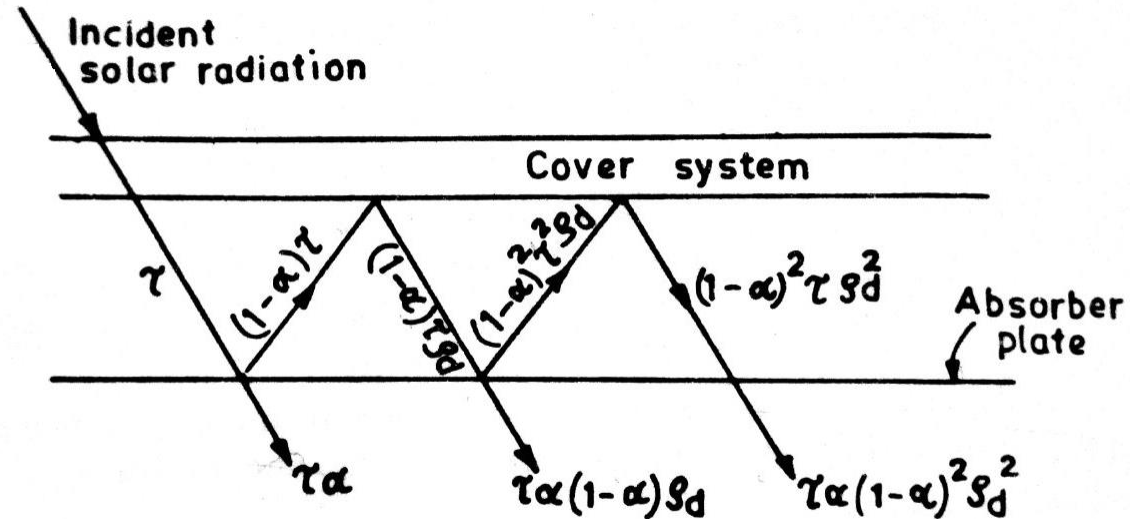
Transmissivity of Cover System

- This difficulty is overcome by:
- First, the transmissivity τ_p is calculated by considering only reflection.
- Then the transmissivity τ_a is calculated by considering only absorption.
- Now the transmissivity τ is given by: $\tau = \tau_p \tau_a$

Transmittance-Absorptance Product

- For solar collector analysis, it is necessary to evaluate the transmittance-absorptance product ($\tau.\alpha$).
- Some of the radiation passing through the cover and striking the plate, is reflected back to the cover, some part of which is again reflected back towards the plate.
- Def. – The transmittance-absorptance ($\tau.\alpha$) product is defined as the ratio of the radiation absorbed in the absorber plate to the radiation incident on the cover system.

Transmittance-Absorptance Product



- Here ρ_d refers to the reflection of the cover plate for diffused radiation.

Transmittance-Absorptance Product

- We can write the summation as:

$$\begin{aligned} \langle \tau\alpha \rangle &= \tau\alpha + \tau\alpha(1 - \alpha)\rho_d + \tau\alpha(1 - \alpha)^2\rho_d^2 + \tau\alpha(1 - \alpha)^3\rho_d^3 + \dots \\ &= \tau\alpha[1 + (1 - \alpha)\rho_d + (1 - \alpha)^2\rho_d^2 + (1 - \alpha)^3\rho_d^3 + \dots] \\ &= \tau\alpha \frac{1}{1 - (1 - \alpha)\rho_d} \\ &= \frac{\tau\alpha}{1 - (1 - \alpha)\rho_d} \end{aligned}$$

- Due to reflection $\langle \tau\alpha \rangle$ would be greater than $\tau.\alpha$
- For an incident angle of 60° , the ρ_d is approx. 0.16, 0.24, 0.29 for one, two & three glasses respectively.

Energy Balance Equation & Collector Efficiency

- The performance of a solar collector is described by an energy balance that indicates the distribution of incident solar radiation into useful energy gain and various losses.
- The thermal losses & their preventive measures are:
 1. Conductive Losses: An overall heat transfer coefficient value of less than $0.69 \text{ W/m}^2 \text{ }^\circ\text{K}$ is suggested to minimise conductive losses.
 2. Convective Losses: The air gap between the cover of 1.25 - 2 cm reduces internal convection losses. Vacuum between absorber and outer cover also reduces losses.

Energy Balance Equation & Collector Efficiency

3. Radiative Losses: to reduce these losses spectral selective absorber coating is used. Such coating have a high absorption of about 0.9 and a low emittance of about 0.1. Therefore these coatings decreases heat losses and increases collector efficiency.

- Under steady conditions:

$$\left(\begin{array}{c} \text{Useful heat} \\ \text{delivered by the} \\ \text{solar collector} \end{array} \right) = \left(\begin{array}{c} \text{Solar energy} \\ \text{absorbed in the} \\ \text{metal surface} \end{array} \right) - \left(\begin{array}{c} \text{heat losses from the} \\ \text{surface to the} \\ \text{surroundings} \end{array} \right)$$

Energy Balance Equation & Collector Efficiency

- This can also be stated as:

$$Q_u = A_c [HR(\tau \cdot \alpha)_e - U_L(t_p - t_a)]$$

where

- Q_u = useful energy delivered by the collector (watts or kCal/Hr)
- A_c = Collector Area (m^2)
- HR = solar energy received on upper surface of collector surface
- H = rate of incident beam or diffuse radiation on a unit area of upper surface

Energy Balance Equation & Collector Efficiency

- R = factor to convert beam or diffuse radiation on upper surface into that on collector plane
- The Beam and Diffuse Radiation are considered separately.

$(\tau.\alpha)$ for beam is determined from the actual angle of incidence.

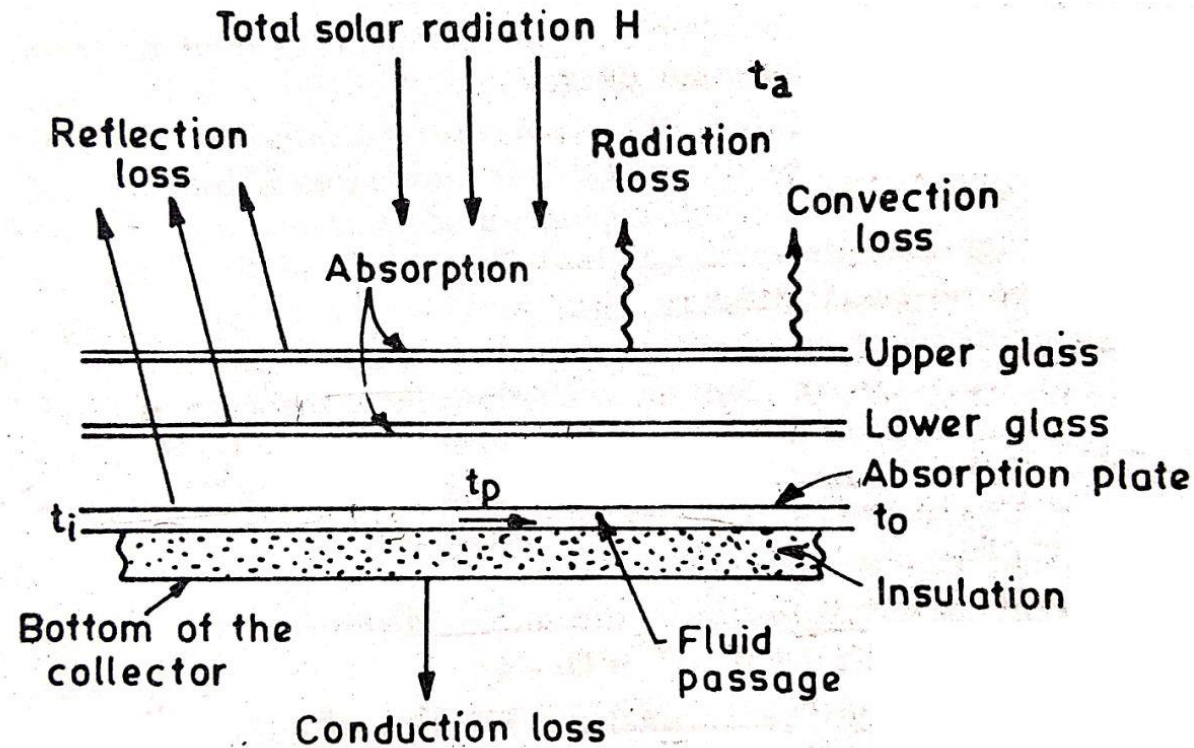
$(\tau.\alpha)$ for diffused radiation can be taken as beam radiation at an angle of 60° .

- τ = Transmissivity, i.e. the fraction of solar radiation that reaches the absorbing surface. (dimensionless)
- α = Absorptivity, i.e. the fraction of solar radiation that is absorbed. (dimensionless)

Energy Balance Equation & Collector Efficiency

- $(\tau.\alpha)_e$ = effective transmittance absorptance product of cover system for beam and diffuse radiation.
- U_L = overall heat loss coefficient ($\text{W/m}^2\text{ }^\circ\text{C}$ or $\text{kCal/Hr.m}^2\text{ }^\circ\text{C}$)
- t_p = average temperature of upper surface of absorber plate ($^\circ\text{C}$)
- t_a = atmospheric temperature ($^\circ\text{C}$)
- The **energy balance equation** can be represented graphically as:

Energy Balance Equation & Collector Efficiency



$$\text{Absorbed Energy} = A_c \cdot H R \cdot \tau \cdot \alpha$$

$$\text{Effective heat loss} = A_c U_L (t_p - t_a)$$

Energy Balance Equation & Collector Efficiency

- For good performance of a solar collector:
 1. the absorption in the plate $HR(\tau.\alpha)_e$ must be higher and the losses $(t_p - t_a)$ must be minimised.
 2. High quality transparent glass or plastic cover must be used which will allow maximum transmission of light through it.
 3. A second transparent cover, with air between the two covers can be used to further reduce the heat loss.
 4. Radiation losses can be reduced by reducing the radiation-emitting characteristics of the absorber.

Energy Balance Equation & Collector Efficiency

5. The thermal radiation emitted by absorber plate may be reduced by reflecting it downward from the lower glass cover by employing an infra-red reflection coating (of tin oxide or indium oxide) on the glass.
6. The collector efficiency also depends on ambient temperature, which can not be controlled and varies with time and geographical location.
7. A collector is more efficient with lower plate temperature, which can be controlled by the fluid circulation beneath it.

Energy Balance Equation & Collector Efficiency

- The energy balance equation on the whole collector can be written as:

$$Q_u + Q_l + Q_s = A_c [HR(\tau.\alpha)_b + HR(\tau.\alpha)_d]$$

- Where b is used for Beam and d of diffused radiation
- Q_u = Rate of useful heat transfer to the fluid
- Q_l = Rate of energy loss from the collector to the surroundings by re-radiation, convection and by conduction through supports for the absorber plate etc.
- Q_s = rate of energy storage in the collector.

Energy Balance Equation & Collector Efficiency

- **Collector Efficiency (η_c):** It is the measure of collector performance and is defined as the ratio of useful gain over any time period to the incident solar energy over the same time period. And is given by:

$$\eta_c = \frac{\int Q_u dT}{\int HR dT}$$

Concentrating Collector (Focusing type)

- In these collectors the radiation falling on a relatively large area is focused into an absorber of smaller area by using reflectors and or refractors (mirrors, lenses).
- It increases the radiation upto 10000 times and the temperature of the fluid in the receiver can go upto 500 °c.
- Certain losses are introduced such as losses due to cover system, reflection & absorption losses, geometrical imperfections in the optical system etc.
- The combined effect of all losses is indicated through **Optical Efficiency**.

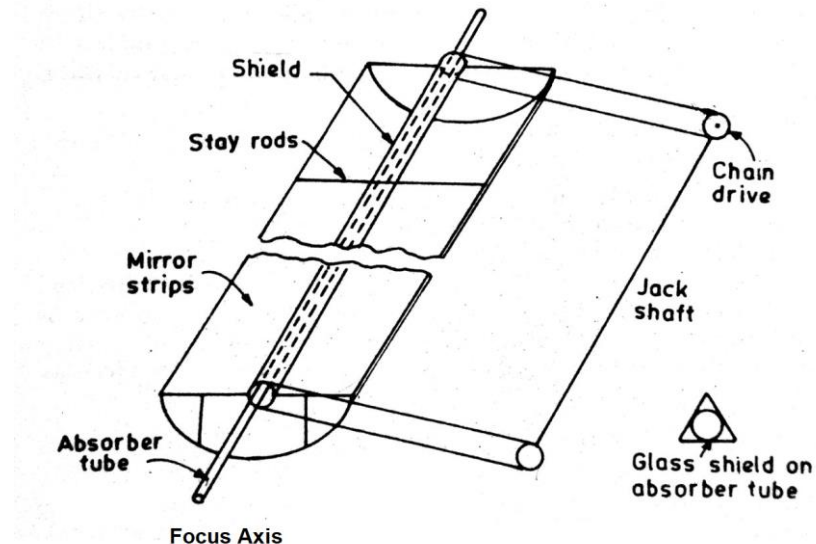
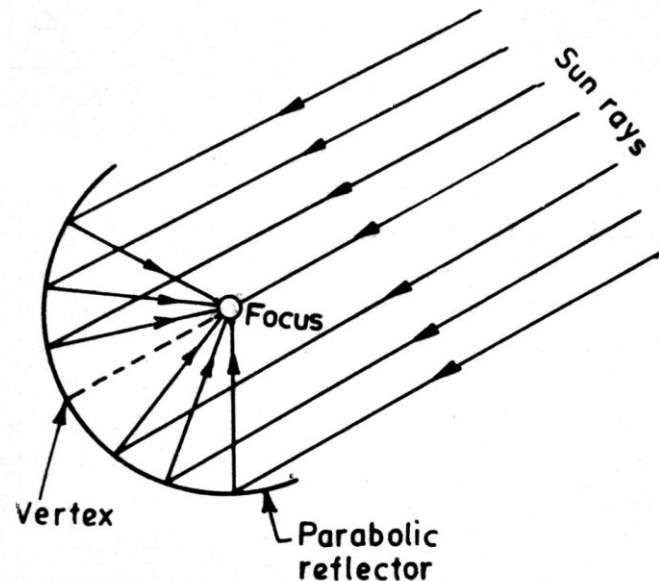
Concentrating Collector

- Two broad categories are:
 1. Line focusing type
 2. Point focusing type
- On the basis of geometry of collector the main types are:
 1. Parabolic trough collector
 2. Mirror strip reflector
 3. Fresnel Lens collector
 4. Flat plate collector with adjustable mirrors
 5. Compound Parabolic Concentrator (C.P.C.)

Line Focusing Collector –

1. Parabolic Trough Collector

- Solar radiation coming from a particular direction is collected over the area of reflecting surface & is concentrated at the focus of parabola.
- If the reflector is in form of trough with parabolic cross-section, the solar radiation is focused along a line.



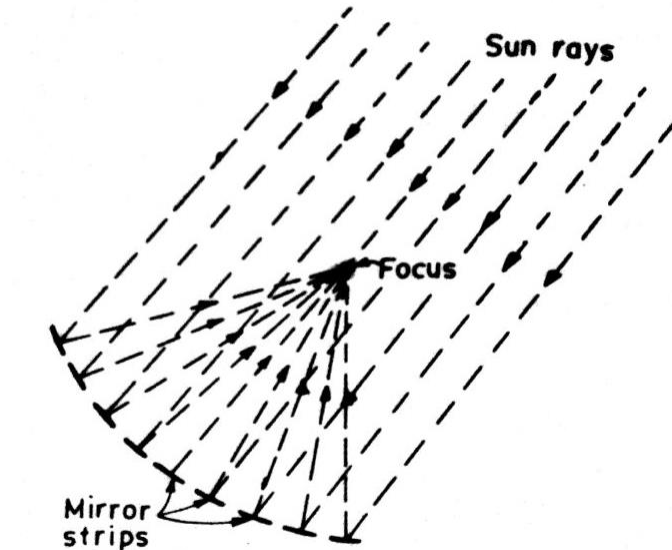
Line Focusing Collector –

1. Parabolic Trough Collector

- Aka Cylindrical parabolic collector.
- The collector pipe (absorber) is placed along the focus axis.
- The dimensions are: length of reflector unit is about 3-5 m and width is about 1.5-2.4 m.
- 10 or more such units are connected in series, end to end, in a row and several rows are connected in parallel.
- Since it can collect solar radiation of a particular direction only, it must be rotated towards the Sun as it changes its position.

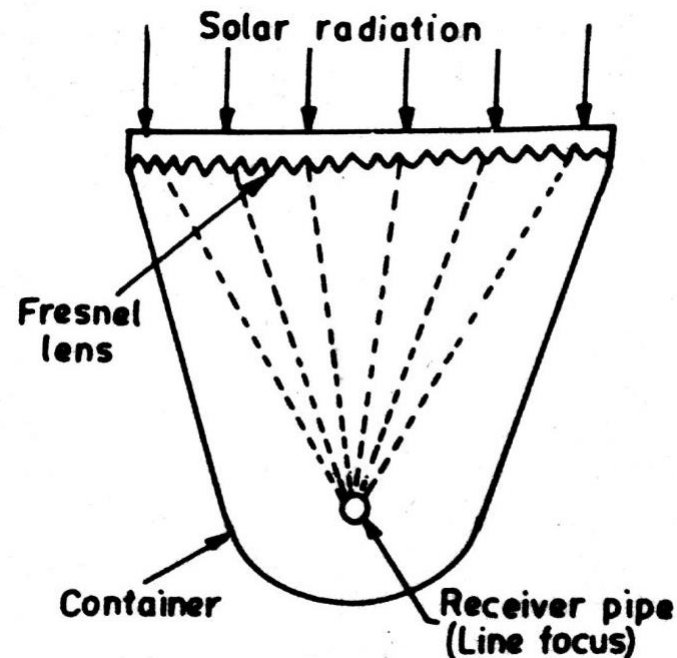
2. Mirror-Strip Reflector

- In this a number of plane or slightly curved (concave) mirror strips are mounted on a flat base.
- Similar to parabolic trough collector, here also the radiation coming from a particular direction is collected and is focused on a line.



3. Fresnel Lens Collector

- It utilises refraction property of light.
- A Fresnel lens is used to focus the radiation. The collector can be either a point or a line

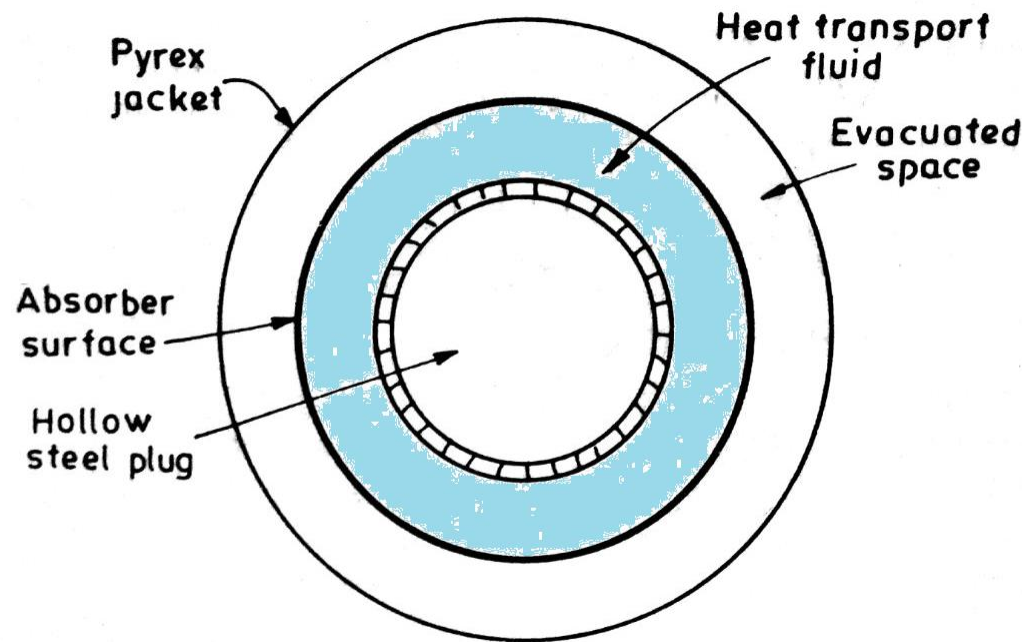


3. Fresnel Lens Collector

- Dimensions: Length = 4.7m, Width = 0.95m.
- To be fully effective the lens must be continuously aligned with the Sun.

Receiver Pipe for Line focusing collectors

- Fig. shows the cross-sectional view of line focusing collector's receiver pipe:



Receiver Pipe for Line focusing collectors

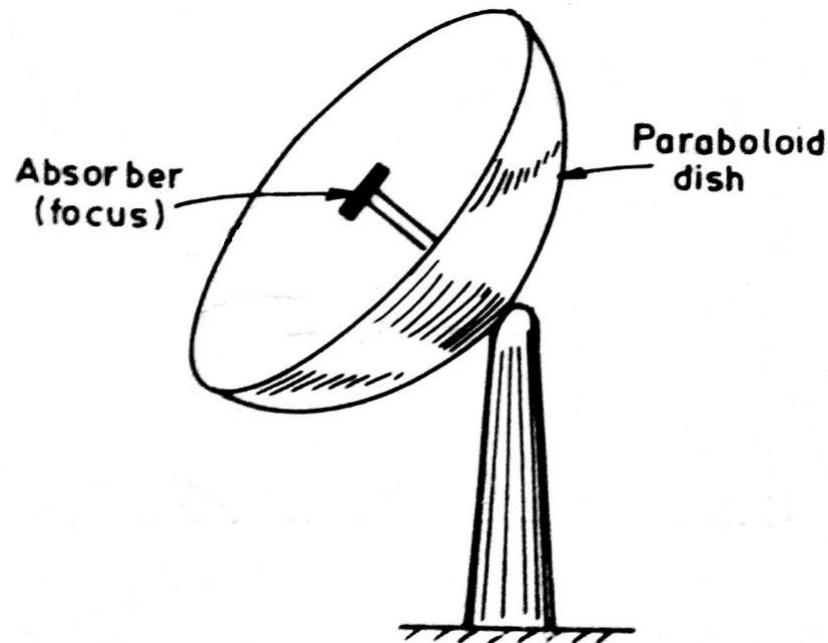
- It has the same general characteristics as that of flat plate collector.
- The solar radiation absorber is the central steel pipe with treated surface.
- An insulated hollow steel plug is at the centre to prevent heat loss from the fluid.
- The absorber pipe is enclosed in a glass jacket, in order to prevent losses by convection and radiation. This space between glass and absorber plate is evacuated (vacuum) to reduce convection loss.

Receiver Pipe for Line focusing collectors

- The diameter of glass jacket is about 5 cm and that of steel absorber is 3 cm. The gap for liquid flow may be as low as about 2.5 mm.
- In Fresnel lens collector, the solar radiation is focused onto the collector surface from top, rather than from bottom as in parabolic reflector type collector.

Point Focusing Collector

- A paraboloid dish is used to focus the solar radiation to a point (a small volume).
- General dimension: diameter of dish = 6.6m



Point Focusing Collector

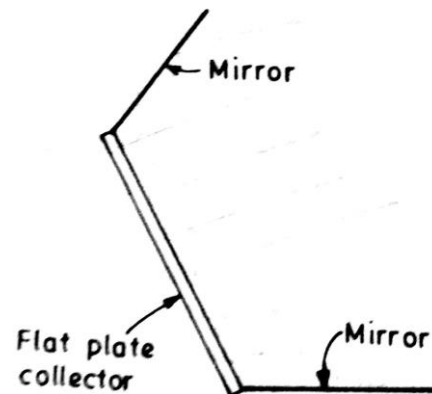
- The dish is fitted with about 200 curved mirror segments forming a paraboloidal surface.
- The absorber located at the focus is a cavity made-up of Zirconium-Copper (Zr-Cu) alloy with a black coating.
- The heat carrying fluid flows in & out of absorber cavity through pipe.
- The dish can be rotated up-down or left-right in order to align it towards the Sun.
- The paraboloidal dish has very high concentration ratio, so it is more efficient.

Point Focusing Collector

- **Concentration Ratio:** It determines the effectiveness of the concentrator and is defined as the ratio of the area of concentrator aperture to the energy absorbing area of the receiver.
- Out of all concentrators, the paraboloidal system has highest concentration ratio, of the order of 10000.

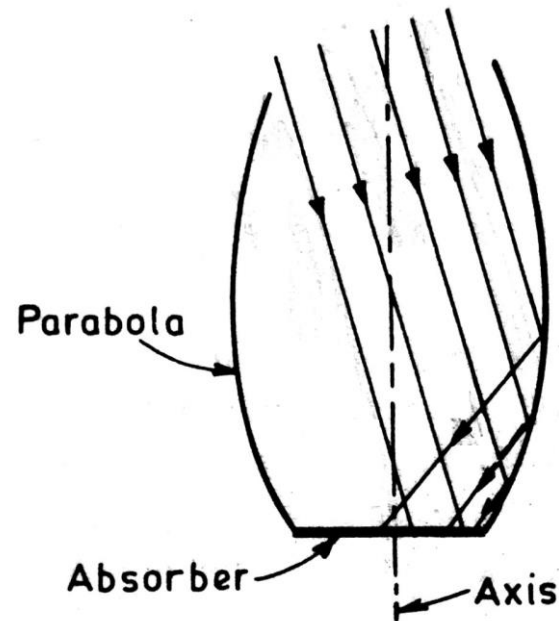
Concentrating Collector – Non-focusing type

- The simplest type of concentrating collector is the mirror-boosted, flat plate collector.
- It consists of a flat plate facing south with mirrors attached to its north & south edges.
- The mirrors are to be set at proper angles so that reflected radiations falls on absorber plate.



Compound Parabolic Concentrator (CPC)

- Aka Winston Collector.
- This is a trough like arrangement of two parabolic mirrors which are facing each other.



Compound Parabolic Concentrator (CPC)

- The CPC is a non-focusing collector, but solar radiation from all directions is reflected towards the bottom of the trough, where the absorber is placed.
- Because of this characteristics, direct beam as well as diffused radiation falls onto the absorber.
- CPC can be designed for any absorber shapes, e.g.
 1. Flat one sided absorber
 2. Flat two sided absorbers (fin)
 3. Tubular absorber etc.

Compound Parabolic Concentrator (CPC)

- Advantages:
 1. There is no need of tracking, as it has high acceptance angle. Only seasonal adjustments are required.
 2. The efficiency for accepting diffuse radiation is much higher than the conventional concentrators.
 3. Its concentration ratio is equal to the max value possible for a given acceptance angle.

Advantages of Concentrating Collectors over Flat-Plate Collectors

1. Reflecting surfaces required less material, and is structurally simpler than the flat-plate collectors. Also the cost per unit area of solar collecting surface is less than that for flat-plate collector.
2. The absorber area of a concentrating collector is smaller than that of flat-plate collector for same energy collection.
3. The working fluid can attain higher temperature in concentrating collectors, because the area from where heat loss occurs is smaller.

Advantages of Concentrating Collectors over Flat-Plate Collectors

4. The selective area treatment and vacuum insulation to reduce the heat loss are more economical in concentration collectors.
5. Concentrating type collectors can be used to generate electricity when they are not being used for heating. Therefore their total operating time is also higher.
6. The temperature attainable with concentrating collectors is higher, the amount of heat which can be stored per unit volume is also higher and so the heat storage cost is less.

Advantages of Concentrating Collectors over Flat-Plate Collectors

7. Concentrating collectors have higher efficiencies
8. Little or no anti-freeze is required to protect the absorber in concentration system, whereas entire absorber surface in flat-plate type requires anti-freeze protection.

Disadvantages of Concentrating Collectors over Flat-Plate Collectors

1. Out of the Beam & Diffused solar radiations only beam component is collected in concentrating collectors because diffuse component can not be reflected and is eventually lost.
2. Concentrating collectors requires more costly Sun tracking systems.
3. Requires more maintenance for reflecting surface against dirt, weather, oxidation etc.
4. Concentration collectors have non-uniform flux on absorber.

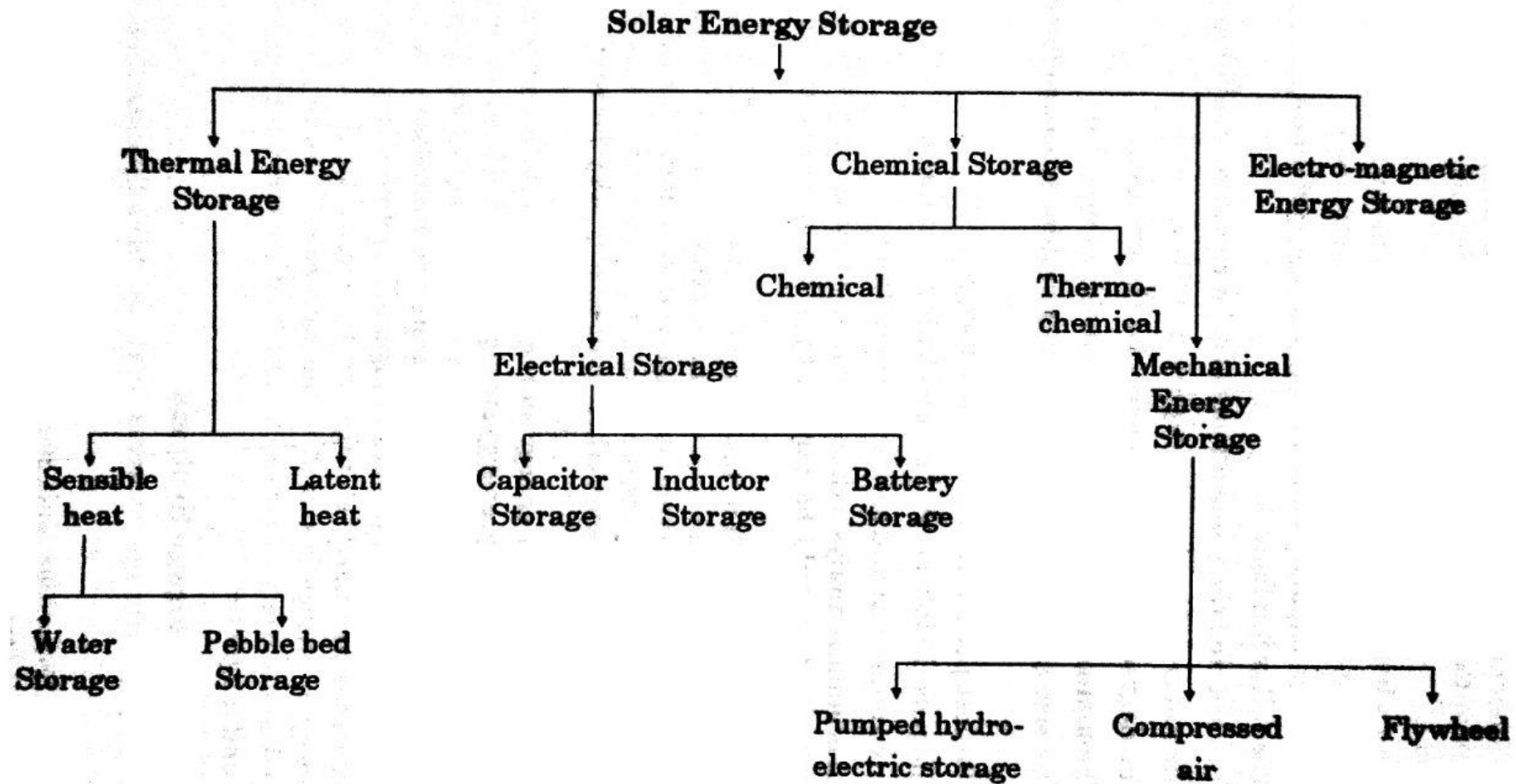
Disadvantages of Concentrating Collectors over Flat-Plate Collectors

5. They have additional optical losses such as reflection loss, intercept loss etc. so more terms appear in the energy balance equation.
6. Higher initial cost.

Solar Energy Storage

- The supply of solar energy is not continuous and varies with time.
- The demand of energy is also not continuous and varies with time. In-fact the demand times may be very different from the supply times.
- So there is need of storage of energy, so that it may meet the demand whenever needed.

Solar Energy Storage



Solar Energy Storage

The solar energy storage systems can be divided into 5 categories:

1. Thermal
2. Electrical
3. Chemical
4. Mechanical
5. Electromagnetic

Solar Energy Storage

Suggested study:

- Why do we need to store solar energy?
- What are the factors in which the optimum capacity of solar energy storage system depends?

1. Thermal Storage

- The energy can be stored by Heating, Melting or Vaporization of materials.
- When the process is reversed, the energy becomes available as **Heat**.
- **Sensible Heat Storage:** Storage causing a material to rise in temperature.
- **Latent Heat Storage:** Storage by phase change (from solid to liquid or liquid to vapour). In this no temperature change is involved.
- It is possible to occur both sensible and latent heat storage to happen in the same material.

1. Thermal Storage

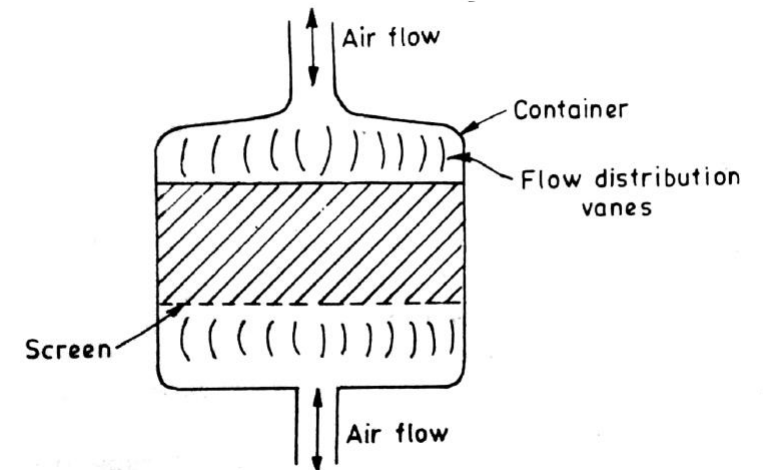
- Applications of thermal energy storage may include TPP, heating of water, house, office, other process industries etc.
- Materials used for thermal storage are water, salts and rocks.
- Glauber's Salt ($Na_2SO_4 \cdot 10H_2O$) is least expensive and readily available salt.
- For high temperature storage (200-300°C) MgO and CaO are used.

1. Thermal Storage

- **Sensible Heat Storage:** It involves use of a material which does not goes under phase change with change in temperature.
- The basic equation for an energy storage unit, operating over a finite temperature difference is:

$$Q_s = (mC_p)_s (T_1 - T_2)$$

Where: Q_s = Energy storage capacity
 T_1 & T_2 = temperature limits
 m = weight of material in kg
 C_p = Specific heat



1. Thermal Storage

- The ability to store thermal energy in a given container of volume V is given by:

$$\frac{Q_s}{V} = \rho C_p \Delta T$$

- Where ρ is density of storage medium.
- Thus the ability to store thermal energy depends upon the product ρC_p , which is highest for water.
- Other materials used are: Rock, gravel or crushed stones, Concrete, Iron, Iron Ore, Magnesium Oxide, Aluminium Oxide, Silica Oxide etc.

1. Thermal Storage

- **Latent Heat Storage:** Materials that undergo a change in phase in a suitable temperature range is used.
- In this system, heat is stored in the material when it melts and extracted from material when it freezes.
- Materials used are Water, Glauber's Salt ($Na_2SO_4 \cdot 10H_2O$), $Fe(NO_3)_2 \cdot 6H_2O$, etc.



2. Electrical Storage

- The Capacitors and Inductors store energy.
- Batteries store the energy and delivers in electrical form.
- Energy stored in Capacitor is given by

$$H_{cap} = \frac{1}{2} V \epsilon E^2$$

- Where V = volume of dielectric
 E = electric field strength
 ϵ = permittivity of material (constant)

2. Electrical Storage

- The electric field strength is limited by breakdown strength E_{br} of the dielectric, and therefore the electrical energy storable is also limited.
- Mica is generally used dielectric material.
- At present capacitive storage is only economical for times no longer than 12 hours.
- More research is needed to make the capacitors suitable for energy storage.

2. Electrical Storage

- While the capacitors store energy at high voltage & low current, the inductors store energy at low voltage & high current.
- The energy stored by an Inductor is given by:

$$H_{ind} = \frac{1}{2} V \mu H_m^2$$

Where H_m = magnetic flux density
 μ = permeability of the material (constant)

2. Electrical Storage

- Battery: A battery is a combination of individual cells. A cell is the elemental combination of materials & electrolyte constituting of the basic electrochemical energy storer.
- Battery storage can also be included in the Chemical Storage category.
- The primary batteries are non rechargeable but the secondary batteries are rechargeable.
- Examples of secondary batteries are: lead-acid, Nickel-Cadmium, Nickel-Hydrogen etc.

2. Electrical Storage

- A generalised cell consists of two electrodes called Anode and Cathode, immersed in suitable Electrolyte.
- When an electric load is connected across the electrodes, charge separation occurs at the interface between the electrode and electrolyte.
- The electrons flow through the external load and the ions through the electrolyte, recombining at the other electrode.

2. Electrical Storage

- Energy efficiency of a battery is defined as

$$\eta_{energy} = \frac{\int_0^{t_1} I_1 E_1 dt}{\int_0^{t_2} I_2 E_2 dt}$$

Where

- I_1 = Battery discharge current
- E_1 = Battery discharge terminal voltage
- t_1 = Battery discharge time
- I_2 = Battery charging current
- E_2 = Battery charging terminal voltage
- t_2 = Battery charging time

2. Electrical Storage

- Two special cases of above equation are possible.
- First, when the charging and discharging occurs at constant voltage, then

$$\eta_{energy} = \frac{E_1 \int_0^{t_1} I_1 dt}{E_2 \int_0^{t_2} I_2 dt} = \frac{E_1 \times \text{Amp. Hr. Output}}{E_2 \times \text{Amp. Hr. Output}}$$

- Second, when the charging and discharging occurs at constant current, then

$$\eta_{energy} = \frac{I_1 \int_0^{t_1} E_1 dt}{I_2 \int_0^{t_2} E_2 dt}$$

2. Electrical Storage

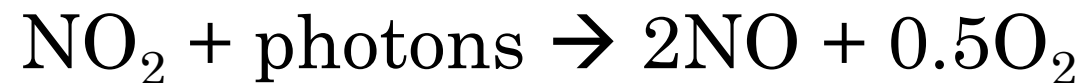
- Battery Cycle Life: It is the number of times the battery can be charged and discharged under specified conditions.
- The cycle life of a battery highly depends on the Depth of Discharge (DOD). The harder the battery works, the sooner it will fail. It means, higher capacity withdrawal would result in reduction in life cycle.
- Temperature is another major factor in battery performance. At higher temperatures there is dramatically more chemical activity inside a battery than at lower temperatures. Therefore, the capacity of a battery is lower when the ambient temperature is too low.

3. Chemical Storage

- a) Storage in form of fuel
- b) Thermo-Chemical storage
- c) Hydrogen storage

3. Chemical Storage

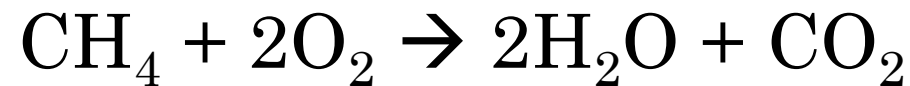
- **Storage in form of fuel:** It is possible to device a storage battery, in which the reactant is generated by a photochemical reaction, caused by solar radiation.
- In this, the battery is charged photo-chemically and discharged electrically.
- Some reactions for this purpose are:



etc.

3. Chemical Storage

- It is also possible to electrolyze the water with solar energy and store the H₂ and O₂, and later recombine them in a fuel cell to regain electrical energy.
- Solar energy can also be used for fermentation of algae for production of Methane (CH₄). Methane is a stable fuel in room temperature and it reacts with O₂ when burnt releasing solar energy in thermal form.



- Photosynthesis is another method of solar energy conversion.



3. Chemical Storage

- **Thermo-Chemical Energy Storage:** These are reversible chemical reactions, and are suitable for medium & high temperature applications.
- Advantages of these systems includes high energy density storage for long periods without thermal losses, and is transportable for long distances.
- This type of storage is represented by a hypothetical relation:



Topics for self study

- Mechanical Storage
- Electromagnetic Storage
- Solar Pond

End of Unit – 2