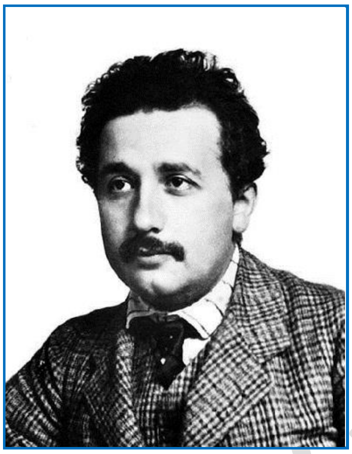
D.R.G.Government Degree College

Tadepalligudem, West Godavari District



V Semester
Domain Subject: PHYSICS
Skill Enhancement Course (Elective)

Solar Energy and Applications

Study Material
(English Medium)

Prepared by
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B Sc	Semester V (Skill Enhancement Course -Elective)	Credits: 4
Course: 7B	Solar Energy and Applications	Hrs/Wk: 4

Learning Outcomes: After successful completion of the course, the student will be able to:

1. Understand Sun structure, forms of energy coming from the Sun and its measurement.
2. Acquire a critical knowledge on the working of thermal and photovoltaic collectors.
3. Demonstrate skills related to callus culture through hands on experience
4. Understand testing procedures and fault analysis of thermal collectors and PV modules.
5. Comprehend applications of thermal collectors and PV modules.

Syllabus: *(Total Hours: 90 including Teaching, Lab, Field Training, Unit tests etc.)*

UNIT I: BASIC CONCEPTS OF SOLAR ENERGY (10HRS)

Spectral distribution of solar radiation, Solar constant , zenith angle and Air-Mass, standard time, local apparent time, equation of time, direct, diffuse and total radiations. Pyrheliometer - working principle, direct radiation measurement, Pyrometer-working Principle, diffuse radiation measurement, Distinction between the two meters.

UNIT II: SOLAR THERMAL COLLECTORS (10hrs)

Solar Thermal Collectors-Introduction, Types of Thermal collectors, Flat plate collector – liquid heating type, Energy balance equation and efficiency, Evacuated tube collector, collector overall heat loss coefficient, Definitions of collector efficiency factor, collector heat-removal factor and collector flow factor, Testing of flat-plate collector, solar water heating system, natural and forced circulation types. Concentrating collectors, Solar cookers, Solar dryers, Solar desalinators.

UNIT III: FUNDAMENTALS OF SOLAR CELLS (10Hrs)

Semiconductor interface, Types, homo junction, hetero junction and Schottky barrier, advantages and drawbacks, Photovoltaic cell, equivalent circuit, output parameters, conversion efficiency, quantum efficiency, Measurement of I-V characteristics, series and shunt resistance, their effect on efficiency, Effect of light intensity, inclination and temperature on efficiency

UNIT IV: TYPES OF SOLARCELLS AND MODULES (10 hrs)

Types of solar cells, Crystalline silicon solar cells, I-V characteristics, poly-Si cells, Amorphous silicon cells, Thin film solar cells-CdTe/CdS and CuInGaSe2/CdS cell configurations, structures, advantages and limitations, Multi junction cells – Double and triple junction cells. Module fabrication steps, Modules in series and parallel, Bypass and blocking diodes

UNIT V: SOLAR PHOTOVOLTAIC SYSTEMS (10hrs)

Energy storage in PV systems, Energy storage modes, electrochemical storage, Batteries, Primary and secondary, Solid-state battery, Molten solvent battery, lead acid battery and dry batteries, Mechanical storage – Flywheel, Electrical storage – Super capacitor

MODEL QUESTION PAPER (Sem - End)

B.Sc DEGREE EXAMINATION
Semester – V (Skill Enhancement Course -Elective)
Paper-7B – Solar Energy And Applications

Time: 3 hrs **Maximum Marks : 75**

SECTION – A

Answer any FIVE Questions **5X5M = 25M**

Explain about the Spectral distribution of Solar radiation
1. Explain the terms : (a) direct (b) diffuse and (c) total
2. Give a short note on thermal collectors radiations
3. Write a short note on Solar desalinators
4. Explain about : (a) homo junction and (b) hetero junction Concepts in semiconductor interfaces.
5. Give a short note on various types of Solar cells
6. Explain about the advantages and limitations of Thin film solar cells.
7. Explain about energy storage modes in PV Systems
8. Explain about the semiconductor interfaces.

SECTION - B

Answer ALL the Questions **5X10= 50M**

9. (a) Explain the principle of Working and direct radiation measurement in Pyrheliometer
(OR)
(b) What is Pyrometer ? Explain the Working principle and direct radiation measurement involved in it.

10. (a) Explain about a Flat plate collector of liquid heating type and obtain Energy balance Equation and Efficiency
(OR)
(b) Explain the Solar Water heating system involving natural and forced circulation types

11. (a) What is a photovoltaic call ? Draw it's equivalent circuit and Explain about : (i) output parameters (ii) Conversion Efficiency and (iii) Quantum Efficiency
(OR)
(b) Explain the following Effects of (i) Series and shunt resistance (ii) light intensity (iii) inclination and (iv) temperature on the Efficiency of solar cells.

12. (a) Explain the configuration, structure, advantages and limitations of CdTe / Cds Thin film solar cell
(OR)
(b) Explain the concepts of (i) Solar module fabrication steps anD (ii) modules in series and Paralle

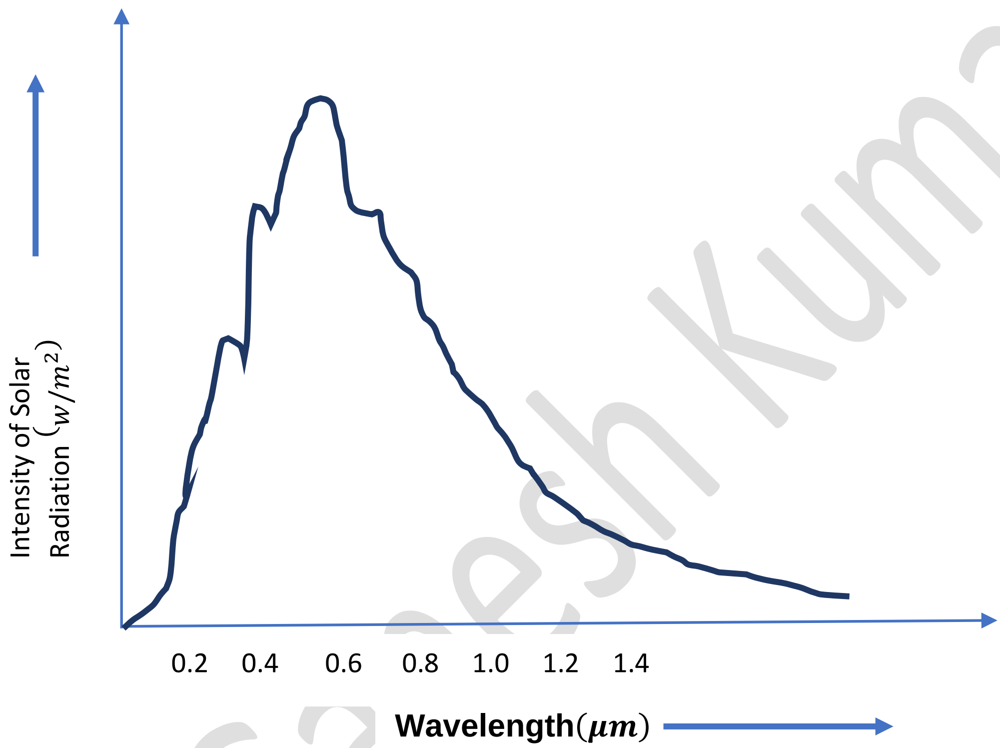
13. (a) Explain about Various primary storage Batteries
(OR)
(b) Explain about Various Secondary storage mechanisms
(i) Fly wheel and (ii) Supercapacitor

Unit-I

Basic Concepts of Solar Energy

Spectral distribution of solar radiation

` We know that the Sun is a spherical body of hot ionized gasses producing energy by nuclear fusion. It radiates this energy in the form of electromagnetic waves known as solar radiation. The spectral distribution of solar radiation is shown in the figure. It is a graph drawn between the intensity of solar radiation and the corresponding wavelength.

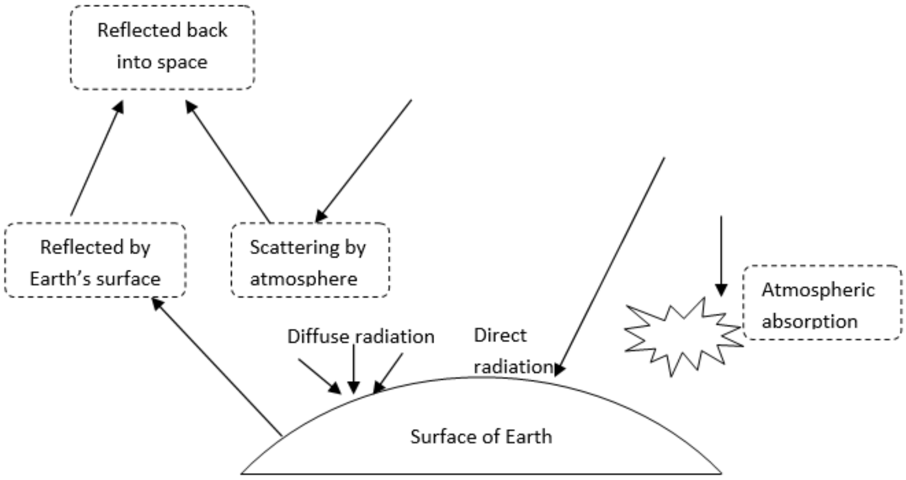


It mainly contains three regions.

S.No	Region	Percentage	Wavelength
1	Ultraviolet	6.4 %	$< 0.38\ \mu m$
2	Visible	48 %	$0.38\ \mu m - 0.78\ \mu m$
3	Infrared	45.6 %	$> 0.78\ \mu m$

- It is clear that most of the radiation emitted by the sun is in the visible region.
- The intensity of solar radiation increases gradually with wavelength and becomes maximum at a wavelength of 0.48 μm. Then it gradually decreases to zero at higher wavelengths.
- 99% of solar radiation is up to a maximum wavelength of $4\ \mu m$
- Solar radiation reaching the Earth is equivalent to a blackbody of temperature of 5779 K.

Direct, diffuse and total radiation



Solar radiation that reaches Earth's surface after passing through the atmosphere is known as terrestrial radiation. The reflection, scattering and absorption of the solar radiation by the Earth's surface and atmosphere are shown in figure. This is known as energy flow diagram to the Earth.

- It is clear from the diagram that a part of the solar radiation is reflected back in to space by the Earth's atmosphere.
- The radiation which enters the atmosphere is partly absorbed by the molecules in the air. For example, Oxygen and Ozone molecules absorb ultraviolet radiation while CO_2 molecules absorb infrared radiation.
- A part of the solar radiation which enters the atmosphere is scattered by the clouds and dust particles in the atmosphere.
- The radiation which is not absorbed or scattered by the atmosphere falls on the Earth's surface directly from the Sun. This radiation is known as direct radiation or beam radiation.
- In addition to the beam radiation, a part of the radiation reflected and scattered by the atmosphere reaches the earth's surface. This radiation is known as diffused radiation. Diffuse radiation comes from all directions unlike the direct radiation which comes directly from the sun.
- The sum of beam radiation and diffuse radiation is called global solar radiation.

Zenith angle (θ_z)

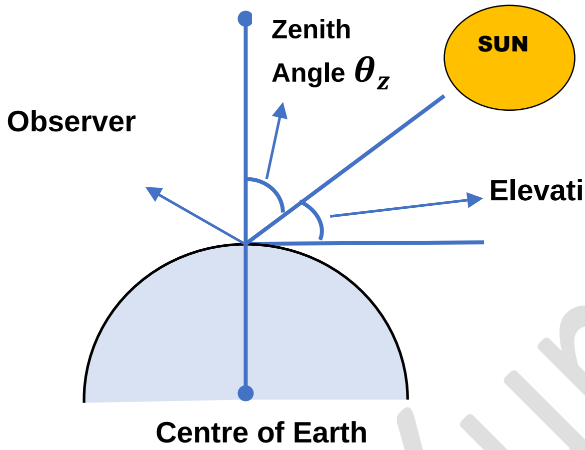
The angle between the Sun's rays and the vertical line perpendicular to the horizontal plane passing through the observer is called solar zenith angle. It is denoted by $\boldsymbol{\theta_z}$.

➢ We know that the imaginary point directly above a particular location on the surface of Earth is called zenith. Zenith angle is the angle between zenith and the Sun's rays.

➢ Solar zenith angle is the complement to the elevation angle (α).

$$\theta_z = \frac{\pi}{2} - \alpha$$

➢ Zenith angle is minimum at solar noon.



Air mass (m_a)

Air mass is defined as the length of the optical path which the solar radiation has to travel through the atmosphere to reach the surface of the Earth. Air mass is defined relative to the length of the optical path in the vertical direction which is assumed to be unity. It is denoted by m_a.

- ➢ Air mass is a measure of how much atmosphere solar radiation has to pass through.
- ➢ If θ_z denotes the solar zenith angle, then the expression for air mass is given by

$$m_a = \frac{1}{\cos\theta_z}$$

- ➢ At solar zenith, $\theta_z = 0$. Hence $m_a = 1$
- ➢ When $\theta_z = 60^0$, $m_a = 2$
- ➢ Just above the Earth's atmosphere, $m_a = 0$

Pyrheliometer- Working principle & Direct radiation measurement

- ➢ **A device which measures the direct solar radiation (or) beam solar radiation is called a pyrheliometer.**

Pyrheliometers measure the solar constant which is a measure of the intensity of direct solar radiation.

Solar Constant:

Solar constant is defined as the energy absorbed by a black surface per unit time and per unit area placed normally to the Sun rays at the mean distance of Earth from the Sun.

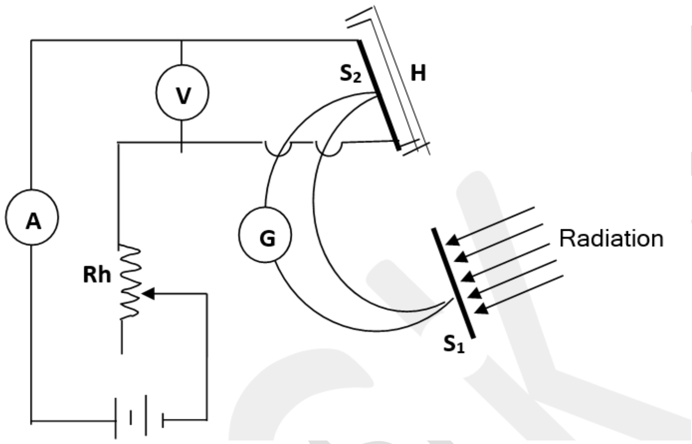
It is denoted by S. The value of solar constant S is 1340 watt/m^2.

Principle:

"Conversion of heat energy in to electrical energy using a thermocouple"

We know that thermocouple contains two junctions of different metals joined together. If there a temperature difference between the two junctions, it produces an e.m.f known as thermo e.m.f. which produces a current in the circuit. Exposing one of the two junctions to direct solar radiation creates a temperature difference which produces an electric current basing on which the intensity of direct solar radiation can be measured.

Construction:



Angstrom's Pyrheliometer

A pyrheliometer contains the following three important parts.

- **Two identical black surfaces**: It contains two identical black surfaces to receive beam solar radiation
- **Thermopile**: It consists of a series of thermo couples to convert the heat energy into electrical energy.
- **Galvanometer**: It compares the electrical currents produced due to the two identical black surfaces.

Working:

✓ When the pyrheliometer is exposed to the sun, one of the two identical black surfaces absorbs the beam solar radiation.

✓ Absorption of beam solar radiation heats the exposed black surface and causes a change in its temperature.

✓ Now the second black surface, which is not exposed to solar radiation, is electrically heated such that its temperature is equal to first black surface.

- ✓ When the temperatures of the two surfaces are equal, the galvanometer shows zero deflection.
- ✓ Since the two surfaces have the same temperatures, the solar radiation absorbed by the exposed surface can be determined by equating it with the electrical energy supplied to the shaded black surface.

Pyranometer-Working principle & Diffuse radiation measurement

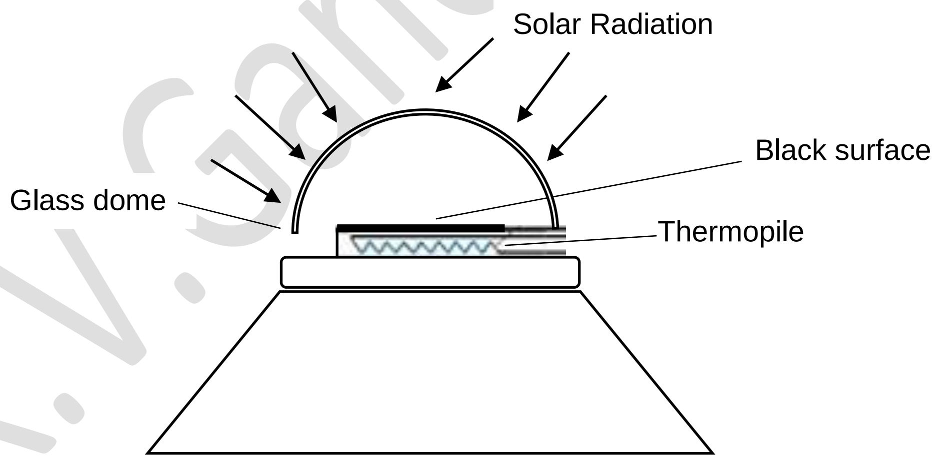
- ➢ **A device which measures the global solar radiation is called a Pyranometer. Pyranometer measures both direct and diffuse solar radiation.**

Principle:

"Conversion of heat energy in to electrical energy using a thermocouple"

We know that thermocouple contains two junctions of different metals joined together. If there a temperature difference between the two junctions, it produces an e.m.f known as thermos e.m.f. which produces a current in the circuit. Exposing one of the two junctions to global solar radiation creates a temperature difference which produces an electric current basing on which the intensity of global solar radiation can be measured.

Construction:



Pyranometer

A pyranometer contains the following three important parts.

- **Black surface** : It receives the diffuse and direct solar radiation.
- **Glass dome** **:** it prevents the loss of radiation received by the black surface.
- **Thermopile** : It consists of a series of thermo couples to convert the heat energy into electrical energy.

Working:

- When the pyranometer is exposed to the sun, the black surface absorbs both direct and diffuse solar radiation.
- Absorption of radiation heats the black surface and causes a change in its temperature.
- The change in temperature of the black surface is detected by the thermopile which produces a thermo e.m.f.
- The value of thermo e.m.f is a measure of the diffuse solar radiation since it is directly proportional to the absorbed solar radiation.

Differences between Pyrheliometer and Pyranometer

Pyrheliometer	Pyranometer
Pyrheliometers measure only direct solar radiation	Pyranometers measure both direct and diffuse solar radiation
Since pyrheliometers measure only direct solar radiation, cosine corrector is needed.	Since pyranometers measure both direct and diffuse solar radiation, cosine corrector is not needed.
Pyrheliometers should always face the sun	Pyranometers need not face the sun
Pyrheliometers require more maintenance as they have a cosine corrector	Pyranometers require less maintenance as they don't have cosine corrector
Pyrheliometers are expensive	Pyranometers are not expensive

Unit-II

Solar Thermal Collectors

Solar thermal Collectors-Introduction

Solar thermal collector is a device which converts solar energy in to heat energy and transfers it to a fluid.

Basic principle:

- Basic principle of solar thermal collectors is "Green House Effect"

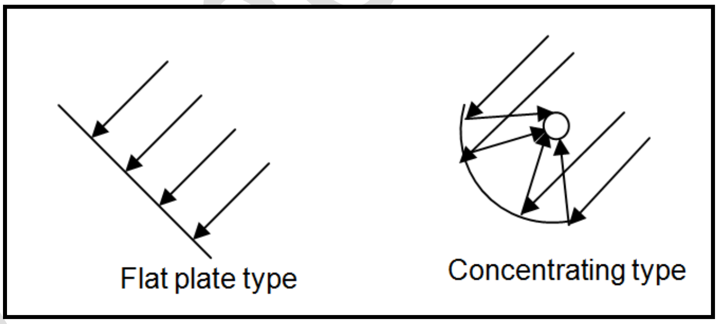
When solar radiation falls on the Earth's surface, the short wavelength visible radiation is absorbed by the Earth's surface and converted in to heat energy. But the long wavelength infrared radiation re-radiated by the Earth's surface is trapped by CO_2 in the atmosphere due to which the temperature of the Earth's surface increases. This is called Green House Effect.

This is the same principle on which any solar thermal collector works. Any solar thermal collector contains a transparent cover like glass which transmits visible radiation and blocks infrared radiation like CO_2 in the atmosphere.

Types of Solar Thermal Collectors:

Collectors can be broadly classified into two types based on their working..

- Flat plate collectors (or) Non-concentrating solar collectors
- Concentrating solar collectors



1. **Flat plate collectors:**

- As the name suggests, flat plate collectors use a flat metal sheet like copper, aluminium or steel to absorb the solar radiation.
- In flat plate collectors, area of the collector is equal to the area of the aperture. Hence they do not concentrate the solar radiation. The concentration ratio of flat plate collectors is one.
- Since flat plate collectors can absorb both beam radiation and diffuse radiation, sun tracking is not needed.

Advantages:

- ✓ Both beam and diffuse solar radiations are used.
- ✓ Require little maintenance
- ✓ Mechanically simpler than concentrating collectors

Disadvantages:

- Low temperature
- Large heat losses by conduction due to large area

Applications:

- ✓ Solar water heating
- ✓ Solar heating and cooling
- ✓ Low temperature power generation

2. <u>Concentrating solar collectors:</u>

- ➢ As the name suggests, concentrating solar collectors optically concentrate the solar radiation onto a small area where it is absorbed and converted into heat energy.
- ➢ In concentrating solar collectors, area of collectors is much smaller than the aperture. Hence they concentrate the solar radiation and the intensity of radiation is very high. Their concentration ratio varies from 1.52 to 10,000.
- ➢ Since concentrating solar collectors absorb only beam radiation, sun tracking is needed to optimize the absorption of solar radiation.

Advantages:

- ✓ High concentration ratio
- ✓ Low heat losses due to small area of the receiver
- ✓ High temperature applications

Disadvantages:

- Mechanically complex than flat plate collectors
- High initial cost
- Need regular maintenance

Applications:

- ✓ Large scale water desalination
- ✓ Large scale cooking
- ✓ Industrial process heat

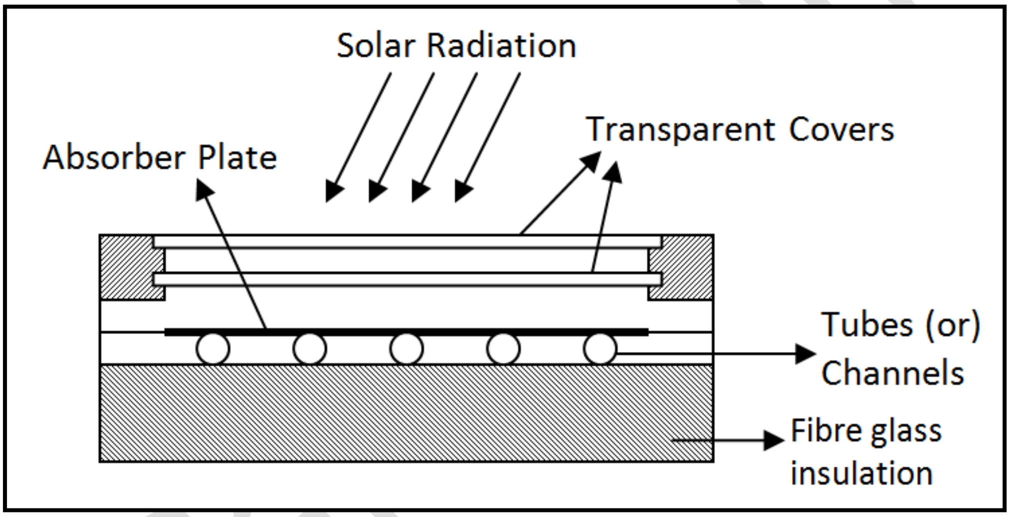
Flat plate collector-Liquid heating type-Energy balance equation and efficiency

Flat plate collector is a device which converts solar energy in to heat energy and transfers it to a fluid.

Basic principle:

- **Basic principle of flat plate collectors is "Green House Effect"**

When solar radiation falls on the Earth's surface, the short wavelength visible radiation is absorbed by the Earth's surface and converted in to heat energy. But the long wavelength infrared radiation re-radiated by the Earth's surface is trapped by CO_2 in the atmosphere due to which the temperature of the Earth's surface increases. This is called Green House Effect. This is the same principle on which any flat plate collector works.



Schematic view of a flat plate collector is shown in figure. It contains four important components.

1. **Absorber plate**: Absorber plate is a black metallic plate of high thermal conductivity made of copper, steel or aluminium which absorb the solar radiation and convert it in to heat energy. Thickness of the absorber plate ranges from 0.5 mm to 1 mm. Recently plastics have also been used for low temperature applications.

2. **Transparent cover:**Flat plate collector contains a transparent covermade of materials like glass, Teflon, marlex etc. with a thickness of 5mm to collect the solar radiation. It is transparent to the incident shortwave solar radiation and opaque to long wavelength infrared radiation re-radiated by the absorber plate such that the absorber plate is heated due to green house effect. Convection losses are minimized by an air layer between absorbing plate and transparent cover.

3. **Tubes or Channels:** Tubes or channels made of metals having a diameter of 1 mm to 1.5 mm soldered to the bottom of the absorber plate through which the liquid to be heated passes. They take the heat away from the absorbing plate and transfer it to the fluid.
4. Fibre glass insulation of thickness 2.5 cm to 8 cm minimizes the heat loss.

Energy balance equation and efficiency:

We know that flat plate collector converts solar energy in to heat energy and transfers it to a fluid. The balance of heat transferred to the fluid after the thermal losses is defined as the useful heat delivered by a solar collector. It is not possible to transfer the entire heat absorbed to the fluid due to thermal losses. Thermal losses are of 3 types.

- **Conductive losses** : It can be minimized by providing insulation on the rear and sides of the absorber plate.
- **Convective losses** : It is minimized by keeping an air gap between absorber plate and the transparent cover.
- **Radiative losses** : It is minimized by choosing a cover such that it blocks the long wavelength infrared radiation.

Hence the useful heat delivered by the solar collector is equal to the heat absorbed by the flat plate collector minus the thermal losses.

$$\boldsymbol{Q_U = A_P S - Q_L}$$

$$Q_U = Useful\ heat\ delivered,\ \ A_P = Area\ of\ the\ absrober\ plate,$$

$$S = Solar\ heat\ energy\ absorbed\ by\ the\ plate,$$

$$Q_L = Rate\ of\ heat\ loss\ by\ conduction, convection\ and\ radiation$$

This is called energy balance equation. It describes the performance of flat plat solar collector.

Collector Efficiency: If I_T is the incident solar flux, then collector efficiency is defined as

$$\boldsymbol{\eta_i = \frac{Q_U}{A_P I_T}}$$

Collector overall heat loss coefficient:

If $\boldsymbol{U_T}$ is the overall heat loss coefficient, then

$$\boldsymbol{Q_L = U_T A_P (T_P - T_a)}$$

$$\boldsymbol{T_P} = Average\ temperature\ of\ absorber\ plate$$

$$T_a = Temperature\ of\ surrounding\ air$$

$$A_P = Area\ of\ absorber\ plate$$

Since the collector loses heat from top, bottom and sides,

$$Q_L = Q_t + Q_b + Q_s$$

$$Q_t = rate\ of\ heat\ loss\ from\ top$$

$$Q_b = rate\ of\ heat\ loss\ from\ bottom$$

$$Q_s = rate\ of\ heat\ loss\ from\ sides$$

If U_t, U_b, U_s represent top loss coefficient, bottom loss coefficient and side loss coefficient, then

$$Q_L = U_t A_P (T_P - T_a) + U_b A_P (T_P - T_a) + U_s A_P (T_P - T_a)$$

Hence the overall heat loss coefficient is given by

$$U_T = U_t + U_b + U_s$$

Its value ranges from $2 \frac{w}{m^2} K$ to $10\ \frac{w}{m^2} K$

Collector heat removal factor:

We know that

$$Q_U = A_P S - Q_L$$

Considering Transmittance and Absorptivity product $\tau.\alpha$

$$S = I_T (\tau.\alpha)_e$$

Useful heat delivered by solar collector is given by

$$Q_U = A_P [I_T (\tau.\alpha)_e - U_T (T_P - T_a)]$$

If F_R is the heat removal factor, then

$$Q_U = A_P [I_T F_R (\tau.\alpha)_e - F_R U_T (T_P - T_a)]$$

This is called Hottel-Whillier-Bliss equation.

Heat removal factor F_R is a measure of the thermal resistance encountered by the absorbed solar radiation in reaching the collector fluid. Its value ranges from 0 to 1.

F_R represents the ratio of actual useful heat gain rate to the gain which would occur if the absorber is at the temperature T_P everywhere.

Solar Cookers

Use of solar energy for cooking is very important because a major portion of the energy consumption is for cooking.

Three important solar cookers are given below.

1. Box-type solar cooker
2. Dish solar cooker
3. Community solar cooker

1. Box-type solar cooker:

Box-type solar cooker as shown in figure. It contains the following parts.

- Outer box made of fiberglass
- Blackened aluminium tray
- Double glass lid
- Reflector
- Insulation
- Cooking pots

When the solar cooker is exposed to the sun, the solar radiation is concentrated by the reflector onto the food placed in the cooking pots. The temperature obtained is less than 100^0C

2. Dish solar cooker:

- In this cooker, a parabolic dish is used to concentrate the solar radiation and obtain higher cooking temperatures.
- Temperatures of the order of 400^0 C may be reached using this cooker.
- This cooker can meet the cooking requirements of 15 persons.
- Since this system employs concentrated solar collectors, sun tracking is needed.

3. Community solar cooker:

- In this cooker, a large parabolic reflector is used to concentrate the solar radiation to obtain higher cooking temperatures.
- It also contains a secondary reflector to concentrate the solar radiation onto the food.
- Hence, temperatures greater than 400^0 C may be reached using this cooker.
- This cooker can meet the cooking requirements of 50 persons.

Solar Drying

- The process of using solar energy for drying of products is known as solar drying.
- In this process, ambient air which is heated due to solar radiation enters a drying chamber by convection.

- The hot air removes moisture from the products and reaches the bottom of the drying chamber after cooling.
- For large scale drying, forced circulation of air may be used by a blower.
- When direct sunlight is not sufficient for drying, a controlled temperature drying is used using a number of solar air heaters. This is called kiln drying. It is used for food grains and products like tea and tobacco.
- Disadvantages:
  - ✓ The dried product is of poor quality due to grit and dirt.
  - ✓ The product is unhygienic due to microorganisms and insects.

Solar Distillation (or) Solar desalinators

The process of converting saline water into pure water by using solar energy is called solar distillation and the device is called solar still.It contains a shallow basin having a black surface called basin liner.A filler supplies the saline water to the basin.The top of the basin is covered with a transparent cover.When the device is exposed to sun, solar radiation enters the basin and heats the basin liner.As a result, the saline water is heated and the water vapours condense over the cool interior.The condensate is collected in troughs installed at the outer frame of the solar still.The distilled water is then transferred into a storage tank.

Advantages:

- Low energy consumption
- Low maintenance cost

Unit-III

Fundamentals of Solar Cells

- Solar cell is a device which converts sun light in to electrical energy.

Basic principle:

Photovoltaic Effect

Solar cell is a sandwich of p-type and n-type semi conducting layers. A depletion region is formed at the junction of the two layers which has a potential gradient (or) potential barrier. When sun light falls on the solar cell, electron-hole pairs are produced. The potential gradient at the junction of the solar cell forces the electron-hole pairs to flow through the external circuit producing electric current.

- If the junction in a solar cell is made of two layers of the same material, the junction is called **homo junction**.
- If the junction in a solar cell is made of two layers of different materials, the junction is called **hetero junction**.
- The potential at the junction of a semiconductor and a metal is called **Schottky barrier**.

Photovoltaic Cell- I-V Characteristics-Equivalent Circuit

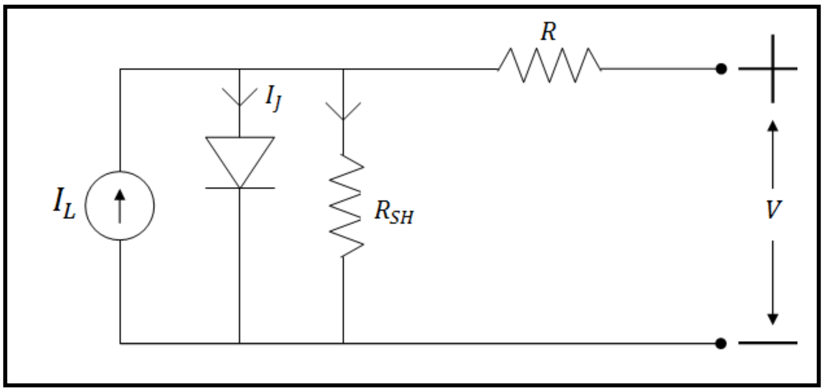
- Photovoltaic cell is a device which converts sun light in to electrical energy.

Basic principle:

Photovoltaic Effect

Photovoltaic cell is a sandwich of p-type and n-type semi conducting layers. A depletion region is formed at the junction of the two layers which has a potential gradient (or) potential barrier. When sun light falls on the solar cell, electron-hole pairs are produced. The potential gradient at the junction of the solar cell forces the electron-hole pairs to flow through the external circuit producing electric current.

Equivalent circuit:



Equivalent circuit of Photovoltaic cell is shown in figure.

A photovoltaic cell can be modelled by a current source in parallel with a diode in parallel with a shunt resistance $\boldsymbol{R_{SH}}$ and external resistance $\boldsymbol{R}$. If $\boldsymbol{I}$ is the electric current flowing through the circuit, then

$$\boldsymbol{I = I_L - I_J}$$

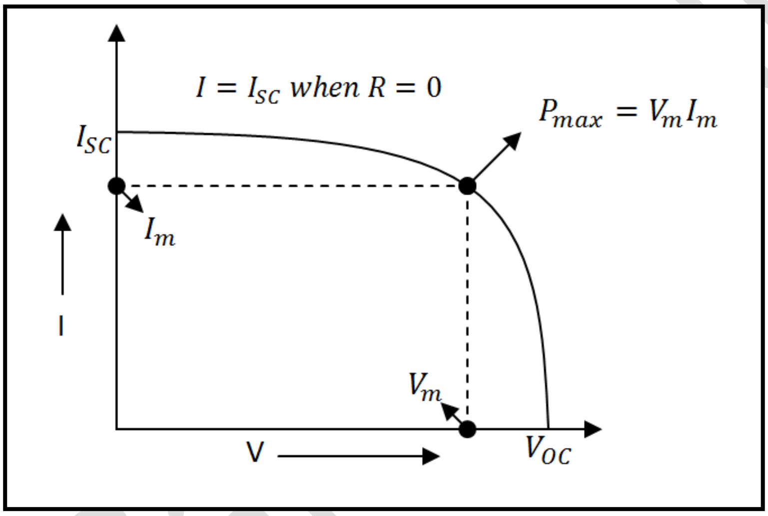
$$I_L = Photo\ generated\ current, \qquad I_J = Diode\ current$$

Diode current is given by

$$\boldsymbol{I_J = I_0 \left(e^{eV/kT} - 1\right)}$$

$$\boldsymbol{I_0} = Saturation\ current$$

V-I Characteristics:



Relation between voltage and current in photovoltaic cell is given by

$$\boldsymbol{I_J = I_0 \left(e^{eV/kT} - 1\right)}$$

V-I characteristics curve of photovoltaic cell is shown in figure. It is clear from the graph that, when the voltage is zero, current is maximum. This is called saturation current or dark current $\boldsymbol{I_{SC}}$. It almost remains constant with increases in voltage and then decreases suddenly to zero at a specific voltage known as open circuit voltage $\boldsymbol{V_{OC}}$. Power delivered by the circuit increases linearly from zero and becomes maximum at a certain voltage. It then decreases to zero at open circuit voltage $\boldsymbol{V_{OC}}$. The current and voltage at which the power is maximum are called maximum power current and maximum power voltage $\boldsymbol{I_m, I_V}$.

Maximum efficiency of a solar cell is given by

$$\boldsymbol{\eta_{max} = \frac{V_m I_m}{I_S A_C} = \frac{(FF) V_m I_m}{I_S A_C}}$$

$$FF = Fill\ Factor$$

$$I_S = Incident\ solar\ flux$$

$$A_C = Area\ of\ the\ solar\ cell$$

Efficiency of a solar cell is only $15\ \%$.

Reasons for low efficiency of solar cells are given below.

- As the temperature of the cell rises due to solar radiation, leakage current also increases which affects the frequency. For silicon, output power decreases by $0.5\ \%$ per o_C
- Excess energy of active photos is lost as heat.
- **Quantum efficiency** of a solar cell is defined as the number of electrons produced in the solar cell to the number of photons of a given energy incident on the solar cell. Low quantum efficiency may also be a reason for low efficiency.
- The metal contacts on the solar cell which reduce series resistance losses, reduce the active surface area of solar cell exposed to solar radiation.

Unit-IV

Types of Solar Cells and Modules

Solar cells can be broadly classified in to two types basing on construction technology and the materials used.

- Crystalline silicon solar cells
- Thin film solar cells

Crystalline silicon solar cells:

Crystalline silicon solar cells are the most widely used solar cells. They are made from semi conductor grade silicon (Se-G) in the form of a thin wafer and doped with p-type and n-type impurities.

Crystalline silicon solar cells are classified in to two types.

- ✓ Single crystalline silicon solar cells
- ✓ Poly crystalline silicon solar cells

Single crystalline silicon solar cells-Construction-V-I characteristics

- Solar cells which are made from single crystalline silicon are called Single crystalline silicon solar cells.

Construction:

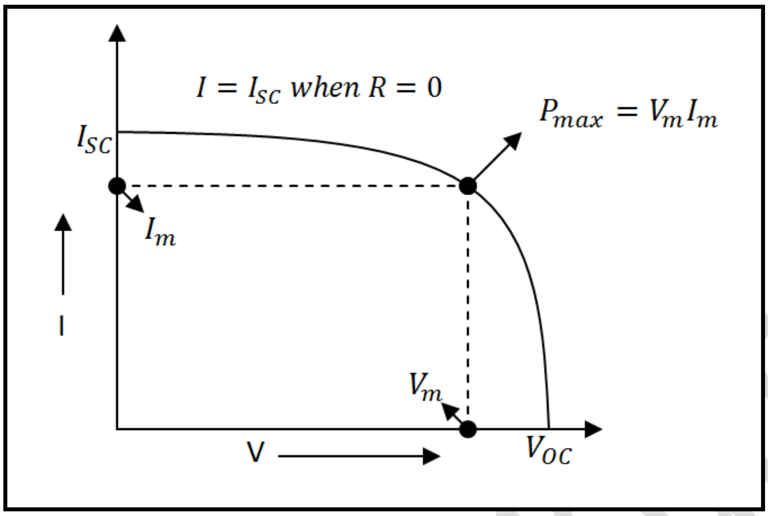
1. Silica (sand) is melted after adding coal to produce CO_2 and metallurgical grade silicon (MG-Si) which contains 1 percent impurities.

$$SiO_2 + 2C \rightarrow Si\ (MG - Si) + 2\ CO$$

2. The metallurgical grade silicon is treated with HCl to form silane gas.
3. This silane is condensed and distilled to form ingots of semiconductor grade silicon (SeG-Si) which is 99.9 % pure.
4. It is sliced in to a number of wafers of thickness $200\ \mu m$ and doped with boron to form p-type wafer.
5. The p-type wafers are passed through a furnace containing phosphorous vapour so that n-type region is also formed.

V-I Characteristics of Crystalline silicon solar cells:

V-I characteristics curve of crystalline silicon solar cell is shown in figure. It is clear from the graph that, when the voltage is zero, current is maximum. This is called saturation current or dark current $\boldsymbol{I_{SC}}$.Italmost remains constant with increases in voltage and then decreases suddenly to zero at a specific voltage known as open circuit voltage $\boldsymbol{V_{OC}}$. Power delivered by the circuit increases linearly from zero and becomes maximum at a certain voltage. It then decreases to zero at open circuit voltage $\boldsymbol{V_{OC}}$. The current and voltage at which the power is maximum are called maximum power current and maximum power voltage $\boldsymbol{I_m, I_V}$.



Maximum efficiency of a solar cell is given by

$$\boldsymbol{\eta_{max} = \frac{V_m I_m}{I_S A_C} = \frac{(FF) V_m I_m}{I_S A_C}}$$

$$FF = Fill\ Factor$$

$$I_S = Incident\ solar\ flux$$

$$A_C = Area\ of\ the\ solar\ cell$$

Advantages:

1. Efficiency is very high
2. Abundance of the raw material silica

Disadvantages:

1. Very expensive
2. Manufacturing is very difficult

Poly crystalline silicon solar cells

- Solar cells which are made from poly crystalline silicon are called poly crystalline silicon solar cells.

Efficiency of polycrystalline silicon solar cells is relatively low compared to that of single crystalline silicon solar cells due to the presence of grain boundaries. But single crystalline silicon solar cells are expensive and their manufacturing is difficult. Hence different crystalline processes have been developed for production of solar cells using polycrystalline silicon. One important observation that led to the acceptance of polycrystalline silicon solar cells is given below.

- ✓ **The efficiency of polycrystalline silicon solar cells with large grain size of the order of 1 cm is comparable to the efficiency of single crystalline silicon solar cells.**

In the manufacturing of polycrystalline silicon solar cells, rectangular ingots with large grain sizes are produced from semi conductor grade (Se-G) silicon. This process is cheaper than the process of forming long cylindrical ingots with small grain sizes in case of single crystalline silicon solar cells. More over efficient polycrystalline silicon solar cells can be fabricated even from solar grade silicon (So-G) which has lesser purity and hence cheaper than Se-G silicon. Most of the current silicon solar cells are made from polycrystalline silicon produced from So-G silicon.

Advantages:

1. Less expensive
2. Manufacturing is relatively easy

Disadvantages:

1. Efficiency is low compared to single crystalline silicon solar cells

Thin film solar cells

Cadmium Telluride (CdTe) Solar Cell-Configuration-Structure-Advantages & Limitations

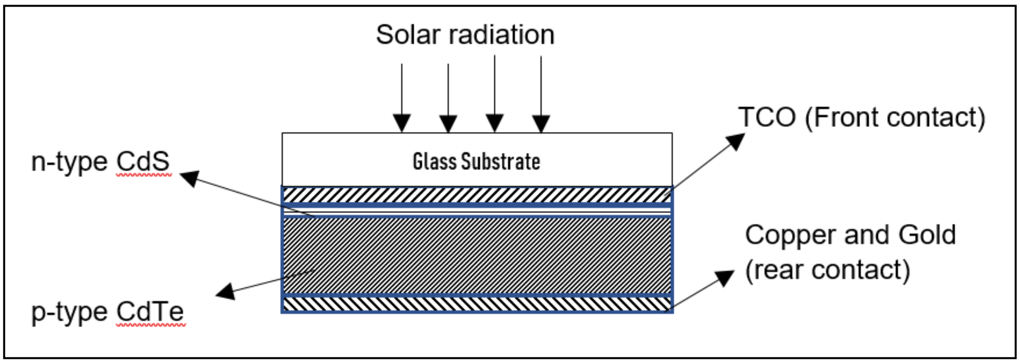
Wafer based crystalline silicon solar cells are the most widely used solar cells due to their high efficiency and the abundant availability of non-toxic raw material silica. Hence these are called first generation solar cells. But recently, production and use of solar cells based on thin film technology is gaining popularity due to the following reasons.

- Thin film solar cells are less expensive than crystalline silicon solar cells
- Less material is required for manufacturing of thin film solar cells

Cadmium telluride is a compound semiconductor. It has an ideal band gap of 1.45 eV to yield maximum efficiency. More over it has high absorption coefficient for photons having energy greater than the band gap. Hence material of small thickness is sufficient. Laboratory efficiency of CdTe solar cells is 21 %. Schematic diagram of CdTe solar cell is shown in figure.

Construction:

- A layer of p-type Cadmium Telluride with a thickness of $1.5\ to\ 8\ \mu m$ placed in contact with n-type Cadmium Sulphide (CdS) of thickness $0.05\ to\ 0.3\ \mu m$ to form a hetero junction.
- Transparent layer of tin oxide called transparent conducting oxide (TCO) is the front contact.
- Thin layer of copper and gold is used for rear contact.



Efficiency of CdTe Solar cell is 16.7 %. Nano structure CdTe cells are being developed to increase efficiency.

Copper Indium Gallium Diselenide(CIGS) Solar Cell- Configuration-Structure-Advantages & Limitations

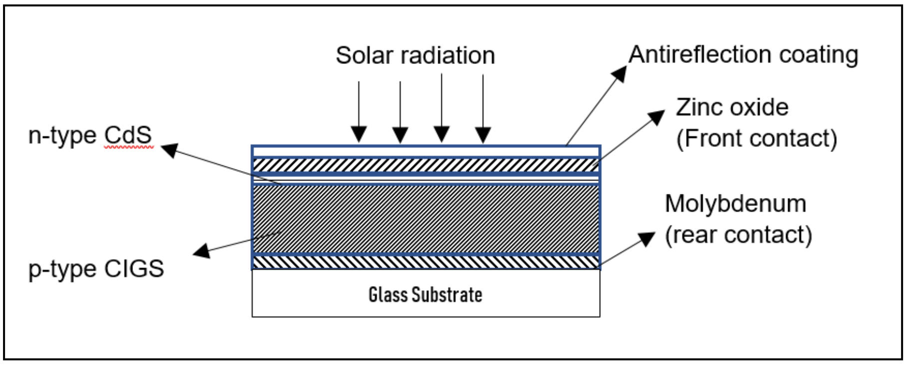
Wafer based crystalline silicon solar cells are the most widely used solar cells due to their high efficiency and the abundant availability of non-toxic raw material silica. Hence these are called first generation solar cells. But recently production and use of solar cells based on thin film technology is gaining popularity due to the following reasons.

- Thin film solar cells are less expensive than crystalline silicon solar cells
- Less material is required for manufacturing of thin film solar cells

Copper Indium Gallium Diselenide (CIGS) is a compound semiconductor. Its band gap can be effectively varied from 1.01 eV to 1.68 eV by varying the percentage of Gallium. This is the reason why CIGS solar cell has the highest efficiency.

Construction:

- A thin film of CdS of thickness $0.05\,\mu m$ is formed on a film of CIGS of thickness $2\ to\ 4\ \mu m$ thickness to form a hetero junction.
- Thin layer of zinc oxide of thickness $0.1\ to\ 0.3\ \mu m$ is the front contact.
- Thin layer of molybdenum of thickness $1\ \mu m$ is the rear contact.
- Anti reflective coating of thickness $0.08 - 1.2\ \mu m$ is provided.



Efficiency of copper Indium Gallium Diselnide (CIGS) solar cell is 21 %. Maximum efficiency of 22.95 % can be achieved with a band gap of 1.48 eV.

Amorphous Silicon

Even though the efficiency of crystalline silicon solar cells is very high, they are expensive and their manufacturing is difficult. Hence amorphous silicon is used for manufacturing thin film solar cells to reduce the manufacturing cost. Hydrogenated alloy of amorphous silicon is used as the solar cell material. It is represented by the symbol **a-Si:H**

Construction:

Amorphous silicon consists of

- P-type amorphous silicon
- Undoped amorphous silicon
- N-type amorphous silicon

- ✓ It is manufactured by chemical vapour deposition technique.
- ✓ Large vacuum chambers are filled with mixture of silane gas, hydrogen and small doping agents.
- ✓ Diborane is used for p-type and phosphine is used for n-type
- ✓ The silane gas dissociates and the amorphous silicon is deposited in a glass substrate.

Advantages:

- ✓ Since the vapour deposition technique is suitable for automobiles, large scale production of large solar cells, manufacturing cost of the solar cells is low.
- ✓ These are primarily used in calculators and watches.

Disadvantages:

- The efficiency of amorphous silicon solar cells is very low of the order of 10%.
- Performance of amorphous silicon will decrease by 10 to 20 percent after every year due to sunlight exposure.
- These are not suitable for photo voltaic power generation.

Multi junction cells (Double & Triple junction cells)

Solar cells which contain two or more junctions are called multi junction solar cells.

- Multi junction solar cells contain two or more materials with different band gaps. Hence they can absorb the solar spectrum more efficiently than the single junction solar cells which contain only one material.
- Multi junction solar cells having two junctions are called bi junction solar cells (or) tandem cells while solar cells containing three junctions are called triple junction solar cells.

- The efficiency of amorphous silicon solar cells can be enhanced by using double and triple junctions.
- For example, efficiencies of multi junction solar cells using micro or nano crystalline silicon are given below.

Type of cell	Area (cm^2)	Efficiency (%)
Double junction (a-Si:H/nc-Si:H)	14300	10.35
Triple junction (a-Si:H/a-Si Ge:H/nc-Si:H)	399.8	11.8
Triple junction (a-Si:H/μc-Si:H/ μc-Si:H)	1.043	13.6

- Multi junction solar cells are also used in compound semiconductor solar cells. These are primarily used for solar concentrators of group III & V elements.

Type of cell	Area (cm^2)	Efficiency (%)
Double junction GaInP/GaAs	0.999	31.6
Triple junction InGaP/GaAs/InGaAs	1.047	37.9

UNIT-V

Solar Photovoltaic Systems

Energy storage modes-Electro chemical storage

We know that solar radiation is intermittent. Hence it is necessary to convert and store solar energy using different methods.

Electrochemical energy storage:

Solar energy can be stored using electrochemical capacitors. These are also known as supercapacitors (or) ultracapacitors. Electrochemical capacitors are classified in to two types.

- Electric Double Layer Capacitors (EDLCs)
- Pseudo capacitors

1. Electric Double Layer Capacitors (EDLCs):

- ✓ Electric charges are stored physically in electric double layers near electrode/electrolyte interfaces.
- ✓ This process is highly reversible.
- ✓ The cycle life is infinite.

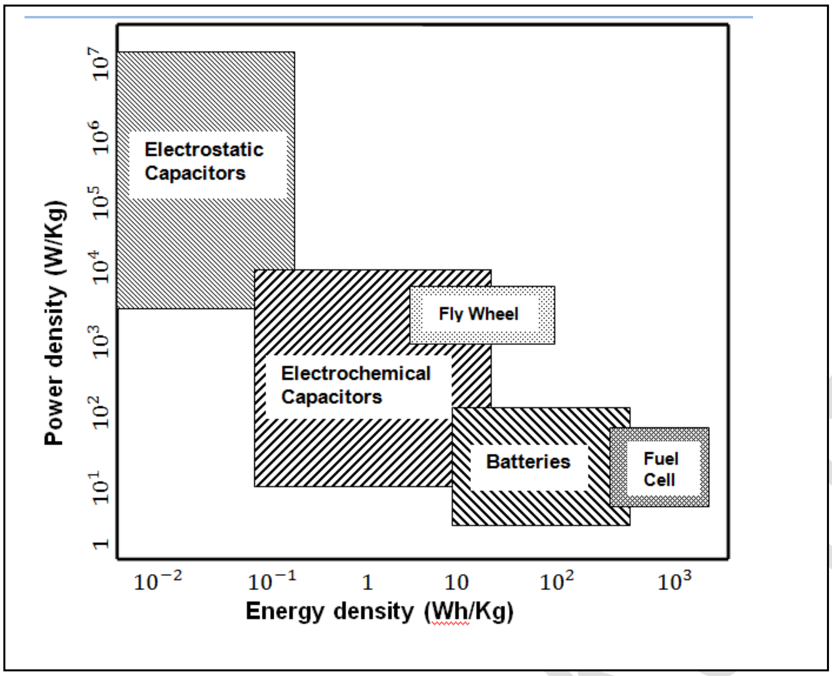
2. Pseudo capacitors:

- ✓ Electric charges are stored not only through electric double layer but also through fast surface oxidation reduction (redox) reaction and ion intercalation in the electrodes.
- ✓ Electrode material used are given below.
    1. Carbon based
    2. Transition metal oxide
    3. Conducting polymers
- ✓ Electrolyte material used are
    1. Aqueous electrolytes
    2. Organic electrolytes
    3. Ionic liquids

Rangone plot:

A graph drawn between energy density on X-axis and power density on Y-axis is called Rangone plot. It describes the performance of electrochemical capacitors. As shown in the Rangone plot, it is clear that,

1. Batteries, fuel cells have high energy density and low power density
2. Capacitors have low energy density and high-power density
3. Electrochemical capacitors are intermediate to batteries and capacitors. They have both high energy density and high-power densities.



Solid state battery

We know that solar radiation is intermittent. Hence it is necessary to convert and store solar energy using different methods.

Batteries which use solid electrodes and solid electrolytes instead of the liquid or polymer gel electrolytes used in Li-ion or Li-polymer batteries are called solid state batteries.

Materials used in solid state batteries:

- ✓ Ceramics: Lithium orthosilicate, glass, sulphides
- ✓ Solid polymers

Applications:

- ✓ Pacemakers
- ✓ RFIDs
- ✓ Wearable devices
- ✓ Electric vehicles

Advantages:

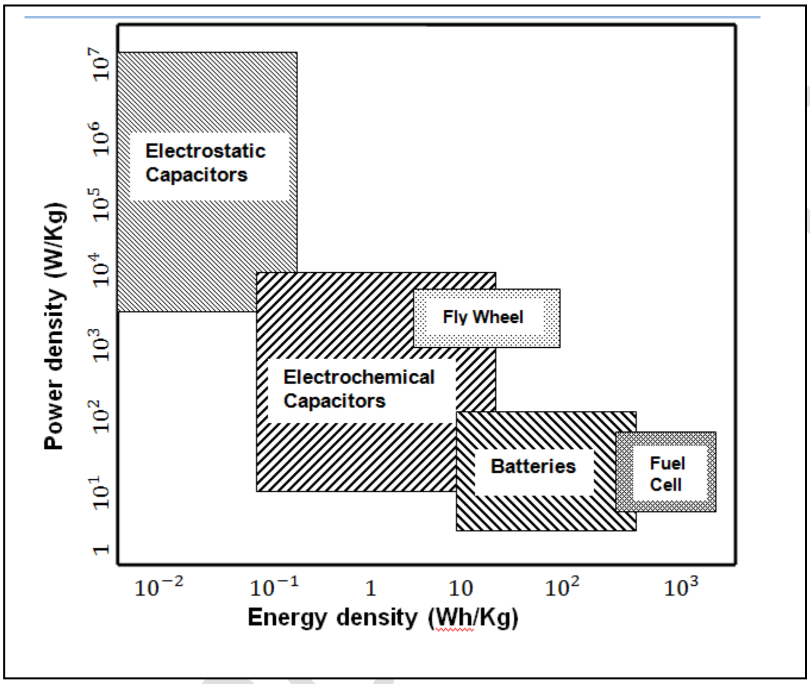
- Solid state batteries have high energy density
- Use of toxic materials like organic electrolytes is avoided.
- Solid electrolytes are non-flammable.
- Faster charging
- High voltages can be produced
- Longer life cycles

➢ Energy density of solid state batteries is higher than that of Li-ion batteries

Disadvantages:

- Solid state batteries are expensive
- Required to maintain low temperatures
- Require high pressure to maintain electric contact
- Mechanical failure due to voltage change in anode and cathode

Rangone plot:



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3. Electrochemical capacitors are intermediate to batteries and capacitors. They have both high energy density and high power densities.

Molten solvent battery

We know that solar radiation is intermittent. Hence it is necessary to convert and store solar energy using different methods.

Batteries which use molten salts as electrolytes are called molten solvent batteries. The components of molten solvent batteries are solids at room temperature. Hence they can be stored inactive for long periods of time.

Unique advantage:

✓ High energy density and high power density

These batteries are primarily used for high energy applications like grid energy storage. During activation cathode, anode and electrolyte layer are separated due to their different densities & immiscibility. The molten salt layer at the centre works as the electrolyte which has high ionic conductivity.

Types of molten-solvent batteries:

- Thermal (Non0rechargable batteries) batteries
- Sodium-Sulphur batteries
- Sodium-Nickel chloride batteries
- Liquid metal batteries

Advantages:

- Use of low cost materials
- Long life time

Disadvantages:

- High operating temperature. However, such temperatures can be maintained in grid scale applications

Lead-acid battery

Batteries which use plate of lead as cathode, plate of lead dioxide as anode and concentrated sulphuric acid as the electrolyte are called lead-acid batteries. They are the most widely used rechargeable battery. These batteries are predominantly used in automobile batteries.

Principle:

Following chemical reactions take place in the lead-acid battery.

Cathode:

$$Pb(S) + HSO_4^- + H_2O \rightarrow 2e^- + PbSO_4(S) + H_3O^+(aq)$$

Anode:

$$PbO_2(S) + HSO_4^-(aq)) + 3H_3O^+(aq) + 2e^- \rightarrow PbSO_4(S) + 5H_2O$$

Lead sulphate is formed at both electrodes.

Advantages:

- ✓ Lead-acid batteries have long life time
- ✓ They are not expensive

Disadvantages:

- Low efficiency

Fly Wheel

We know that solar radiation is intermittent. Hence it is necessary to convert and store solar energy using different methods.

Fly wheel is a device which stores energy in the form of mechanical energy. It convents the electrical energy produced from solar radiation in to mechanical energy using a rotating wheel (or) rotor. It uses the same rotor to reverse the mechanical energy in to electrical energy. Flywheels are alternative for lead acid batteries for storage of solar energy.

Flywheel contains a mass rotating about an axis. If ω is the angular velocity of the rotating body and I is the moment of inertia, then the rotational kinetic energy is given by

$$E = \frac{1}{2} I\omega^2$$

It is clear that the rotational energy depends on the following factors.

- Directly proportional to the square of angular velocity
- Directly proportional to the moment of inertia

Hence the amount of energy a fly wheel can store can be maximized by designing it such that the angular velocity and moment of inertia are maximum. Flywheels are used for output powers of 100 kW to 2 MW and for duration of 12 seconds to 60 seconds.