MODULE:02

Solar thermal energy collectors

1. Types of Solar collectors:

To utilize thermal energy from the sun, the collectors can be subdivided into the following categories, They are;

(i) Flat plate collectors.
  - (a) Flat plate Air collectors.
  - (b) Flat plate liquid collectors.

(ii) Concentrating collectors.
  - (a) Stationary concentrating collector.
  - (b) Tracking concentrating collector.

(iii). Evacuated tube collector.

(iv) Compound parabolic collector.

(v) Heliostat field collector.

(vi) parabolic through collector.

(vii) Cylindrical through collector.

i) Flat plate collectors:

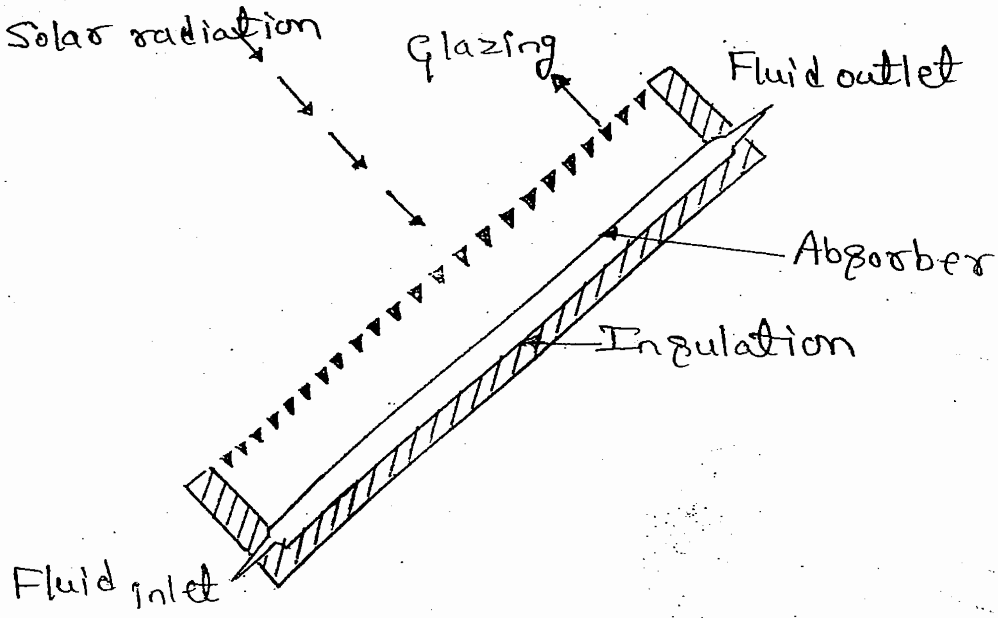

Figure 1. Flat plate collectors.

• Flat plate collectors are the most common type, are also referred to as non concentrating collectors.

* It has the same area for intercepting & for absorbing solar radiation.

* Figure 1 shows typical flat plate collector, it has five important parts

(i) Dark flat plate absorber of solar energy:- The absorber consist of a thin absorber sheet / thermally stable polymeric meterials such as aluminium, steel or copper to which a black or selective coating is applied, because metal is a good heat conductor.

(ii) Transparent cover/glazing: This allows solar energy to pass through, but reduces heat losses.

(iii) Heat - transport fluid: To remove heat from the absorber, fluid is usually circulated through tubing to transfer heat from the absorber to an insulated water tank.

(iv) Heat insulation backing;

(v) Insulated casing: It is made of a glass or polycarbonate cover.

Flat plate Air collectors

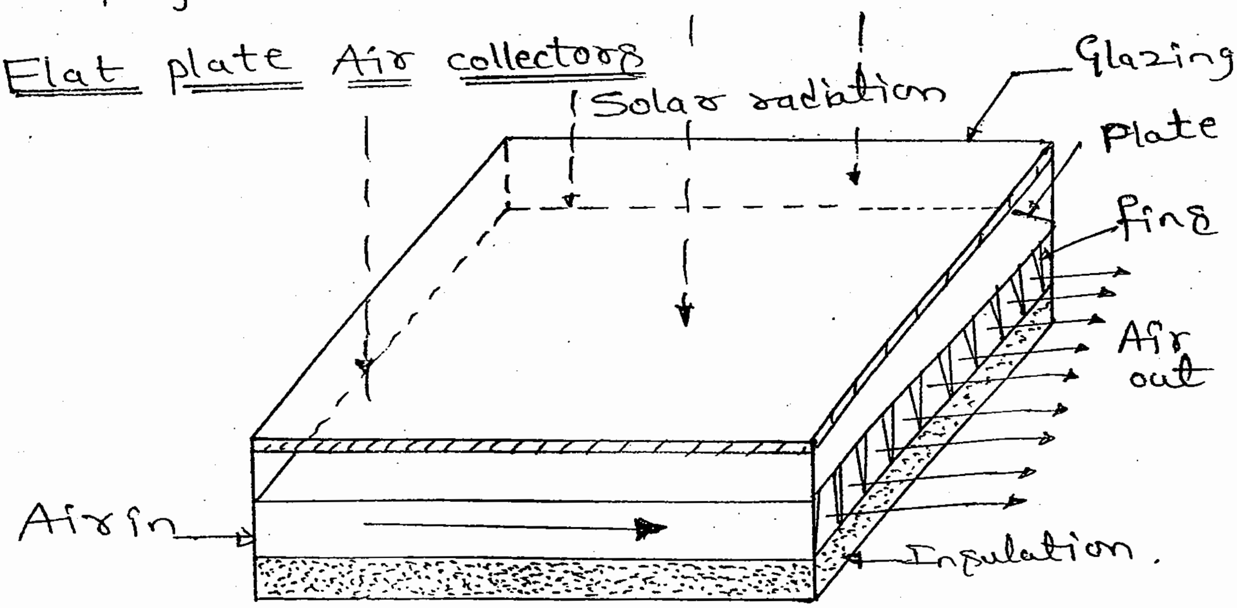

Figure 2. Flat plate air collectors

• It uses air as the heat transport medium.
• It used mainly for solar space heating.

Flat plate liquid collectors.

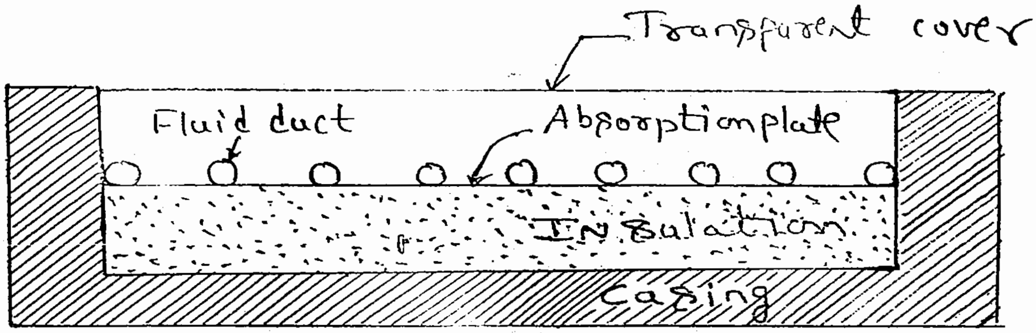

Figure 3. Flat plate liquid collectors

- These collectors use liquid as the heat transport medium.
- It heat liquid as it flows through tubes in or adjacent to the absorber plate.
- Solar pool heating uses liquid flat plate technology.
- The tubes can be welded to the absorbing plate.

Concentrating collectors

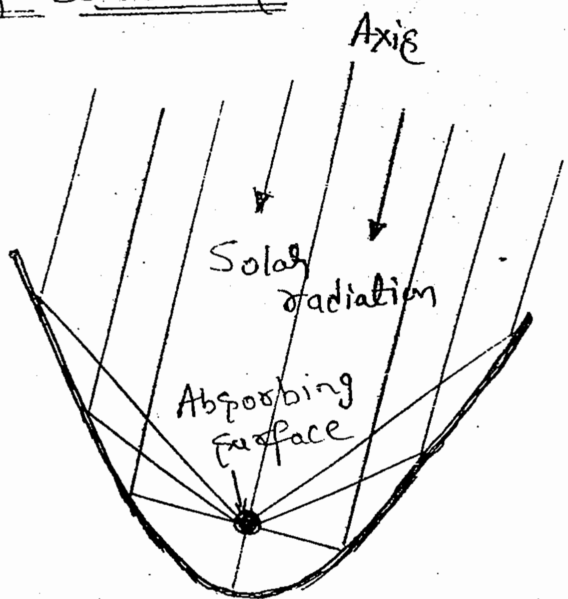

Figure 4. Concentrating collector with parabolic reflector

- It is used for high temperature applications such as steam production for the generation of electricity & thermal detoxification.
- These collectors are best suited to climates that have an abundance of clear sky days.
- Application; Solar cooker, Air conditioning.

2. Configurations of Certain Practical Solar thermal collectors.

There are many different methods for collecting the solar energy from incident radiation. The following are list of some popular types of solar thermal collectors.

i) Flat plate collectors.

→ A typical flat plate collector is an insulated metal box with a glass or plastic cover & dark coloured absorber plate.

→ These collectors heat liquid or air at temperature less than 90°C.

(a) Liquid flat plate collectors: It use sunlight to heat a liquid that is circulating in a "Solar loop". The solar loop transfers the thermal energy from the collectors to a thermal storage tank.

(b) Air flat plate collectors:-

→ The absorber plates in air collectors can be metal sheets, layers of screen or non-metallic materials.

→ The thermal energy collected from air-based solar collectors can be used for ventilation, air heating, space heating & crop drying.

* The most commonly configuration of air & liquid based solar thermal collectors are as follows.

(i) Glazed flat plate solar thermal collectors.
(ii) Unglazed flat plate solar thermal collectors
(iii) Unglazed perforated flat plate solar thermal collectors
(iv) Back-pass flat plate solar thermal collectors.
(v) Batch flat plate solar thermal collectors.
(vi) Solar cookers
(vii) Evacuated (vaccum tube) flat plate solar thermal collectors
(viii) Concentrating flat plate with flat reflectors.

→ Glazed flat plate collectors are better suited for moderate temperature applications where the demand temperature 30°C - 70°C.

→ Unglazed flat plate collectors are best suited for low temperature applications where the temperature demand is below 30°C. It is usually made of black plastic that has been stabilized to withstand ultraviolet light.

→ addition of reflector on collector increases the solar yield on the collector & over all thermal performance of the collector.

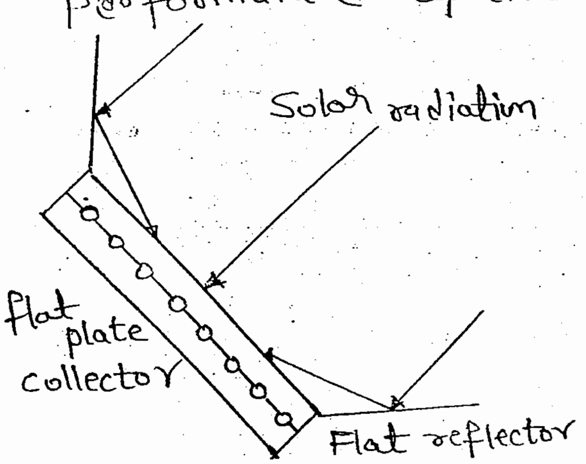

Figure 5. flat plate collector with flat reflector

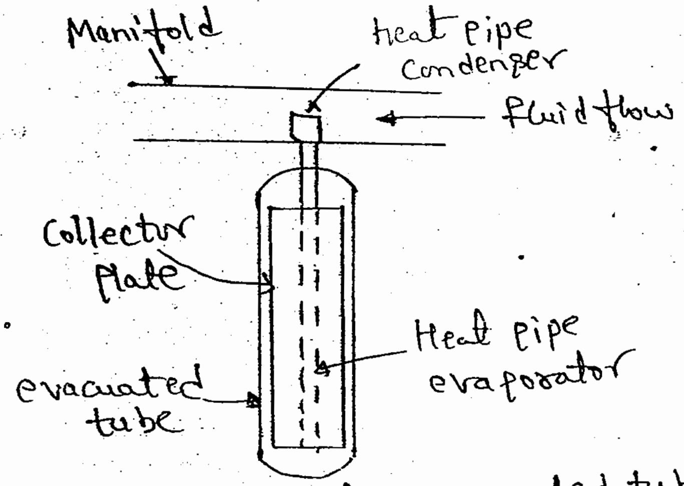

Figure 6. Schematic evacuated tube solar collectors.

→ Evacuated tube collectors can achieve extremely high temperature 75°C - 180°C.

→ evacuated tube collectors are more expensive than flat plate collectors, as their unit area cost about twice than that of the latter.

→ evacuated tube are efficient at high temperatures

→ Thermal losses are very low in evacuated tube collectors.

→ Evacuated tube solar thermal collectors found applications in, heating of domestic & commercial hot water, buildings & indoor swimming pools. cooling of buildings by regenerating refrigeration cycles.

3. Material aspects of Solar collectors:-

(i) Absorber:-

The following are the types of solar flat plate absorbers material that are most frequently used

(a) All copper plates are with integrated water passage

(b) all copper (copper tube on copper sheet)

(c) copper tube or aluminium fin

(d) Iron or steel

(e) plastic (polymers)

Specification requirement of an absorber coating for a flat plate collector is as follows.

(a) It must not degrade under ultraviolet exposure.

(b) It must withstand temperature up to 200°C

(c) It must withstand many temperature cycles over ± 40°C

(d) It must withstand many cycles of low to high relative humidity

(e) It must not chalk, fade or chip.

(ii) Glazing:-

Glazing materials are

(a) glass & fiberglass

(b) Tedlar when bonded to the fiberglass, it acts as a good glazing material.

(c) Optical rating must not change during its service life

(d) A glazing material must be resistant to UV radiation.

(e) plastic glazing can easily withstand for temperature shock.

(iii) Insulation Shell:

A solar flat plate collector must be insulated against excessive heat losses on its back side & on its edges as follows;

1. Back side – 3.5 inch of fibreglass insulation or 2 inch of foam insulation
2. Side – 1 inch of fibreglass or 0.5 to 0.75 inch of foam insulation.

Insulating material withstand the maximum collector stagnation temperature 200°C without damage.

4. Concentrating Collectors:

Concentrating collectors are of various types & can be classified many ways, They may be as follows:

(i) Based on means of concentration: reflecting type mirrors or refracting type use fresnel lenses.
(ii) Based on reflecting surfaces used; parabolic; spherical or flat.
(iii) Continuous or segmented
(iv) Based on the formation of the image; imaging or non imaging.
(v) Imaging concentrator may focus on a line or at a point.
(vi) On the basis of collector concentration ratio or operating temperature range.
(vii) By the type of tracking.

Figure 7. non imaging concentrators.

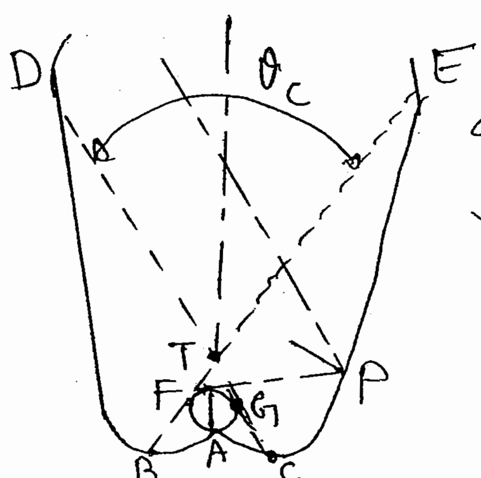

Figure 7. Compound parabolic solar collecter

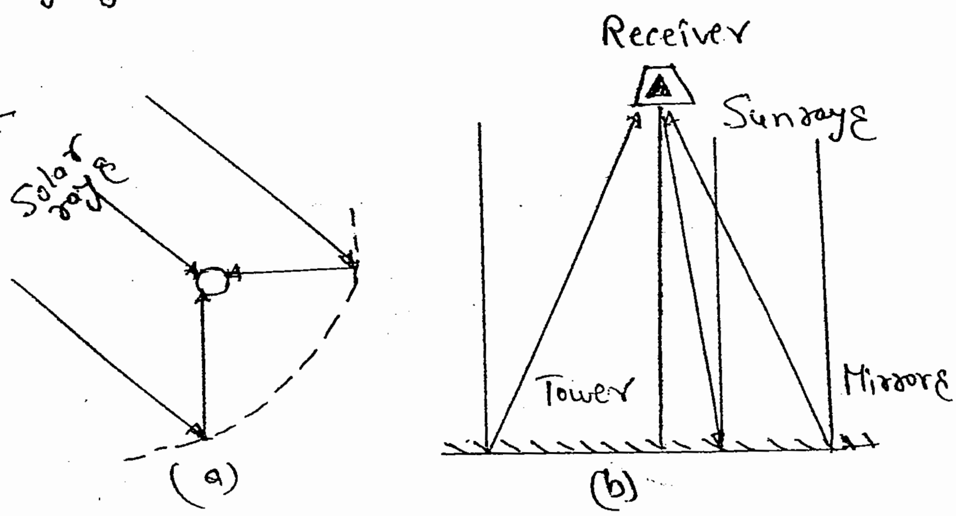

Figure 8. Fresnel through collector (a) parabolic b) linear

→ Parabolic Fresnel collector can effectively produce heat at temperature between 50°C & 400°C.

→ When the parabola is pointed towards the sun, parallel rays incident on the reflector are refected onto the receiver tube. Figure 8.a.

→ Linear fresnel reflector (LFR) technology relies on an array of linear mirror strips that concentrate light on to a fixed receiver mounted on a linear tower. (figure 8.b).

→ The advantage of LFR system is that it uses flat or elastically curved reflectors that are cheaper when compared to parabolic glass reflectors.

→ one demerit of LFR is avoidance of shading & blocking between adjacent reflectors leads to increased spacing between reflectors.

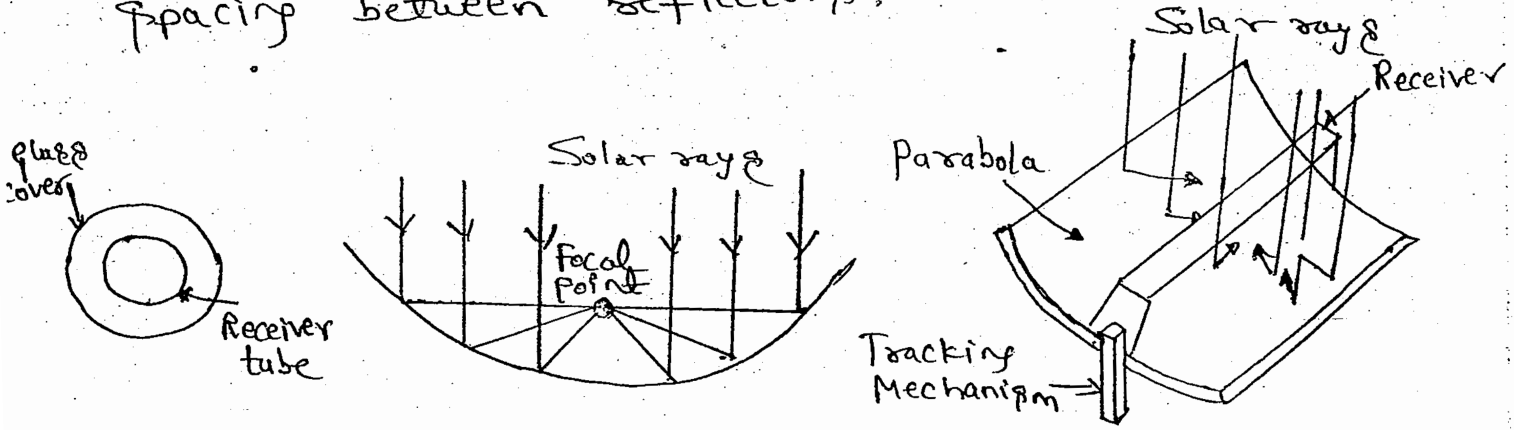

figure 9. parabolic trough reflector.

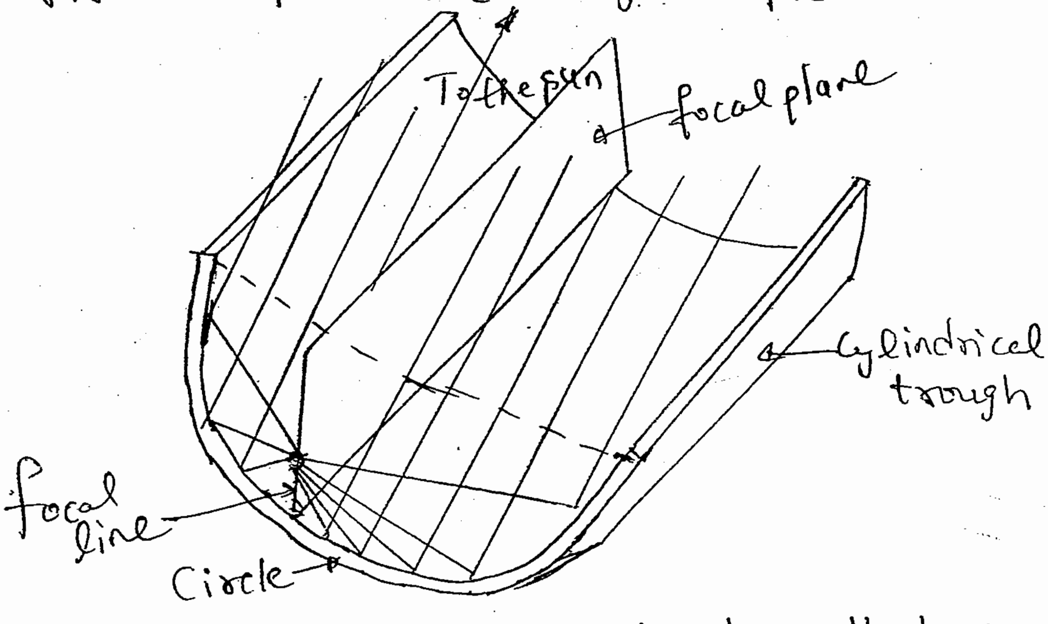

figure 10. Cylindrical trough solar collectors.

→ Parabolic trough are devices that are shaped like the letter "U" shown in figure 9.

→ Parabolic solar thermal collector can produce heat at temperature between 50°C & 400°C, made by metal black tude, covered with a glass tube to reduce heat losses, is placed along the focal line of the receiver.

→ Figure 10, linear translation does not introduce defocusing of the concentrated radiation, the aperture of a cylindrical trough need not track at all to maintain focus.

→ To avoid a dispersed focus, cylindrical troughs would have to be designed with low rim angles inorder to provide an approximate line focus.

→ The advantage of cylindrical mirror geometry is that it need not track the sun in any direction as long as some means is provided to intercept the moving focus.

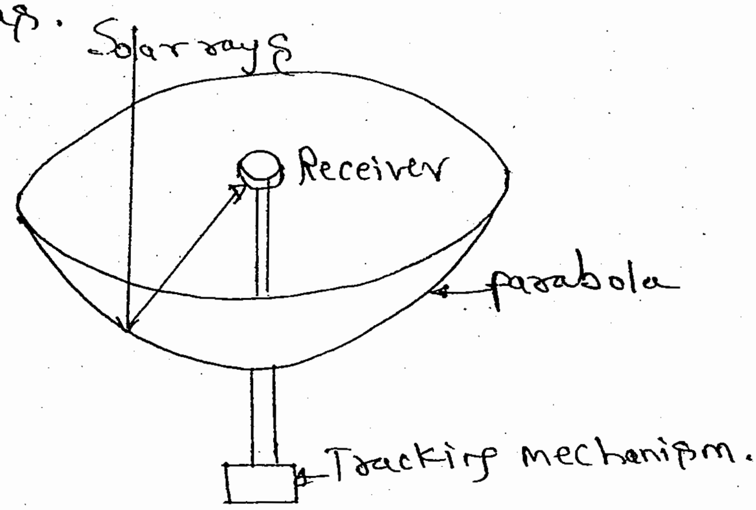

Figure 11. Parabolic dish solar thermal collector.

→ A parabolic dish collector is similar in appearance to a large satellite dish shown in Figure 11.

→ It uses a dual-axis sun tracker.

→ It is a point-focus collector that tracks the sun in two axes.

* Concentrating solar energy onto a receiver located at the focal point of the dish

* The dish structure must track fully the sun to reflect the beam into the thermal receiver.

→ Parabola dish system can acheive temperature in excess of 1500°C. it is also called distributed receiver system.

→ Advantages of parabolic dish reflectors.

i) They are the most efficient of all collector systems as they are always pointing the sun.

ii) It have concentration ratio in the range 500–2000 & highly efficient at thermal energy absorption & power conversion systems.

iii) It have modular collector & receiver units that can either function independently or as part of a large system of dishes.

→ **Heliostat field solar collectors**: Heliostal is a mirror-based system that is used to continuously reflect sunlight onto a central receiver as shown in figure 12.

→ A heliostat uses a field of dual axis sun trackers that directs solar energy to a large observer located on a tower.

→ around 1000°C temperature can be reached.

→ Hence high pressure steam is generated to produce electricity.

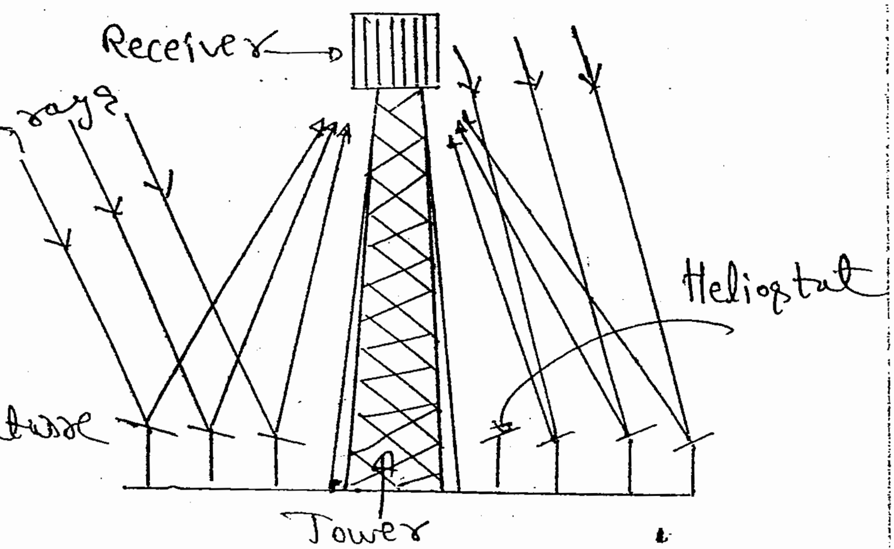

Figure 12. Heliostat field solar collector.

5. Parabolic Dish Stirling Engine System.

The major parts of a parabolic dish-stirling engine system are as follows.

i) Solar dish concentrator: parabolic dish systems that generate electricity from a central power converter collect the absorbed sunlight from individual receivers & deliver it via a heat-transfer fluid to the power conversion systems.

ii) Power conversion unit: The power conversion unit includes the thermal receiver & the heat engine.

* The thermal receiver absorbs the concentrated beam of solar energy, converts it to heat & transfers the heat to the heat engine.
* A thermal receiver can be bank of tubes with a cooling fluid circulating through it.
* The heat engine system takes the heat from the thermal receiver and uses it to produce electricity.
* The engine-generators have several components,
  (a) Reciver to absorb the concentrated sunlight to heat.
  (b) Conversion unit, which converter thermal energy into mechanical work.
  (c) Alternator - which convert mechanical work into electricity.
  (d) Waste-heat exhaust system, to vent excess heat to the atmosphere
  (e) Control system to match the engine operation to the available solar energy.

* The stirling engine is the most common type of heat engine used in dish-engine systems.

iii) ~~Tracking~~ system: A parabolic dish system uses a computer to track the sun & concentrate the sun's rays onto a receiver located at the focal point in front of the dish.

6. Working of Stirling or Brayton Heat Engine:

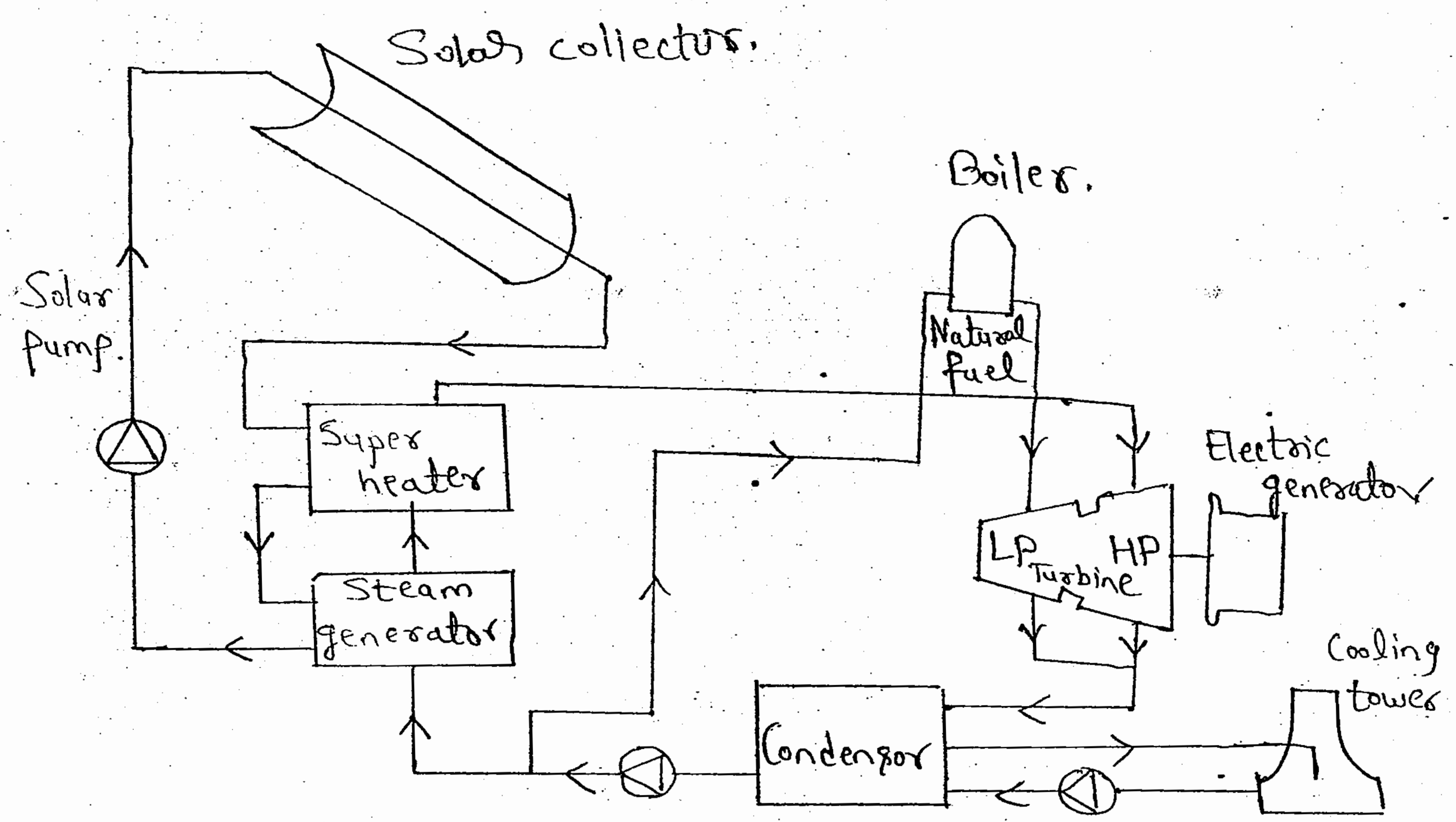

Fig 13. Schematic of stirling / Brayton heat engine. for solar electric generation.

→ Once the array of mirrors focuses the sunlight, the concentrated sunlight then heats up the working fluid to temperatures of around 750°C within the receiver.

→ The heated high temperature working fluid is then used in either a stirling or Brayton heat engine cycle to produce mechanical power via rotational kinetic energy & then electricity for utility use with an electric generator, shown in figure 13.

→ In the Brayton cycle, the concentrated sunlight focused on the solar fluid heats up the compressed working fluid of the cycle i.e., air, replacing altogether or lowering the amount of fuel needed to heat up the air in the combustion chamber for power generation.

→ All Brayton cycles, the hot compressed air is then expanded through a turbine to produce rotational kinetic energy, which is converted to electricity using the alternator.

→ A recuperator is also utilized to capture waste heat from the turbine to preheat the compressed air & make the cycle more efficient.

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7. Solar collector system into Building services.

Availability of solar energy is intermittent & unpredictable it is rarely cost effective to have energy demands from solar energy alone.

The main components of the building heating systems are as follows:

1. Air handling unit : a fan & two motor-driven dampers.
2. Heat storage unit
3. Temperature control system
4. Solar collectors.

Two motor driven dampers say A & B, three modes of system operation can be acheived.

(i) Dampers A & B open :- This is the normal day time solar heating mode. The storage unit is bypassed

(ii) Damper A open & Damper B closed : This mode is used whenever solar heat is collected but no space heating is required at same time.

(iii) Damper A closed & damper B open: This mode is used during cloudy periods or during the night hours.

8. Solar water heating systems:-

Most solar water heating systems have two main parts: a solar collector and a storage tank.

Solar water heating system can be either active or passive systems.

i) Active systems, which are most common, rely on pumps to move the liquid between the collector & the storage tank.

ii) The passive system rely on gravity & the tendency for water to naturally circulate as it is heated.

8.1 Active Solar Water heating system

i) Active Solar space heating.

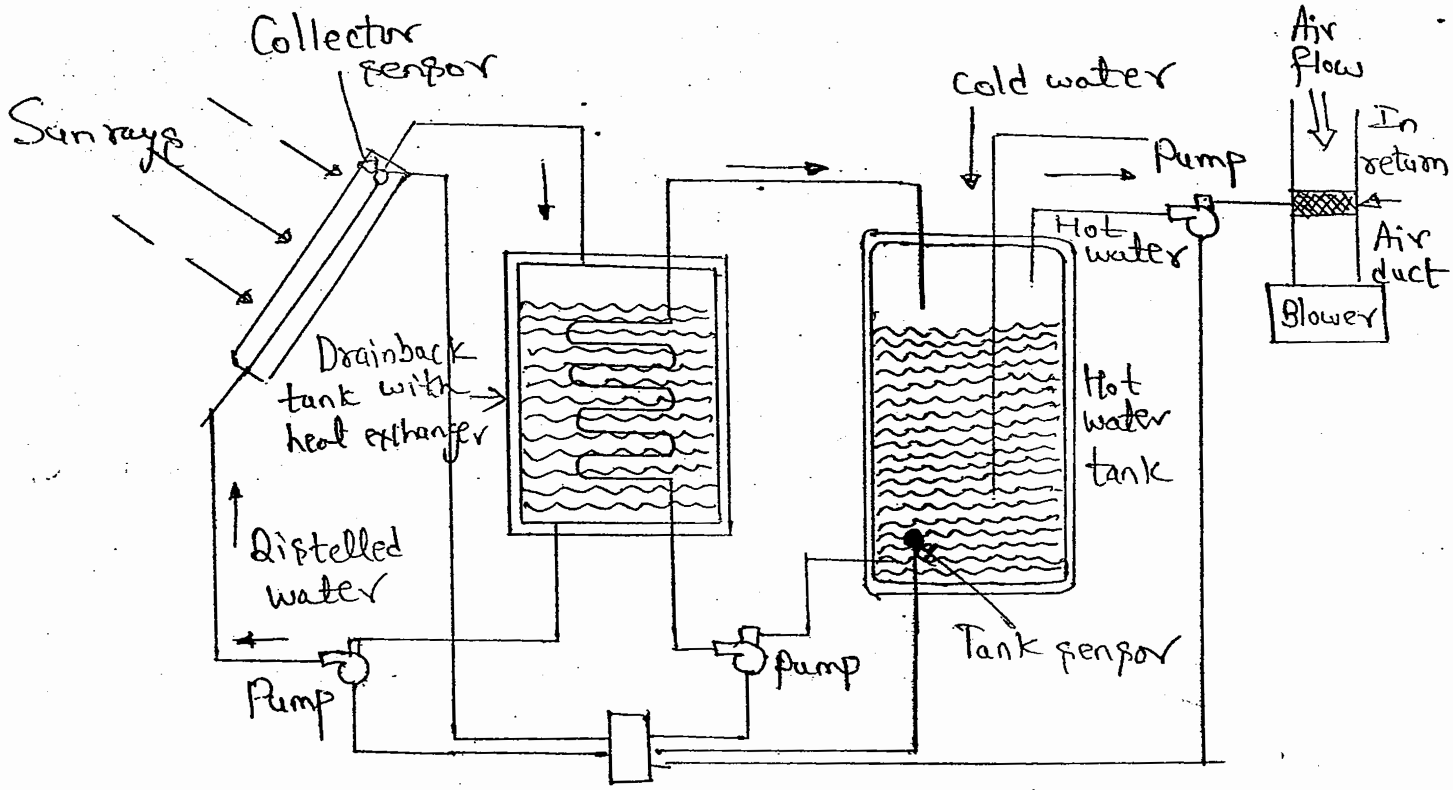

Figure 14. Typical space heating system.

→ The active solar space heating system can use the same operational components as the domestic water heating system as shown in Figure 14. but ties into a heating distribution system that can use heated fluids as a heat source.

→ The distribution system includes hydronic radiator, floor coil systems & forced air systems.

→ <u>Air distribution system</u>: The heated water in the storage tank is pumped into a coil located in the return air duct whenever the thermostat calls for heat.

→ <u>Hydronic system with radiators</u>: The heated water is circulated in series with a boiler into radiators located in the living spaces, Modern baseboard radiators operate effectively at 140°C.

→ <u>Hydronic system with in-slab heat</u>: The solar heated water is pumped through distribution piping located in the floor of the home. Lower temperature are used in this type of system around 80°C.

The space heating system, like the domestic water heating system, must be backed up by an auxiliary heating system.

The storage system should be sized to approximately 1.5 gallons of storage for each square foot of collector area.

2) <u>Active Solar Space Cooling</u>:-

→ Solar space cooling is quite costly to implement.

→ It is best to use a solar system that serves more than just the cooling needs of a house to maximize the return on investment & not leave the

System idle when cooling is not required.

- Significant space heating/water heating can be accomplished with the same equipment used for the solar cooling system.
- Active solar absorption cooling is presented in figure 15. in which (T) represents the sequence of flow.

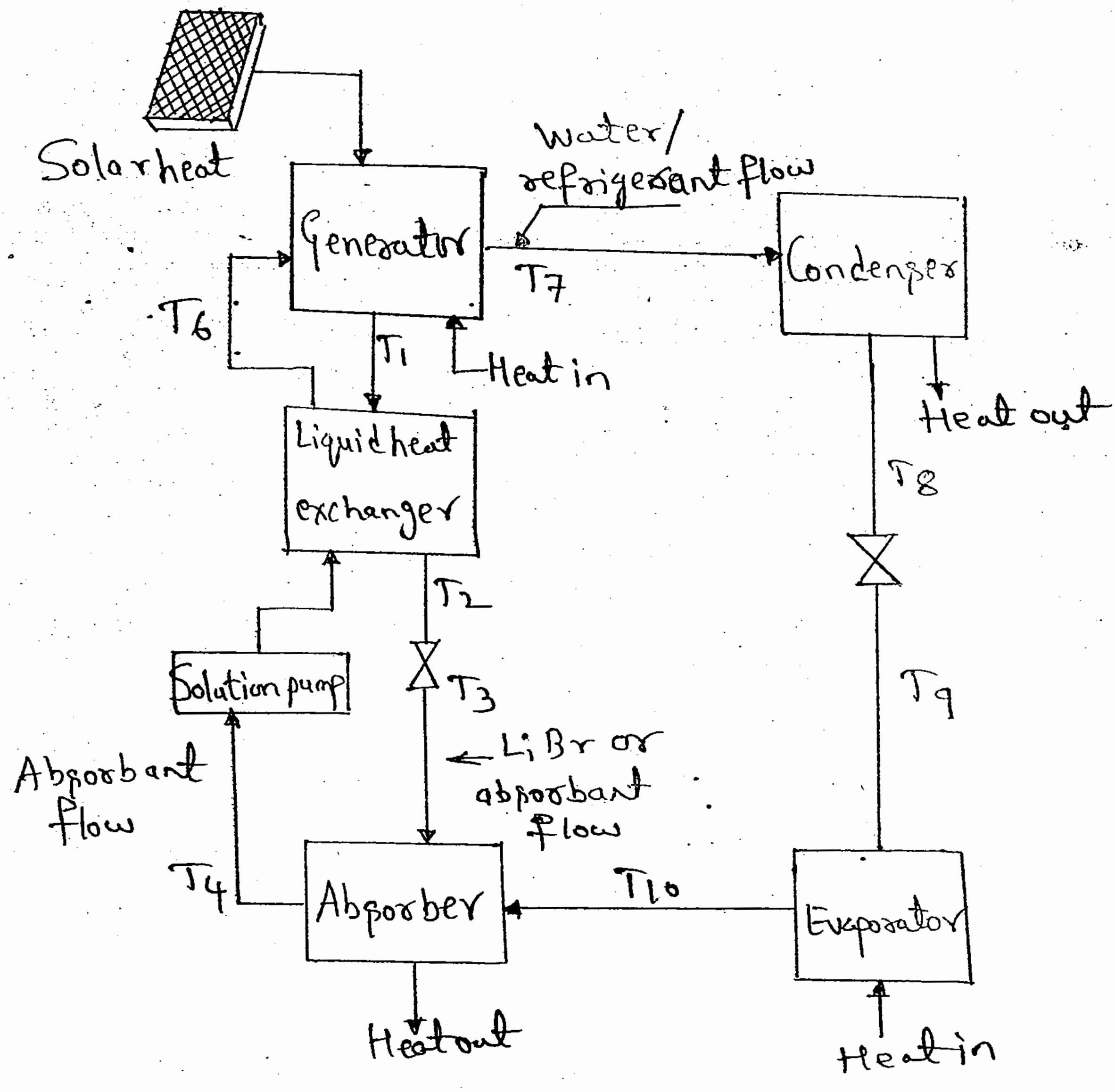

Figure 15. Solar space cooling.

- Heat from solar collectors separates a low boiling refrigerant in a generator that receives the pressurized refrigerant from an absorber.
- Solar heat can also be used in the evaporation stage of the cycle.

3. Active Solar Air Heating :-

→ Solar heat is non-polluting and best of all, it incurs no fuel costs

→ It is mainly for buildings & Industries

→ It includes solar collectors, Temperature control systems. Heat storage unit/rock bed & Air handling unit / Dampers.

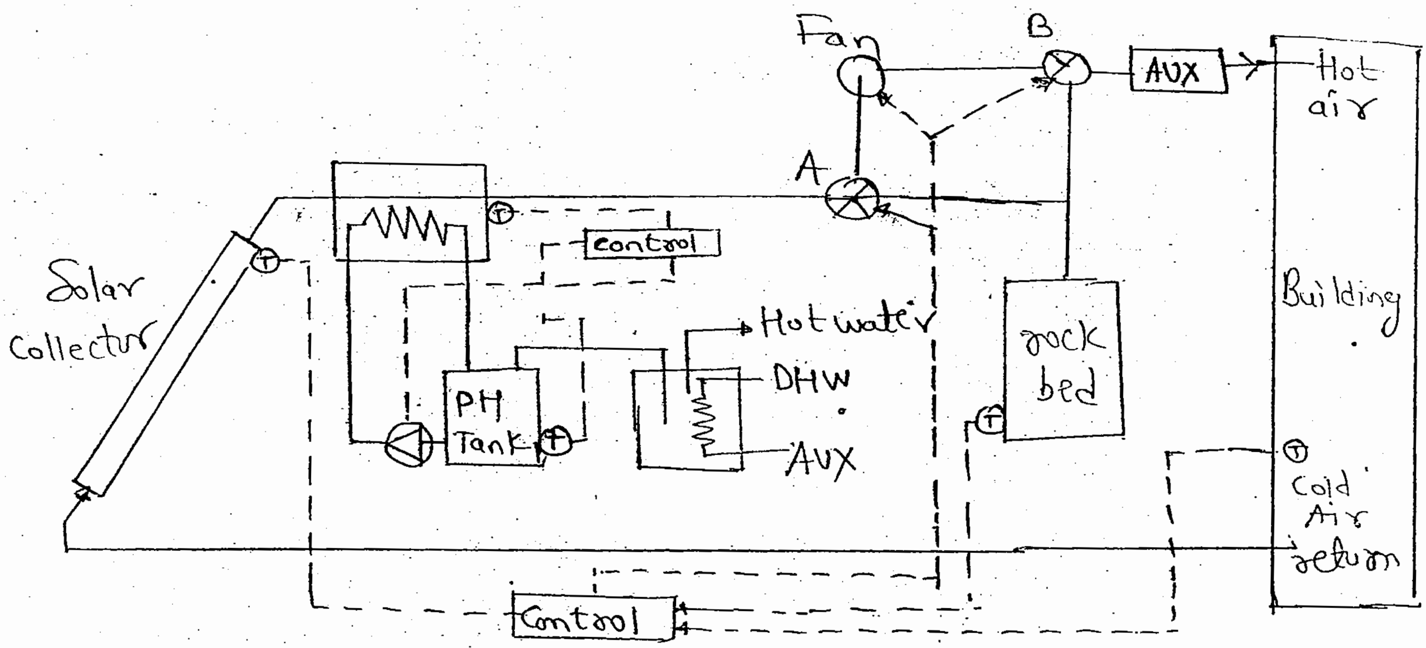

Figure 16. Solar Air Heating system.

→ A & B are dampers (motor driven & fan)

→ If Both Dampers are open, then it is the normal day time solar heating mode

→ If Damper A open & damper B closed, Then used whenever solar heat is collected but no space heating is required at the same time.

→ If Damper A closed & Damper B open, Then used during cloudy periods or during the night hours.

→ The fan blows the solar heated air through the rock bed for thermal storage.

→ Auxiliary furnace is activated automatically if the temperature is insufficient to meet the demand.

8.2 Passive solar water heating systems

→ A passive solar water heating system uses natural convection or household water pressure to circulate water through a solar collector to a storage tank or to the point of use.

→ passive system is generally less efficient than active systems, but passive approach is simple & economical.

→ Two types of passive water heaters.
(i) Batch system (ii) thermosiphon system.

(i) Batch system:

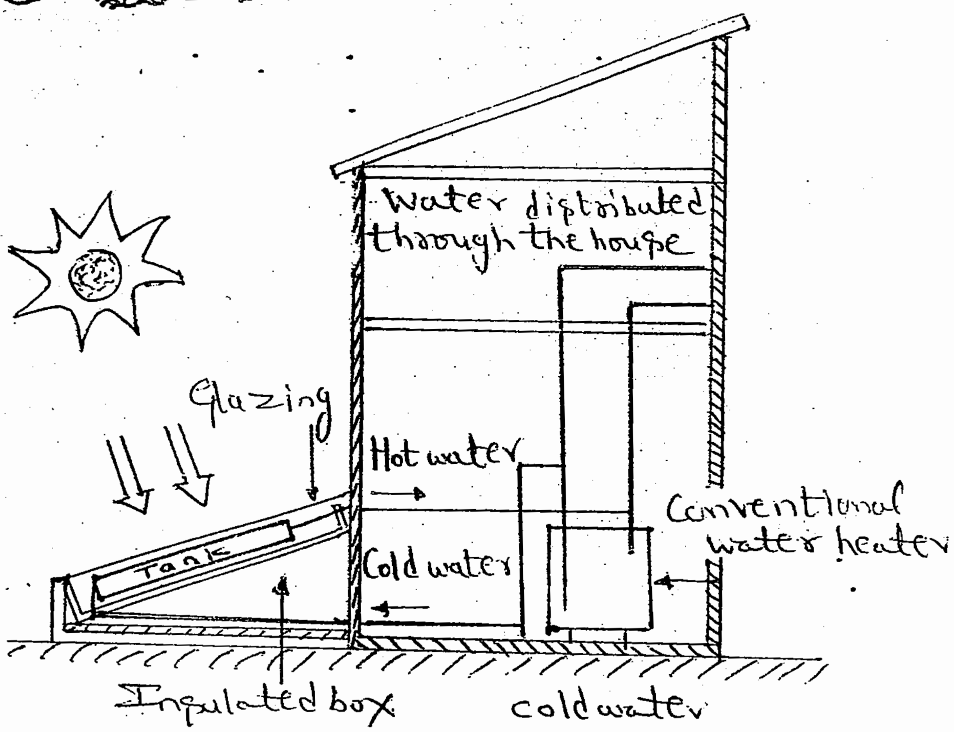

Figure 17. batch type domestic water heating system.

→ The batch system is the simplest of all solar water heating systems as depicted in Figure 17.

→ It consists of one or more metal water tanks painted with a heat absorbing black coating & placed in an insulating box or container with a glass or plastic cover that admits sunlight to strike the tank directly.

- The water in the batch heater itself will not freeze because there is adequate mass to keep it from freezing.
- The most effective use of a batch water heater is to use hot water predominantly in the afternoon & evenings when the temperature in the tank will be the highest.

(ii) Thermosiphon system;

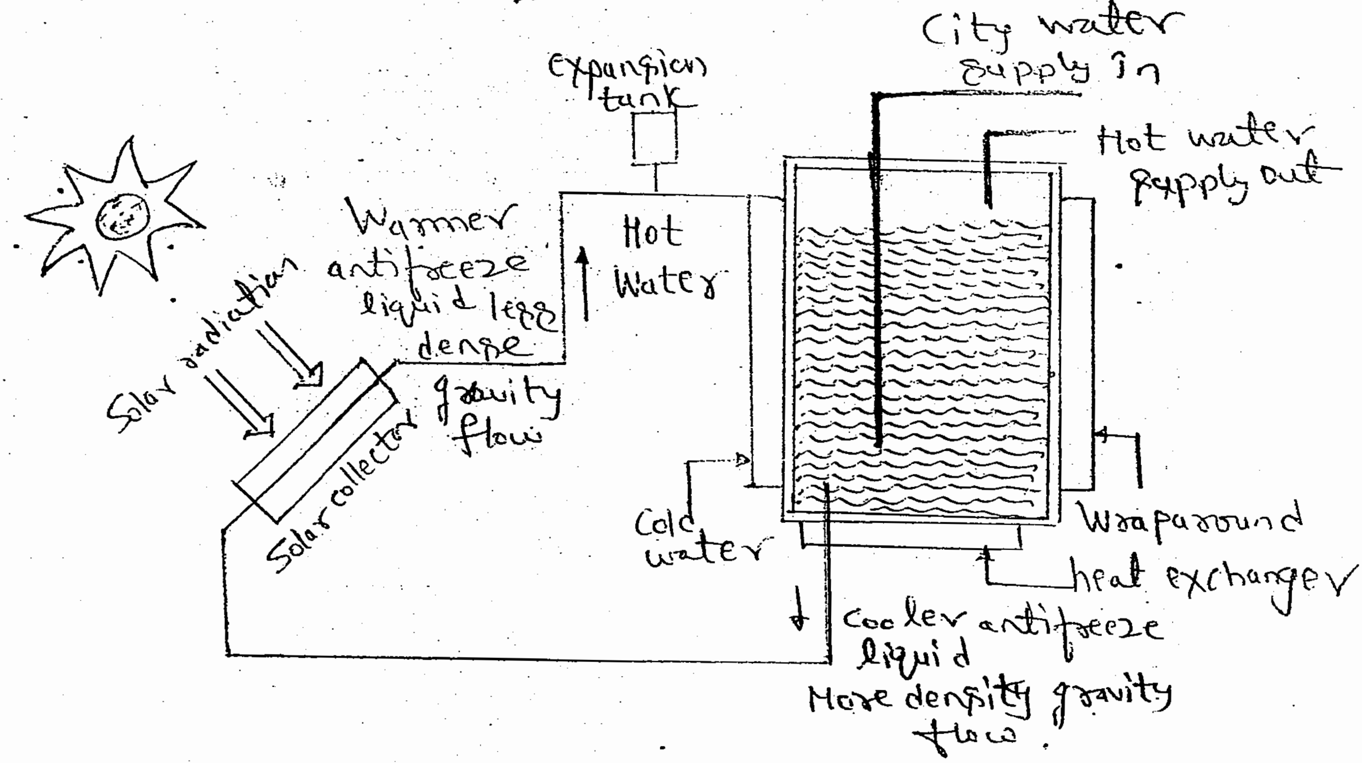

Figure 18: Thermosiphon system.

- The thermosiphon system uses a flat plate collector & a separate storage tank that must be located higher than the collector shown in Figure 18.
- The storage tank located above collector receives heated water coming from the top of the collector into the top of the storage tank.
- The storage tank may or may not use a heat exchanger.
- The thermosiphon system is more complex & costly than the batch system.
- Cold water from the bottom of the storage tank will be drawn into the lower entry of solar collector to replace the heated water that was thermosiphoned upward.

9. Applications of Solar water heating systems.

The following are few industrial applications of solar water heaters.

1. Hotels : bathing, kitchen, washing, laundry applications
2. Dairies : Ghee production, cleaning & sterlizing, pasteurization.
3. Textiles: bleaching, boiling, printing, dyeing, curing ageing & finishing.
4. Breweries & distilleries : bottle washing, work preparation, boiler feed heating.
5. Chemical/bulk drug units : fermentation of mixes, boiler feed applications.
6. Electroplating or galvanizing units : heating of plating baths, cleaning, degreasing applications.
7. Pulp & paper industries : boiler feed applications, soaking of pulp.

10. Solar Dryers:

Solar dryers find numerous applications in industries such as textiles, wood, fruit & food processing, paper, pharmaceutical & agro-industries.

Advantages

→ Drying process is completed in the most hygienic & eco-friendly way.

→ It have low operation & maintenance costs.

→ Solar dryers last longer, A typical dryer can last 15-20 years with minimum maintenance

Limitations

1. Drying can be performed only during sunny days, unless the system is integrated with a conventional

energy-based system

2. Due to limitations of solar energy collection, the solar drying process is slow in comparison with dryers that use conventional fuels.

3. Normally, solar dryers can be utilized only for drying at 40°C - 50°C.

Commonly used solar Dryers are (i) Rice solar dryer (ii) Rock-bed solar dryer.

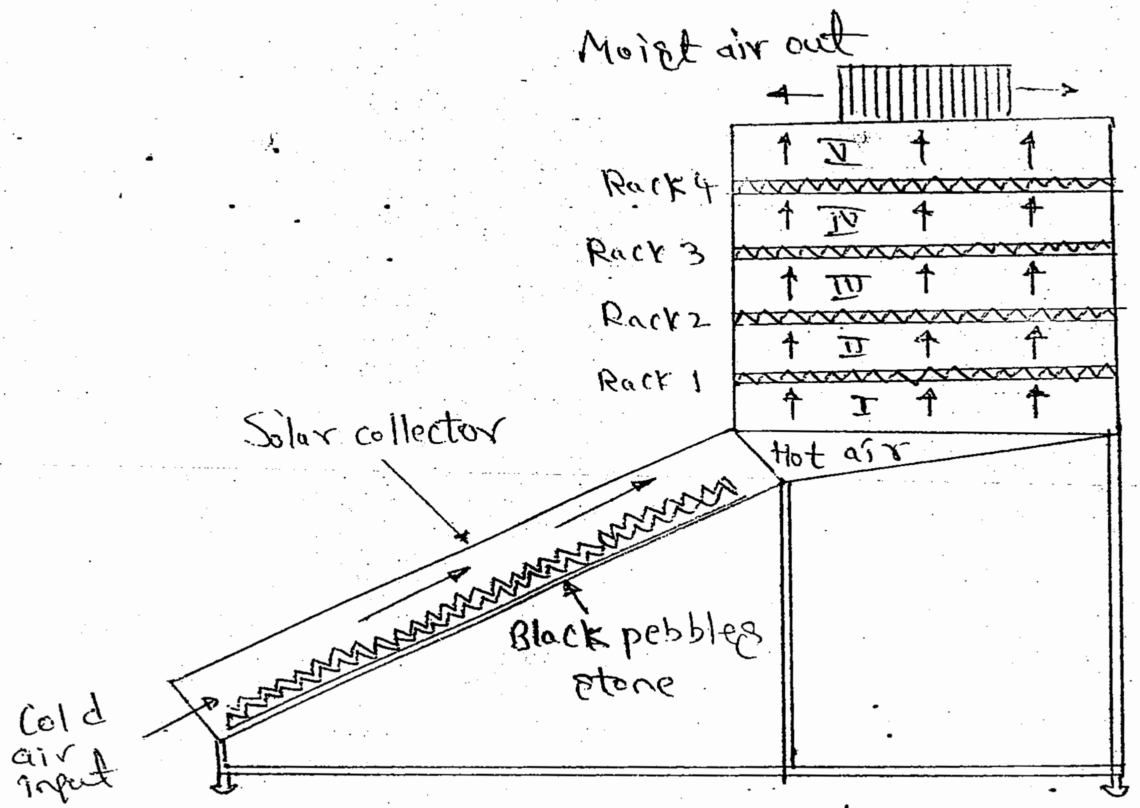

Figure 19. A rice solar dryer.

→ Air is drawn through the dryer by natural convection, it is heated as it passes through the collector & then partially cooled as it picks up moisture from the rice.

→ The rice is heated both by the air & directly by the sun.

→ Warm air can hold more moisture than cold air so the amount required depends on the temperatures to which it is heated in the collector as well as the amount held when it entered the collector.

A ~~rock~~ rock bed dryer is shown in figure 20.

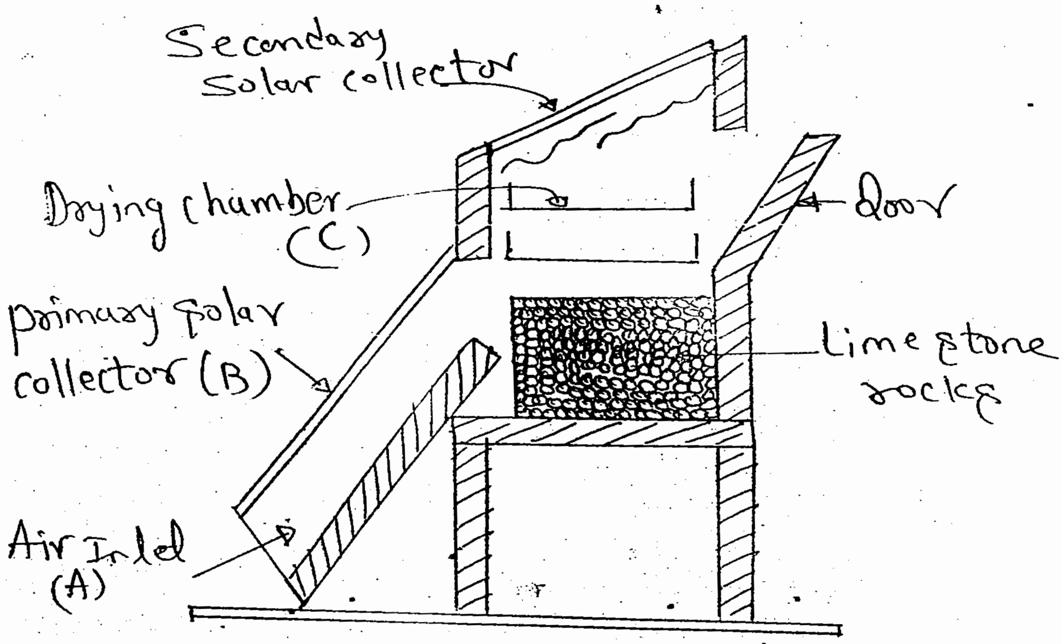

Figure 20. Rock-bed solar dryer.

→ In this dryer, air drawn by natural convection through an air inlet (A), circulates the heat collected by the primary solar energy collector (B), throughout the drying chamber (C), which is packed with limestone rocks of relatively uniform diameter.

→ It requires very little maintenance.

→ Solar-heated air can be used to dry
(i) Crops, timber, distillers grains & textiles
(ii) Tea, coffee, beans, tobacco etc.,
(iii) Food for dehydration or processing
(iv) sludge, manure & compost.

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11. <u>Solar cookers;</u>

People use solar cookers primarily to cook food & pasteurize water, although additional uses are food preferences, traditional cooking fuels.

Many types of cookers exist, simple solar cookers use the following basic principles —

1. Concentrating sunlight; A reflective mirror of polished glass, metal or metalized film is used to concentrate light & heat from the sun into a small cooking area.
2. Converting light to heat.
3. Trapping heat.
4. Greenhouse effect.

Types of solar cooker
(i) Box-type solar cooker
(ii) Reflector type solar cooker.
(iii) parabolic cookers.

*/. Imp Advantages & disadvantages of solar cooking.

Advantages;

1. Cooking with solar energy saves fuel wood / chemical fuels.
2. It is clean & healthy & reduce health problems related to kitchen smoke
3. Solar cooking enables individual families, hence money can be saved.
4. Solar cooking saves time
5. Food cooked in box-type solar cookers cannot burn & does not have to be stirred or watched.
6. Food cooked in box-type solar cooker is cooked gently so that of more nutrients & flavour of the food are conserved.

Disadvantages:-

1. Solar cooking requires good weather with relatively steady sunshine

2. Solar cooking cannot completely replace the conventional wood, gas or kerosene fire.

3. It is only possible during the daytime but not in morning & evening

4. Most types of solar cookers require industrially manufactured components, impossible to repair or replace them with local material.

5. Some solar cooking boxes do not attain high temperatures, requires long cooking time.

6. Boiling, roasting & grilling require high temperatures & thus, it is only possible in a few types of solar cookers.

7. Some reflector-type solar cookers demand understanding, skill & almost constant attention when handling & cooking with them.

8. The person doing cooking has to stay out in the sun to avoid the risks of being dazzled or burnt.

9. Generally, families that need solar cookers mostly cannot afford them.

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12. Solar pond;

→ One of the best ways of harnessing solar energy is through solar ponds

→ It is basically a pool of water that collects & stores solar energy.

→ Solar pond has Layers of salt solutions of differing concentrations, different densities to a certain depth.

→ The solar pond is filled with three layers of water.

1. The top layer is cold and has relatively little salt content.

2. Intermediate insulating layer has a salt gradient that maintains density gradient.
This gradient helps in preventing heat exchange with the natural convection of water.

3. The bottom layer is hot up to 100°C & has a high salt content.

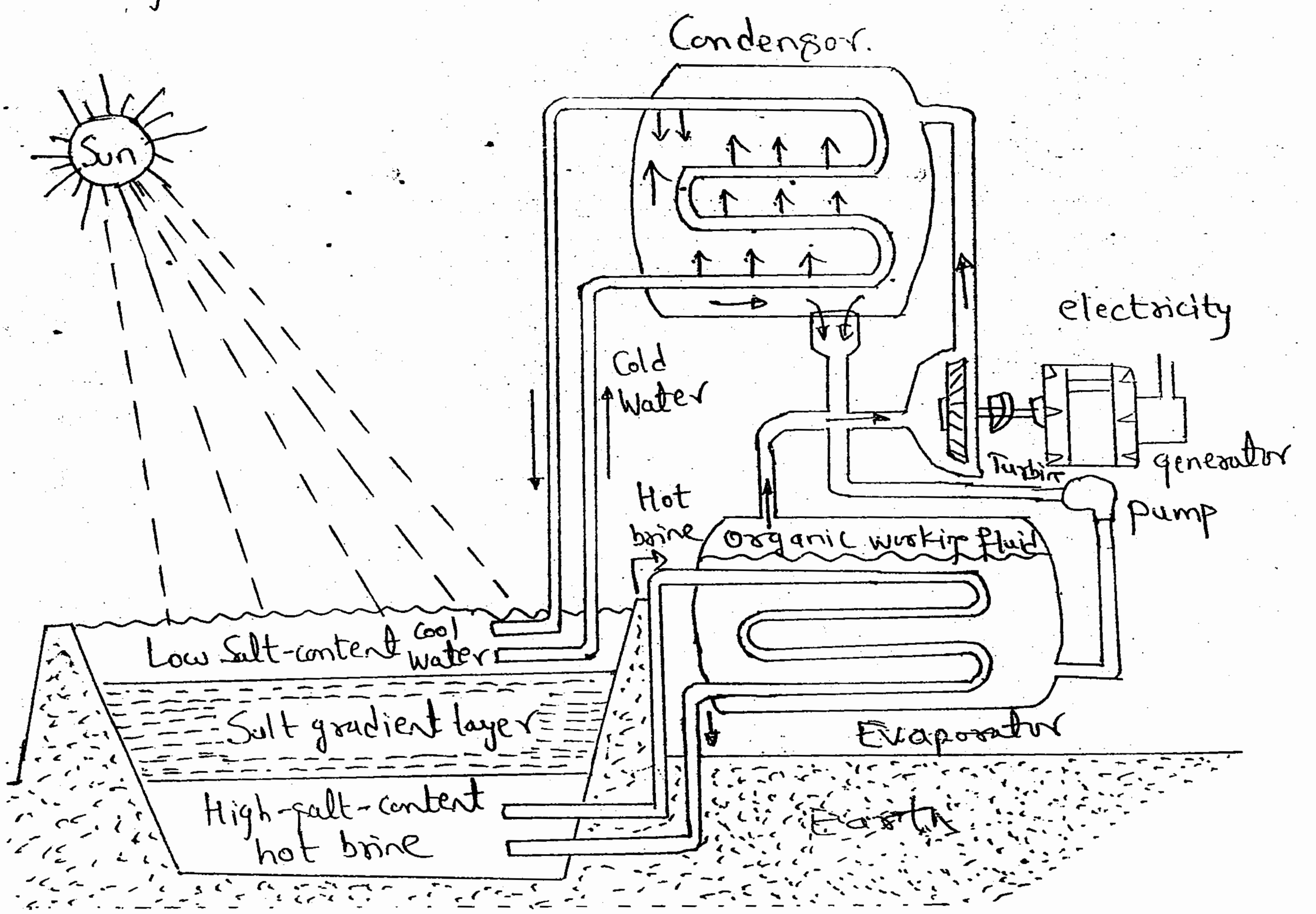

Figure : 21

Working:

→ When solar radiation strikes the pond, most of it is absorbed by the layer at the bottom of the pond. therefore

→ The temperature of the dense salt layer therefore increases

→ If the pond contained no salt, the bottom Layer would be less dense than the top layer as the heated water ponds. The less dense layer would then rise up & the layers would mix.

→ But the salt density difference keeps the layers of the solar pond separate.

→ The denser salt water at the bottom prevents the heat being transferred to the top layer of fresh water by natural convection, due to which the temperature of the lower layer may rise to as much as 95°C to 100°C

Advantages

1. Environment friendly energy - no pollution
2. Reliable energy source
3. stores heat, so it can be used . 24*7*365
4. Can be constructed according to requirements
5. Low maintenance costs.

Solar Cell.

1. Components of Solar cell system:-

(i) Photovoltaic cell: Semiconductor material that generate voltage & current when exposed to sunlight

(ii) Module: PV cell wired together & laminated between a clear strait glazing & encapsulating substrate.

(iii) Array: One or More modules with mounting hardware & wired together at specific voltage.

(iv) Charge controller: Power-conditioning equipment to regulate battery voltage.

(v) Battery storage: A medium that stores direct current (DC) electrical energy.

(vi) Inverter: An electrical device that changes DC to AC to operate loads that requires AC.

(vii) DC load : Appliances, motors & equipment powered by DC.

(viii) AC load : Appliances, motors & equipment powered by AC.

2. Elements of Silicon Solar cell ;

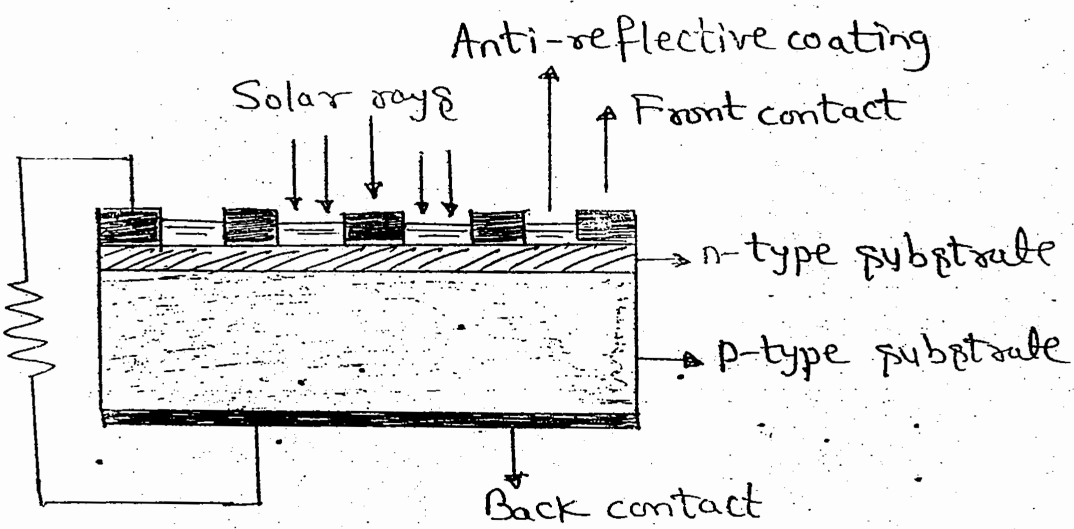

Figure 22. element of PV cell.

The elements of a solar cell is described in Figure 22. The following are basic elements.

(i) Substrate; It is an unpolished p-type wafer referred to as p-region base material. The important parameter to be kept in mind while choosing a wafer for solar cell are its. orientation, resistivity, thickness & doping. Wafer may be single crystalline or multi-crystalline.

(ii) Emitter; The emitter formation involves the doping of silicon with pentavalent impurities such as phosphorus, arsenic & antimony, for solar cell applications, phosphorus is the widely used impurity.

(iii) Electrical contacts: It bridge the connection between the semiconductor material & the external electrical load.

It includes.

(a) Back contact: It is a metallic conductor completely covering back. The back contact of a cell is located on the side away from the incoming sunlight & is relatively simple. Its layer made of aluminium or molybdenum metal.

(b) Front contact: The front contact is located on the side facing the light source & is more complicated, when light falls on the solar cell
a current of electrons flow over the surface.
If contacts are attached at the edges of the
cell, it will not work well due to the great
electrical resistance of the top semiconductor
layer, only a small number of electrons will make it to the contact.

(c) Anti-reflective coatings: It is applied to reduce surface reflection & maximize cell efficiency in solar glass & silicon solar cell. It allows more light to reach the semiconductor film layer, increasing solar cell efficiency.

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3. Solar cell Materials:

A solar cell consists of semiconductor materials.

1. Silicon : most popular material for solar cells.
   - (i) Monocrystalline or single crystal silicon
   - (ii) Multi-crystalline silicon
   - (iii) Poly crystaline silicon
   - (iv) Amorphous silicon
   - (v) Copper indium diselenide ($CuInSe_2$)
   - (vi) Cadmium telluride (CdTe).
2. Thin film: Thin film solar cells use layers of semiconductor materials only a few micrometer thick.

(i) Rooftop or solar shingles
(ii) Roof tiles
(iii) Building facades
(iv) Glazing for skylight

4. Practical Solar cells:

(i) Crystalline silicon cells: The modules have long lifetime (20 years or more) & their best production efficiency is approaching 18%.

(ii) Amorphous silicon solar cell: cheaper type of solar cell but less efficiency. (5 to 10% η_{cy})

(iii) Cadmium telluride & copper indium diselenide; Low cost & acceptable conversion efficiency (5–8% η_{cy}).

(iv) High-efficiency solar cells: gallium arsenide, indium phosphide has high efficiency, used for power satellites or system operate under high-intensity concentrated sunlight. (18–25% practical efficiency).

5. Solar Cell performance.

In analysing the cell performance, the photovoltaic process of solar cell can be modelled as a macroscopic equivalent circuit as shown in figure-23.

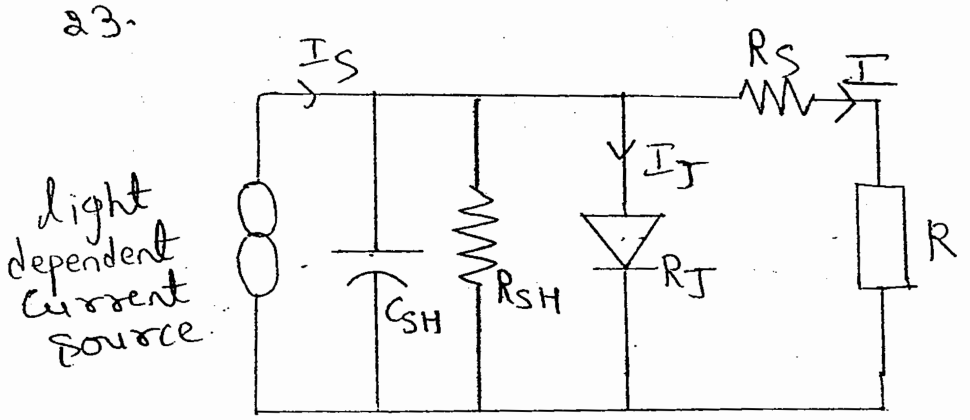


Figure 23: Equivalent circuit of photovoltaic cell.

The circuit consists of light-dependent current source supplying current I_s to a network of resistances including.

1. Junction resistance R_J 2. Internal shunt resistance R_{SH} 3. Internal series resistance R_s 4. Internal shunt capacitance C_{SH} 5. External load resistance R.

R_{SH} is larger than R so that most of the available current can be delivered to load. & R_s is less than R. ∴ simplified circuit is shown in figure 24.

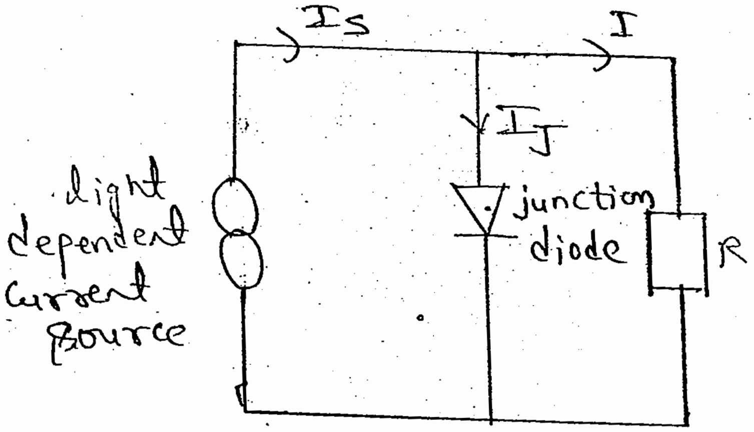


Figure 24. Simplified equivalent ckt of PV cell.

Load current, $I = I_s - I_J \rightarrow (1)$

& $I_J = I_0\left[\exp\left(eV/kT\right) - 1\right] \rightarrow (2)$

I_0 = reverse saturation current V = voltage developed/applied across the junction. e = electron charge k = Boltzmann's constant & T = absolute temperature.

under short circuit condition

$V = 0$ & $I = I_s$

under open circuit condition $I = 0$, maximum open-circuit voltage becomes V_{oc}.

$I = I_s - I_0\left[\exp(eV/kT) - 1\right]$

Applying open circuit conditions, $I = 0$, $V = V_{oc}$.

$$\exp(eV_{oc}/kT) - 1 = \frac{I_s}{I_o}$$

or

$$V_{oc} = (kT/e)\left[\ln\left\{I_s/I_o\right\} + 1\right]$$

5.1. I-V characteristics of solar cells.

The voltage output of a cell, in general, can be obtained as

$$V = (kT/e)\log_e\left[1 + (I_s - I)/I_o\right]$$

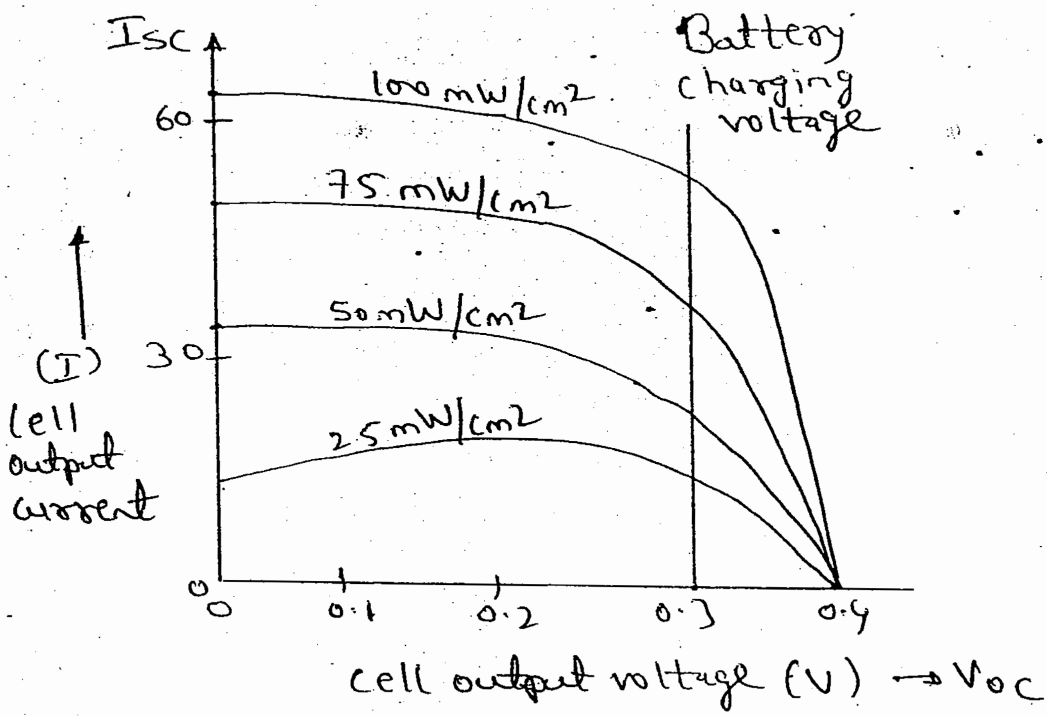


Figure 25; I-V characteristic of solar cell under different illumination levels.

1. The short circuit current (I_{sc}) is the current produced when the positive & -ve terminals of the cell are short-circuited & the voltage between the terminals is zero which corresponds to a load resistance of zero.

2. The open circuit voltage (V_{oc}) is the voltage across the positive & negative terminals under open-circuit conditions when the current is zero, which corresponds to a load resistance of infinity.

5.2 Output power

cell output power, $P = I \times V$

output power depends on the value of load resistance for a given light intensity.

$$\boxed{P = \left[I_s - I_o \{Exp(eV/kT) - 1\}\right] \cdot V} \rightarrow (1)$$

5.3 Maximum output power of the cell.

differentiating equ (1) w.r.t V & setting the derivative equal to zero.

$\frac{dP}{dV} = 0$ put $V = V_{MP}$

$$0 = \left[I_s - I_o \{Exp(eV_{MP}/kT) - 1\}\right] + V_{MP}\left[-I_o\{(e/kT) Exp(eV_{MP}/kT)\}\right]$$

can be rearranged as.

$$\boxed{\left[Exp(eV_{MP}/kT)\right]\left[1 + eV_{MP}/kT\right] = (1 + I_s/I_o)} \rightarrow (2)$$

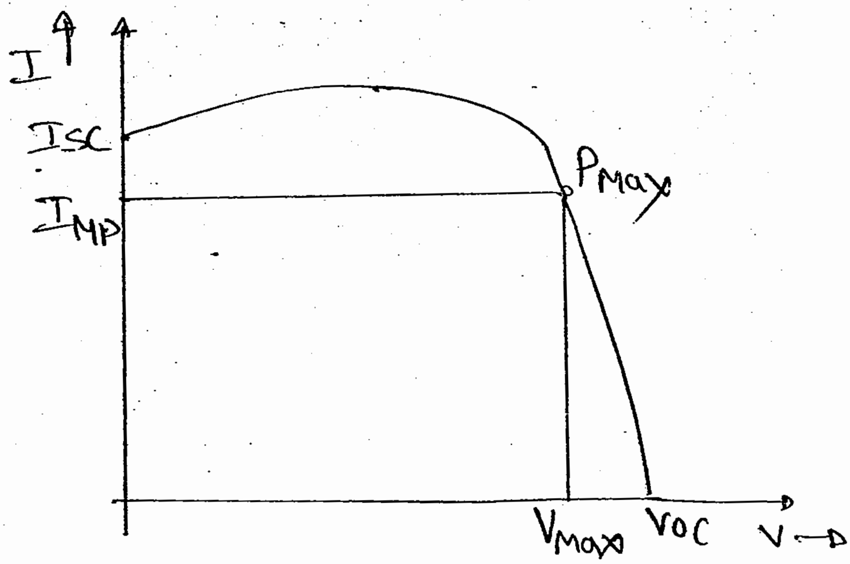


figure 26 I-V characteristic of ideal solar cell.

The load current (I_{MP}) that maximizes the output power can be found as,

$$\boxed{I_{MP} = \{(eV_{MP}/kT)/(1 + eV_{MP}/kT)\}(I_s - I_o)} \rightarrow (3)$$

5.4 Efficiency of Solar cells

Energy conversion efficiency $\eta = \frac{\text{Maximum output power}}{\text{irradiance} \times \text{area}}$.

$$\boxed{\eta = \frac{P_{max}}{E \times S}}$$

E = input light power W/m^2

S = surface area of the solar cell (S in m^2).

5.5. Fill Factor:

$$FF = \frac{\text{Maximum output power}}{(\text{open circuit voltage}) \times (\text{short-circuit current})}$$

$$\boxed{FF = \frac{P_{max}}{V_{oc} \times I_{sc}}}$$

$$\boxed{FF = \frac{V_{MP} \times I_{MP}}{V_{oc} \times I_{sc}}}$$

$$\boxed{FF = \frac{\eta \times S \times E}{V_{oc} \times I_{sc}}}$$

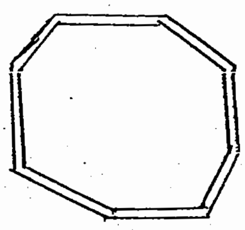
Fill factor is directly affected by the values of cell's series & shunt resistances.

Increasing R_{SH}, decreasing R_s leads Higher fill factor ∴ greater efficiency.

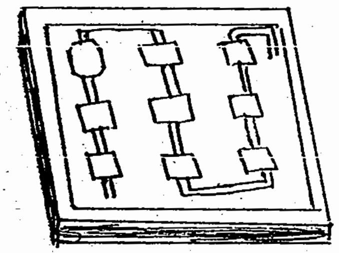
6. Photovoltaic panels:

Single solar cell has a working voltage & current of about 0.5V & 50mA respectively, they are usually connected together in series to provide

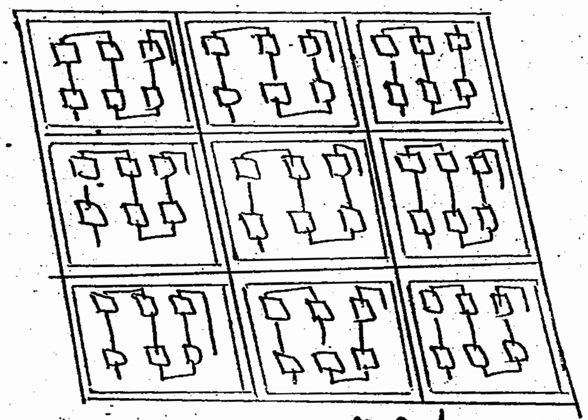
larger voltages.
parallel connection of several strings of cells will give rise to higher current output when compared with single series string of cells.



Single Solar cell



Solar Module.



Series-parallel Array

N_S = Number of cell in series

N_P = number of parallel string

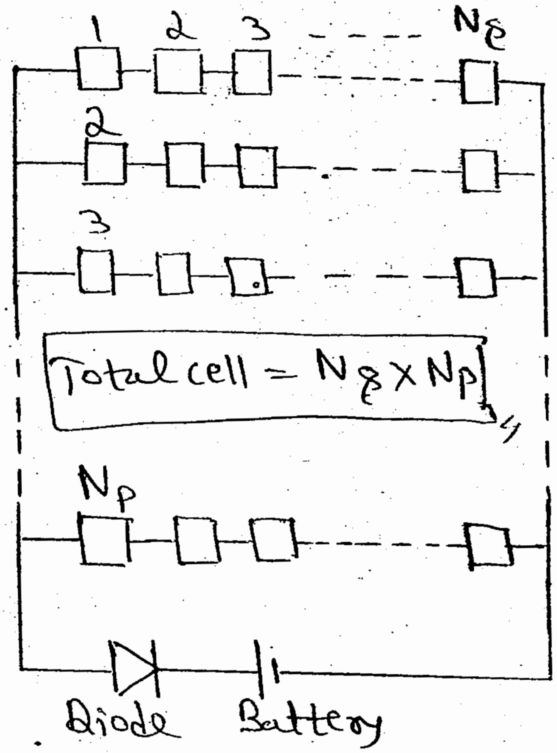


Figure 27. Assembly of series-parallel Array with diode & Battery.

1. Number of Solar cell required in series

$$\boxed{N_S = \frac{V_B + V_D + V_W}{V_{MP}}}$$

$V_D = 0.7V$ [diode drop].
V_B = Bus voltage
V_W = voltage drop in wiring

V_{MP} = solar cell voltage at maximum power

2. Number of Solar cell in parallel String.

$$\boxed{N_P = \frac{I_L}{I_{MP}}}$$

I_L = load current.
I_{MP} = current at maximum power.

7. Application of Solar cell systems

(i) Solar water pumps
(ii) Solar vehicle
(iii) Solar lanterns
(iv) Solar panels on spacecraft
(v) Grid-connected Photovoltaic Power system
(vi) Cathodic protection system.
(vii) Electric fences
(viii) Remote lighting systems
(ix) Telecommunications & Remote Monitoring systems
(x) Rural electrification
(xi) Water treatment systems.

8. Problems on Solar cell, η_y, FF & Arrays.

Q1) For a typical PV cell, the following performance parameters are obtained from the I-V characteristics
$V_{oc} = 0.611$, $I_{sc} = 2.75$, $V_{MP} = 0.5$ & $I_{MP} = 2.59$.
calculate fill factor of the cell.

Sol^n;

$$\text{Fill factor} = \frac{V_{MP} \times I_{MP}}{V_{oc} \times I_{sc}}$$

$$FF = \frac{0.5 \times 2.59}{0.611 \times 2.75}$$

$$\boxed{FF = 0.7707}$$

Q2) Certain solar cell type has an output capability of 0.5 A at 0.4V. Assume that an array of such cells with 100 parallel strings & each string with 300 cells in series is to be building up. What will be the array output voltage (V_a), array current (I_a) & array output power P_a?

Soln.;

No of cell in series, $N_s = 300$
No of parallel string, $N_p = 100$ } given data

Voltage of one cell $= 0.4V = V_C$
Current of one cell $= 0.5A = I_C$ } given data

$\therefore$ array output voltage, $V_a = N_s \times V_C$
$= 300 \times 0.4$
$\boxed{V_a = 120 \text{ volt}}$

$\therefore$ array output current $I_a = N_p \times I_c$
$= 100 \times 0.5$
$\boxed{I_a = 50A}$

$\therefore$ Array output power, $P_a = V_a \times I_a$
$= 120 \times 50$
$P_a = 6000W$
$\therefore \boxed{P_a = 6 \text{ KW}}$

Q3) A certain 120V, 60Hz AC motor is to be powered by solar cell array during the day & at night, by a 120V public utility. A DC to AC converter is available that changes the array DC output into a 120V, 60Hz AC with 90% efficiency independent of load phase angle, while running motor has a DC resistance of 300Ω & an inductance of 0.3H. How much power output must be array provide?

Soln.; Inductive reactance of motor, $X_L = 2\pi f L = 2\pi \times 60 \times 0.3$
$\boxed{X_L = 113\,\Omega}$

∴ Motor impedance $Z = R + jX_L$

$$Z = 300 + j113$$

$$|Z| = 320\,\Omega \quad \text{i.e., } \sqrt{300^2 + 113^2}$$

Motor current, $I = \frac{V}{|Z|} = \frac{120}{320} = 0.375\,A$ //

Power drawn by motor $P_m = I^2 R = (0.375)^2 \times 300 = 42.2W$

or

$$P_m = VI\cos\phi = VI \cdot \frac{R}{Z} = 0.375 \times 120 \times \frac{300}{320}$$

$$P_m = 42.2W.$$

Hence, array power = input power of motor $= \frac{P_m}{\eta_m}$

$$= \frac{42.2}{0.9}$$

$$\boxed{P_a = 46.9W} //$$

Q4) A solar cell array is required to deliver 100W peak output at 120 V DC bus voltage. The solar cells to be used are rated for 0.1 W peak output at 0.4V. Assuming that there are no assembly losses & define the array.

Soln, Maximum power rating of each cell $P_c = 0.1W$ given data

Let N_T = Total number of solar cells. $V_{MP} = 0.4V$ given data

Total output power of array $P_{max} = 100W$ given data

Hence $N_T = \frac{P_{max}}{P_c} = \frac{100}{0.1} = 1000$ cells //

Number of cells in series, $N_s = \frac{\text{Array output voltage } (V_a)}{V_{MP}}$ | $V_a = 120$ given data

$N_s = \frac{120}{0.4} = 300$ cells //

Since $N_T = N_S \times N_p$ ——

$\therefore N_p = \dfrac{N_T}{N_S} = \dfrac{1000}{300} = 3.33$ parallel strings

$\therefore$ a decision must be be taken to use either 3 or 4 parallel strings.

with $N_p = 4$ $N_T = 1200$ & $P_a = 0.1 \times 1200 = 120W$

with $N_p = 3$ $N_T = 900$ & $P_a = 900 \times 0.1 = 90W$ //

Q5) Determine the load profile for the power system shown in Figure 1. Assume that the battery has normally 25V & the loads are as follows.

Load 1 is a constant power load that draws 50W continuously, day & night.

Load 2 is an electric motor water pump that operates three times a day for 1h: once before sunrise, once near noon & once after sunset & draws starting current of 20A for 5s & running current of 4A.

Load 3. is a scientific instrument that operates every 2h for 6min, day & night & approximately draws a current of 3A.

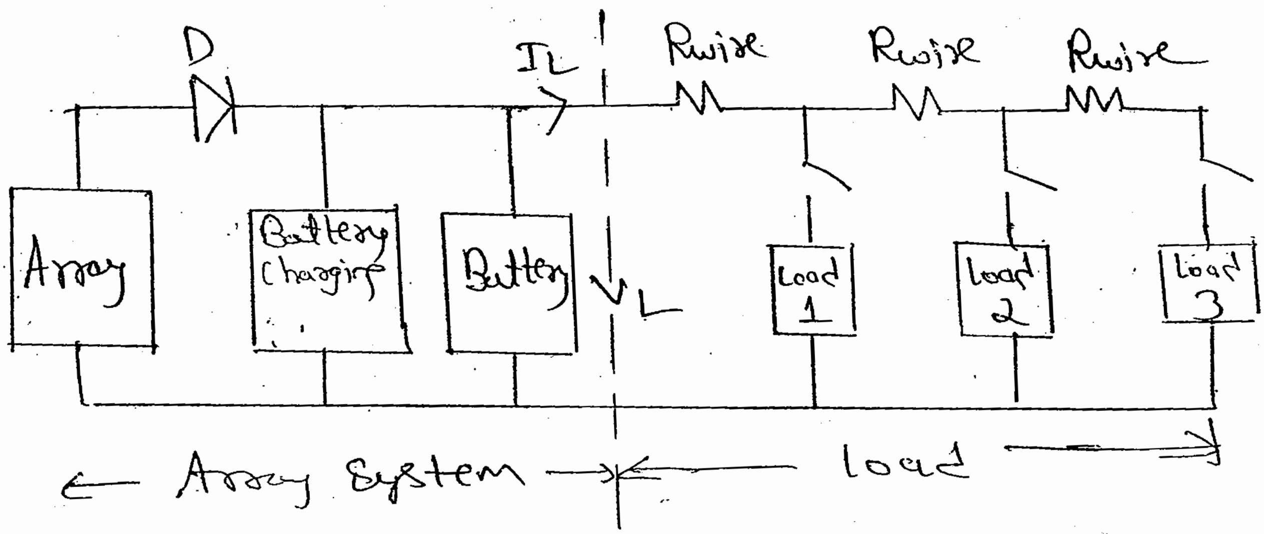


Figure. 1.

Soln; **Load 1.**

Current drawn by load 1, $I_1 = \frac{P}{V_L} = \frac{50}{25} = 2A$.

Thus, Load 1 = I × hours = 2A × 24h = 48 Ah.

load 2.

load 2
At starting :- 3 times × 20 A × 5 s = 300 As

$= \frac{300\ As}{3600\ s} = 0.08\ Ah$.

+

At running = 3 × 1h × 4A = 12 Ah.

Load 3.

Instrument is operated for 12 ... in 24-h day & night. (6 min = 0.1 hour)

Load 3 = 12 × 0.1h × 3A = 3.6 Ah

∴ Combined load = Load 1 + Load 2 + load 3

= 48 + 0.08 + 12 + 3.6

$\boxed{\text{Combined load} = 64\ Ah}$

Average combined load current = $\frac{\text{Combined load}}{24\ \text{hour}}$

$I_L = \frac{64\ Ah}{24\ h} = 2.7A$

Hence, load = 2.7A × 25V = 67W

peak current from the battery [

$I_P = 2 + 20 + 3 = 25\ A$

Q6) Find the number of solar cells for the array area of 28.5 m² if each cell has a diameter of 2.25 inches.

Soln: Area of each cell (A_c) is calculated as

$$A_c = \frac{\pi d^2}{4} = \frac{\pi (5.715 cm)^2}{4} = 25.65 cm^2$$

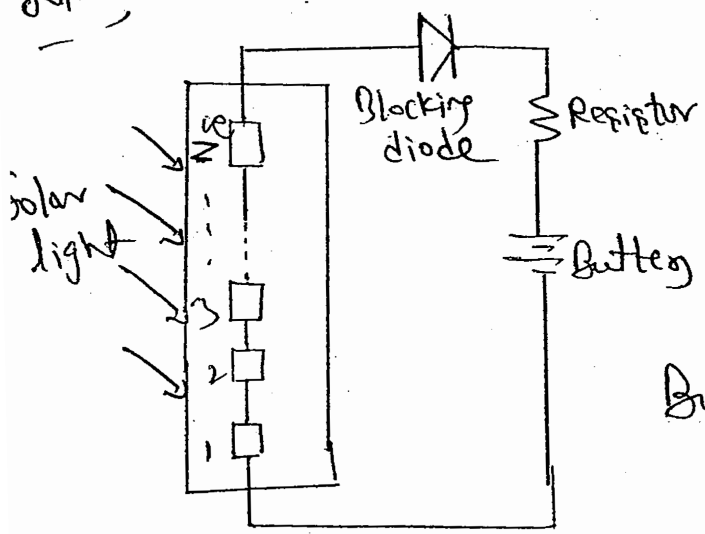
dia = 2.25 inches = 5.715 cm   1 inch = 2.54 cm

Number of solar cells for the array area required $= \frac{S_A}{A_c} = \frac{28.5 m^2}{25.6 cm^2} = \frac{28.5 m^2}{25.65 \times 10^{-4} m^2}$

No. of solar cells = $\underline{11100}$

Q7) A 12V battery is to be charged by connecting 50 silicon PV cells in series with it. Each cell is of size 2cm x 2cm & is rated at 0.45 (V_{oc}) & 50mA (I_{sc}). Battery charging voltage is 0.3V. What current will be obtained when these are connected across the battery? Let the existing battery voltage be 11.5 volts & that a diode connected in series with the battery has a dropping voltage of 0.6 volt & total resistance of the series circuit is 80Ω.

Soln:



Battery charging voltage o/p of solar cell = 50 × 0.3 = 15V

Existing battery voltage + diode voltage = 11.5 + 0.6 = 12.1V

Battery current $= \frac{(15 - 12.1)}{80}$

= 36.25 mA

N_s = Number of cell in series