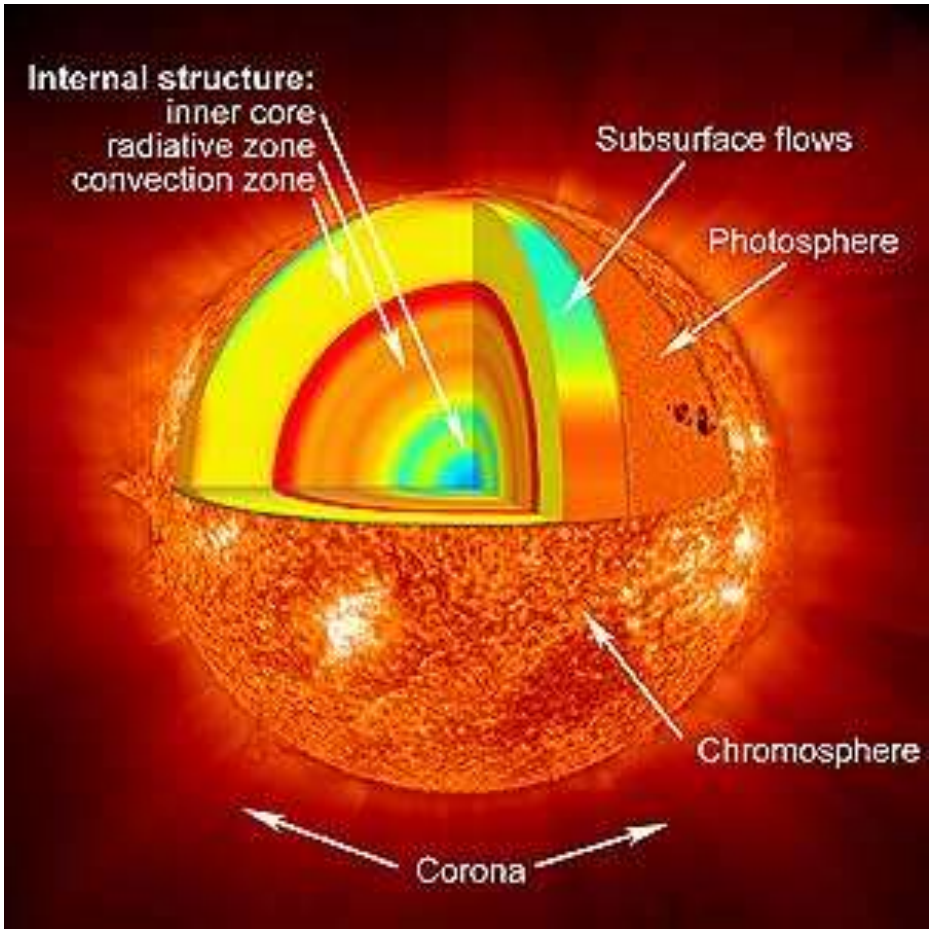
Solar Energy Technologies and Applications

Dr. Sudhir Kumar
Sr. Fellow & Head,
Center for Solar Energy,
World Institute of Sustainable Energy
Mb No. +91 96650 20206
Email: drsk22@gmail.com

The Sun

- The sun is a source of renewable energy, sits at the center of the solar system and emits energy as electromagnetic radiation at an extremely large and relatively constant rate.
- The Sun's outer visible layer is called the photosphere and has a temperature of 6,000°C (11,000°F).
- The chromosphere is above the photosphere. Solar energy passes through this region on its way out from the center of the Sun.
- The corona is the outer part of the Sun's atmosphere.



Characteristics of the Sun

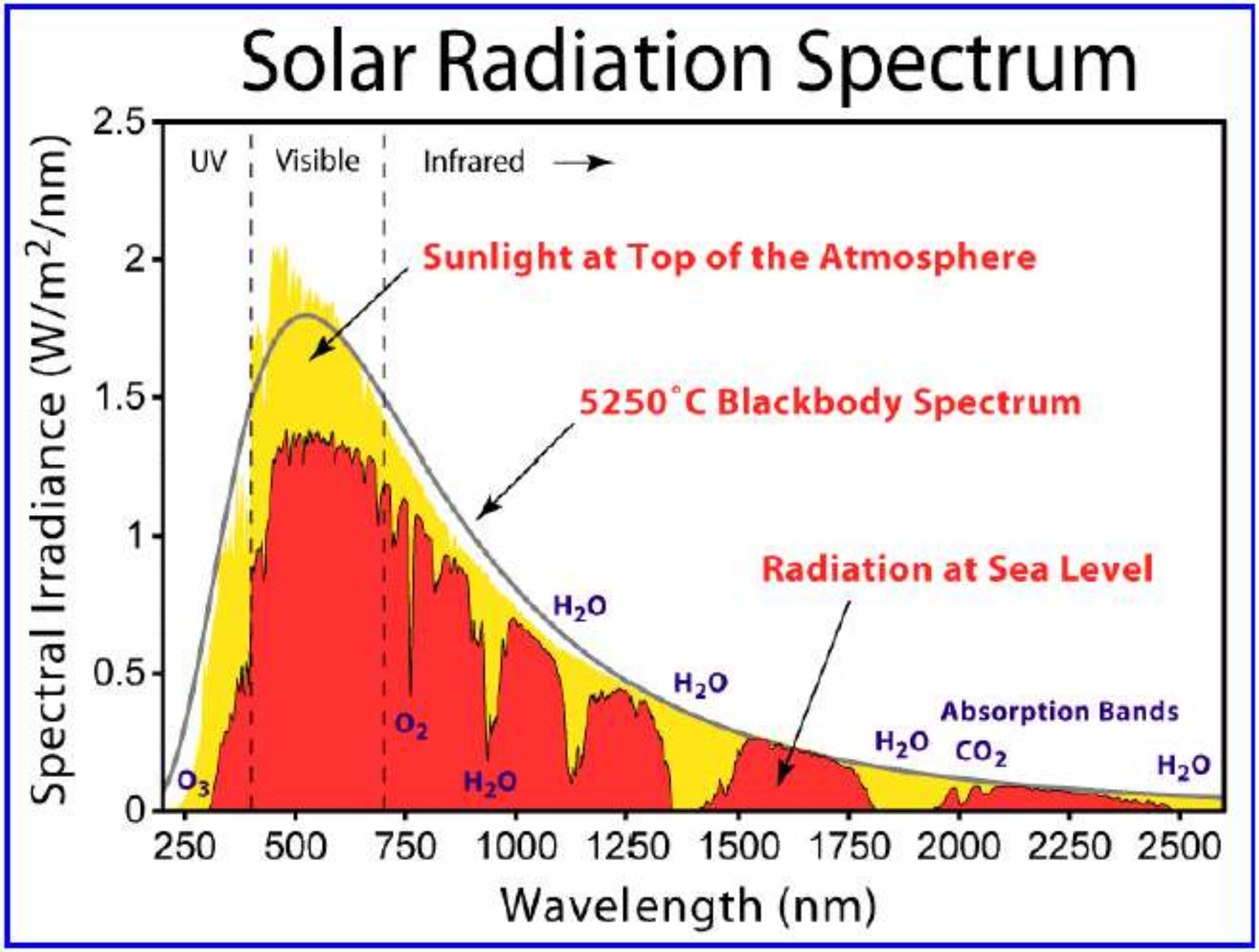
1	Mass (kg)	1.989×10^{30}
2	Diameter (km)	1.39×10^{6}
3	Mean density (gm/cm^3)	1.410
4	Mean surface temperature	6,000°C
5	Age (billion years)	4.5

Solar radiation and their approximate wavelength ranges:

- **Ultraviolet: 200 - 400 nm**
- **Visible: 400 - 800 nm**
- **Near-Infrared: 800 – 4000 nm**
- **Infrared: 4000 – 10000 nm**

Approximately 99% of solar or shortwave radiation at the earth's surface is contained in the region from 300 to 3000 nm while most of terrestrial or long wave radiation is contained in the region from 3500 to 50000 nm.

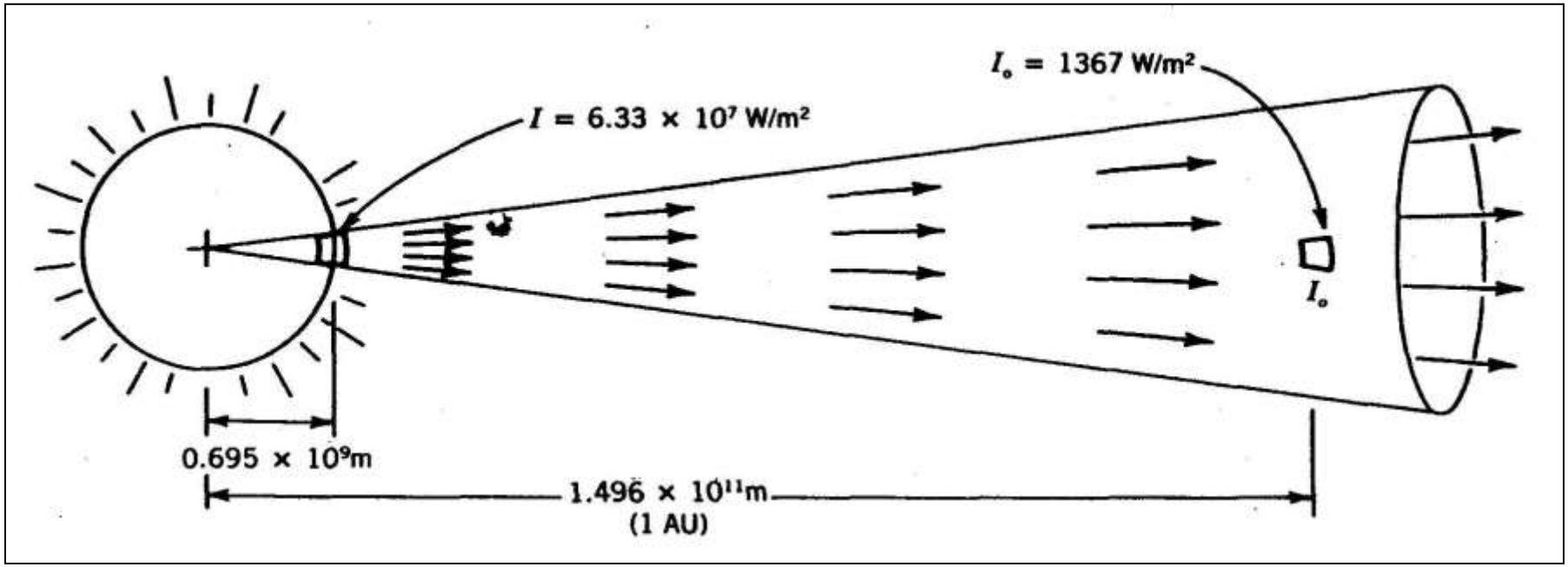
45 % of the sun’s energy – Earth- at wavelengths in the visible spectrum (400 – 800 nm)


Solar Radiation Spectrum
Spectral Irradiance (W/m²/nm)
2.5
2
1.5
1
0.5
0
UV
Visible
Infrared
Sunlight at Top of the Atmosphere
5250°C Blackbody Spectrum
Radiation at Sea Level
O3
O2
H2O
H2O
H2O
H2O
CO2
H2O
Absorption Bands
250
500
750
1000
1250
1500
1750
2000
2250
2500
Wavelength (nm)

Solar Constant

- The radiation intensity on the surface of the sun is approximately 6.33 × 10^7 W/m^2.
- Solar constant is the rate at which energy is received from the sun on a unit area perpendicular to the rays of the sun, at the mean distance of the earth from the sun. (1.496 × 10^{11} m or 1 AU is the average earth-sun distance)

- The intensity of the radiation leaving the sun is relatively constant. Therefore, the intensity of solar radiation at a distance of 1 AU is called the solar constant (Isc) and has a currently accepted of 1367 W/m^2 value.
- 1971 standard value of Solar Constant was adopted as 1353 W/m^2.



Solar Radiation Terminology

- ***Radiant energy:*** Energy that is emitted or propagated in the form of particles or electromagnetic radiation. It is measured in joules (J).

- ***Radiant flux:*** Rate of flow of radiant energy w. r. t. time (Watt).

- ***Insolation:*** The actual amount of sunlight falling on a specific geographical location is known as insolation or incident solar radiation.

- ***Irradiance (E):*** Amount of radiant energy incident on a surface per unit area per unit time (Watt/m^2). (J/m^2/sec)

- ***Irradiation:*** It is the incident irradiance on a unit area integrated over a specified time interval generally over an hour or a day (Watt/m^2/day).

- ***Direct solar radiation:***

  The solar radiation that reaches the Earth's surface without being diffused is called direct or beam solar radiation. Atmospheric conditions can reduce direct beam radiation by 10% on clear, dry days and by 100% during thick, cloudy days. Direct solar radiation is measured by **Pyrheliometer.**

- ***Diffuse solar radiation:***

  As sunlight passes through the atmosphere, some of it is absorbed, scattered and reflected by the air molecules (Rayleigh scattering), water vapour (Mia Scattering), clouds, dust, pollutants, forest fires and volcanoes. This is called diffuse solar radiation.

- ***Global Radiation:***

  The sum of the diffuse and direct solar radiation is called global solar radiation. The global solar radiation measured by **pyranometer.** The measured global horizontal solar irradiance is

$$I_{gh} = I_{bn} \cos \theta_c + I_{dh}$$

Where,

- I_{bn} represents the irradiance coming directly from the sun's disk, measured normal to the rays and
- I_{dh} represents the diffuse radiation falling on a horizontal surface
- θ_c represents Solar zenith angle at the mid-time between sunrise and solar noon for the monthly average day.

- ***Terrestrial radiation***

  Terrestrial radiation is the long wave radiation that is emitted by the earth surface back into the atmosphere. Most of it is absorbed by the water vapour in the atmosphere, while less than 10 % is radiated directly into space.

  Electromagnetic radiation originating from Earth and its atmosphere.

- ***Extra-terrestrial radiation***

  Solar radiation outside of the earth's atmosphere is called extraterrestrial solar radiation. The top of the atmosphere is about 40 km from the earth's surface.

- ***Clearness index:***

  It is the ratio of global horizontal solar radiation at a site to the extraterrestrial horizontal solar radiation above that site.

$$K_T = H_{th} / H_{oh}$$

Air mass

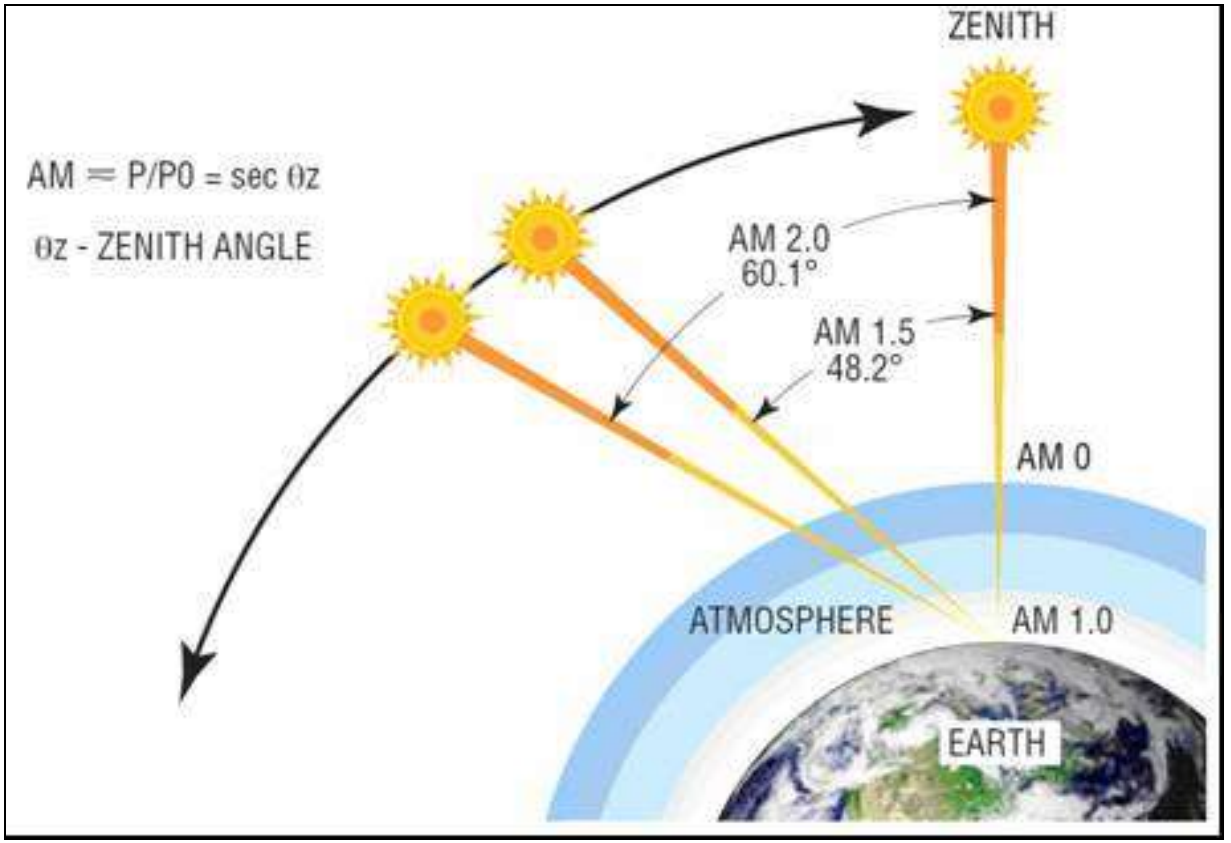
Ratio of the distance that solar radiation travels through the earth's atmosphere (path length), to the distance (path length) it would travel if the sun were directly overhead.

Spectrum outside the atmosphere - AM 0, at the zenith - AM 1 and at 60° altitude - AM 2.

$$\text{Air Mass} = 1.0 / [\cos(z) + 0.50572 \times (96.07995 - z) - 1.6364]$$

A typical spectrum for moderate climate is AM 1.5, which correspond to an angle of incidence of solar radiation of 48º relative to the surface normal.

The power density of AM 1.5 light is about 1,000 W/m^2 at 25 °C; The energy spectrum AM 1.5 is regarded as the standard spectrum for measuring the efficiency of solar cell.

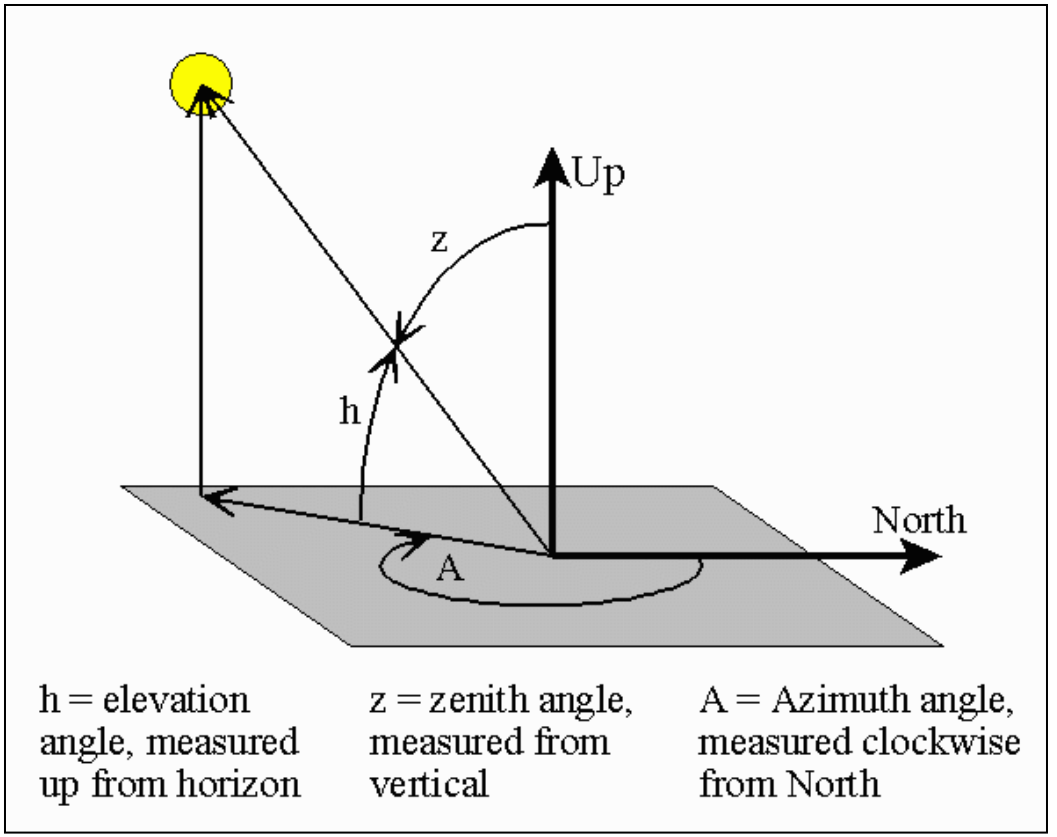


Earth Sun Angles

***Solar altitude* angle (h):**
It is the angle between the radiation from the sun and its projection on horizontal plane.

Zenith angle (z):
It is the angle between the radiation from the sun and line perpendicular to the horizontal plane.

Solar azimuth angle (A):
It is the angle, measured clockwise on the horizontal plane, from the north-pointing coordinate axis to the projection of the sun's central ray.



Solar Energy Components

- Light
  - Photovoltaics
    - lighting, motive power, grid power
- Heat
  - Thermal Technologies
    - Cooking, water / air heating, grid power

Solar Power Generation Technologies

1. Solar Photovoltaic System

Photovoltaic systems contain cells that convert sunlight into electricity. Inside each cell there are layers of a semi-conducting material. Light falling on the cell creates an electric field across the layers, causing electricity to flow. The intensity of the light determines the amount of electrical power each cell generates. Solar PV system uses global radiation.

- Solar Photovoltaic
  - Crystalline SPV
  - Thin film SPV
  - Concentrating SPV

Solar Power Generation Technologies

2. Solar Thermal System

Solar thermal power uses direct sunlight, so it must be sited in regions with high Solar thermal/Concentrating solar power (CSP) plants produce electric power by converting the sun's energy into high-temperature heat using various mirror configurations. The heat is then channelled through a conventional generator. The plants consist of four parts: a concentrator, a receiver, some form of heat transport, storage and power conversion equipment direct solar radiation.

- Solar Thermal (Concentrating Solar Power)
  - Parabolic Trough
  - Solar Tower
  - Parabolic Dish Stirling System
  - Compact Linear Fresnel Reflector

1. Solar Photovoltaic System:

- **Types of solar PV technology:**

- Single-crystal silicon (also known as Mono-crystalline)
- Efficiency- 13% and 17%.

- Multi-crystal silicon (also known as Poly-crystalline).
- Efficiency- 11% and 15%.

- Amorphous silicon (also known as thin film silicon).
- Efficiency- 6% and 8%.

- Concentrating SPV (Silicon, GaAs, CIS, CIGS, CdTe, etc.)
- Efficiency- 25- 30%

Photovoltaic Materials

Sr. No.	Material	Typical Cell Voltage at Open-Circuit	Typical Cell Current at Short-Circuit
1	Crystalline and Polycrystalline Silicon (x-Si)	~0.6 Volts	~35 mA/cm^2
2	Gallium Arsenide	~1.0 Volts	~27 mA/cm^2
3	Amorphous Si (a-Si)	~0.9 Volts	~15 mA/cm^2
4	Tandem a-Si	~1.8 Volts	~10 mA/cm^2
5	Copper-Indium-Diselenide (CIS)	-0.4 volts	~35 mA/cm^2
6	Cadmium Sulfide, Cadmium Telluride	-0.7 volts	~25 mA/cm^2

A Thin-Film Solar Cell (TFSC)

- A Thin-Film Solar Cell (TFSC), also called a Thin-Film Photovoltaic Cell (TFPV), is a solar cell that is made by depositing one or more thin layers (thin film) of photovoltaic material on a substrate. The thickness range of such a layer is wide and varies from a few nanometres to micrometers.

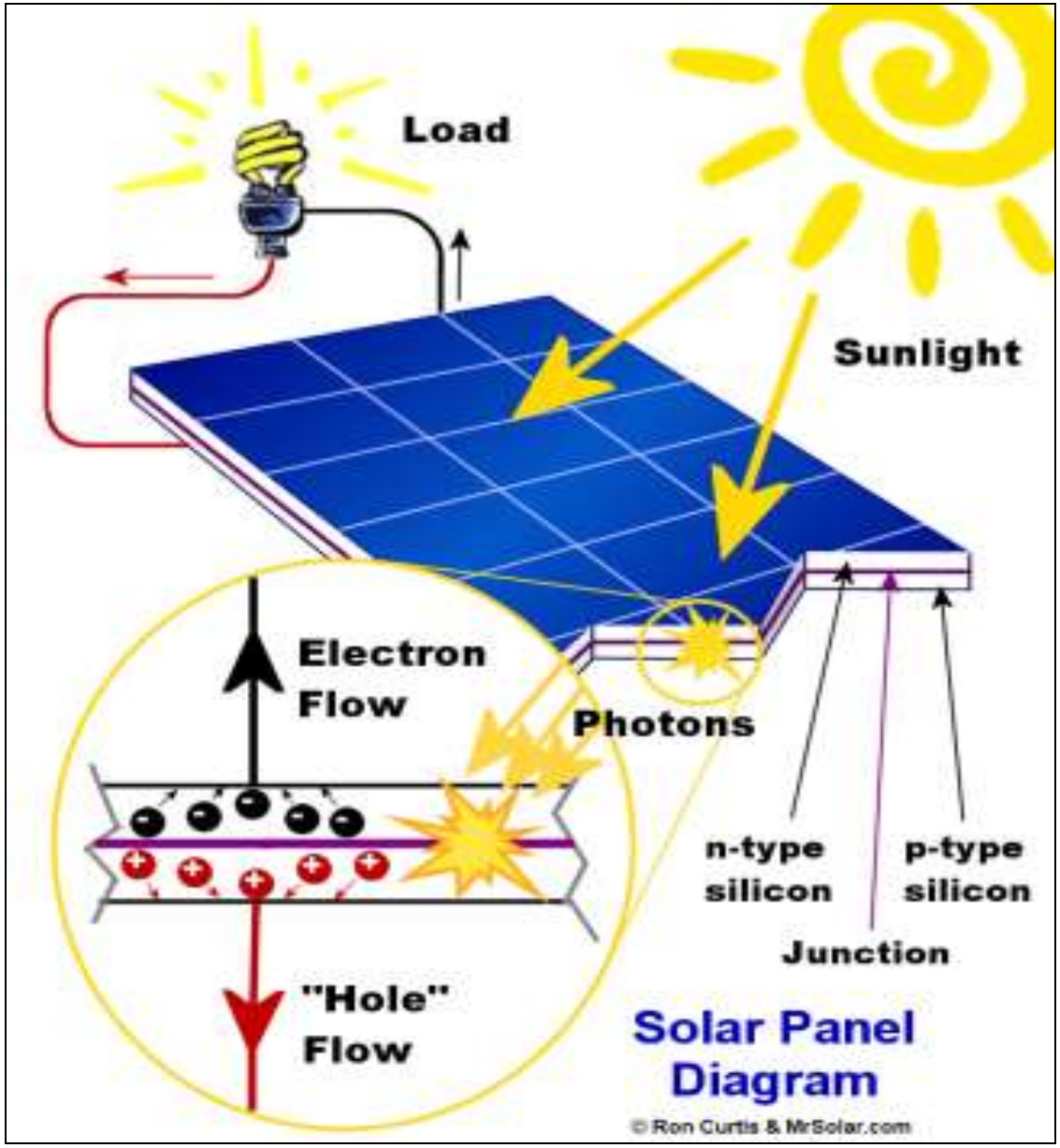
- Thin Film Solar Cells are usually categorized according to the photovoltaic material used. The following categories exist:

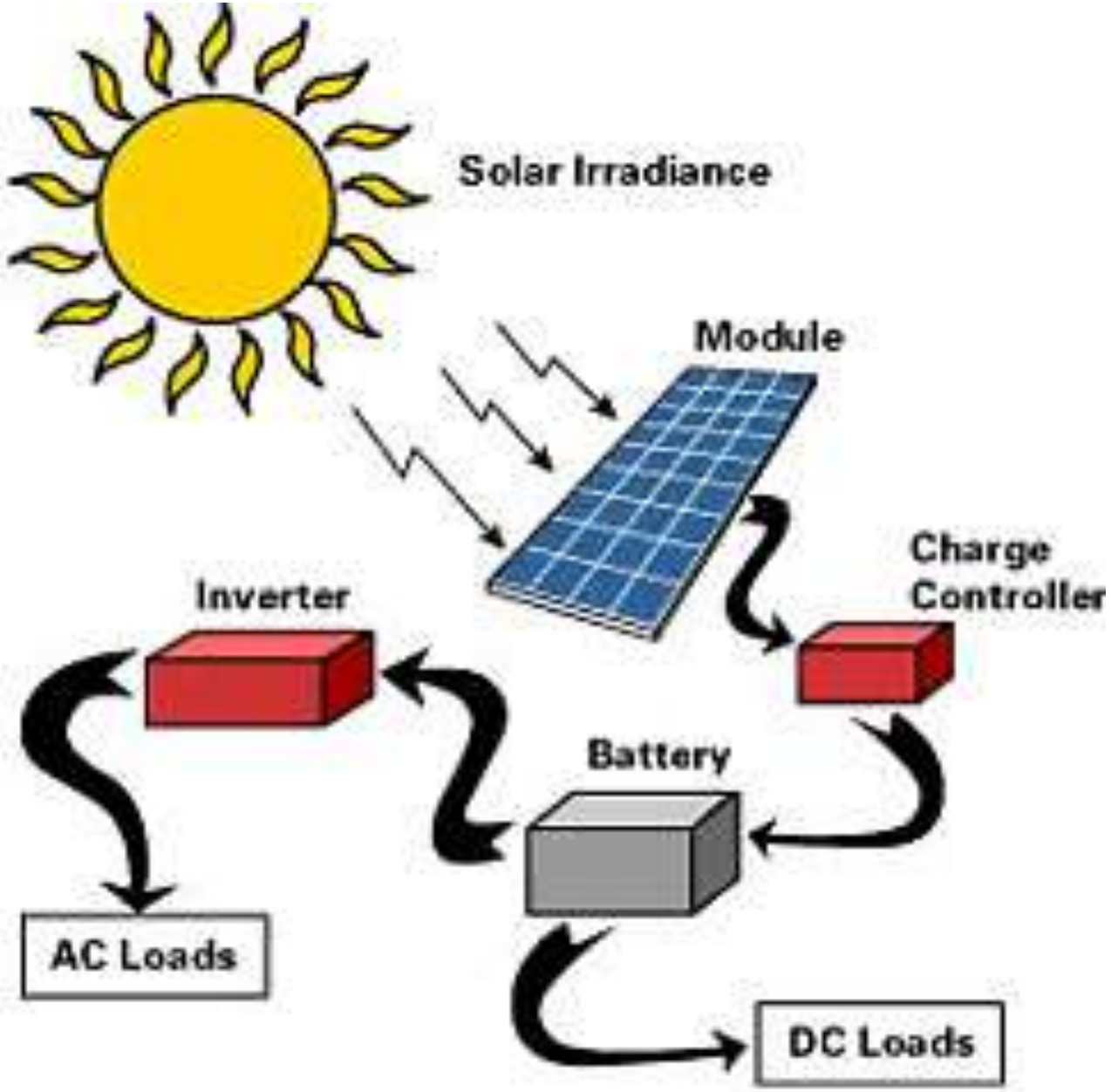
a) Cadmium Telluride (CdTe)
b) Copper indium selenide (CIS)
c) Gallium arsenide (GaAs) multijunction
d) Dye-sensitized solar cells (DSSC)
e) Organic/polymer solar cells
f) Thin-film silicon (TF-Si)

Cells, Modules & Arrays

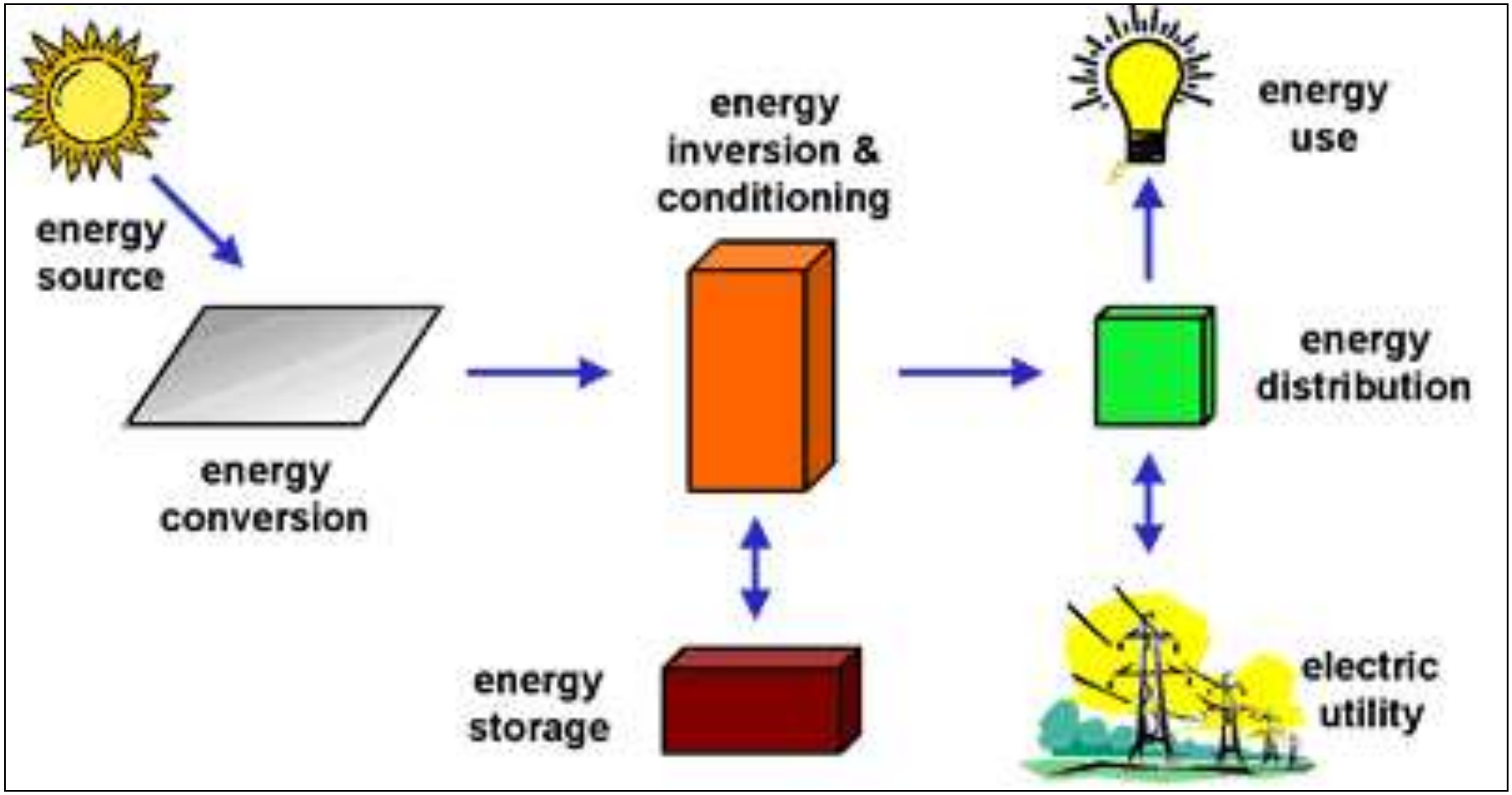
- Photovoltaic cells are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels. Photovoltaic modules consist of PV cell circuits sealed in an environmentally protective laminate and are the fundamental building blocks of PV systems. Photovoltaic panels include one or more PV modules assembled as a pre-wired, field-installable unit. A photovoltaic array is the complete power-generating unit, consisting of any number of PV modules and panels.

- The performance of PV modules and arrays are generally rated according to their maximum DC power output (watts) under Standard Test Conditions (STC). Standard Test Conditions are defined by a module (cell) operating temperature of 25 ^{o}C (77 ^{o}F), and incident solar irradiance level of 1000 W/m^{2} and under Air Mass 1.5 spectral distribution.


Load
Sunlight
Electron
Flow
Photons
n-type
silicon
p-type
silicon
Junction
"Hole"
Flow
Solar Panel
Diagram
© Ron Curtis & MrSolar.com


Solar Irradiance
Module
Charge Controller
Inverter
Battery
AC Loads
DC Loads

Working of PV Power Generation Systems



Solar PV System Components

Solar Panels – Convert light into electricity

Combiner Box- Strings of modules are fed through fuses to produce a single output.

Charge Controllers - Controls the energy flow and protects your battery

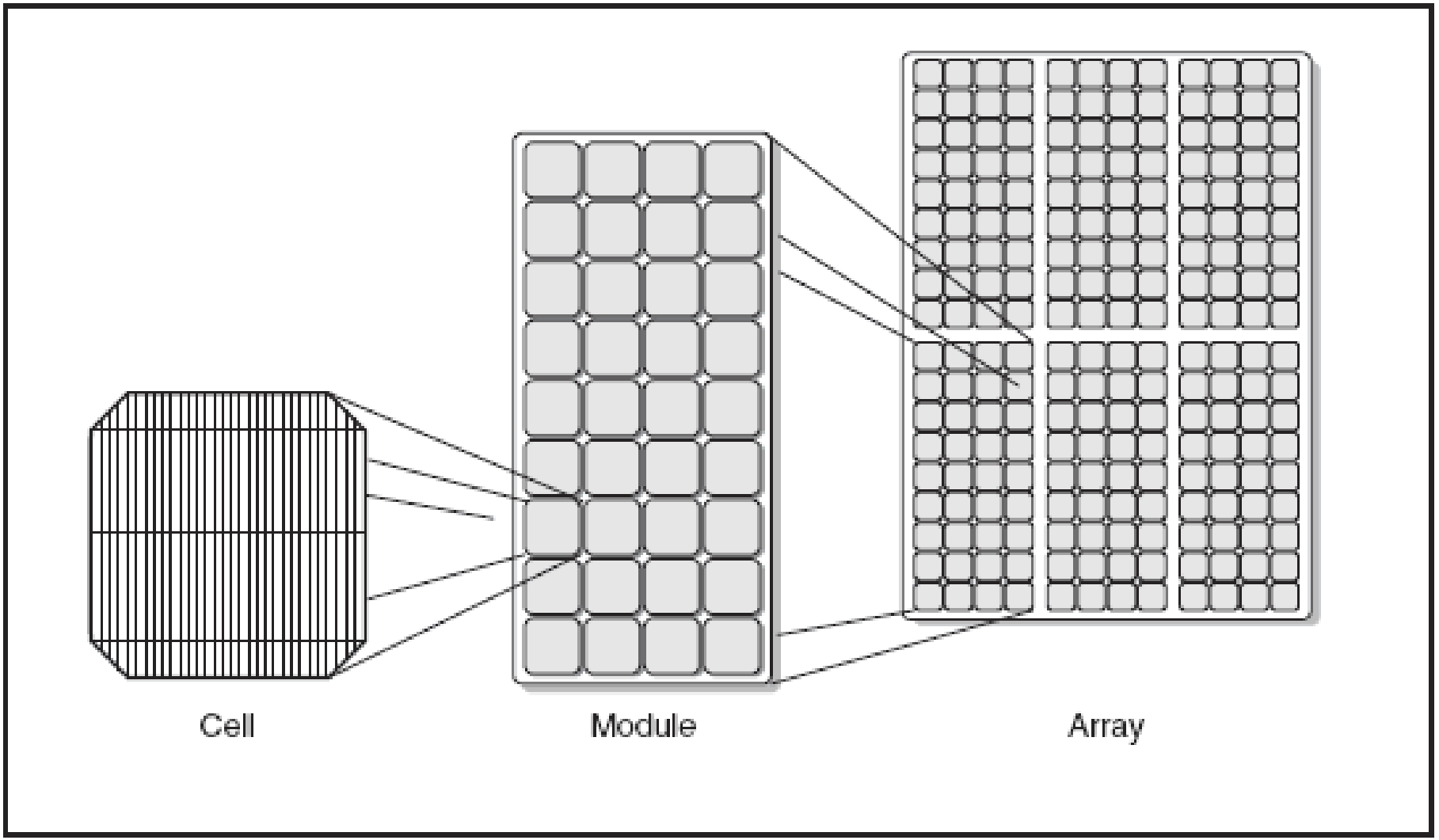
Solar Batteries - Batteries that survive frequent charging and discharging

Inverters - the component that transforms DC into AC

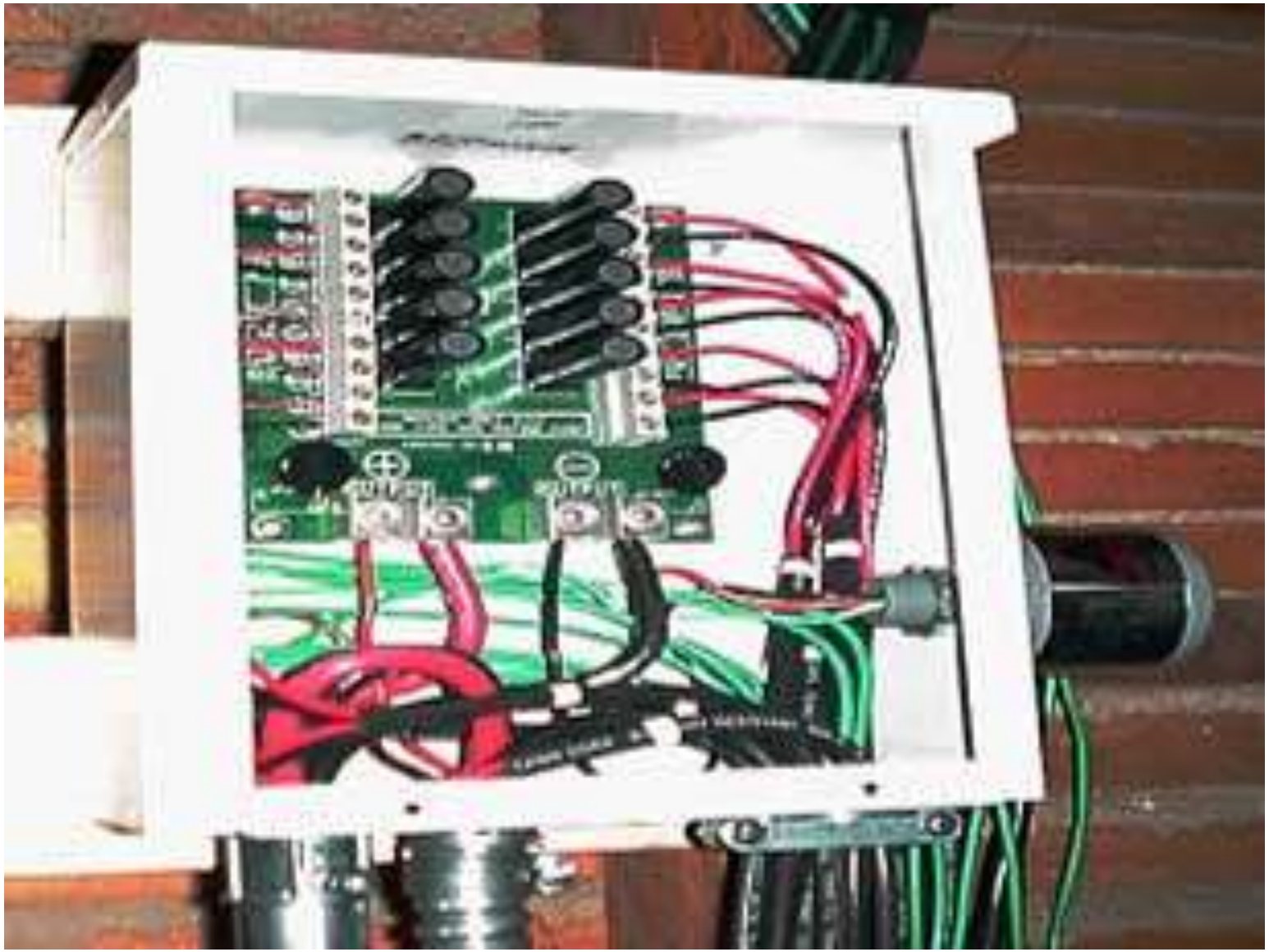
Mounting Structures – Structure that holds your panel in optimum tilted position

Solar panel tracking – It adjust panels for optimum sun exposure

Cells, Modules & Arrays

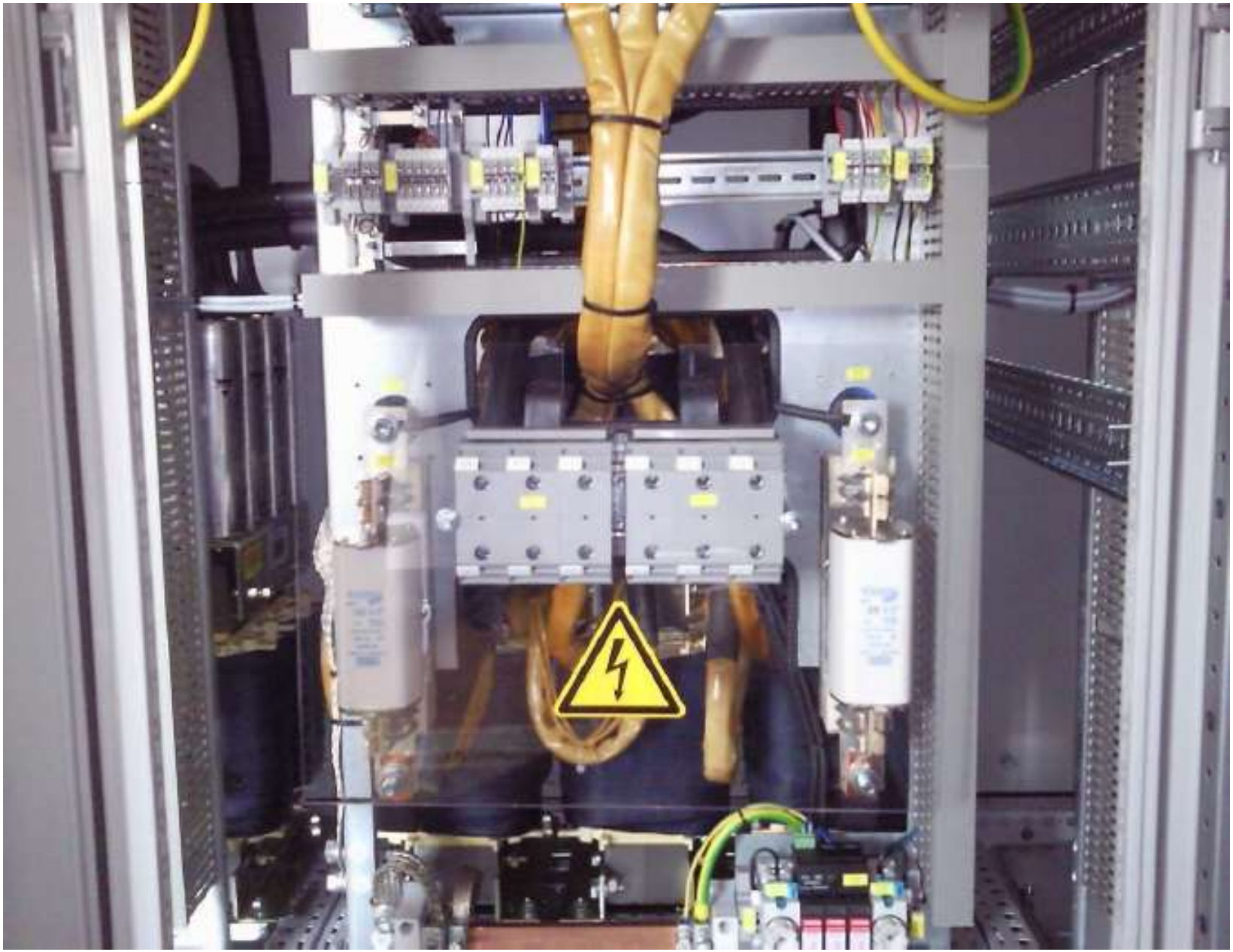


Combiner / Junction Box



Solar Inverter

Inverter



Inverters

Module Mounting Structure

3 MW Solar PV Power Plant at Kolar, Karnataka

3 MW Solar PV Power Plant at Kolar, Karnataka

3 MW Solar PV Power Plant at Kolar, Karnataka

High Pressure Module Cleaning System

Solar Lantern

Solar Lantern is a powerful & compact lighting system which uses sun energy and gives free power forever. It consist of Solar Photo voltaic Module (panel), Electronic Circuit, Battery and Compact fluroscent Lamp.

Performance specifications:

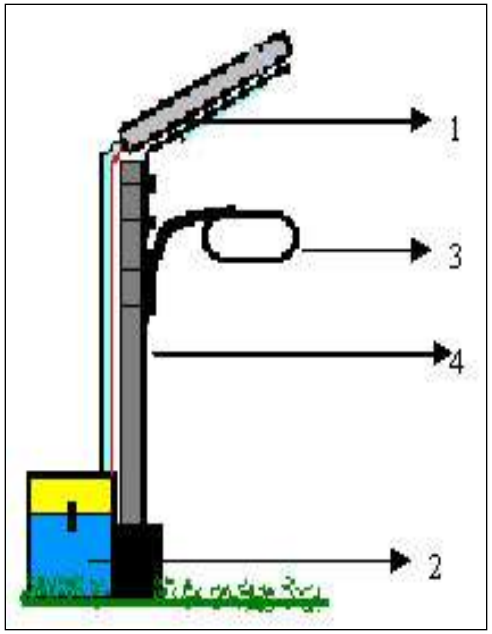
Light Source	W-LED luminaire, dispersed beam, soothing to eyes with the use of proper optics
Mounting of light	Top or base mounted
PV Module	between 3 to 5 Wp under STC
Battery	Sealed maintenance free Lead acid or NiMH or Lithium Ion, with a capacity up to 7 AH, at voltages up to 12V @ C/20 rate of discharge. Max. DoD 75% or equivalent capacity
Electronics	Min 85% total efficiency
Average duty cycle	4 hours a day
Autonomy	Minimum of 3 days (Minimum 14 operating hours per permissible discharge)

Solar Street Light

Solar Street Lighting system is a most efficient system, which provides light for the whole night.

The main components of solar street lights are-

1. SPV Module
2. Battery Box
3. Lamp with charge controller
4. Lamp Post



Performance specifications:

Light Source	White Light Emitting Diode (W-LED)
Light Out put	White colour minimum 15 LUX when measured at the periphery of 4 meter diameter from a height of 4 meter. The illumination should be uniform without dark bands or abrupt variations, and soothing to the eye.
Mounting of light	Minimum 4 metre pole Mounted
PV Module	40 Wp under STC, measured at 16.4 V at load. Module Voc minimum of 21V
Battery	Tubular Lead acid or gel type VRLA , 12 V- 40 AH @ C/10, Max DoD 75%
Electronics	Min 85% total efficiency
Average duty cycle	Dusk to dawn
Autonomy	3 days (Minimum 42 operating hours per permissible discharge)

Solar power packs

These systems can effectively replace small generators based on kerosene and petrol.

The main components of solar power packs ar

- SPV panel
- Rechargeable batteries
- Inverter

Advantages are-

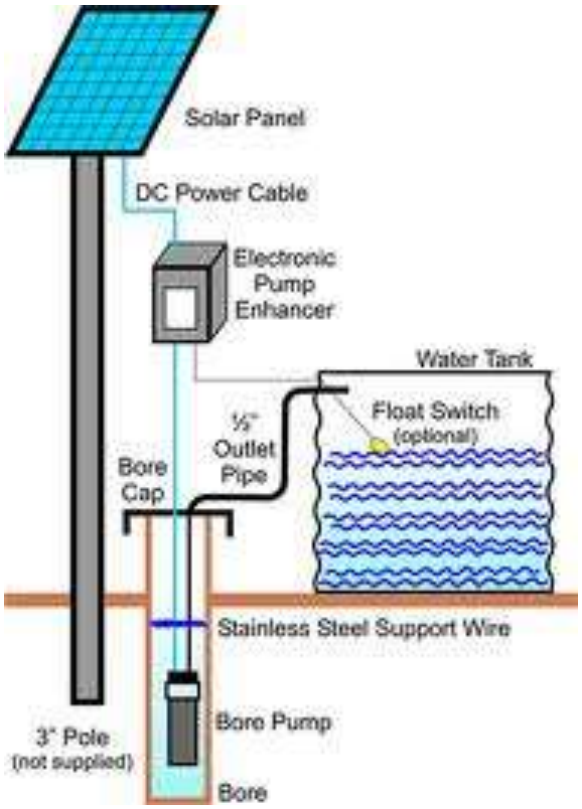
- Reliable and cost effective.
- Absolutely pollution free.
- Clean and silent.
- Easy to install and requires negligible maintenance
- Dual charging facility (Solar and AC mains charging)
- Battery charging with temperature compensation for increased battery life.
- Available in 12V, 24V, 48V, 96V, and 110V input DC versions with the output Power rating from 500W, 1000W, 1500W, 2000W, 2500W and 3000W. (also available as per customer requirements)

Solar Garden Light

- Solar Garden lighting systems, is a device that operates using the Light energy available from the sun to provide lighting during night time.
- The Solar PV outdoor lighting is a reliable and an efficient stand-alone system.
- It consists of a Solar PV module, a Battery & a Luminary with very high efficient electronics all mounted onto a pole with necessary hardware & cables.
- The Solar Garden Lighting Systems can be used for roadways, parking lots & other general lighting applications.
- It is powered by a Solar Photovoltaic Panel and is completely independent from utility power.

Solar pumping system

- The system operates on power generated using solar PV (photovoltaic) system. The photovoltaic array converts the solar energy into electricity, which is used for running the motor pump set.



Components of SPV water pumping system are-

- Solar PV panel
- One of the following motor-pump sets compatible with the photovoltaic array:
  - Surface mounted centrifugal pump set,
  - Submersible pump set,
  - Floating pump set,
  - Any other type of motor-pump set, after approval from MNRE
- Pipes
- Storage batteries will not constitute a part of the SPV water pumping system.

Subsidy from Central Government (MNRE)

SPV System	CFA for General Category State	CFA for Special Category States	Administrative Charge
Solar Lanterns (10 W module, 7 W CFL)	Nil	Rs. 2,400	Rs. 100
Solar Home System Model 1 (18 W Module, 1 light)	Rs.2500	Rs.4500	Rs.200
Solar Home System Model 2 (37 W Module, 2 lights)	Rs.4800	Rs.8660	Rs.200
Solar Home System Model 3 (37 W Module, 1 light, 1 fan)	Rs.4800	Rs.8660	Rs.200
Solar Home System Model 4 (74 W Module, 2 lights, 1 fan)	Rs.4800	Rs.8660	Rs.200
Solar Home System Model 5 (74 W Module, 4 lights)	Rs.4800	Rs.8660	Rs.200
Street Lighting System (74 W Module, 1-2 lamps)	Rs.9600	Rs.17300	-
Stand Alone Power Plant of capacity more than 1 kWp	Rs. 1,25,000 / kWp	Rs. 2.25,000 / kWp	Rs. 10,000
Stand Alone Power Plants of capacity more than 10 kWp with Distribution Line	Rs.1,50,000 /kW	Rs.2,70,000 / kW	Rs.10,000
Solar Pumps	Rs. 30/Wp, subject to a maximum of Rs. 50,000/- per system	Rs. 30/Wp, subject to a maximum of Rs. 50,000/- per system	Rs. 2,000

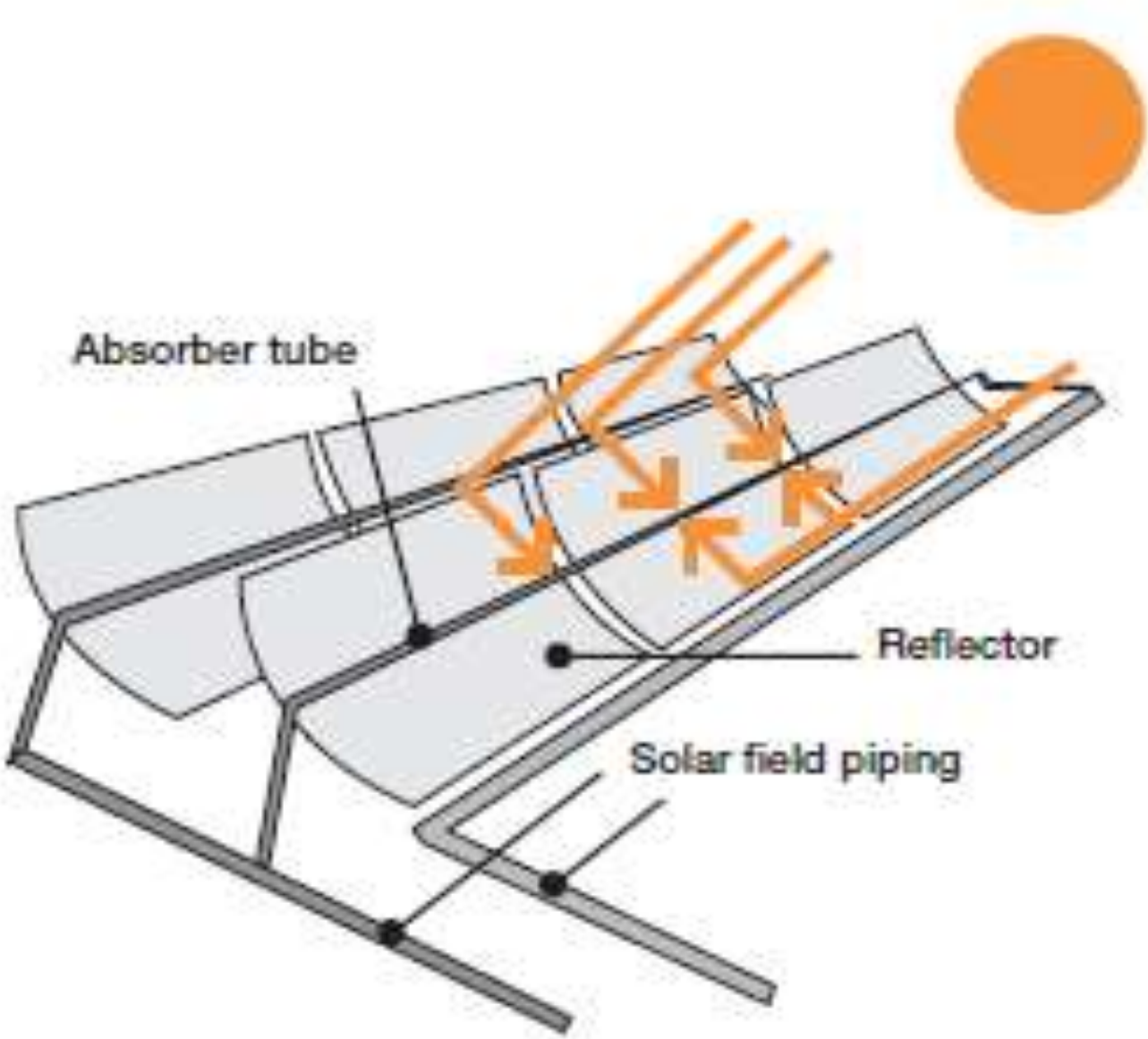
2. Solar Thermal System

- There are four solar thermal technologies
  - Parabolic Trough
  - Central Receiver/Solar Tower
  - Parabolic Dish
  - Compact Linear Fresnel Reflector (CLFR)

Parabolic Trough

- Parabolic trough-shaped mirror reflectors are used to concentrate sunlight on to thermally efficient receiver tubes placed in the trough focal line.
- In these tubes a thermal transfer fluid is circulated, such as synthetic thermal oil. Heated to approximately 400°C by the concentrated sun’s rays, this oil is then pumped through a series of heat exchangers to produce superheated steam.
- The steam is converted to electrical energy in a conventional steam turbine generator, which can either be part of a conventional steam cycle or integrated into a combined steam and gas turbine cycle.
- The rest of the system works the same way as a fossil fuel driven thermal power plant, where primary heat source is the sun instead of hydrocarbons.

Parabolic trough

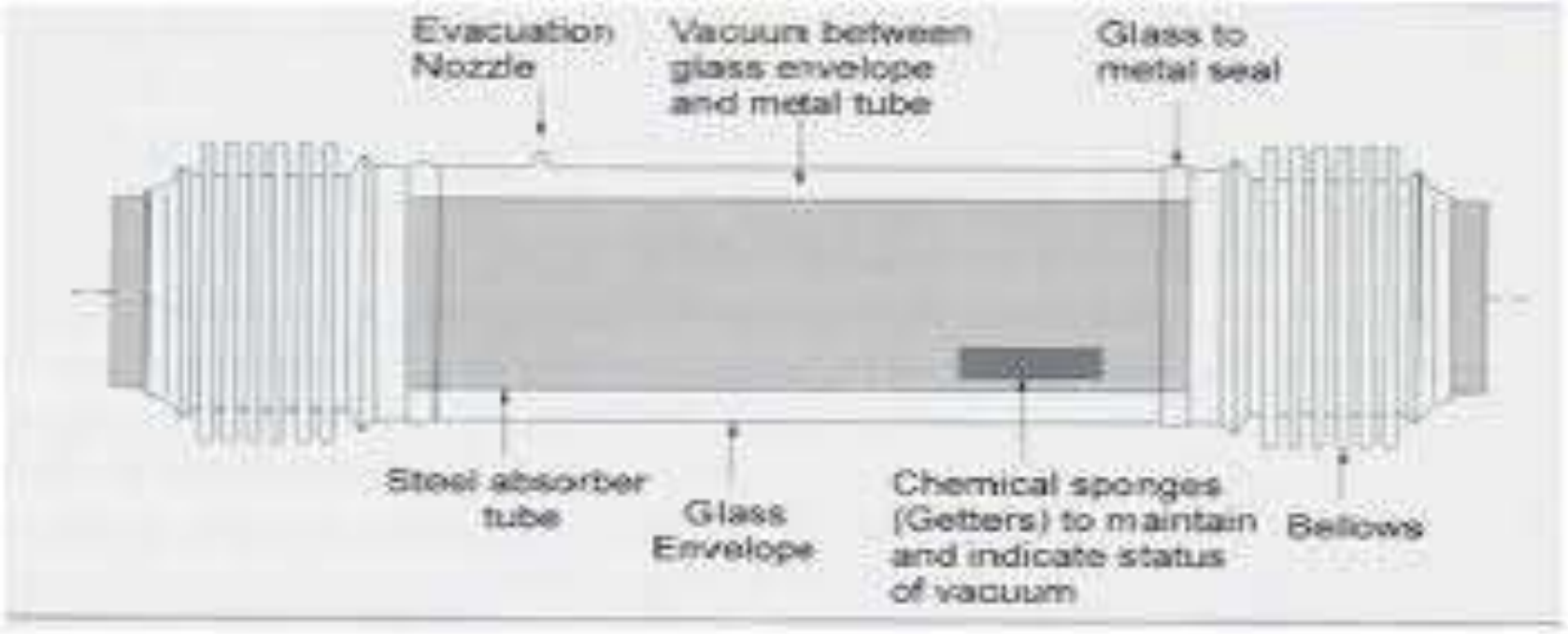


Parabolic trough power plants

Parabolic trough-shaped mirror reflectors

Parabolic trough-shaped mirror reflectors structure

Parabolic trough-receiver



Central Receiver/Solar Tower

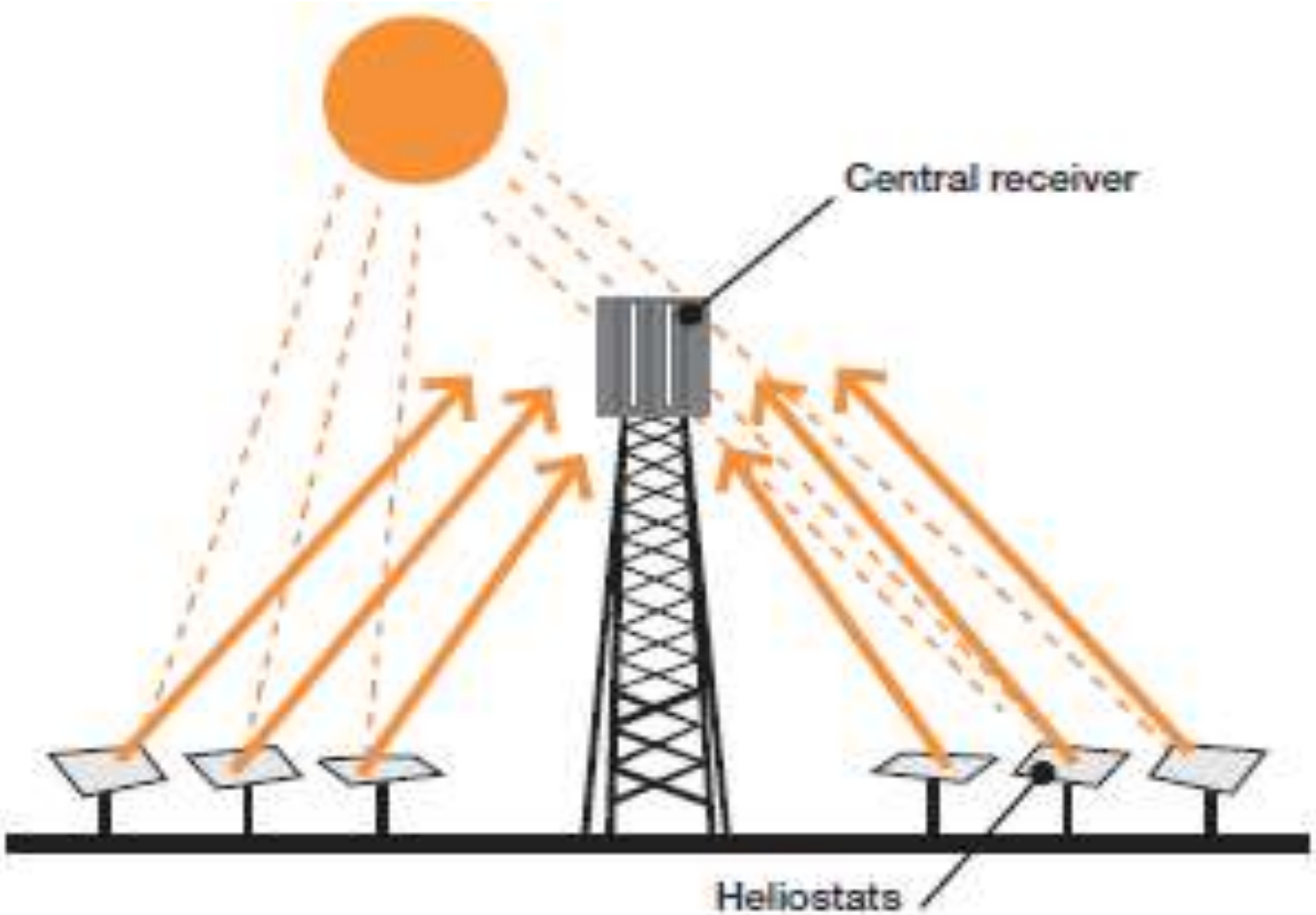
A circular array of heliostats (large individually-tracking mirrors) is used to concentrate sunlight on to a central receiver mounted at the top of a tower.

A heat transfer medium in this central receiver absorbs the highly concentrated radiation reflected by the heliostats and converts it into thermal energy to be used for the subsequent generation of superheated steam for turbine operation.

Heat transfer media so far demonstrated include water/steam, molten salts, liquid sodium and air. If a gas or even air is pressurised in the receiver, it can be used alternatively to drive a gas turbine (instead of producing steam for a steam turbine).

The usable operating range of molten nitrate salt, a mixture of 60% sodium nitrate and 40% potassium nitrate, matches with that of Rankine Cycles.

Solar Power Tower

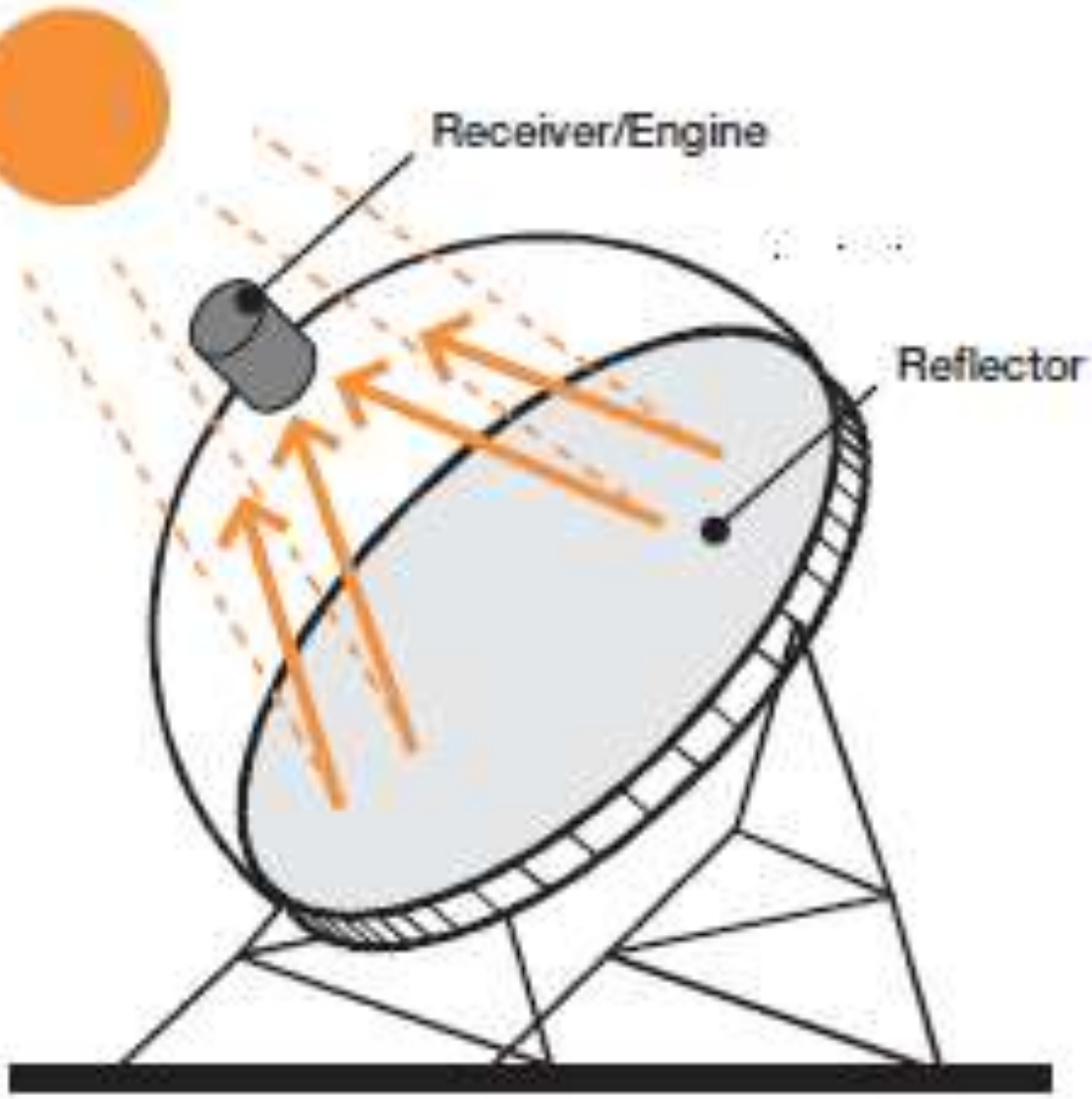


Solar Tower Power Plant

Parabolic Dish

- A parabolic dish-shaped reflector is used to concentrate sunlight on to a receiver located at the focal point of the dish.
- This absorbs energy reflected by the concentrators, enabling fluid in the receiver to be heated to approximately 750°C.
- This is then used to generate electricity in a small engine, for instance Stirling engine or a micro turbine, attached to the receiver.

Parabolic dish



Parabolic Dish

Parabolic Dish

Compact Linear Fresnel Reflector (CLFR)

- CLFR technology is similar to solar trough technology.
- Sunlight is reflected by a series of mirrors onto a receiver tube, thus CLFR, like solar trough, is a linear line concentrator.
- Instead of using a parabolic shaped mirror, however, the “parabola” in CLFR is divided into ten flat mirrors that each rotate to follow the sun.
- This arrangement enables the mirrors to remain near the ground to avoid wind loads, and avoids the higher costs of both the curved mirrors and the specialized receiver tubes of trough systems.
- The receiver tubes in the case of CLFR contain water, and the plant creates saturated steam at about 545 ºF that drives a turbine to generate electricity.

Compact Linear Fresnel Reflector (CLFR)

Comparison of Solar Thermal Power Technologies

	Parabolic Trough	Central Receiver	Parabolic Dish
Applications	Grid-connected plants, process heat (Highest solar unit size built to date: 80 MWe)	Grid-connected plants, high temperature process heat (Highest solar unit size built to date: 10 MWe)	Stand-alone applications or small off-grid power systems (Highest solar unit size built to date: 25 kWe)
Advantages	• Commercially available – over 10 billion kWh operational experience; operating temperature potential up to 500°C (400°C commercially proven) • Commercially proven annual performance of 14% solar to net electrical output • Commercially proven investment and operating costs • Modularity • Best land use • Lowest materials demand • Hybrid concept proven • Storage capability	• Good mid-term prospects for high conversion efficiencies, with solar collection; operating temperature potential up to 1000°C (565°C proven at 10MW scale) • Storage at high temperatures Hybrid operation possible	• Very high conversion efficiencies – peak solar to electric conversion of about 30% • Modularity • Hybrid operation possible • Operational experience of first prototypes
Disadvantages	• The use of oil based heat transfer media restricts operating temperatures to 400°C, resulting in moderate steam qualities • Land availability, water demand	• Projected annual performance values, investment and operating costs still need to be proved in commercial operation	• Reliability needs to be improved • Projected cost goals of mass production still need to be achieved

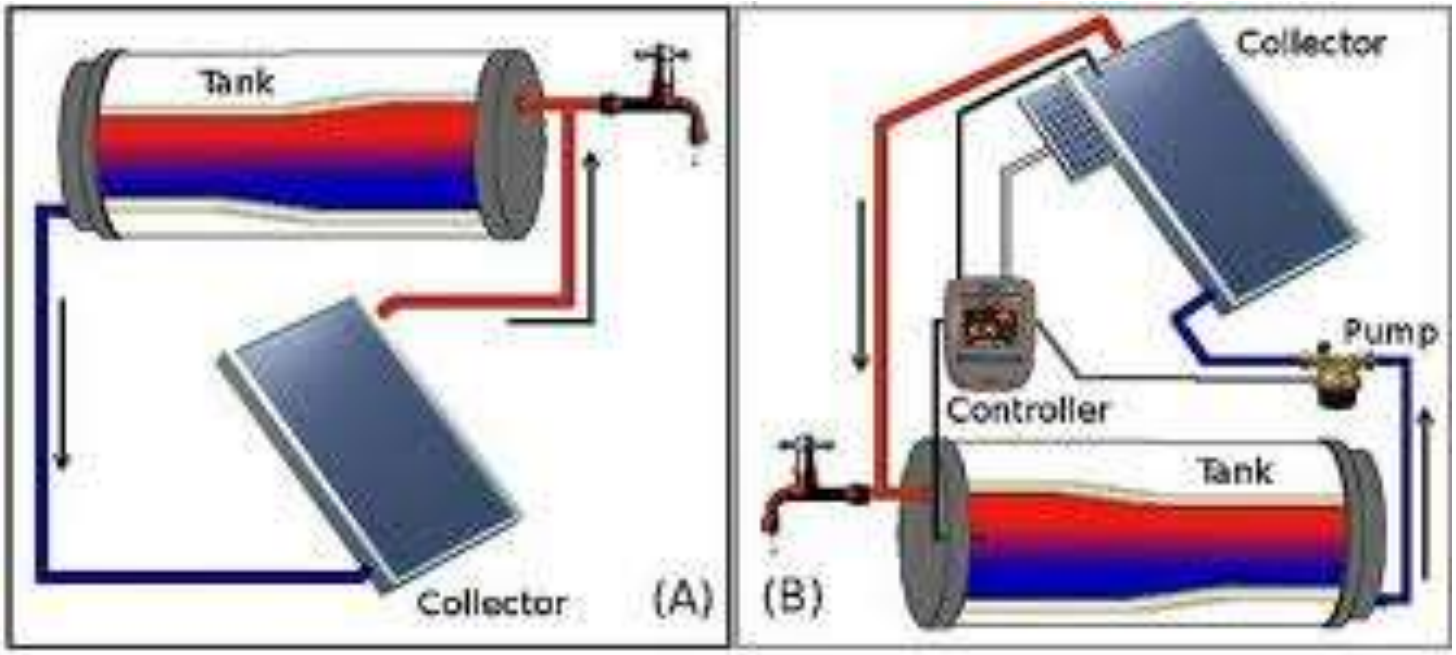
Solar Water Heater

Working of Solar Water Heaters

- The Sun's rays fall on the collector panel A black absorbing surface (absorber) inside the collectors absorbs solar radiation and transfers the heat energy to water flowing through it. Heated water is collected in a tank which is insulated to prevent heat loss. Circulation of water from the tank through the collectors and back to the tank continues automatically due to thermo siphon system.

Components of SWH system:

- Solar Collector(to collect solar energy)
- Insulated tank (to store hot water)
- Supporting stand
- Connecting pipes and instrumentation etc.

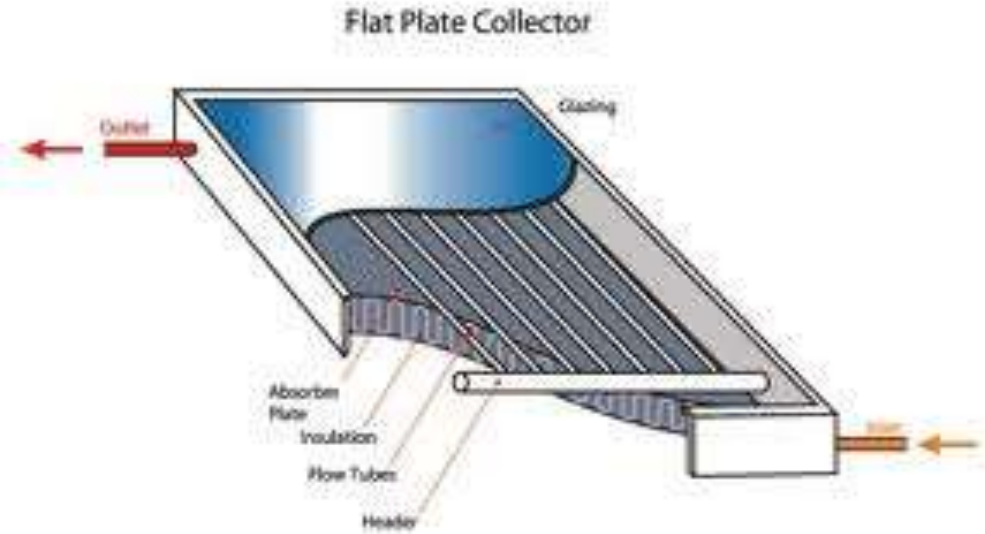


Solar water heating: Benefits

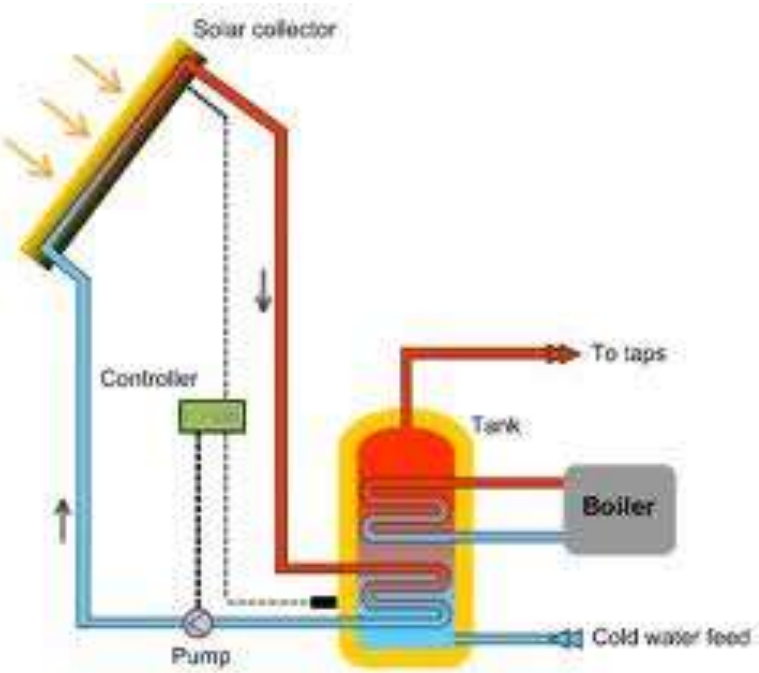
- Solar water heating system is a device that helps in heating water by using the energy from the SUN. This energy is totally free.
- Solar energy (sun rays) is used for heating water. Water is easily heated to a temperature of 60-80^{o} C.
- Solar water heater of Solar water heaters (SWHs) of 100-300 litres capacity are suited for domestic use.
- Larger systems can be used in restaurants, canteens, guest houses, hotels, hospitals etc.
- A 100 litres capacity SWH can replace an electric geyser for residential use and may save approximately 1500 units of electricity annually.
- The use of 1000 SWHs of 100 litres capacity each can contribute to a peak load saving of approximately 1 MW.
- A SWH of 100 litres capacity can prevent emission of 1.5 tonnes of CO_2 per year.

Types of Collector

- **Flat Plate solar water heater:** A black absorbing surface (absorber) inside the flat plate collectors absorbs solar radiation and transfers the energy to water flowing through it.

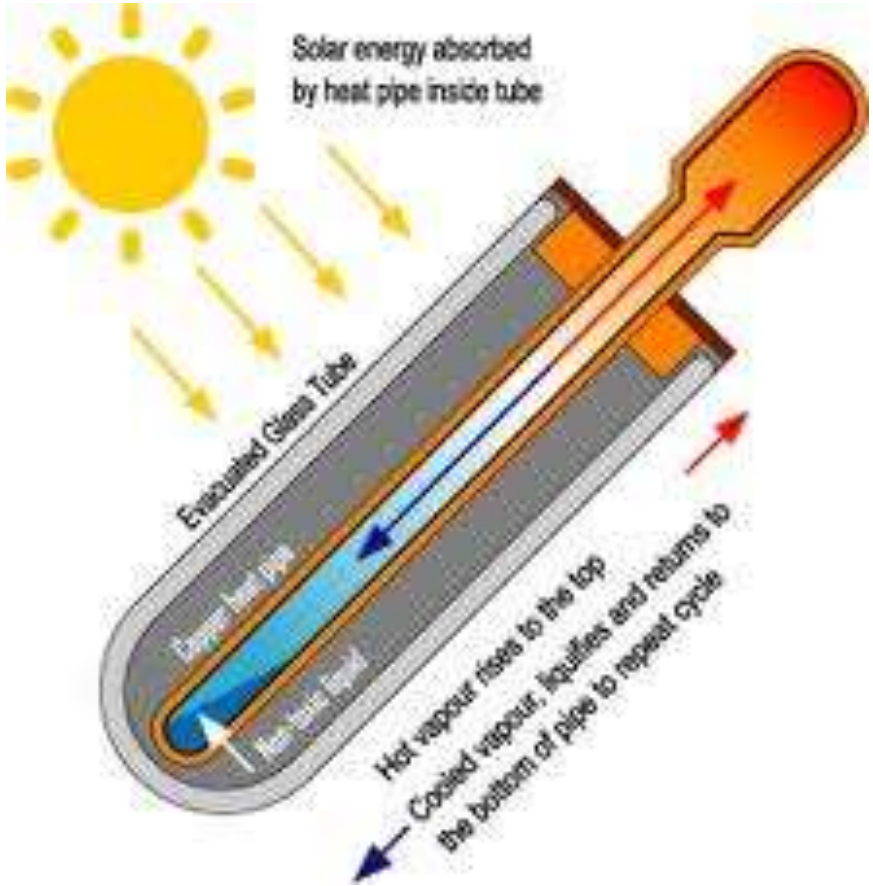


Solar Water Heaters: Industrial use



1,20,000 LPD SWHS AT GOĐAVARI FERTILISERS, A.P.

Evacuated Tube Collector: Here the collector is made of double layer borosilicate glass tubes evacuated for providing insulation. The outer wall of the inner tube is coated with selective absorbing material. This helps absorption of solar radiation and transfers the heat to the water which flows through the inner tube.



Solar Cooking: Family Type

Solar Mass Cooking

From 30th July 2009 Worlds ‘s largest
Now is Shirdi Temple
that cook s 50,000 meals per day

Already >50 Solar Systems installed

Sangi Industies, Hyderabad for their industrial canteen to cook for 650 workers.

Rishi Samskruti Vidya Kendra near Bangalore to cook for 500 students

Muni Seva Ashram School to cook for 500 people

Sri Saibaba Santhan Shirdi to cook for 3000 people per day

SOLAR AIR HEATING

- Pharmaceutical
- Leather
- Textiles
- Ceramics
- Chemical
- Industrial Process heat
- Latex rubber
- Coir mattress
- Laundry drying
- Fabricated components drying
- Preheated combustion air to boilers

KURINJI ORGANIC SOLAR FRUITS DRYING, BATLAGUNDU

PEN

590 sq.m solar collector for SAKTHI MASALA (P) LTD, ERODE, India

PEN

Thank you