University of Sallahadin
College of Engineering
Electrical Engineering Dept.

Distributed Generation

Chapter Four

Solar Energy

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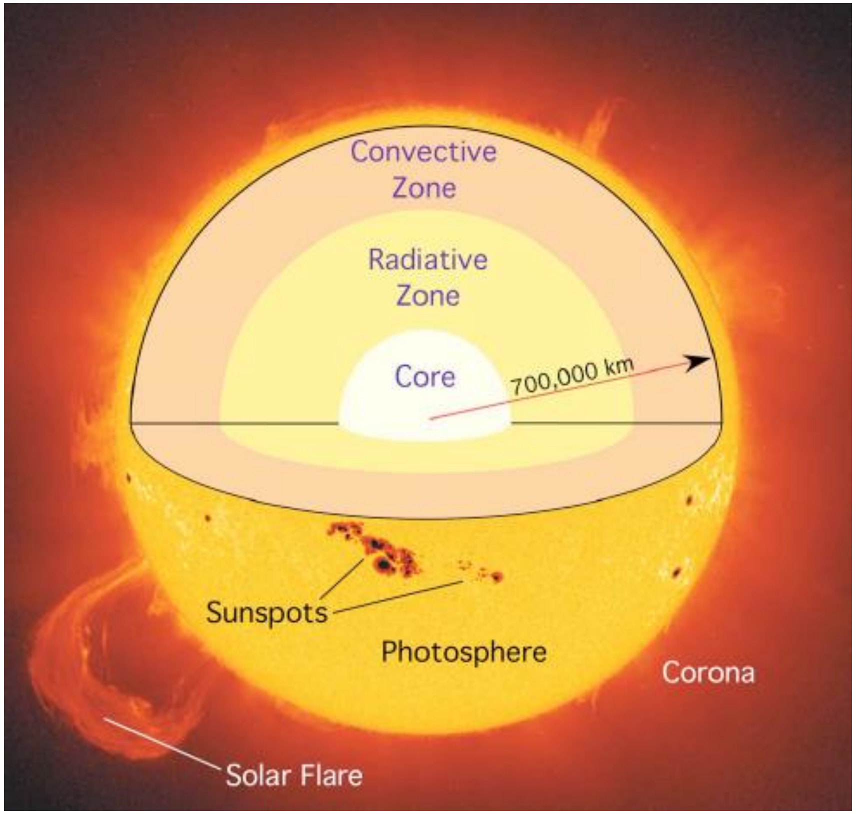
- Solar tracker

The Sun

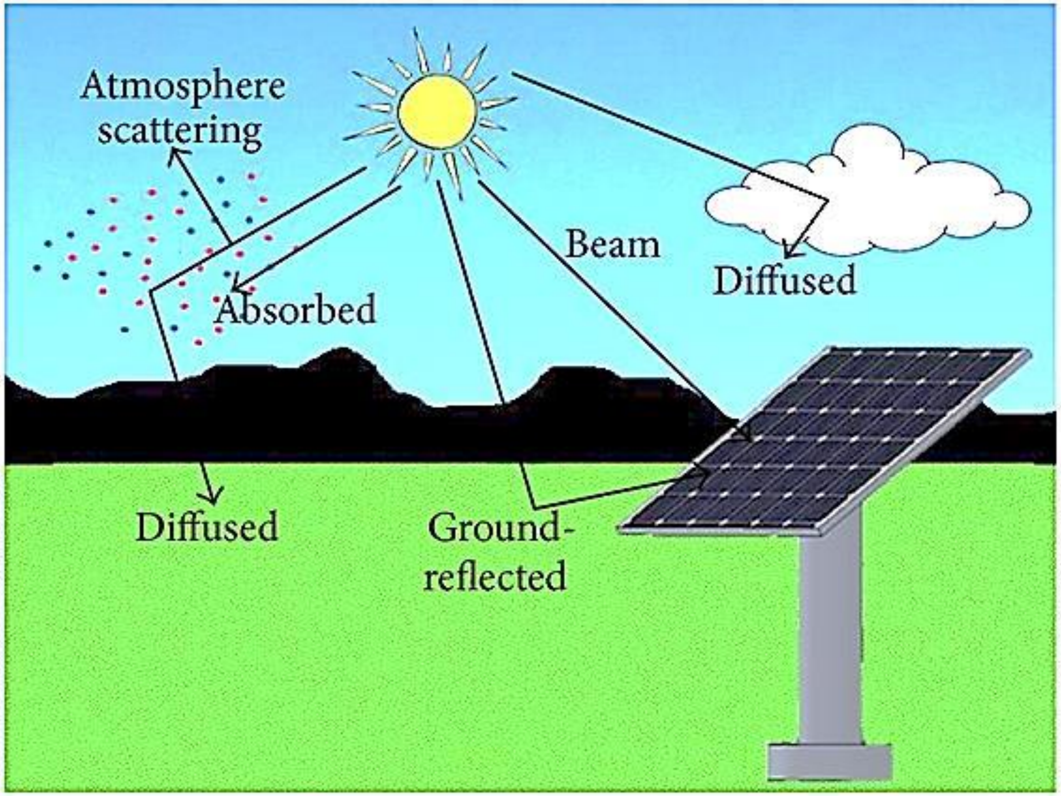
- The sun, the energy for our solar system.
- Sun produces: energy via nuclear fusion, hydrogen nuclei into helium nuclei which releases energy.



The Sun

- ***Solar irradiance*** is the power of solar radiation per m^2.
- Maximum solar irradiance reaches the Earth’s surface is about **1000 W/m^2**.
- A **pyranometer** measures total global solar irradiance from the whole sky.

Components of Solar Radiation

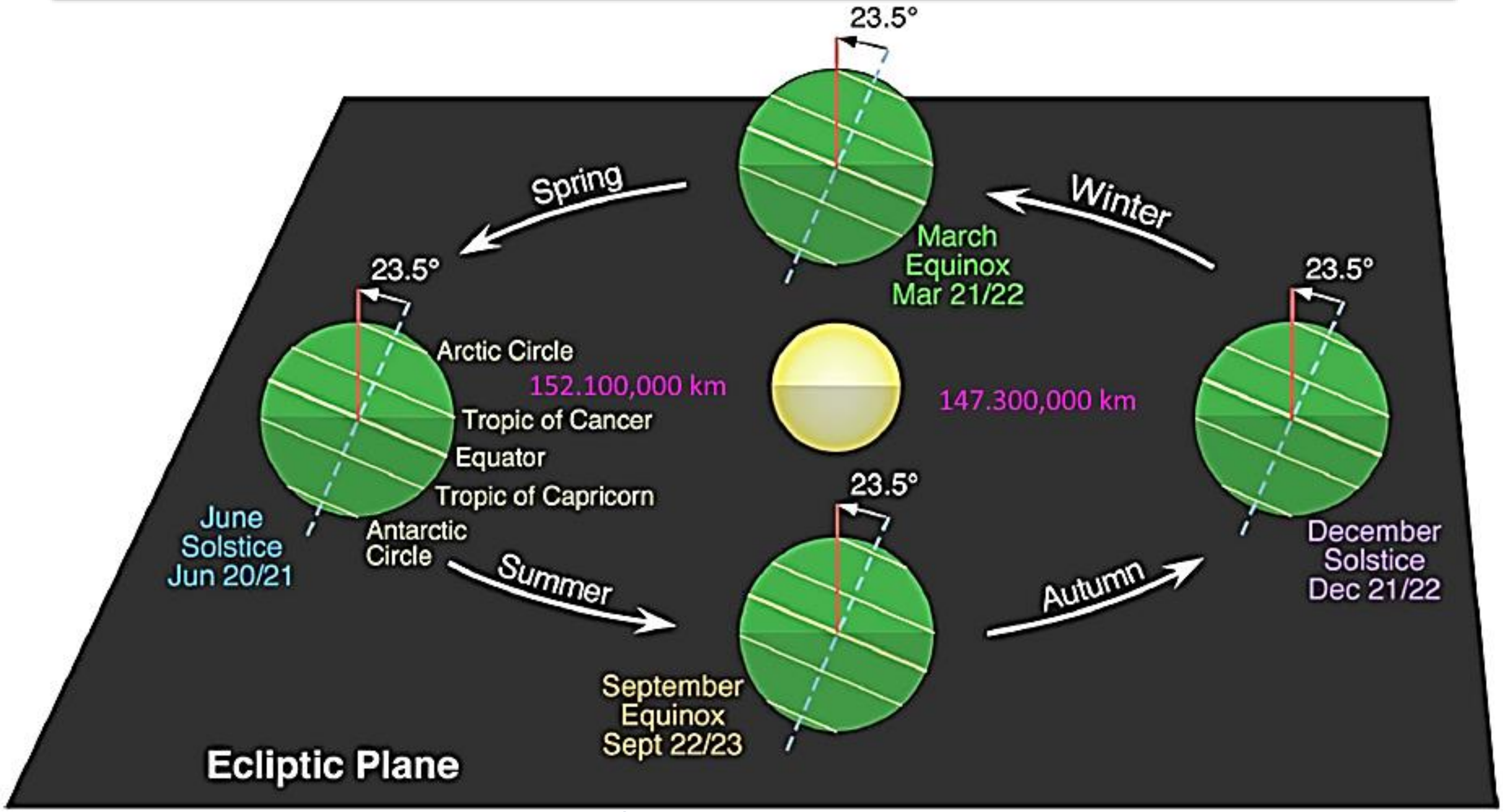


Beam radiation: direct solar radiation

Diffuse radiation: sky radiation

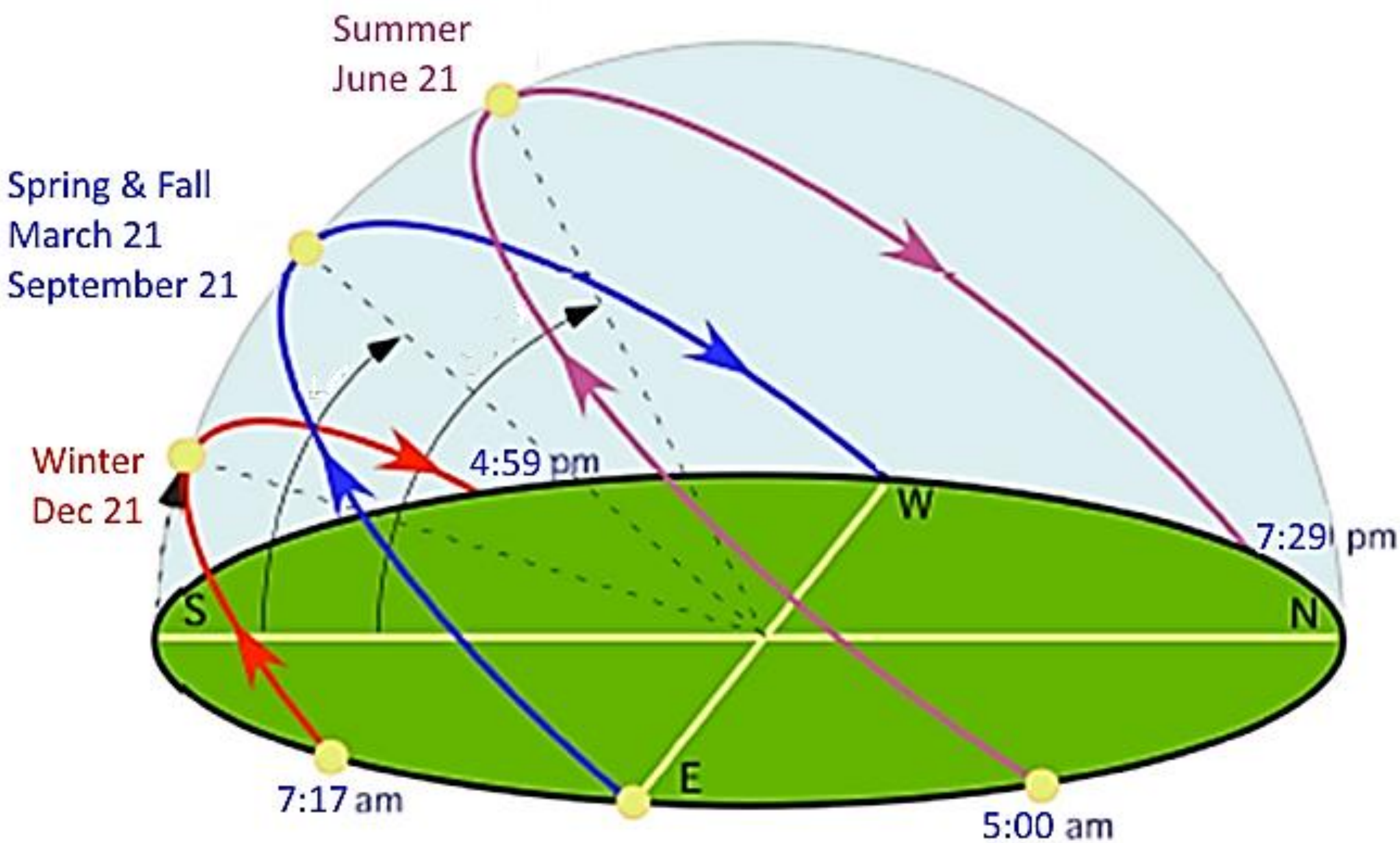
Irradiation: Radiant exposure Isolation, Irradiance (G: W/m^2)

Solar Plane and Angles

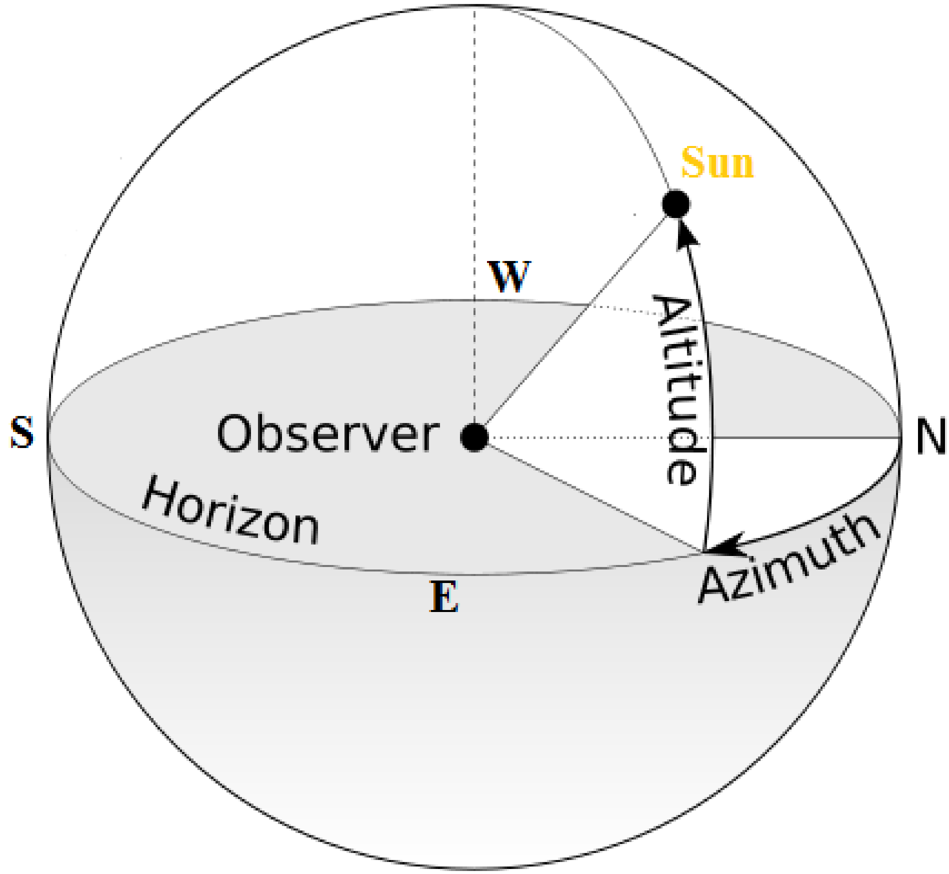


- **Annual motion of the Earth about the Sun**
- **The mean Sun-Earth distance 149.6X10^{6}Km**

Solar Plane and Angles



Solar Plane and Angles



The Sun’s position , Azimuth and Altitude Angles.

Solar Time

- **Solar time** is estimating the passage of time based on the Sun's position in the sky.

- Two types:
  - **AST:** Apparent solar time (sundial time)
  - **MST:** Mean solar time (clock time).

Apparent Solar Time

Apparent solar time or true solar time is based on the apparent motion of the actual Sun.

Sundial

Apparent Solar Time

$$AST = LST + (4\,\text{min}/deg)(LSTM - Long) + ET$$

$\boldsymbol{AST}$: *Apparent Solar Time*
$\boldsymbol{LST}$: *Local standard time for the time zone* (may need to adjust for daylight savings time, *DST*, that is *LST* = *DST* – 1 hr)

$\boldsymbol{LSTM}$: *local longitude of standard time meridian*

$$\boldsymbol{LSTM} = 15° \times \left(\frac{Long}{15°}\right)_{round\ to\ integer}$$

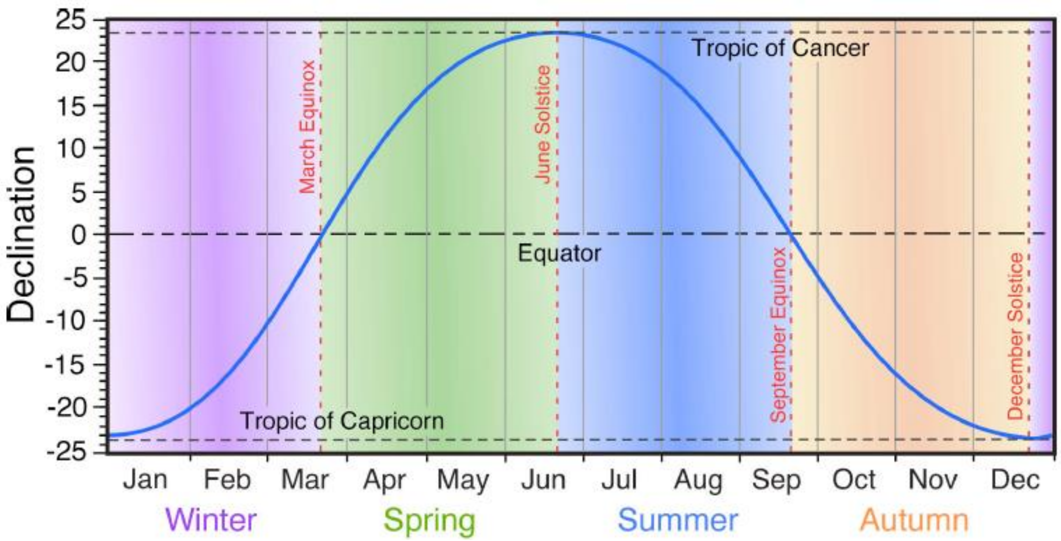
$\boldsymbol{Long}$: *Local longitude of the position of interest*

$$\boldsymbol{ET} = 9.87\sin(2D) - 7.53\cos(D) - 1.5\sin(D)$$

$$\boldsymbol{D} = \frac{360°(n - 81)}{365}$$

Solar Angles Calculation

The **declination** is the angular distance of the sun north or south of the earth's equator.



The ***declination angle***, **δ**, for the Northern Hemisphere is:

$$\boldsymbol{\delta = 23.45° sin\left[\frac{n + 284}{365} \times 360°\right]}$$

(Reverse the declination angle's sign for the Southern Hemisphere)

Solar Angles Calculation

The ***hour angle***, ***H***, is the azimuth angle of the sun's rays caused by the earth's rotation, and *H* can be computed from:

$$\boldsymbol{H = \frac{No.of\ minutes\ past\ midnight.AST - 720\ mins}{4\ min/deg}}$$

The hour angle as defined here is negative in the morning and positive in the afternoon (*H* = 0° at noon).

Solar Angles Calculation

The ***solar altitude angle,*** $\boldsymbol{\beta}$, is the apparent angular height of the sun in the sky if you are facing it. The ***zenith angle,*** $\boldsymbol{\theta_z}$, and its complement the ***solar altitude angle,*** $\boldsymbol{\beta}$ are given by:

$$\boldsymbol{\theta_z = H_s(sin(\beta))}$$

$$\boldsymbol{\beta = asin[cos(L)\, cos(\delta)\, cos(H) + sin(L)\, sin(\delta)]}$$

Where:

L = Latitude (positive in either hemisphere) [0° to +90°]

δ = Declination angle (negative for Southern Hemisphere) [–23.45° to +23.45°]

H = Hour angle

Solar Angles Calculation

The ***noon altitude*** is:

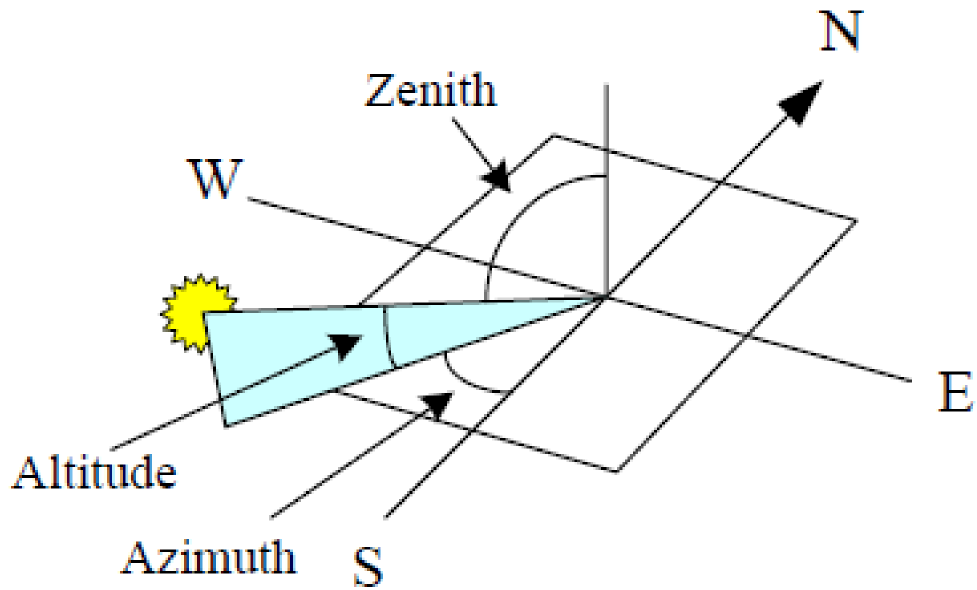
$$\beta_N = 90^\circ - L + \delta$$

The hour angle at sunset or sunrise, H_S, can be found from using when $\beta = 0$

$$H_s = acos(-tan(L)\,tan(\delta))$$

Where H_S is negative for sunrise and positive for sunset.

Solar Angles Calculation



The ***Solar Azimuth*,*α***, is the angle away from North.

$$\boldsymbol{\alpha = sign(H)acos\left[\frac{sin(\beta)\,sin(L) - \sin(\delta)}{cos(\beta)\,cos(L)}\right] + 180°}$$

Solar Angles Calculation

Example:

Erbil is located at 44.01°E longitude and a latitude of 36.19°N. For 9:00A.M Mean solar time on April 13:

1. Find the Apparent Solar Time (AST).
2. Determine the solar altitude and azimuth angles.

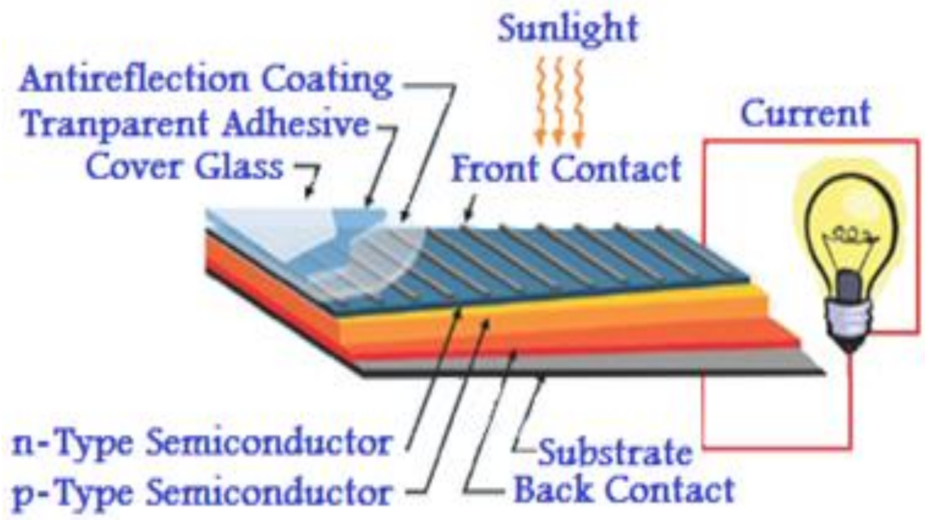
Photovoltaic cells

- A **Photovoltaic Cell (PV)**, is a device that converts sunlight energy into electric energy using the photovoltaic effect.
- The term "**photovoltaic**", ***Photo*** means **light** in Greek and ***Volta*** is the **unit for electrical voltage**.
- A few semiconductor materials such as **silicon (Si)**, **Cadmium Sulphide (CdS)**, and **Gallium Arsenide (GaAs)** can be used to fabricate solar cells. The most commonly used for fabrication of solar cells is **silicon**.
- For creating the PV effect, **sunlight** hits a photovoltaic cell.

Photovoltaic cells

- Two layers of a semi-conducting material are combined to create this effect, typically silicon. The industry refers to these layers as P and N.

- When photons with sufficient energy hit the cell, they cause electrons to move from N to P causing excess electrons in the N-layer and a shortage in the P-layer.



Photovoltaic Generations: 1st Generation

Crystalline Silicon (c-Si)

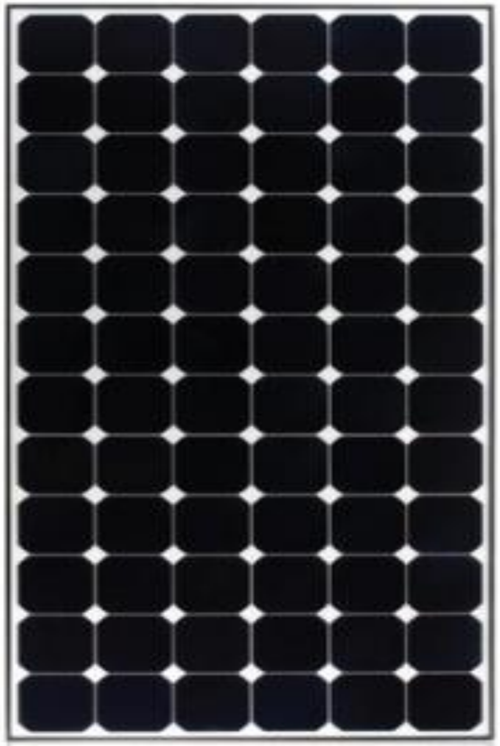
- Crystalline silicon (or wafer-based) technologies constitute about 85% of the current PV market.
- **Crystalline Silicon Types:**

1. Monocrystalline (Single crystalline)
2. Polycrystalline (Multi crystalline)
3. Amorphous Silicon Cells
4. Hybrid Silicon Cells

Photovoltaic Generations: 1st Generation

1. Monocrystalline or Single crystalline (sc-Si)

- Monocrystalline solar panels are made from single silicon crystal.
- Typically, the cells are a few inches across.
- The oldest solar cell technology.
- The most popular, longest life and efficient.
- They have a higher efficiency (up to 24%)
- **High temperatures and shading** have more impact on solar panel performance.
- Color: **black** or **iridescent blue color**.



Photovoltaic Generations: 1st Generation

2. Polycrystalline or multicrystalline (mc-Si)

- Multicrystalline semiconductor wafers are cut from solidified blocks.
- Requires less silicon and reduces the initial costs and it also reduces the efficiency.
- They are cheaper, less life and less efficient (up to 19.3%)
- **High temperatures and shading** have less impact on solar panel performance.
- The color of this type panels are typically **blue**.

Photovoltaic Generations: 1st Generation

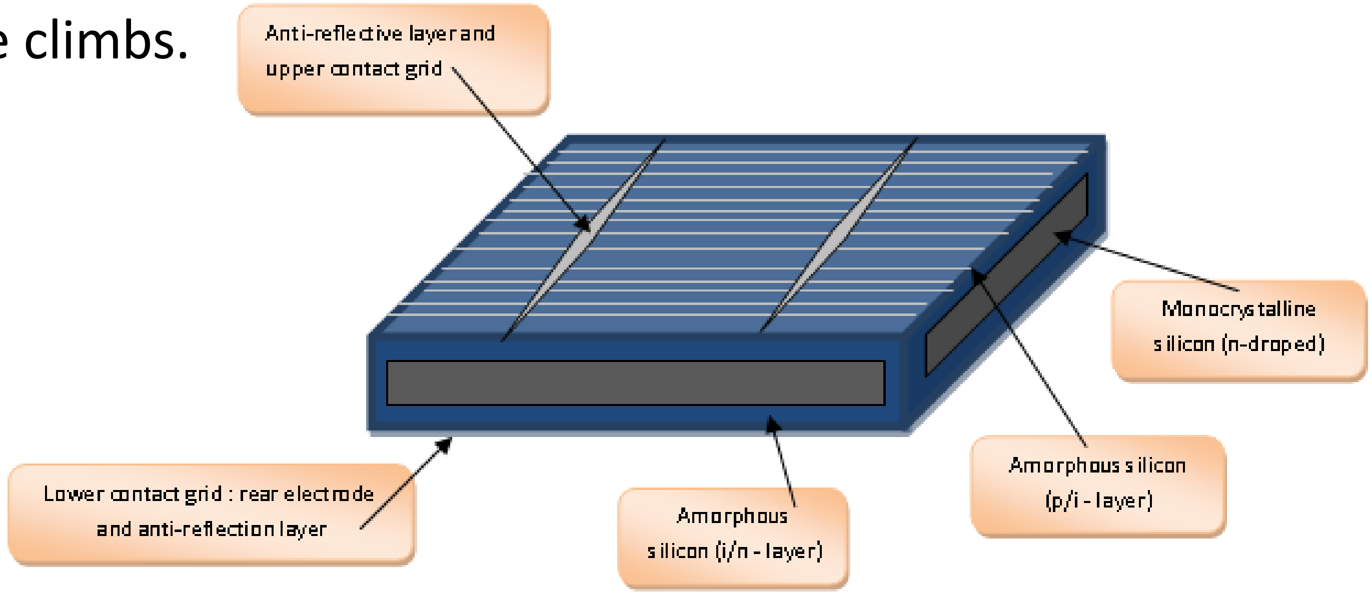
3. Amorphous Silicon Cells (a-Si)

- Silicon is deposited in a very thin layer on to a backing substrate – such as metal, glass or even plastic.
- The panels can be made flexible.
- They are shortest life and much less efficient per unit area (up to 10%).
- **High temperatures and shading** have less impact on solar panel performance.
- Generally not suitable for roof installations.

Photovoltaic Generations: 1st Generation

4. Hybrid Silicon Cells

- A layer of amorphous silicon is deposited on single crystal wafers.
- The result is an efficient solar cell that performs well in terms of indirect light and is much less likely to lose efficiency as the temperature climbs.

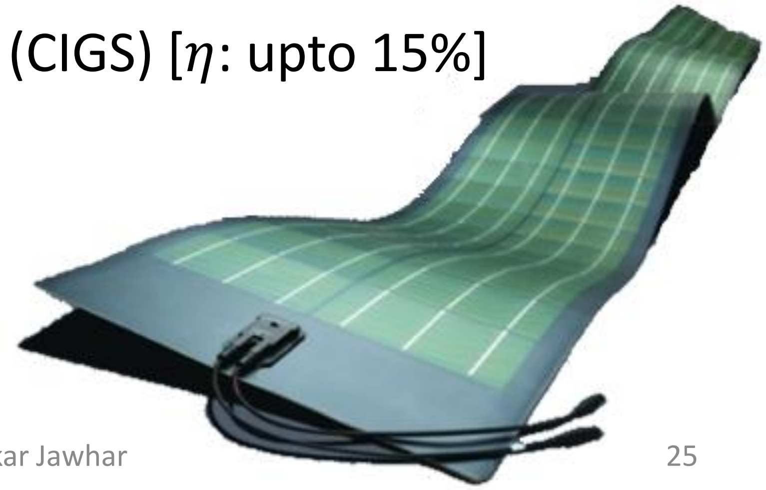


Photovoltaic Generations: 2nd Generation

- Usually called **Thin Film:**
- Cheaper but less efficient.
- These types use a much thinner level of photovoltaic material than mono-crystalline or multi-crystalline solar panels.

The most common thin-film semiconductor materials are:

1. **Amorphous silicon** (a-Si) [η: upto 4.8%]
2. **Cadmium Telluride** (Cd-Te) [η: upto 16.7%]
3. **Copper - Indium – Gallium - Selenide** (CIGS) [η: upto 15%]



Photovoltaic Generations: 3rd Generation

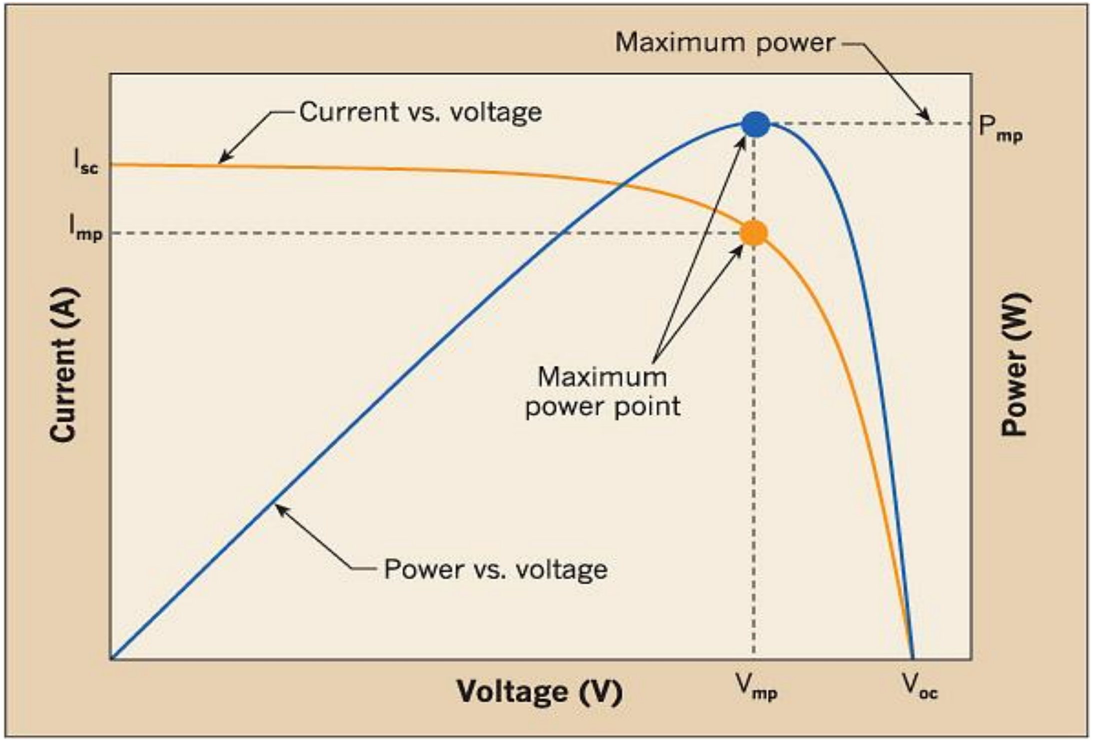
- Currently there is a lot of solar research going on in what is being referred to in the in the industry as Third-generation solar cells.

- They are being made from variety of new materials besides silicon, including:

1. Nanotubes
2. Silicon wires
3. Solar inks using conventional printing press technologies
4. Organic dyes
5. Conductive plastics.

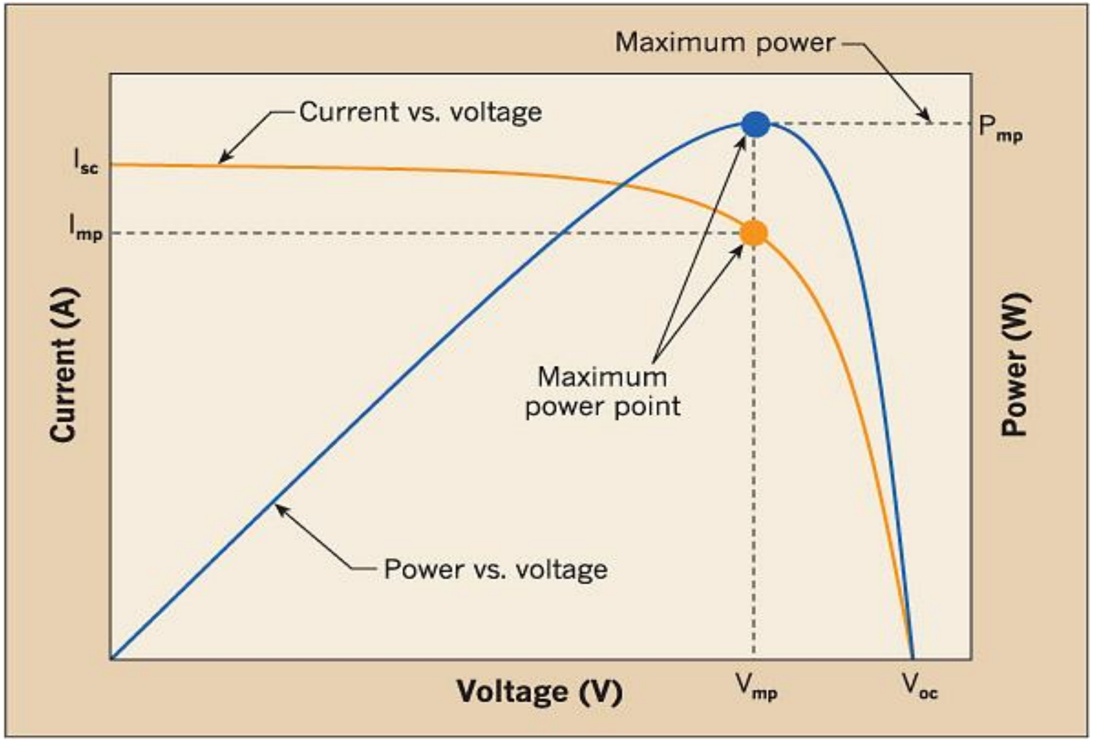
- More efficient and less expensive.
- Currently, most of the work on third generation solar cells is being done in the laboratory, and being developed by new companies and for the most part is not commercially available.

PV Characteristics



- The characteristic of solar cells is quite similar to that of diode.
- The results are recorded in so-called IV curve.
- The IV curve are derived from the short circuit current (I_{sc}) and the open circuit voltage (V_{oc}) to gain the maximum power (P_{mp}).

PV Characteristics



- The amount of irradiation and the environmental temperature also influence IV characteristics.
- The more irradiation the more power produced.
- The lower temperature the more power produced.

PV Parameters

Short Circuit Current (I_{sc})

The short circuit current can be measured by shorting the output terminals of the solar panels when the voltage is zero.

Open Circuit Voltage (V_{oc})

The open circuit current measured when the output terminals of the solar panels are open when the current is zero.

PV Parameters

Maximum Power (P_{mp})

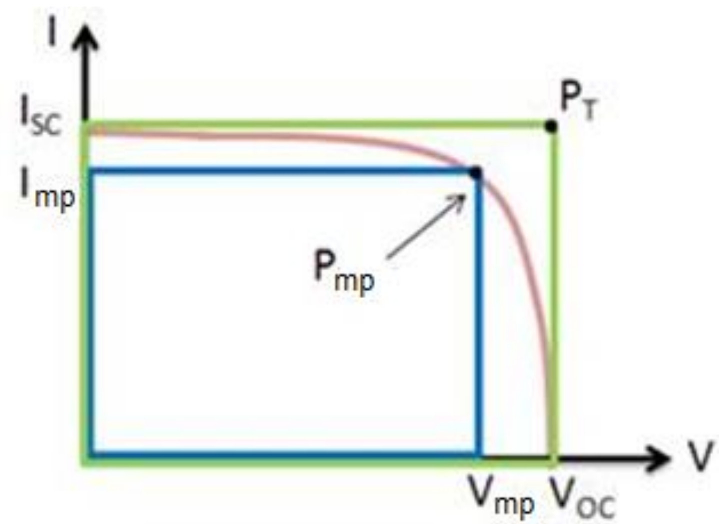
The maximum power P_{mp} provided by the device is achieved at a point on the characteristics, where the product of IV at that point is maximum. This point is called Maximum Power Point.

$$P_{mp} = I_{mp} \times V_{mp}$$

The Fill Factor

- The **FF** is defined as the ratio of **the maximum power** from the solar cell to **total power** P_T or the product of I_{sc} and V_{oc}.
- Higher FF, the performance of a solar cell is better.
- In practice FF is always less than 1. The maximum FF value for silicon is 0.88.

$$FF = \frac{P_{mp}}{P_T} = \frac{I_{mp} \times V_{mp}}{I_{sc} \times V_{oc}}$$



- The fill factor indicates how well a junction was made in the cell, and how low series resistance and high parallel resistance has been made .

Efficiency (η)

- Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun.

$$\boldsymbol{Solar\ efficiency = \frac{electrical\ power\ output}{solar\ power\ recived\ by\ solar\ cell}}$$

$$\boldsymbol{\eta = \frac{P_{mp}}{P_{in}} = \frac{I_{mp} \times V_{mp}}{I_{(t)} \times A_c} = \frac{I_{sc} \times V_{oc} \times FF}{I_{(t)} \times A_c}}$$

$I_{(t)}$: Incident solar irradiance in W/m^2.
$\mathrm{A_c}$: Area of solar panel in m^2

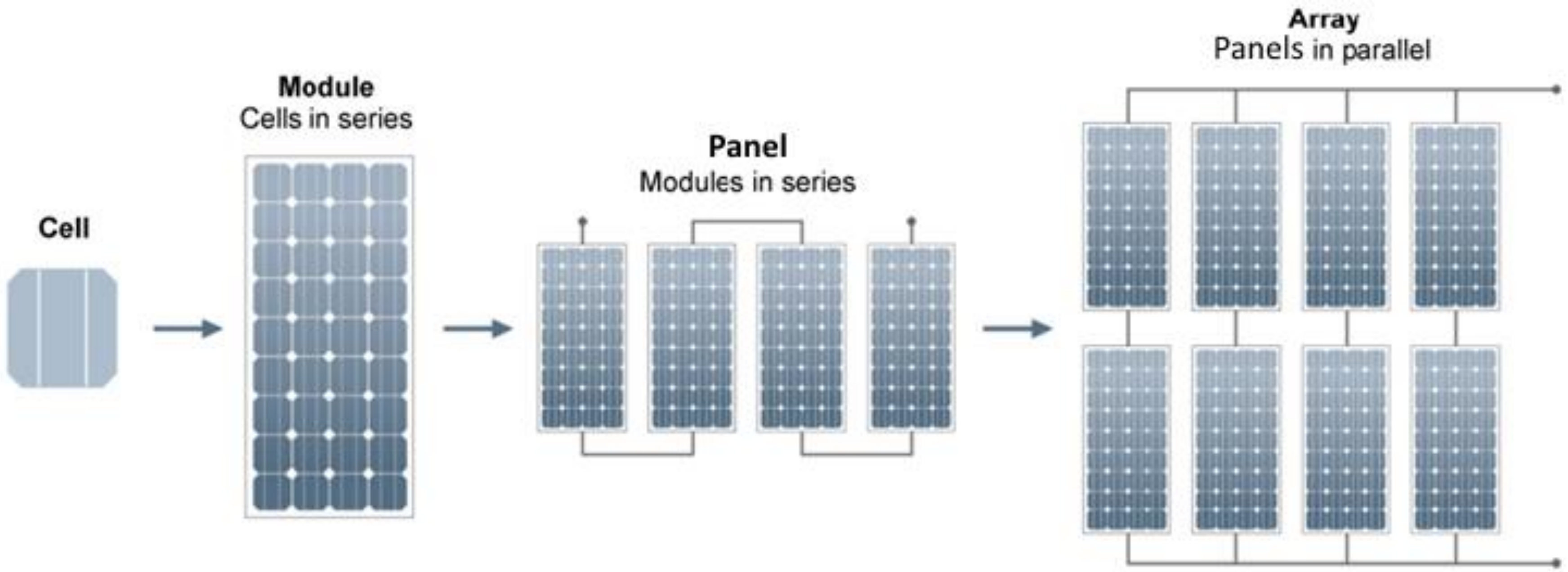
Standard Test Conditions (STC)

- Irradiance : 1000 W/m^2
- Air mass (AM) : 1.5
- Angle of incidence (AOI) : 0°
- Temperature : 25°C

PV System arrangement

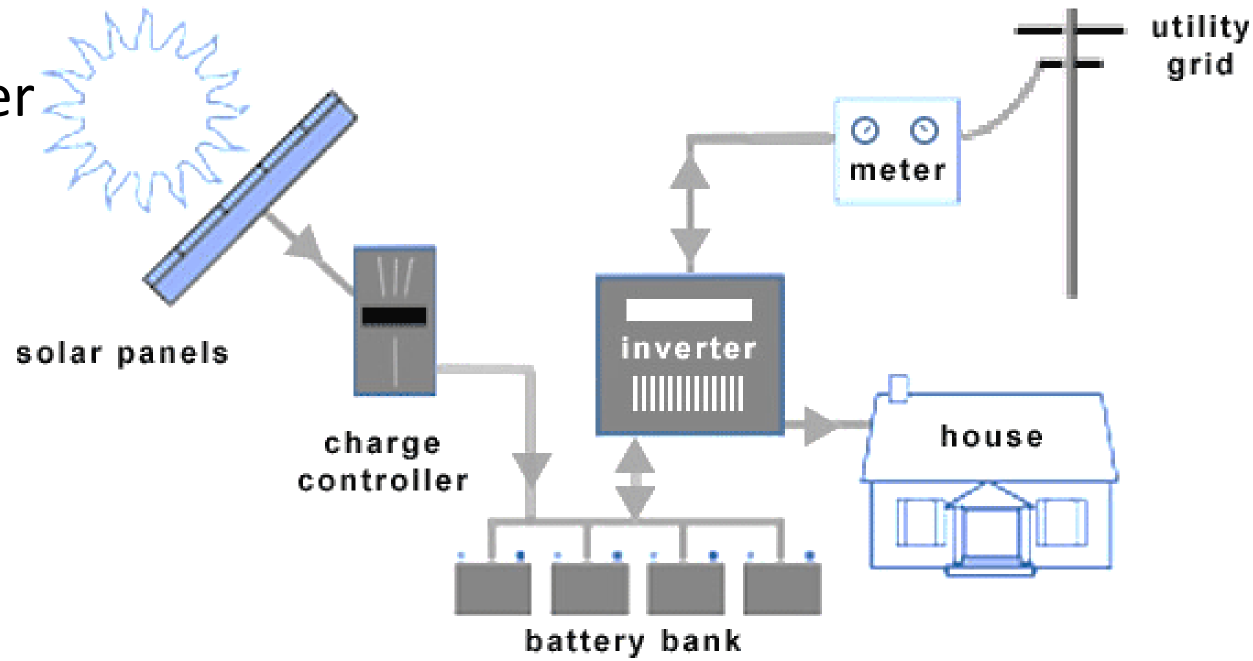
- The open circuit voltage of a single solar cell is about 0.5V.
- Much higher voltage is required for practical application.
- Solar cells are connected in series to increase its open circuit voltage.

PV system arrangement are: Cell, Module, Panel and Array.



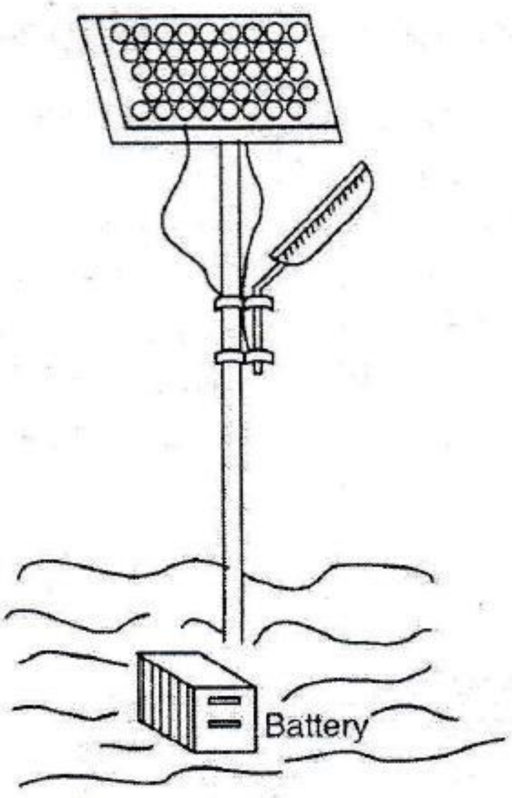
PV System components

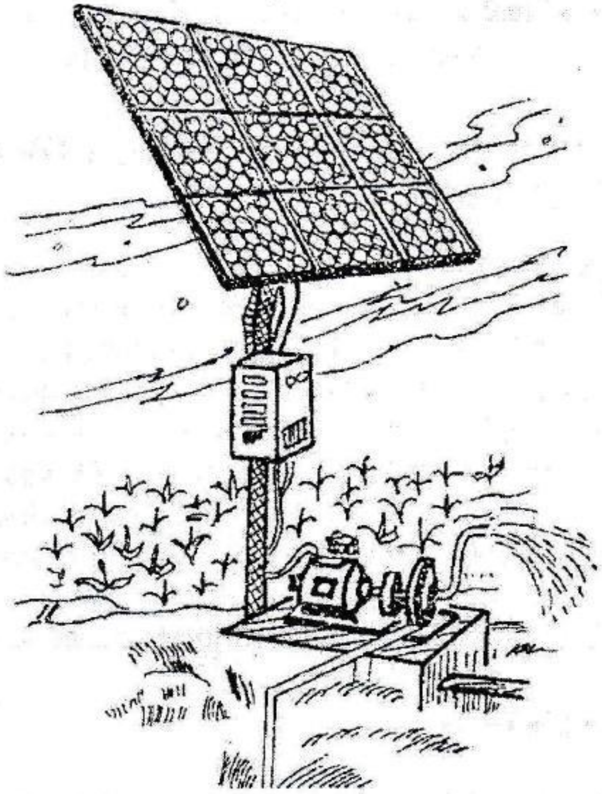
- PV Panel
- Mounting
- DC Isolator
- Charge controller
- Batteries
- Invertor
- AC Isolator
- Circuit Breaker
- Cabling
- MPP tracking
- Tracking System
- Loads
- Electricity Meter



Types of PV Systems

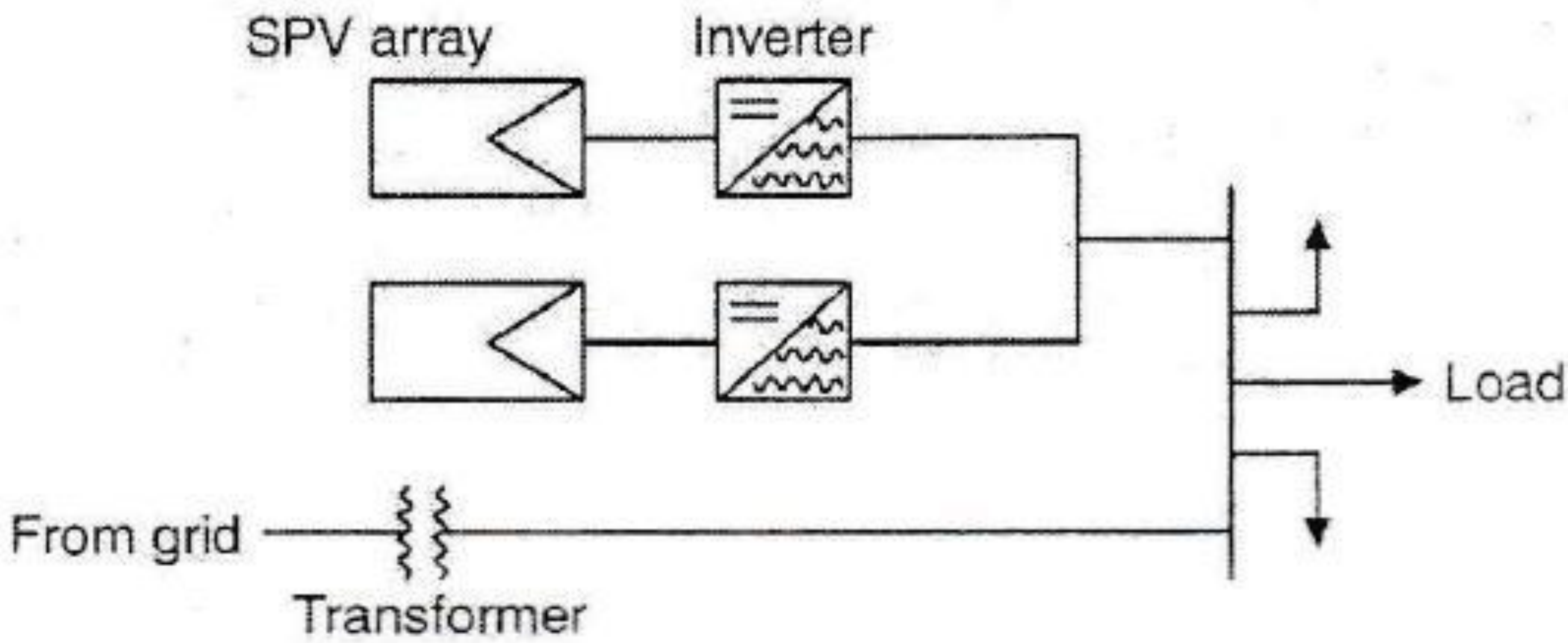
- Stand-Alone Systems (off-Grid PV Systems)





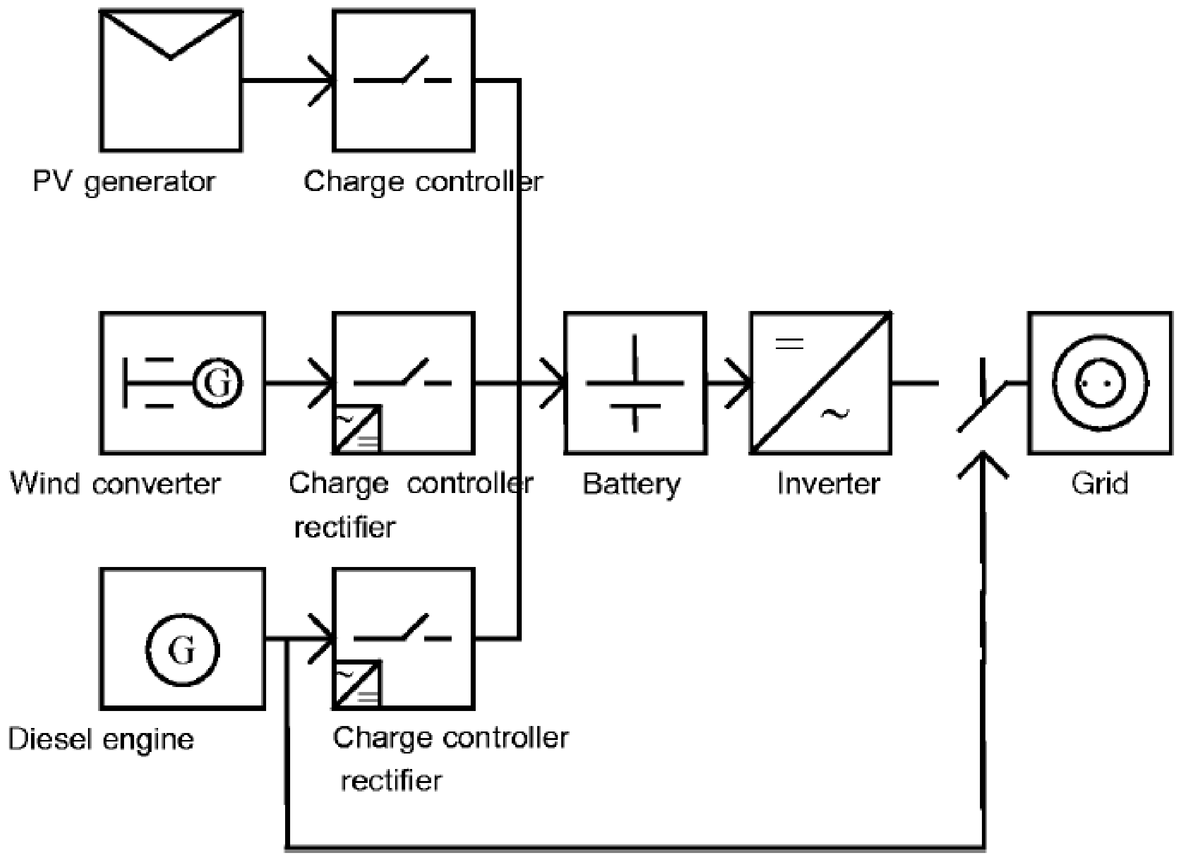
Types of PV Systems

- Grid-Connected Systems



Types of PV Systems

- Hybrid Systems (combination of PV modules and a complementary means of electricity generation)

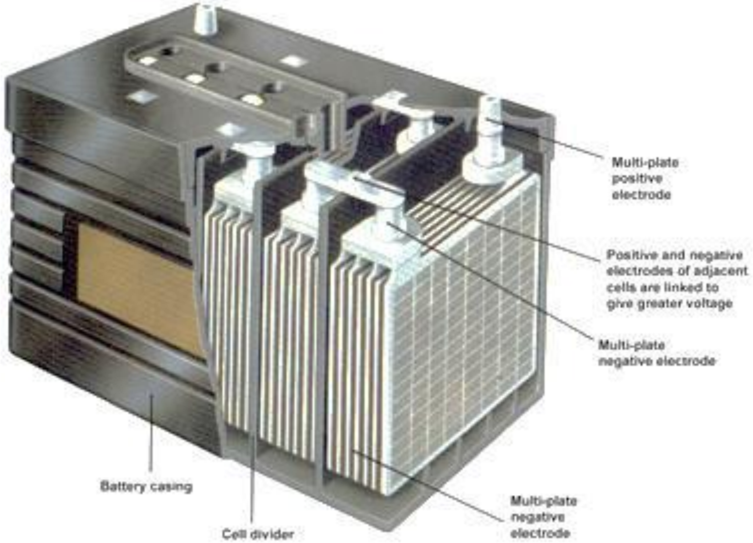


PV System components

Batteries

Lead Acid

- The electrodes are grids of metallic lead containing lead oxides that change in composition during charging and discharging.
- They are still the battery of choice for 99% of solar and backup power systems.



PV System components

Batteries

Nickel Cadmium (NiCad)

Alkaline storage batteries in which the positive active material is nickel oxide and the negative contains cadmium. Downsides:

1. Very expensive
2. Low efficiency (65-80%)
3. Non-standard voltage and charging curves.

PV System components

Batteries

Nickel Iron (NiFe)

The nickel-iron battery (NiFe battery) is a storage battery having a nickel(III) oxide-hydroxide cathode and an iron anode, with an electrolyte of potassium hydroxide. Very long life.

PV System components

Batteries charging

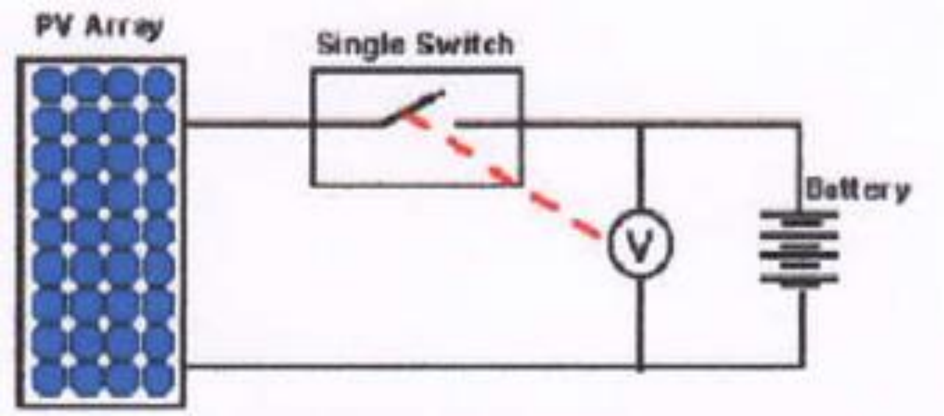
The charger has three key functions

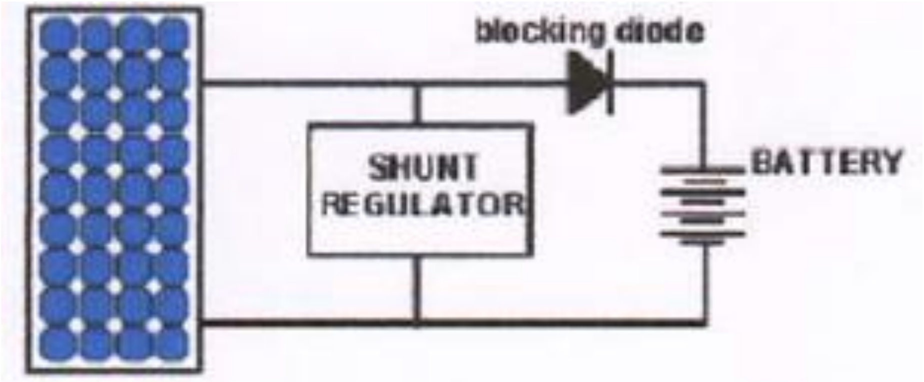
- Getting the charge into the battery (Charging)
- Knowing when to stop (Terminating)
- Optimizing the charging rate (Stabilizing)

PV System components

Batteries charging

- Types of charging

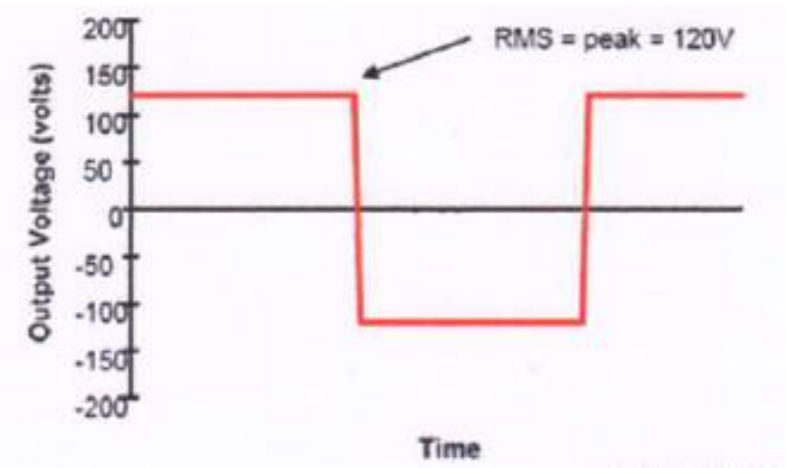


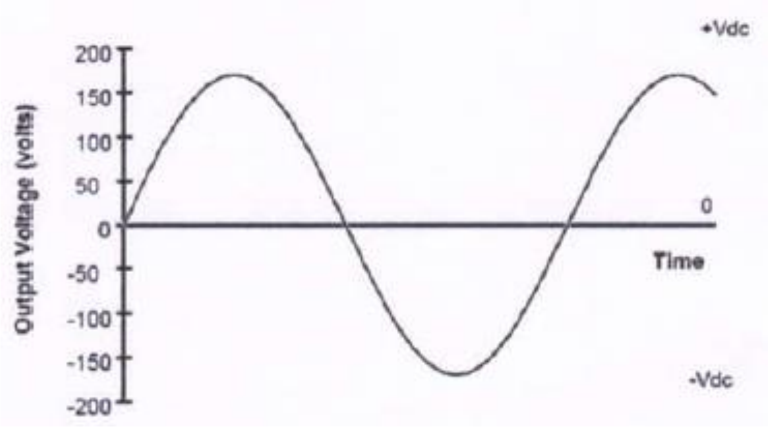


PV System components

Inverters

- Function: Converting DC to AC power
- Input & output voltages: Input 6, 12, 24V. Output 110, 220V
- Power quality
  - Square wave & modifies square wave





PV System Design Guide

1. Determine the total load current and operational time.

2. Add system losses.

3. Determine the solar irradiation in daily equivalent sun hours.

4. Determine total solar array current requirements.

5. Determine optimum module arrangement for solar array.

6. Determine battery size for recommended reserve time.

Problems

Problem 1: Photovoltaic panel with dimensions 80cm x 60cm having following parameters: Isc =3.5A, Voc=20V, Imp=3.2A and Vmp=18V. Find PV panel Fill factor and efficiency at $900W/\mathrm{m}^2$ irradiance.

Problems

Problem 2: A Photovoltaic panel having following parameters: Isc =3.5A, Voc=20V, Imp=3.2A and Vmp=18V. What will be the area required to have efficiency of 15% at 900 W/m^2 irradiance.

Problems

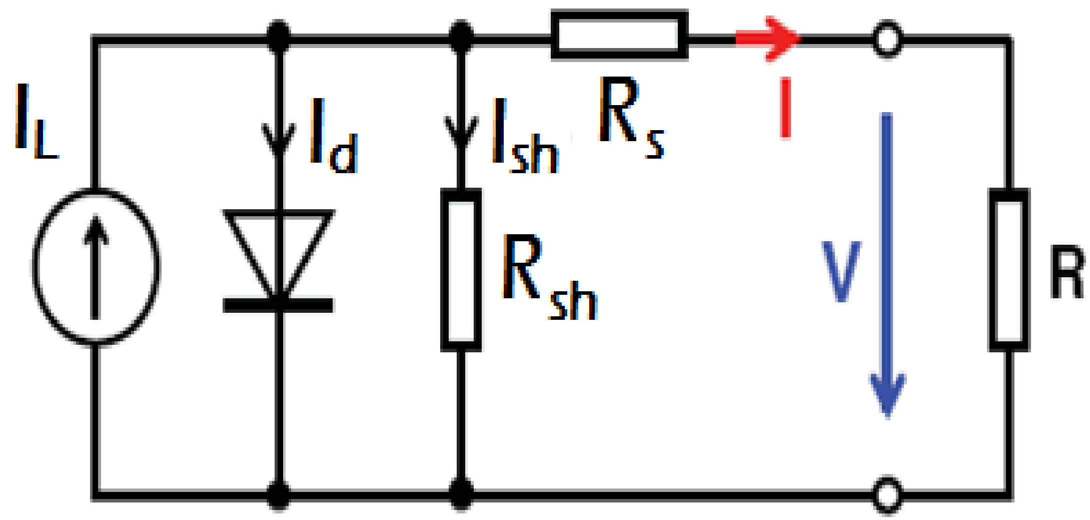
Problem 3: A Photovoltaic panel having following parameters: Isc =3.5A, Voc=20V, FF=0.83. What will be the area required to have efficiency of 15% at $800W/\mathrm{m}^2$ irradiance.

Problems

Problem 4: An AC computer and TV set are connected to the PV system. The computer, which has rated power 40W, runs 2 hours per day and the TV set with rated power 60W is 3 hours per day in operation. The nominal module voltage of the system is 24V. Calculate:

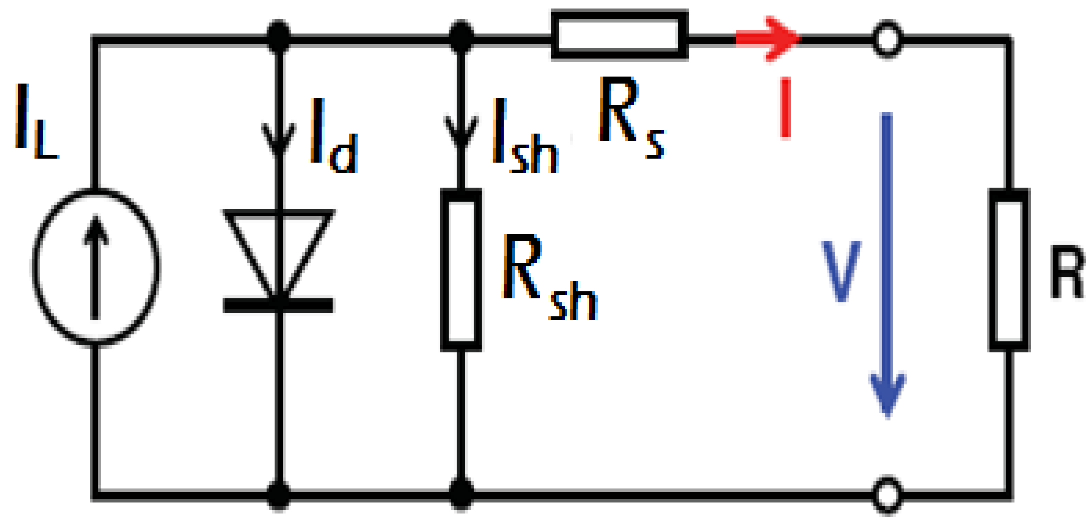
1. The daily energy requirements of the devices
2. The daily Dc current required if the voltage of the PV is 12V.
3. Total DC requirements of loads of the system losses (20%).
4. The solar irradiation if the daily sun hours is 3 hours.
5. The optimum module arrangement for solar array.
6. The battery size for 5 days reserve time.

The Equivalent Electrical Circuit



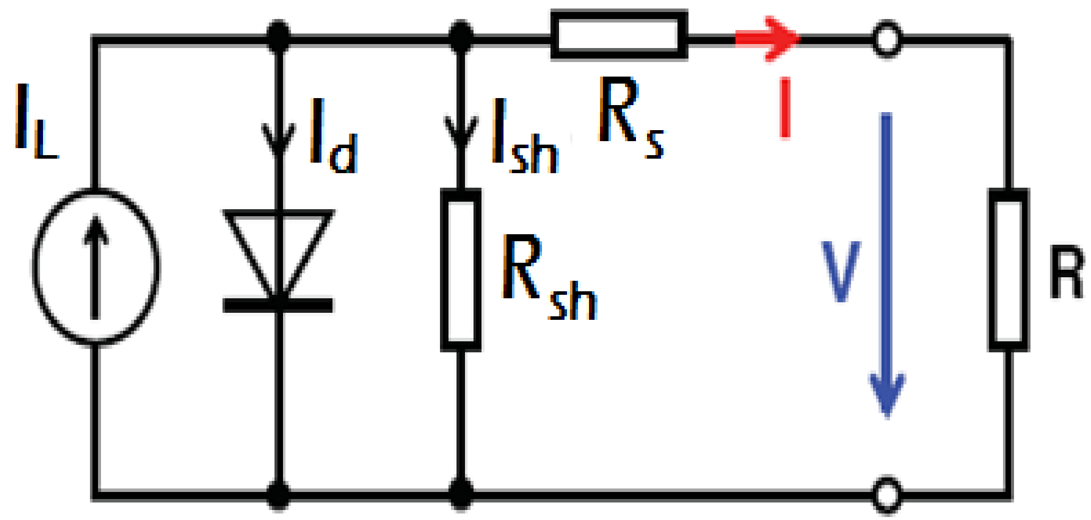
- The **series resistance** R_s represents the internal resistance, depends on the p-n junction depth, the impurities and the contact resistance.
- The **shunt resistance** R_{sh} is inversely related with leakage current to the ground.
- In an ideal PV cell, $R_s = 0$, & $R_{sh} = \infty$.

The Equivalent Electrical Circuit



- In a typical high quality one square inch silicon cell, $R_s = 0.05\ to\ 0.10\ \Omega$ and $R_{sh} = 200\ to\ 300\Omega$.
- The PV conversion efficiency is **sensitive** to **small variations in $\boldsymbol{R_s}$**, but it is **insensitive** to **variations in $\boldsymbol{R_{sh}}$**.
- A **small increase** in $\boldsymbol{R_s}$ can **decrease** the PV output **significantly**.

The Equivalent Electrical Circuit



$$I = I_L - I_d - I_{sh}$$

I : Output terminal current
I_L : Light-generated current
I_d : Diode-current
I_{sh} : Shunt-leakage current

The Equivalent Electrical Circuit

At the reference conditions:

$$a_{ref} = \frac{\mu_{V,oc} T_{c,reff} - V_{oc,reff} + \epsilon N_s}{\frac{\mu_{I,sc} T_{c,reff}}{I_{L,reff}} - 3}$$

a_{ref}: $curve\ fitting\ parameter$ *at reference conditions*

T_c: *cell temperature in* $kelvin$ *,= C° + 273*

$T_{c,reff}$: *cell reference temperature in* $kelvin\ (298K)$

$\mu_{V,oc}$: *Temperature coefficient of open circuit voltage*

$\mu_{I,sc}$: *Temperature coefficient of short circuit current*

ϵ : $The\ material\ bandgap\ energy$

$= for\ \mathbf{silicon\ 1.12\ eV}\ \&\ for\ \mathbf{gallium\ arsenide\ 1.35\ eV}$

N_s: $Total\ number\ of\ cells\ in\ series$

At reference conditions: $I_{L,ref} = I_{sc}$

The Equivalent Electrical Circuit

Diode reverse saturation current at the reference conditions $\boldsymbol{I_{o,ref}}$:

$$I_{o,ref} = I_{L,ref}\, exp\left(-\frac{V_{oc}}{a_{ref}}\right)$$

Diode reverse saturation current at given temperature:

$$I_o = I_{d,ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 \exp\left[\frac{\epsilon N_s}{a_{ref}}\left(1-\frac{T_{c,ref}}{T_c}\right)\right]$$

Series resistance at the reference conditions $\boldsymbol{R_{s,ref}}$:

$$R_{s,ref} = \frac{a_{ref}\, ln\left(1-\frac{I_{mp}}{I_{L,ref}}\right) - V_{mp} + V_{oc,reff}}{I_{mp}}$$

The Equivalent Electrical Circuit

Curve fitting parameter at given temperature:

$$a = \frac{a_{ref} T_c}{T_{ref}}$$

Light-generated current at given temperature:

$$I_L = \frac{I_t}{I_{t,ref}} \left[I_{L,ref} + \mu_{I,sc} \left(T_c - T_{c,ref} \right) \right]$$

I_t *: Given Irradiance in W/m²*

$I_{t,ref}$ *: Irradiance at reference conditions = 1000 W/m²*

$$\textit{Maximum power} = P_{mp} = I_{mp} \times V_{mp}$$

$$\textit{Maximum efficiency} = \eta_{mp} = \frac{I_{mp} \times V_{mp}}{I_{(t)} \times A_c} = \frac{I_{sc} \times V_{oc} \times FF}{I_{(t)} \times A_c}$$

The Equivalent Electrical Circuit

Output terminal current:

$$I = I_L - I_d - I_{sh}$$

Light-generated current at given temperature:

$$I = I_L - I_o\left[\exp\left[\frac{q(V + R_S I)}{NKT}\right] - 1\right] - \frac{(V + R_S I)}{R_{sh}}$$

V *: Output terminal voltage*

R_{Sh} *: Shunt resistance*

q *: electron charge =* 1.602×10^{-19} *C*

N : Ideality factor of the diode and its less than 1.

K *: Boltzmann's constant =* 1.38×10^{-23} *J/K*

T *: Cell junction temperature* $= T_c + \frac{(T_{c,ref} - 20)}{0.8} \times I_t$

Example

A PV module with 36 cells in series and an area of 0.427 m^2 has the following measured characteristics at reference conditions: Short circuit current = 2.9A, Open circuit voltage = 20V, Maximum power point current = 2.67A and Maximum power point voltage = 16.5V. The temperature coefficient of the short circuit current and the open circuit voltage are 1.325E-3 A/K and -0.0775 V/K, respectively.

For the model at the reference conditions and at a cell temperature of 67.2℃ and consider both $I_{(t)}$&$I_{(t)reff}$=1000 W/m determine the values of:

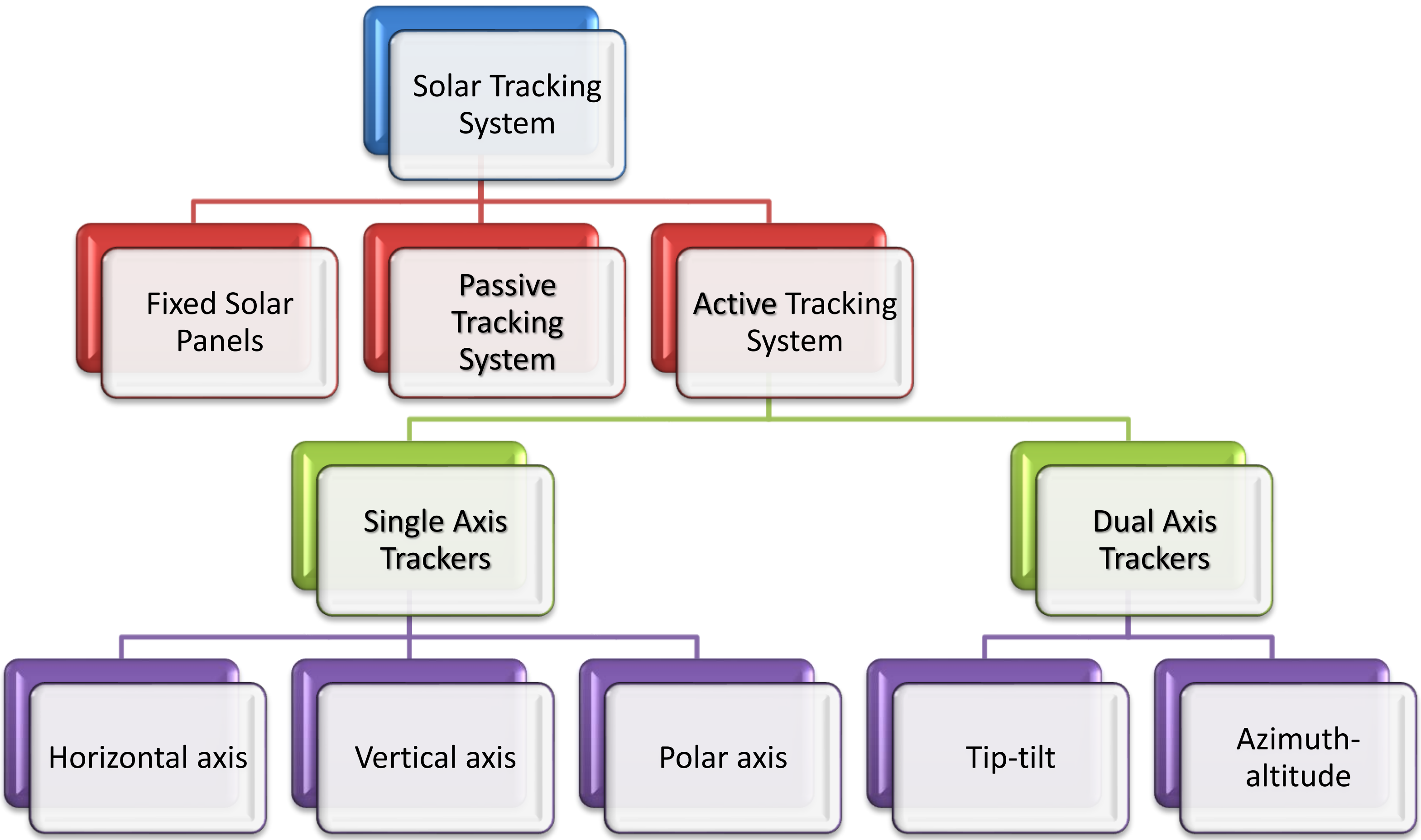
1. *Series resistance*
2. *Curve fitting parameter*
3. *Light-generated current*
4. *Diode reverse saturation current*
5. *Maximum power*
6. *Maximum Efficiency*

Solar Tracker

Solar Panels With Tracker System

- A mechanism is needed to track the sun's position during the day, allowing the solar radiation to remain perpendicular on the solar cell. .

Solar Tracker



Solar Tracker

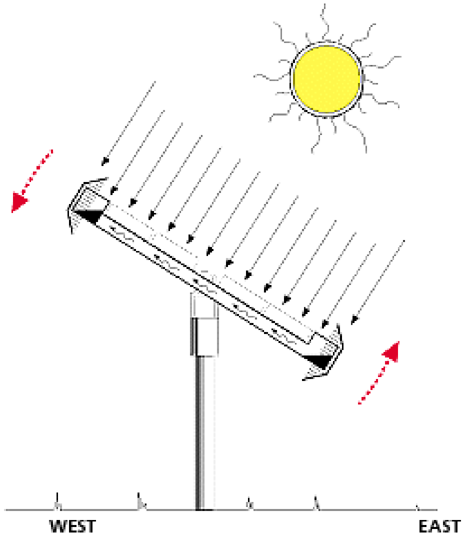
Fixed Solar Panels

- Most of solar panels are fixed toward the south, so in the morning and afternoon the radiation hits the panels at a tilt angle, giving lower efficiency.

Types of Solar Trackers

Passive Trackers

A thermo hydraulic system consisting of two tube tanks is placed at the sides of the photovoltaic panels, if the PV array is not aligned with the Sun, the fluid in the tanks will heat resulting in pressure difference that will drive the fluid through a connecting pipe into the tube tank with the lowest temperature.



Types of Solar Trackers

Active Tracker: Single Axis Tracker

In single axis tracking, the axis rotates in one direction to follow the sun in the sky throughout the day.

There are three types of single axis trackers:

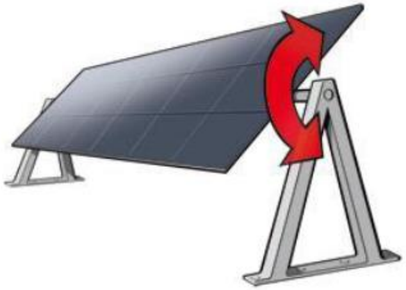
- horizontal axis
- Vertical axis
- Polar axis.

Types of Solar Trackers

Active Tracker: Single Axis Tracker

Horizontal Single Axis Trackers

Horizontal single axis trackers have a horizontal axis of rotation parallel with the ground.

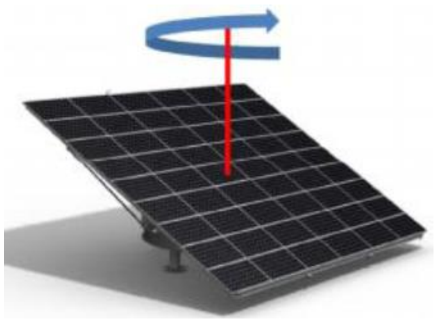


Types of Solar Trackers

Active Tracker: Single Axis Tracker

Vertical Single Axis Trackers

The panels are mounted at an inclination angle relative to horizontal and moved around the vertical axis, depending on the ground, from east to west during the day.



Types of Solar Trackers

Active Tracker: Single Axis Tracker

Polar Single Axis Trackers

A polar single axis tracker has an axis which is not horizontal or vertical on the ground, but rather its axis is parallel to the axis of rotation of the earth around the north and south poles

Types of Solar Trackers

Active Tracker: Dual Axis Trackers

A dual axis tracker can track the sun in the sky perfectly by using two axes of motion to follow the direction of the sun: East-West and North-South.

There are two types of dual axis tracking:

- Tip-tilt
- Azimuth-altitude.

Types of Solar Trackers

Active Tracker: Dual Axis Trackers

Tip-Tilt Dual Axis Trackers

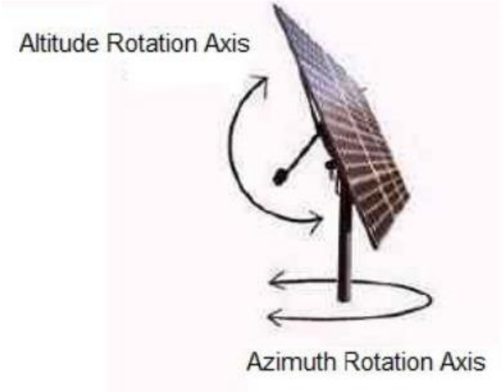
A Tip–Tilt Dual Axis Tracker has its primary axis horizontal to the ground, and the secondary axis is usually normal to the primary axis. The axes of these trackers are aligned either along a true north meridian or an east-west line of latitude, but they are flexible and can be aligned in any direction desired.

Types of Solar Trackers

Active Tracker: Dual Axis Trackers

Azimuth-Altitude Dual Axis Trackers

An Azimuth–Altitude Dual Axis Tracker has its primary axis vertical to the ground, which allows the panel to rotate in a circle from east to west; this axis is called the azimuth. The secondary axis is typically aligned normal to the primary axis, allowing the panel to move up and down; this axis is called the altitude.



Next Lecture

- Solar Thermal Energy

Questions and Thank you