MECH 453 Introduction to Renewable Energy

CHAPTER TWO

Solar Energy, Solar Motion and Photovoltaics

Course lectures Slides prepared by

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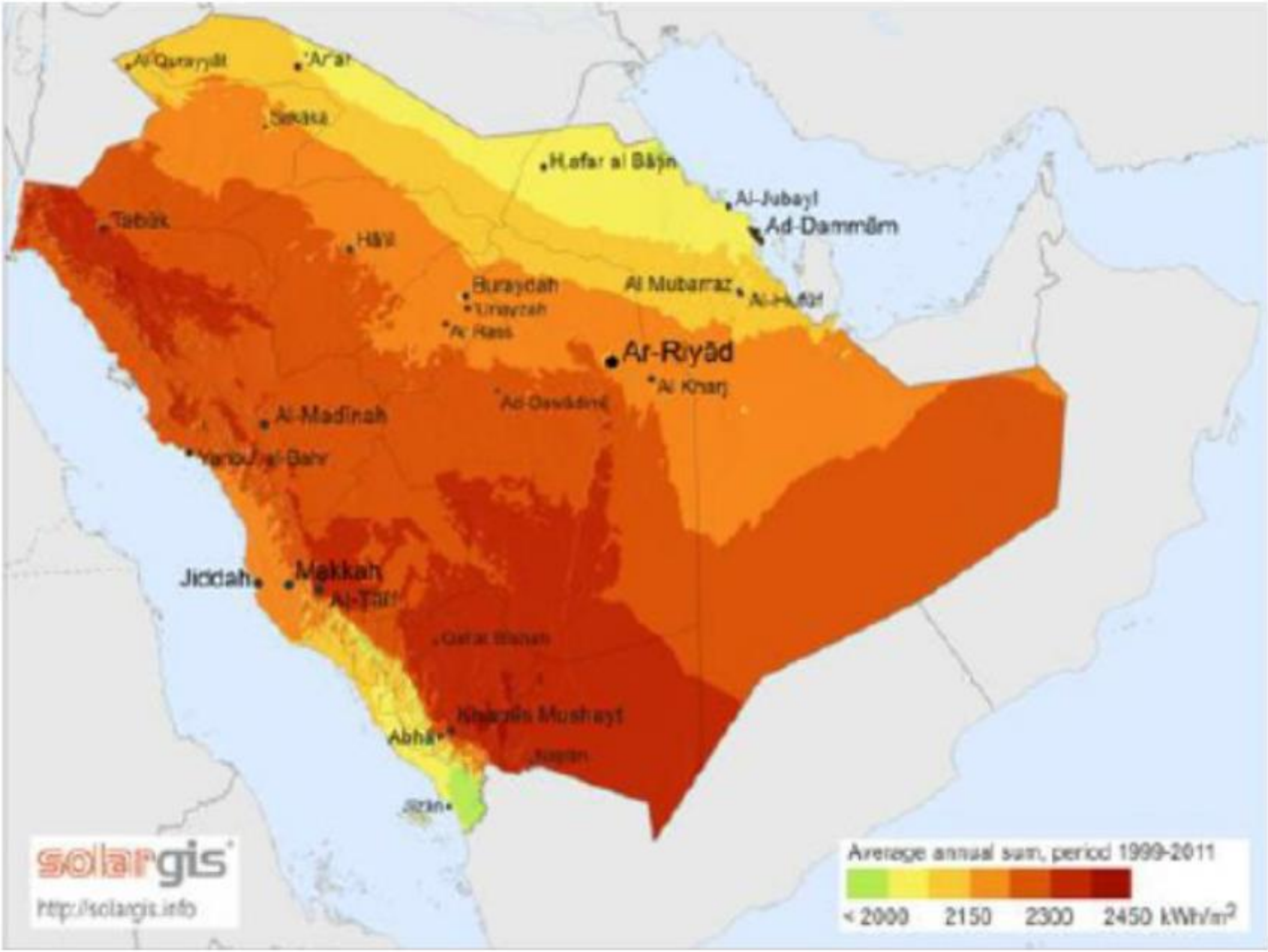
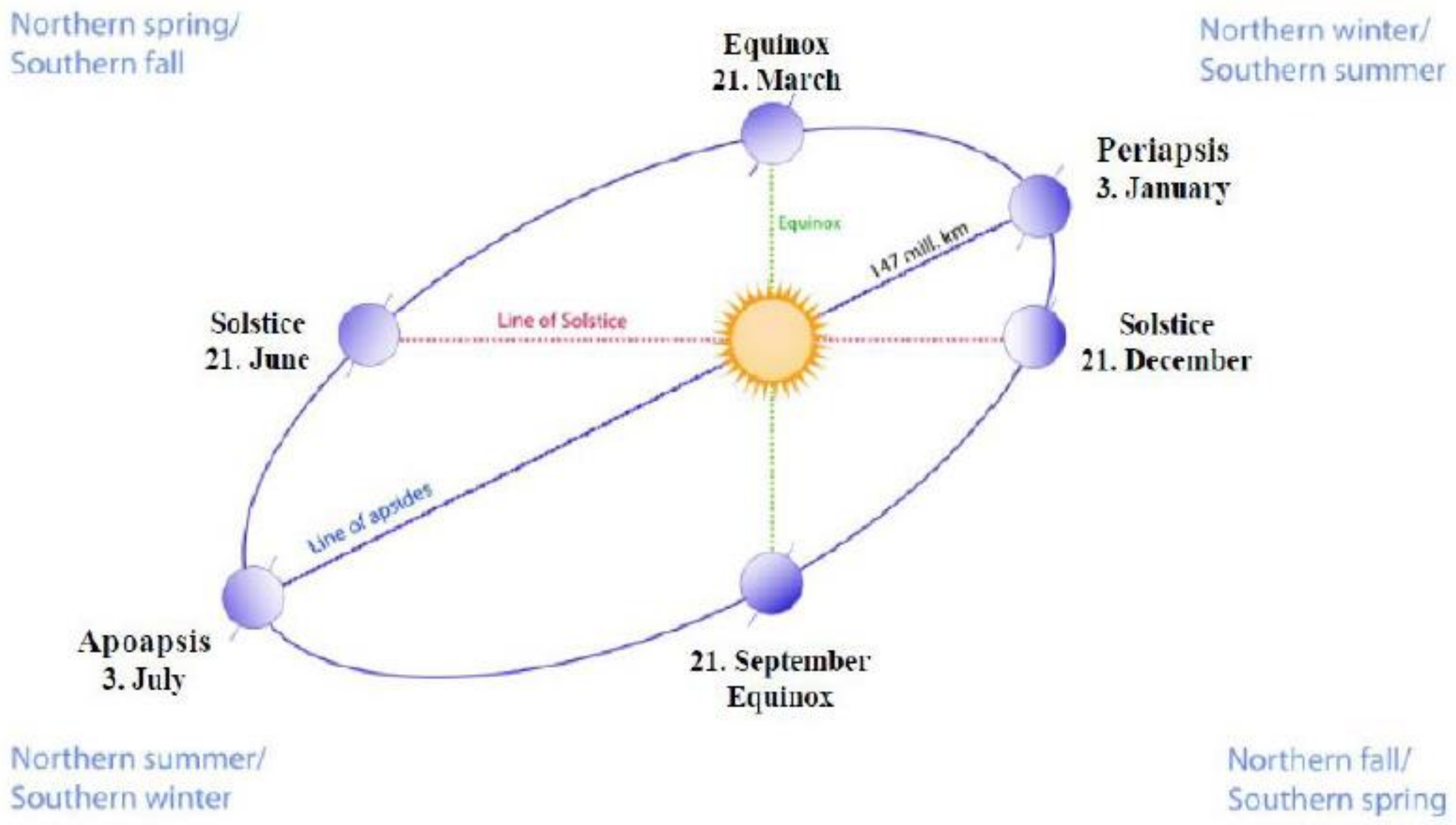
Solar Irradiance in Saudi Arabia



Earth’s Orbit and Positioning



Distance Relations of Earth

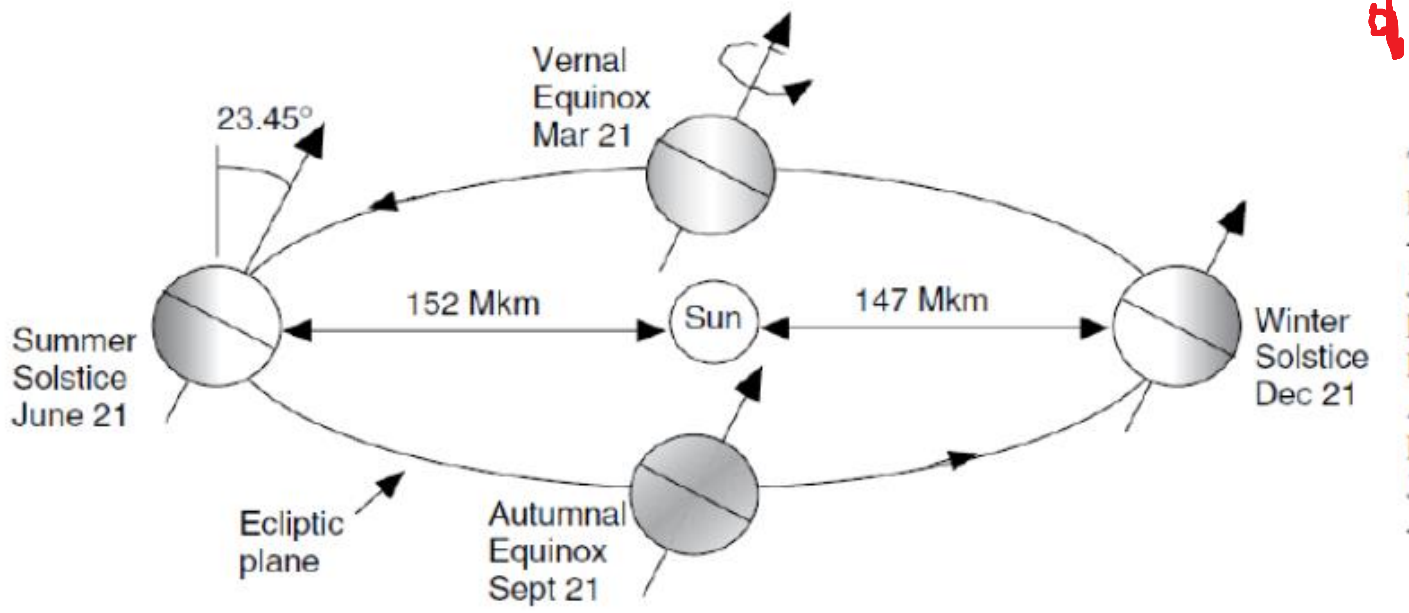


Figure 7.5 The tilt of the earth's spin axis with respect to the ecliptic plane is what causes our seasons. "Winter" and "summer" are designations for the solstices in the Northern Hemisphere.

TABLE 7.1 Day Numbers for the First Day of Each Month

January	$n = 1$	July	$n = 182$
February	$n = 32$	August	$n = 213$
March	$n = 60$	September	$n = 244$
April	$n = 91$	October	$n = 274$
May	$n = 121$	November	$n = 305$
June	$n = 152$	December	$n = 335$

$$d = 1.5 \times 10^8 \left[1 + 0.017 \sin\left[\frac{360(n-93)}{365}\right]\right] \quad \text{(km)}$$

Altitude angle of solar irradiance

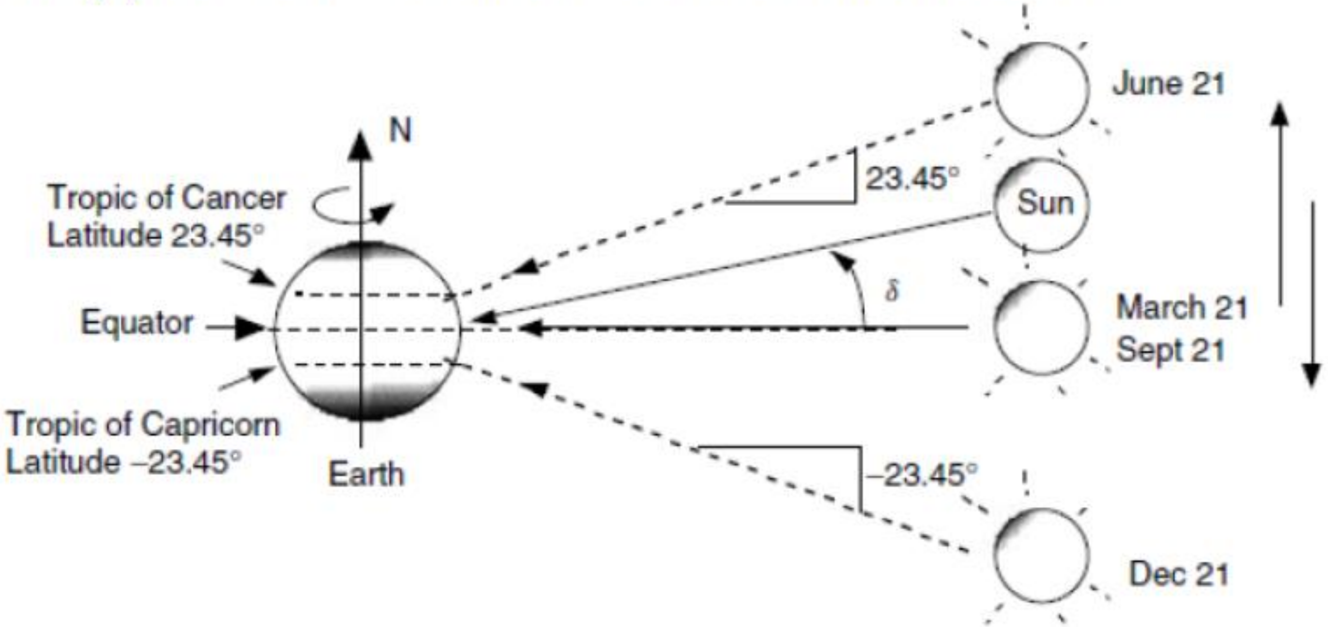


Figure 7.6 An alternative view with a fixed earth and a sun that moves up and down. The angle between the sun and the equator is called the solar declination δ.

$$\delta = 23.45 sin\left[\frac{360}{365}(n - 81)\right] \quad \text{(degrees)}$$

TABLE 7.2 Solar Declination δ for the 21[st] Day of Each Month (degrees)

Month:	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
δ:	−20.1	−11.2	0.0	11.6	20.1	23.4	20.4	11.8	0.0	−11.8	−20.4	−23.4

Solar panels placement

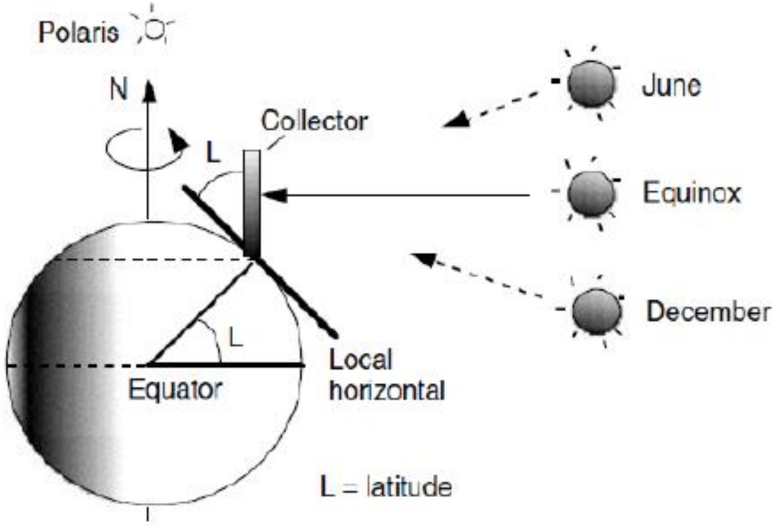
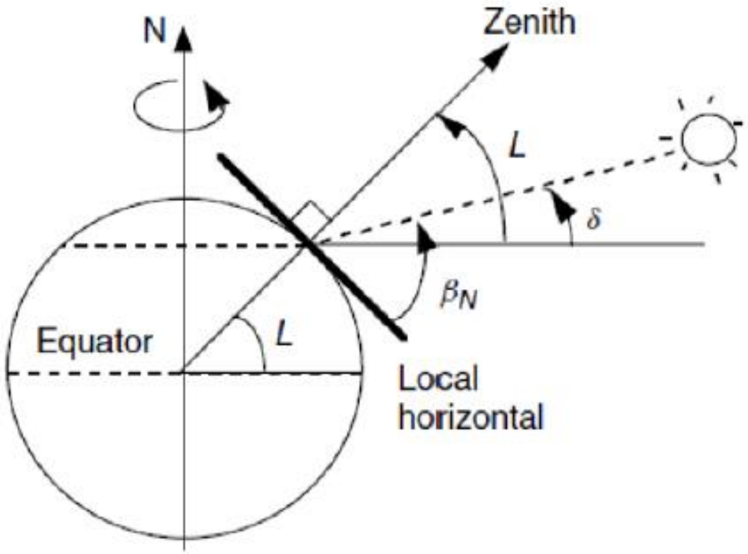


Figure 7.8 A south-facing collector tipped up to an angle equal to its latitude is perpendicular to the sun's rays at solar noon during the equinoxes.



The *altitude angle* β_N of the sun at solar noon can be expressed as:

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

where L is the latitude of the site.

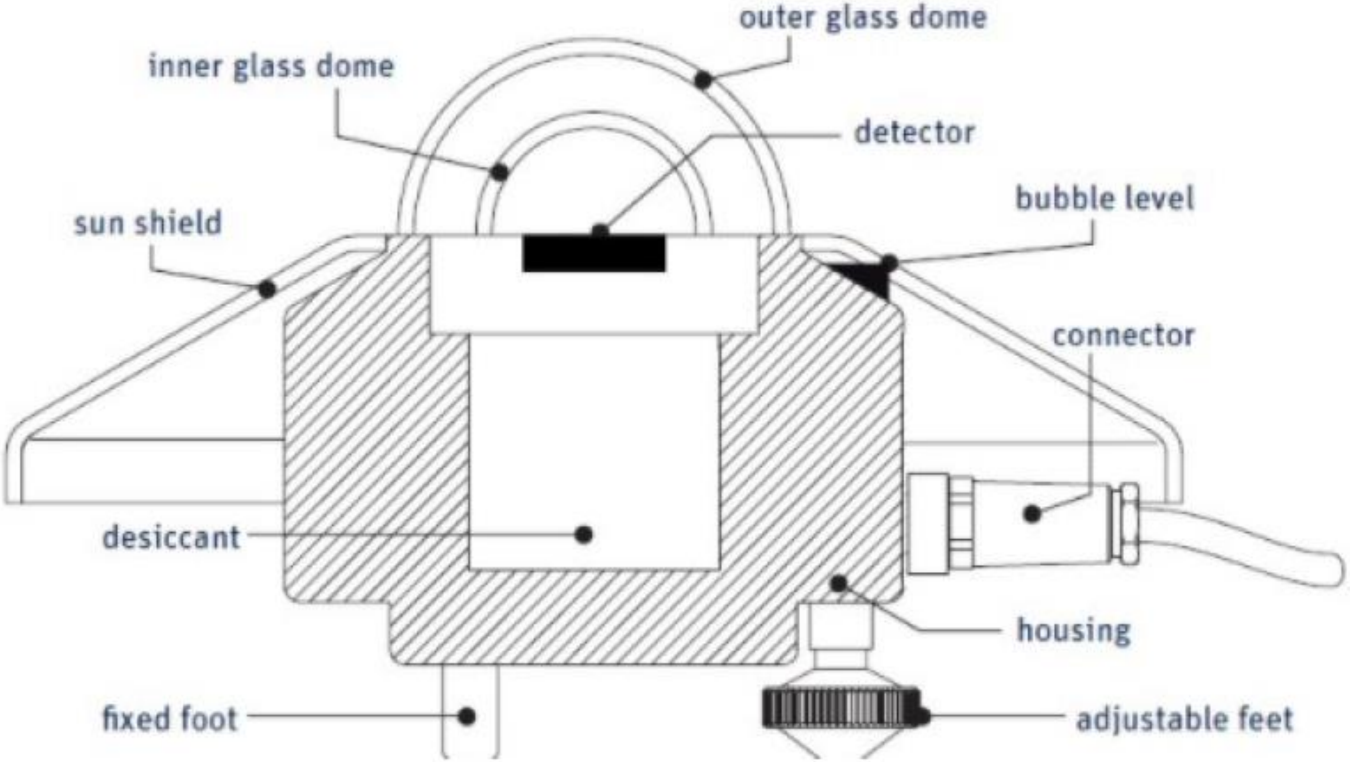
How to measure solar irradiance?

- There are two devices: *pyranometer* and *pyrheliometer*

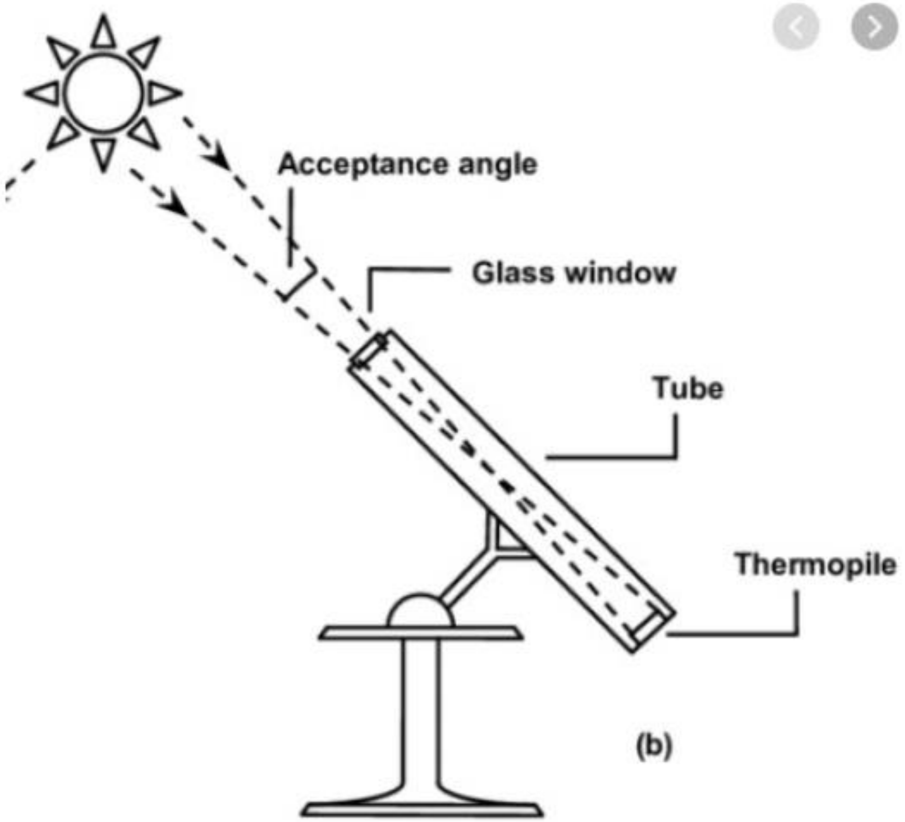
Pyranometer – measures all directions

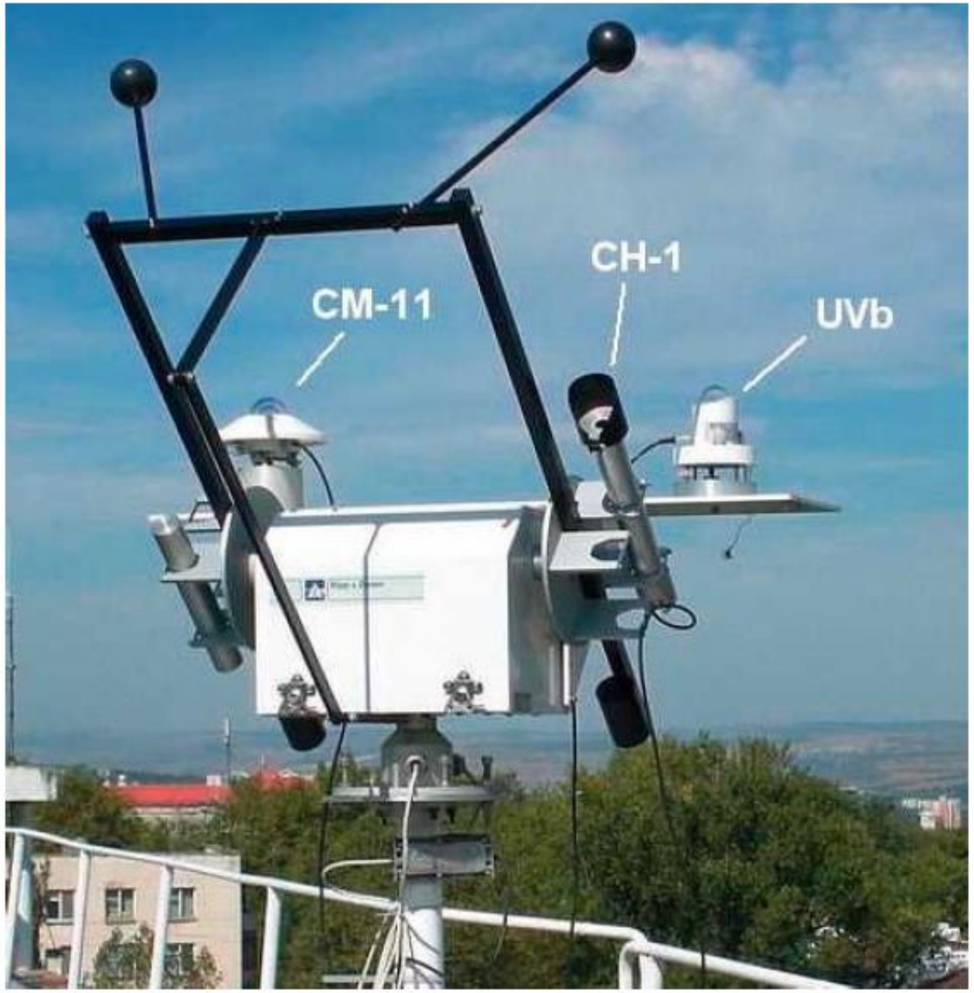
Pyrheliometer – measures direct radiation

Pyranometer



Pyrheliometer





Physics of semiconductors;

Band gap energy (E_g) : is the amount of energy, required for electron to jump from the filled band to the conductive band across the forbidden band. It is measured in eV (electron-volts) 1eV=1.6*10^{-19} J

- For Silicon: E_g=1.12 eV
- *To promote energy is required. For PV –energy is given by photons of electromagnetic energy from the Sun.*

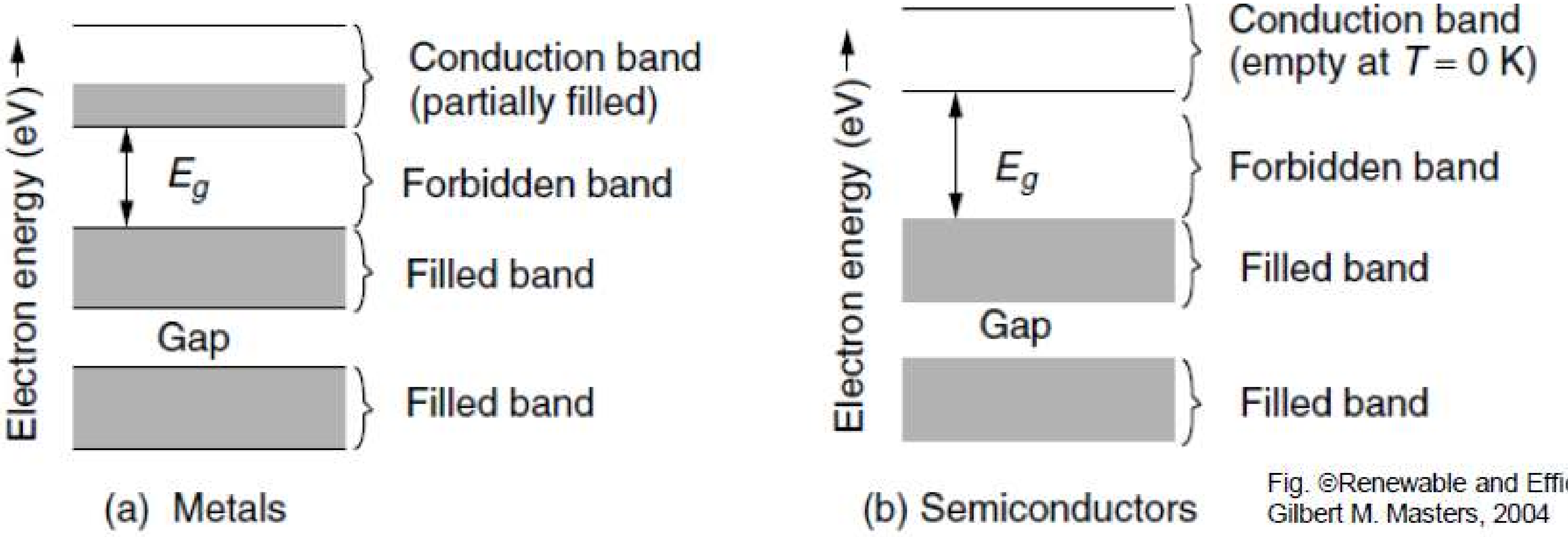


Fig. ©Renewable and Efficient Electric Power Systems
Gilbert M. Masters, 2004

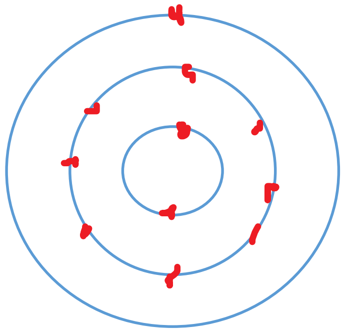


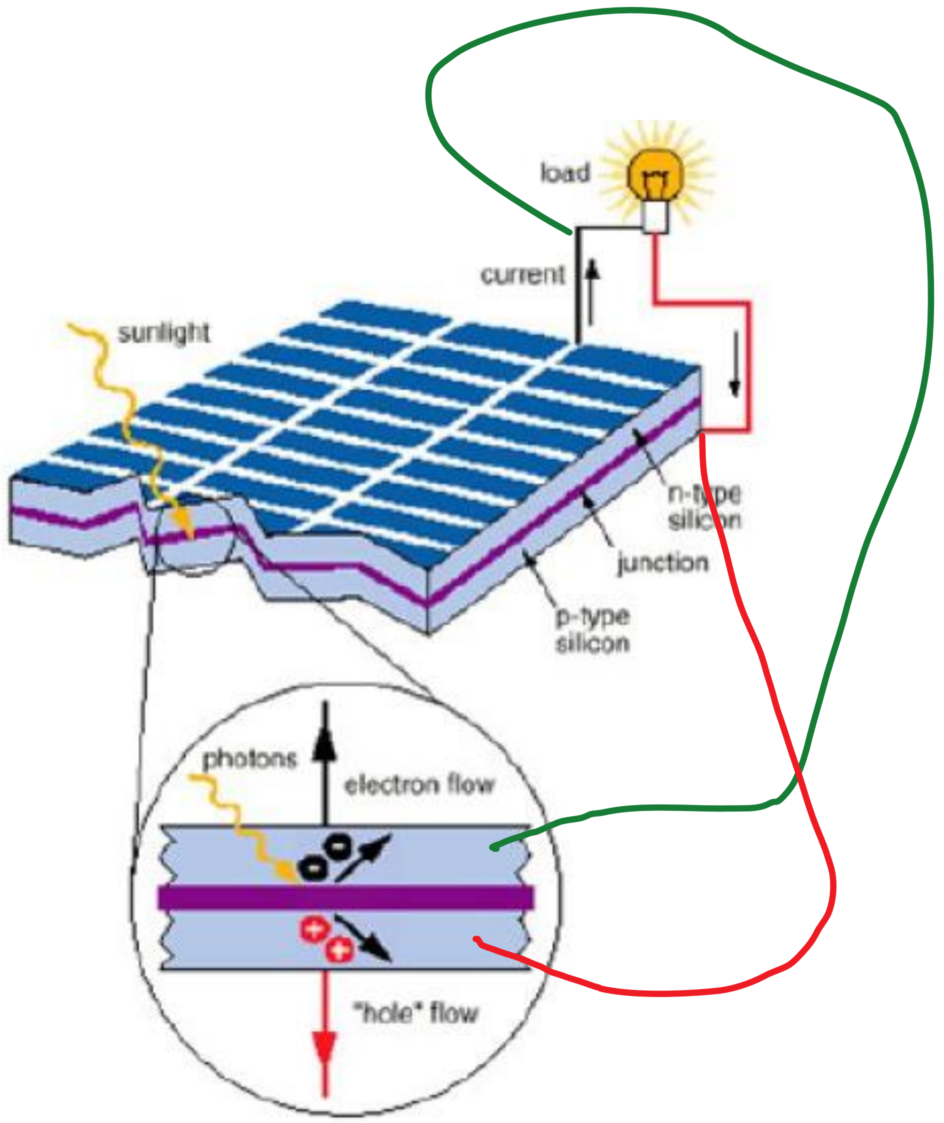
Figure 8.6 Energy bands for (a) metals and (b) semiconductors. Metals have partially filled conduction bands, which allows them to carry electric current easily. Semiconductors at absolute zero temperature have no electrons in the conduction band, which makes them insulators.

Photovoltaics Operation

1) *Photons are absorbed by material and the formation of electron hole pairs is possible.*

2) *Created junction separate positively charged items (" holes") and negative electrons to form internal electric field.*

3) *If the circuit is connected and photons are being absorbs, power is produced from the motion of the electrons over the junction and recombine with the holes.*

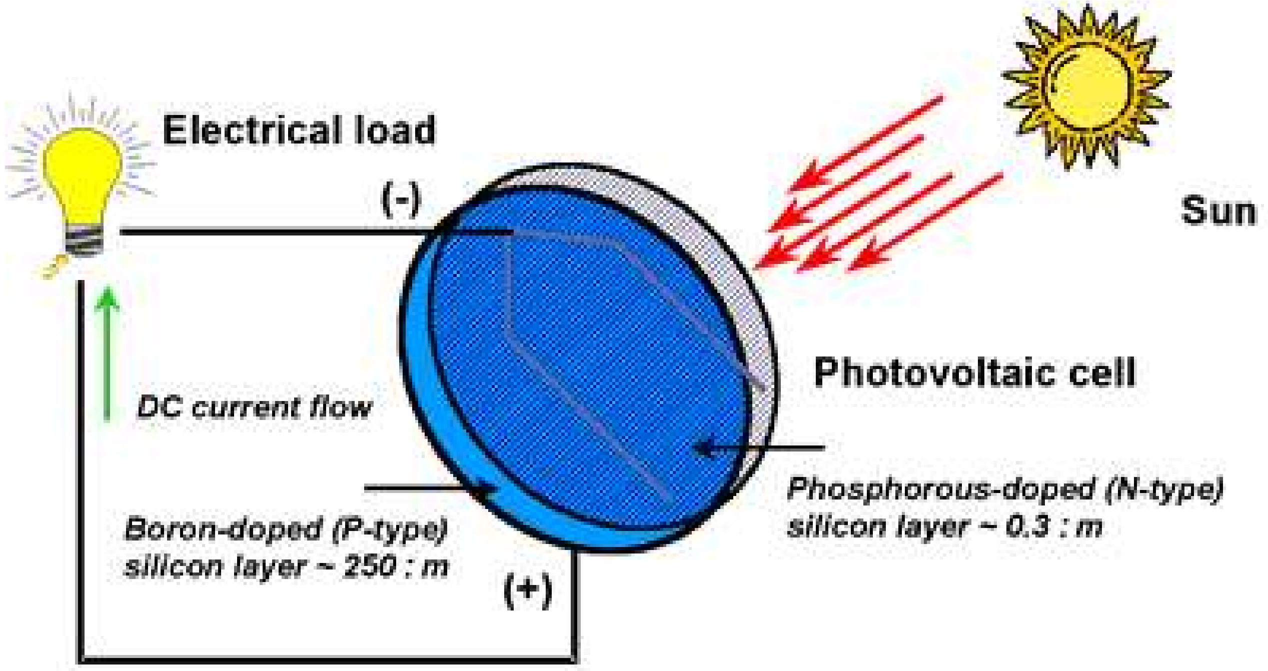


Sub-outcome 1: Analyze photovoltaic operation, technology and applications.

PV technology basics

A typical silicon PV cell is composed of a thin wafer consisting of **an ultra-thin** layer of phosphorus-doped (**N-type**) **silicon on top of a thicker layer** of boron-doped (**P-type) silicon.** An electrical field is created near the top surface of the cell where these two materials are in contact, called the **P-N junction**.

When sunlight strikes the surface of a PV cell, this electrical field provides momentum and direction to light-stimulated electrons, resulting in a flow of current when the solar cell is connected to an electrical load.



Simple Equivalent Circuit for PV cell

The current equation of a PV cell with a load $I = I_{SC} - I_d$

Since $I_d = I_0(e^{\frac{qV}{kT}} - 1) \Rightarrow$ $I = I_{SC} - I_0(e^{\frac{qV}{kT}} - 1)$

To find $V_{OC} \Rightarrow \quad I = 0 \Rightarrow$ $V_{OC} = \frac{kT}{q} \ln\left(\frac{I_{SC}}{I_0} + 1\right)$

at 25°C : $I = I_{SC} - I_0(e^{38.9V} - 1)$; $V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right)$

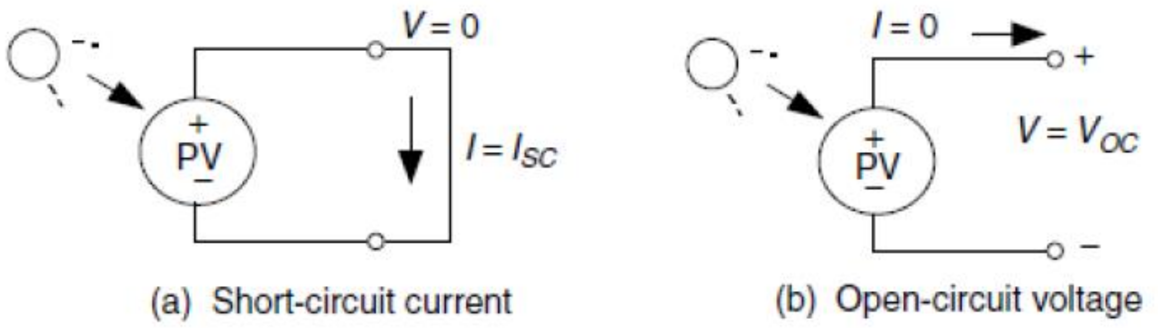


Figure 8.19 Two important parameters for photovoltaics are the short-circuit current I_{SC} and the open-circuit voltage V_{OC}.

Fig. ©Renewable and Efficient Electric Power Systems
Gilbert M. Masters, 2004

1-1. Mechanism of generation

- **Mechanism of generation**

The solar cell is composed of a P-type semiconductor and an N-type semiconductor. Solar light hitting the cell produces two types of electrons, negatively and positively charged electrons in the semiconductors.

Negatively charged (-) electrons gather around the N-type semiconductor while positively charged (+) electrons gather around the P-type semiconductor. When you connect loads such as a light bulb, electric current flows between the two electrodes.

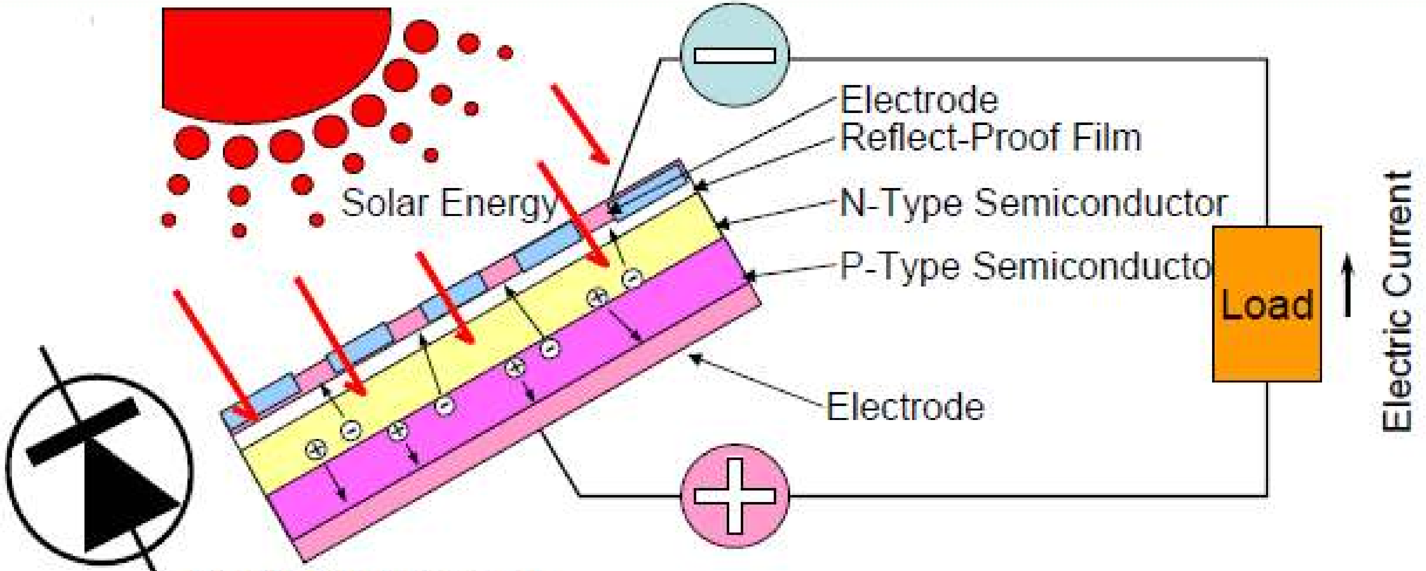
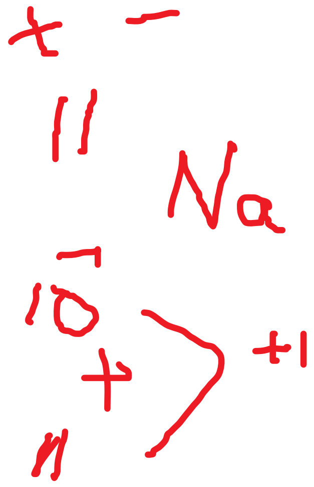
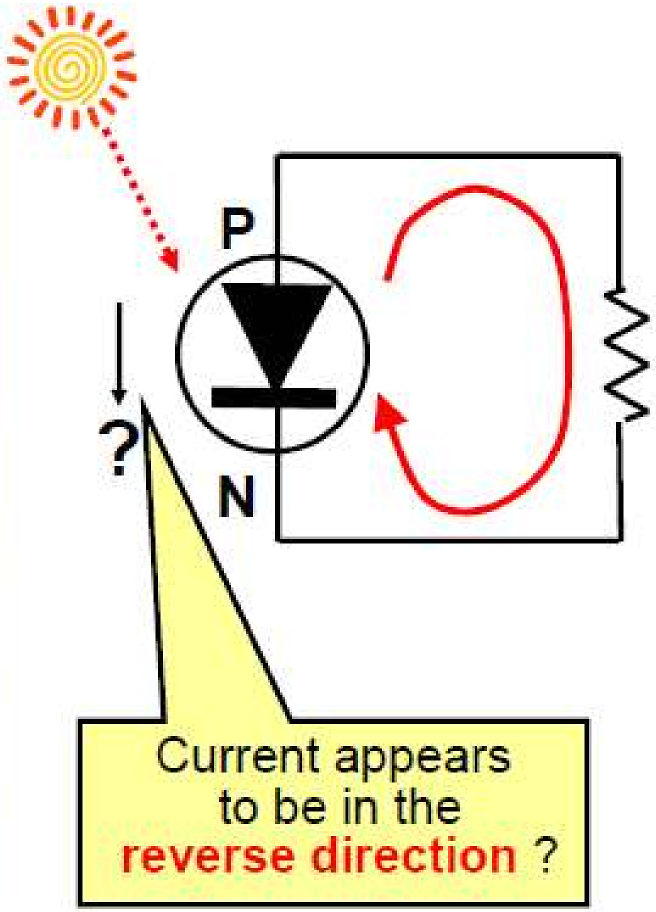


Photo Voltaic cell

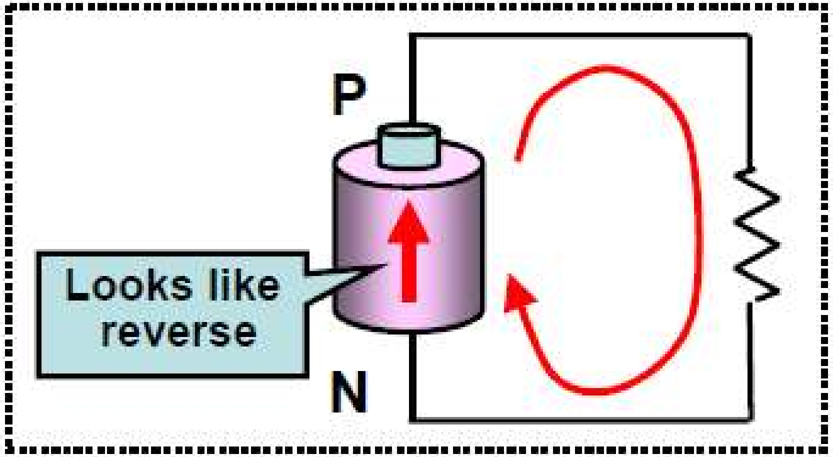


1-1. Mechanism of generation

- **Direction of current inside PV cell**



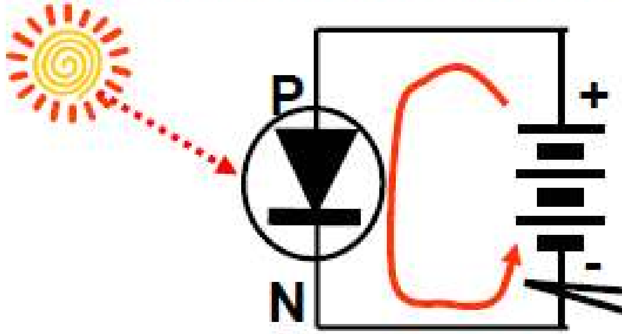
- Inside current of PV cell looks like "Reverse direction." Why?
- By Solar Energy, current is pumped up from N-pole to P-pole.
- In generation, current appears reverse. It is the same as for battery.



1-1. Mechanism of generation

- **Illegal use**

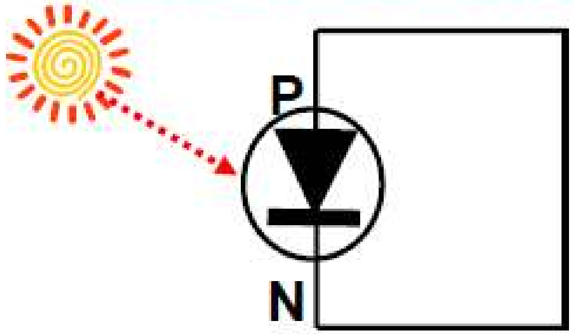
Do not charge PV by another power source.



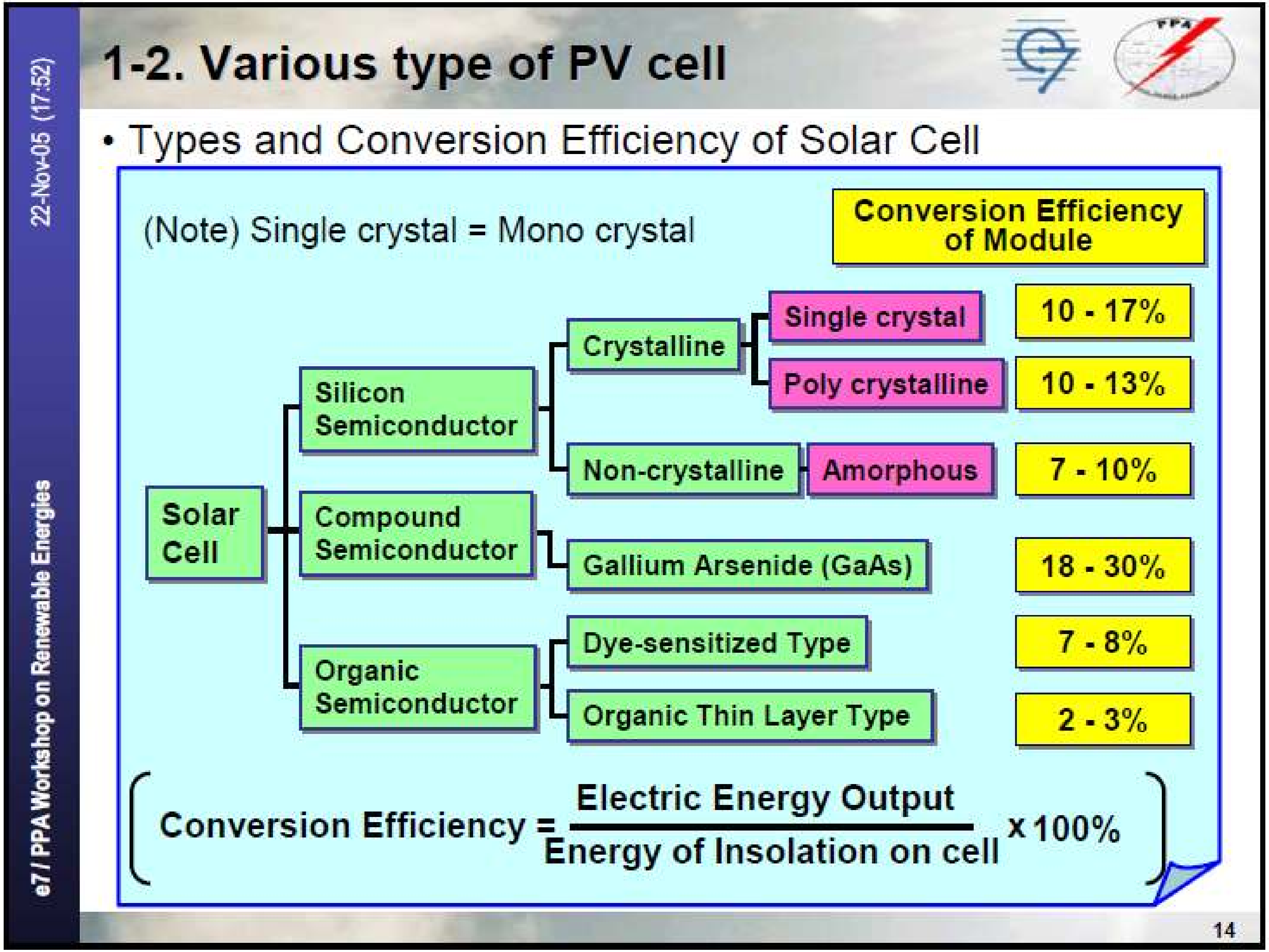
If you charge PV by another power source and try to make normal direction current, the PV will heat up and cease to function.

Force to make normal direction current

Do not create a short circuit when sunshine is being received.

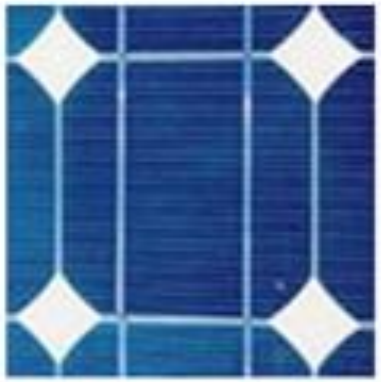


If a short circuit is created during insolation, large current will heat up PV cell and cell will cease to function.



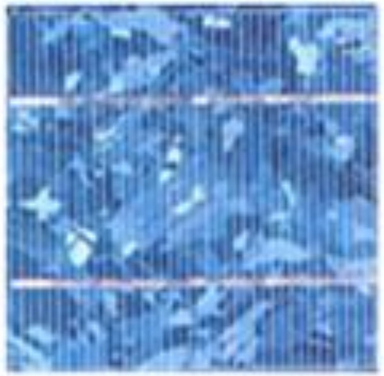
These efficiency values can be changed over the time

Various Types of PV Cells



mono crystalline

mono crystalline



poly crystalline

Mono Crystalline

Poly Crystalline

Thin Film

PV technology basics

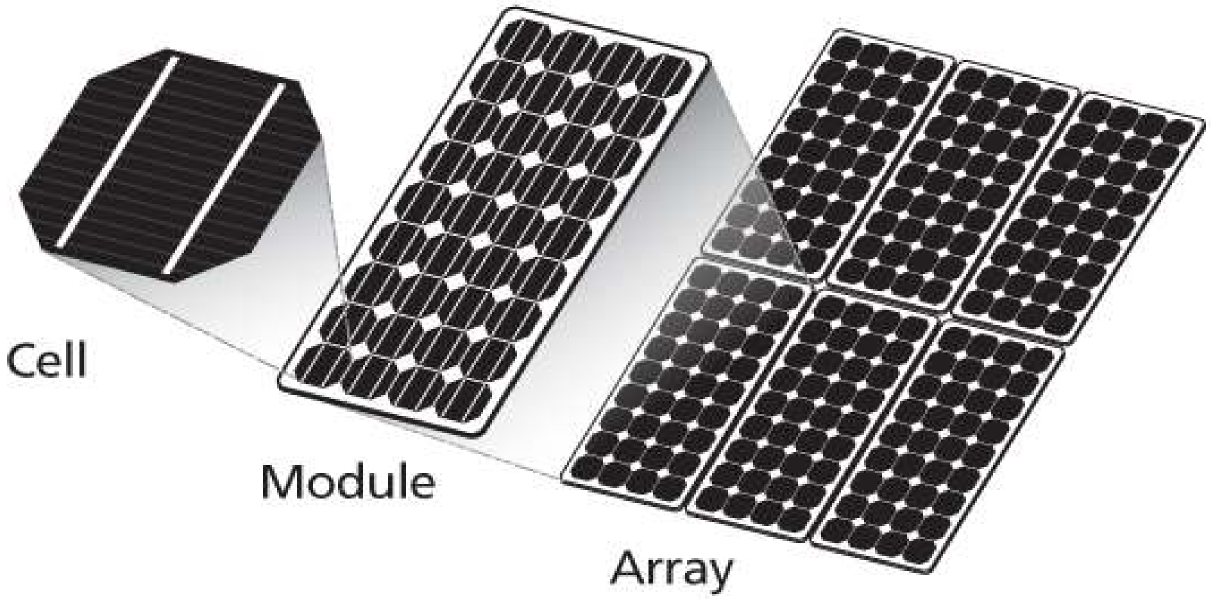
In the case of a single-junction device, the efficiency of the solar cell, the ratio of the power produced, and the incident light power are limited.

Photons with energies below the bandgap of the material produce only heat. Excess energy above that needed to generate electron-hole pairs also produces heat.

A multijunction device, in which two or more solar cells are stacked on top of each other, can exploit different portions of the solar spectrum.

For example, a four-junction device with bandgaps of 1.8, 1.4, 1.0, and 0.7 electron volts (eV) results in a theoretical efficiency of more than 52%.

The multijunction approach, however, presents significant challenges in both materials preparation and device design.



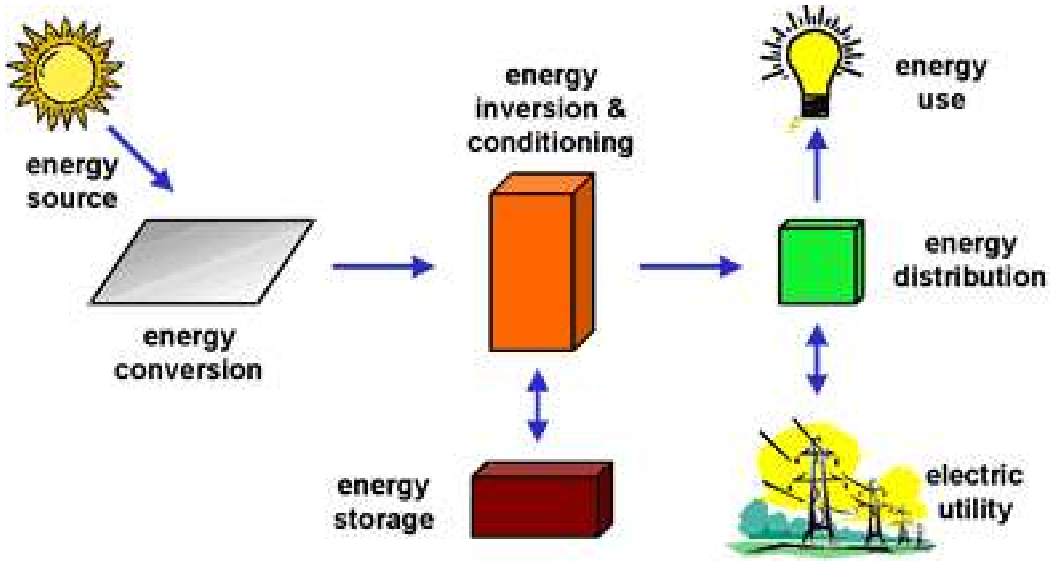
Photovoltaic cells are connected **electrically in series and/or parallel circuits to produce higher voltages,** currents and power levels.

Photovoltaic modules consist of PV cell circuits sealed in an environmentally protective laminate, and are the fundamental building block 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.

How a PV System Works

PV systems are like any other electrical power generating systems, just the equipment used is different than that used for conventional electromechanical generating systems.



Depending on the functional and operational requirements of the system, the specific components required, and may include major components

DC-AC power inverter,
battery bank,
system and battery controller,
auxiliary energy sources

and sometimes the **specified electrical load (appliances).**

In addition, an assortment of balance of system (BOS) hardware, Including wiring, overcurrent, surge protection and disconnect devices, and other power processing equipment.

Advantages and **Disadvantages** of PV

Photovoltaic systems have a number of merits and unique advantages over conventional power-generating technologies.

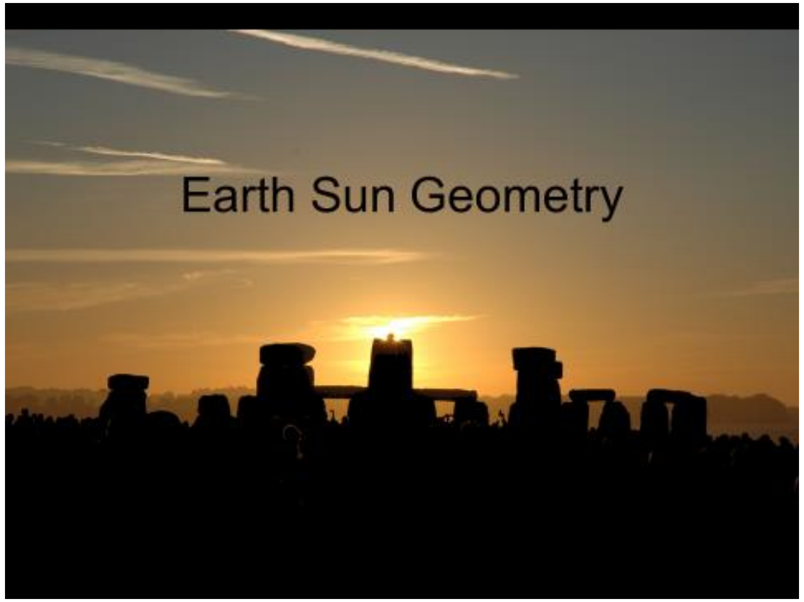
PV systems can be designed for a variety of applications and operational requirements, and can be used for either centralized or distributed power generation.

PV systems have no moving parts, **are modular, easily expandable and even transportable in some cases. Energy independence and environmental compatibility are two attractive features of PV systems.**

The **fuel (sunlight) is free**, and **no noise or pollution** is created from operating PV systems. In general, PV systems that are well designed and properly installed require **minimal maintenance** and have long service lifetimes.

At present, **the high cost of PV modules** and equipment (as compared to conventional energy sources) is the **primary limiting factor for the technology.** Consequently, the economic value of PV systems is realized over many years. In some cases, the surface area requirements for PV arrays may be a limiting factor. Due to the diffuse nature of sunlight and the existing sunlight to electrical energy conversion efficiencies of photovoltaic devices, surface area requirements for PV array installations are on the order of 8 to 12 m^2 (86 to 129 ft^2) per kilowatt of installed peak array capacity.

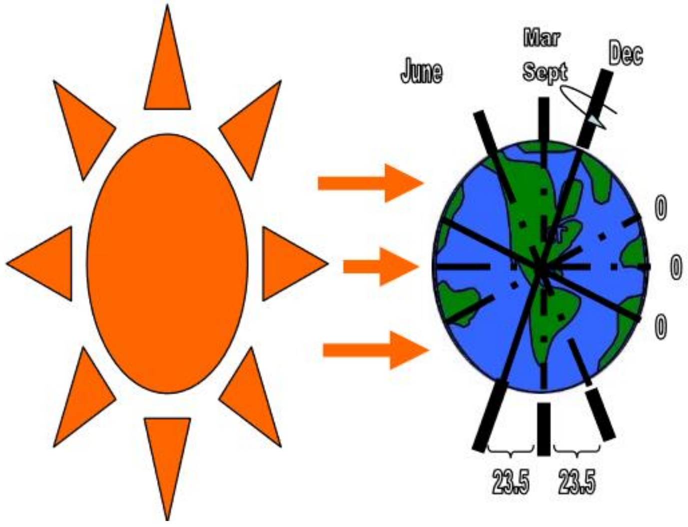
Sub-outcome 2:Explain methods used to maximize solar power generation.



Earth-Sun Geometry

- Driving variable of environmental processes on Earth
- Geometry determines the amount and intensity of incoming solar radiation (insolation) reaching particular earth
- Geometry (and how it changes) determines:
  - Seasonality (1 yr)
  - Glacial (cold) and interglacial (warm) periods (1000's of years)

Seasons



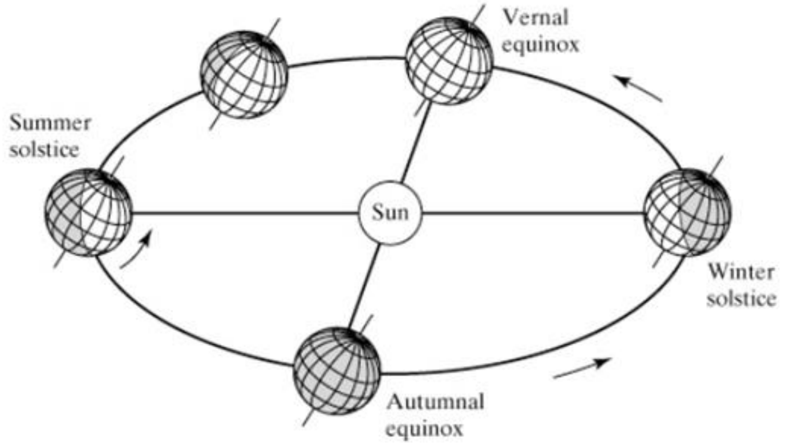


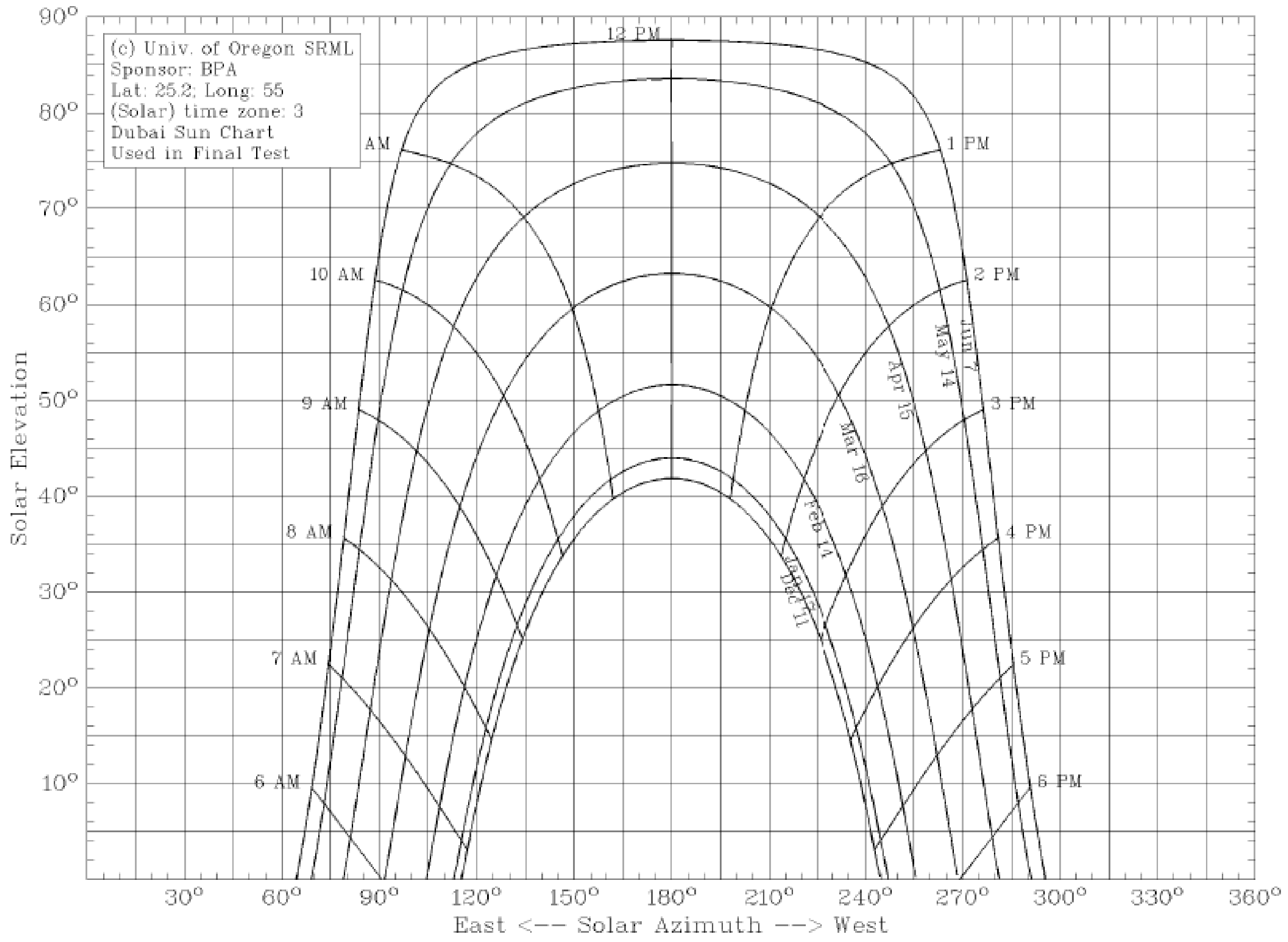
Figure 1: The earth's revolution about the sun

Seasons are caused by the Earth axis which is tilted by 23.5

Sun path, sometimes also called day arc, refers to the daily and seasonal arc-like path that the Sun appears to follow across the sky as the Earth rotates and orbits the Sun. The Sun's path affects the length of daytime experienced and amount of daylight received along a certain latitude during a given season.

The relative position of the Sun is a major factor in the heat gain of buildings and in the performance of solar energy systems.

Sun Motion – Azimuth & Inclination



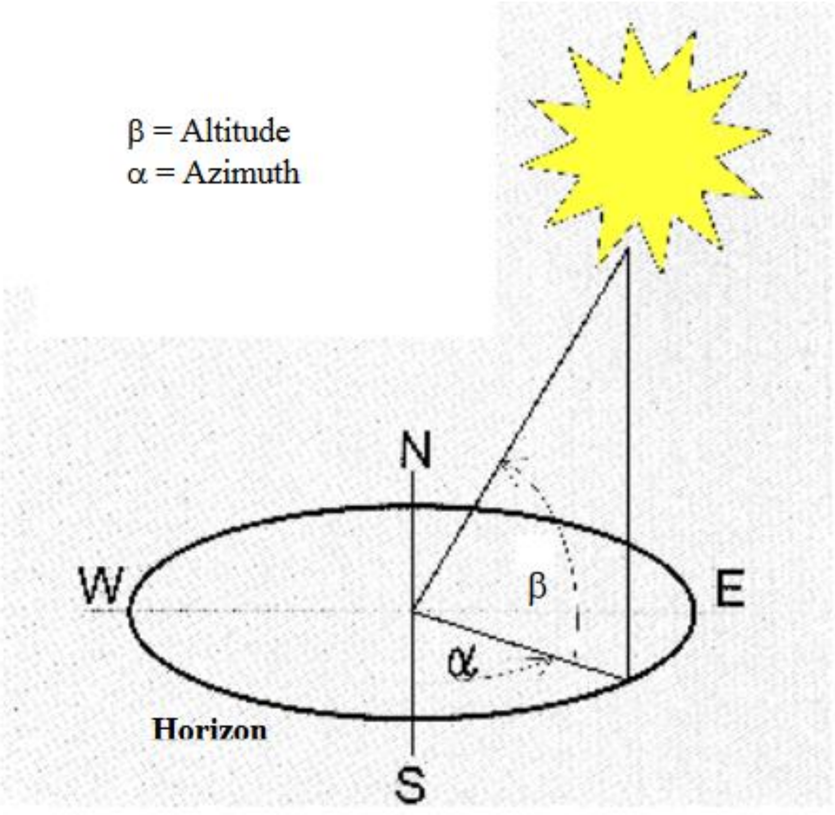
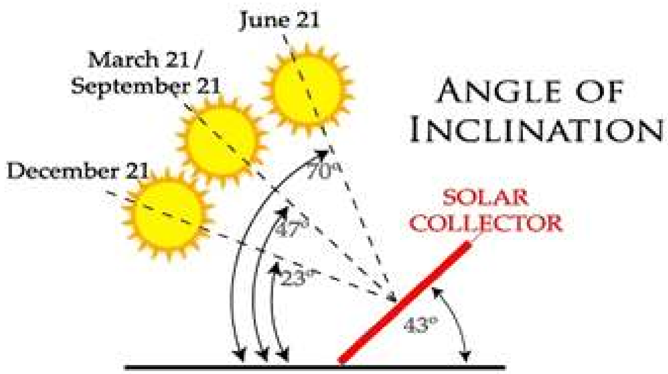
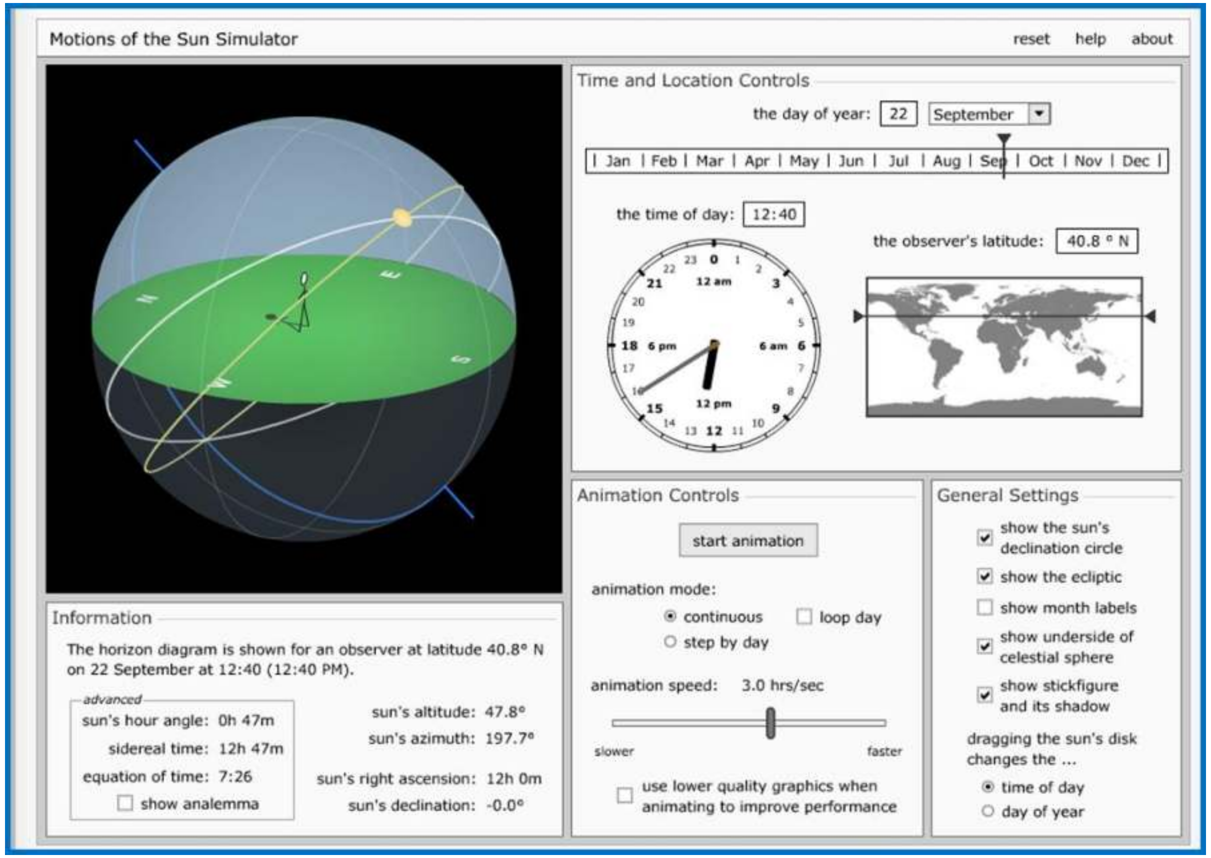


Figure 2.1c Azimuth and Altitude

http://astro.unl.edu/naap/motion3/animations/sunmotions.html Motion of The Sun Simulator.





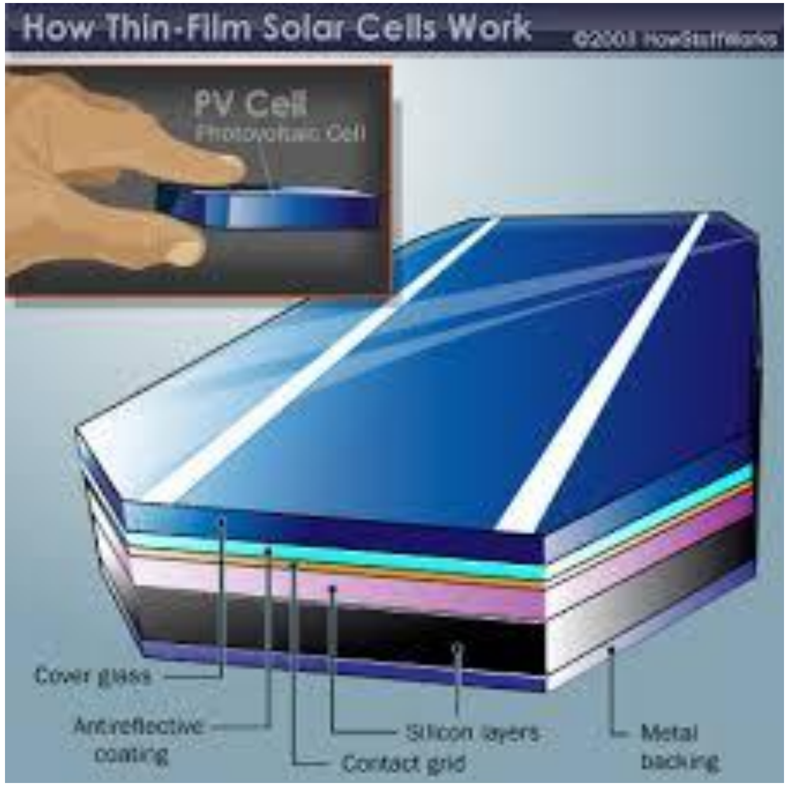
Methods used to maximize solar power generation.

There are a number of means available to increase solar panel output and efficiency

Solar Cell Technology

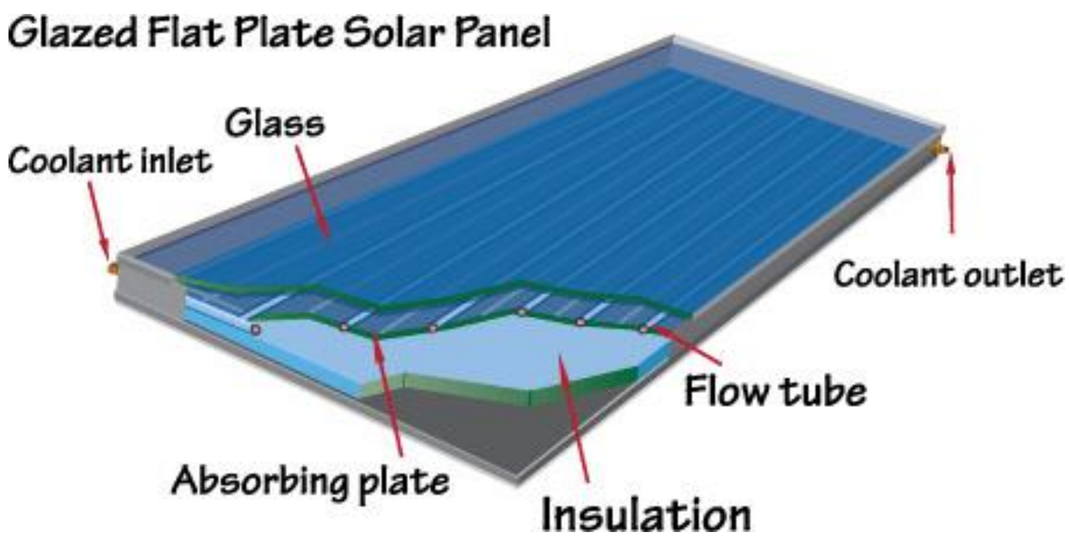
There are a number of technologies being researched and there are continual advancements. Experimental technologies and highest **efficiencies** include:

- Multi-cell gallium arsenide – **44%**
- Single cell gallium arsenide – 29%
- Crystalline silicon – 25%
- Thin film copper-indium-gallium-selenide – 20%
- Emerging PV technologies (dye-sensitive cells etc.) – 11% (low efficiency, but very inexpensive)



Check out this link for an informative solar cell research chart: http://upload.wikimedia.org/wikipedia/commons/7/71/

Methods used to maximize solar power generation



Solar Cells Glazing

For long life, solar cells must be protected from the elements (rain, snow, hail, bird dropping etc). Polycarbonate or low-iron glass is generally recommended due to high optical transmissivity — perhaps 90%. Surface coating treatments reduce reflections for even higher transmissivity. Ordinary window glass reduces the output by about 40% — not recommended.

Methods used to maximize solar power generation

Solar Panel Orientation

For highest output, solar panels must be perpendicular to the sun's rays. However, it is generally practical and common for roof-top installations to follow the roof pitch and orientation. For other types of fixed installations, the azimuth is oriented to the south and tilt adjusted for the winter sun.

- **Solar tracking** is a great way of increasing the output power. It rotates the panel or array of panels so that they always directly face the sun. However, the larger the array, the more difficult will be the mechanics of this task. Some trackers are simply driven by a "clock" motor like a telescope so that it follows the sun (or wherever it is supposed to be in the cloudy sky). Others have active circuitry that adjusts the orientation for maximum power output. Others may be controlled by a shadow feedback signal technique.

Sub-outcome 3: Explain maximum power point testing techniques, photovoltaic quality testing and international certification

Photovoltaic Maximum Power Point

- **What is MPPT?**

Maximum power point (MPP): The point on a power (I-V) curve that has the highest value of the product of its corresponding voltage and current, or the highest power output.

Efficiency: **The ratio of the useful energy delivered by a PV ay mpp to the energy received from sun.**

I-V curve: **The curve produced when the value of a panel's current is plotted with respect to different voltages, from 0 to VOC (I = current, in amps; V = voltage, in volts)**

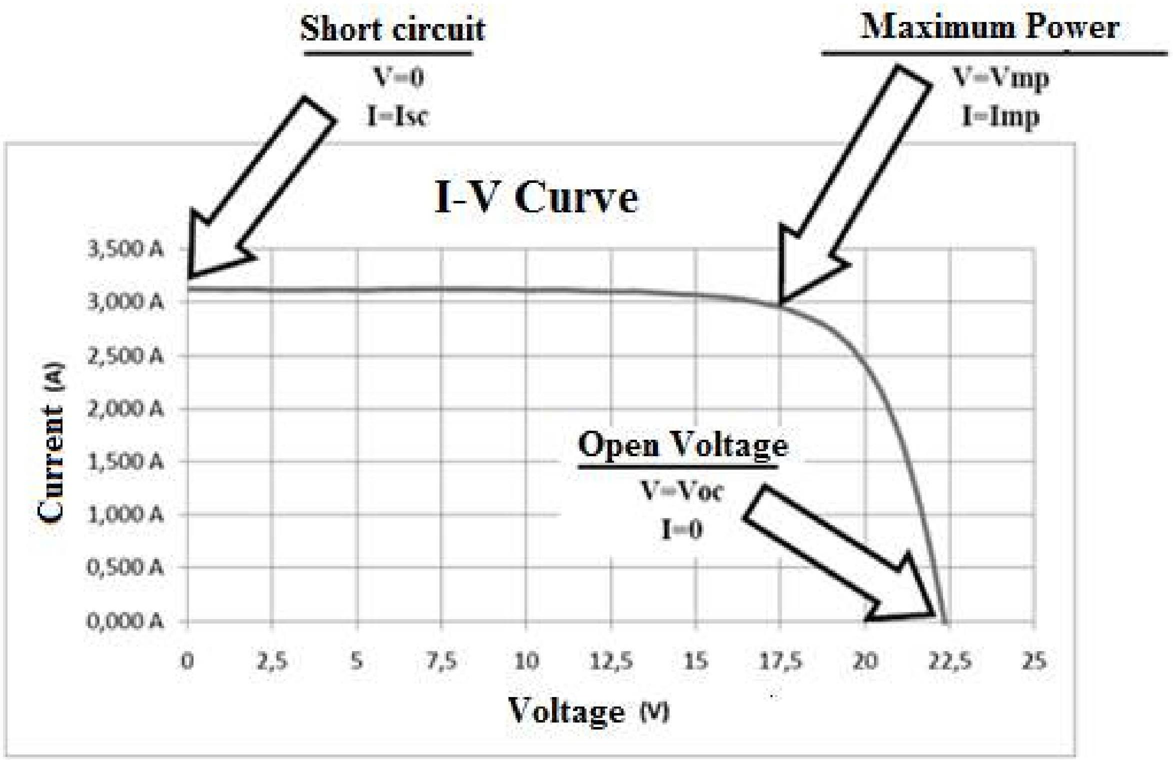
Maximum power point tracker (MPPT): **A device that continually finds the MPP of a solar panel or array.**

Open circuit voltage (VOC): **Voltage available from PV in an open circuit, I = 0.**

Potentiometer: **A device that allows the user to vary the electrical resistances in a circuit.**

short circuit current (Isc): **Current drawn from a PV when load is short circuited**

V – I Curve



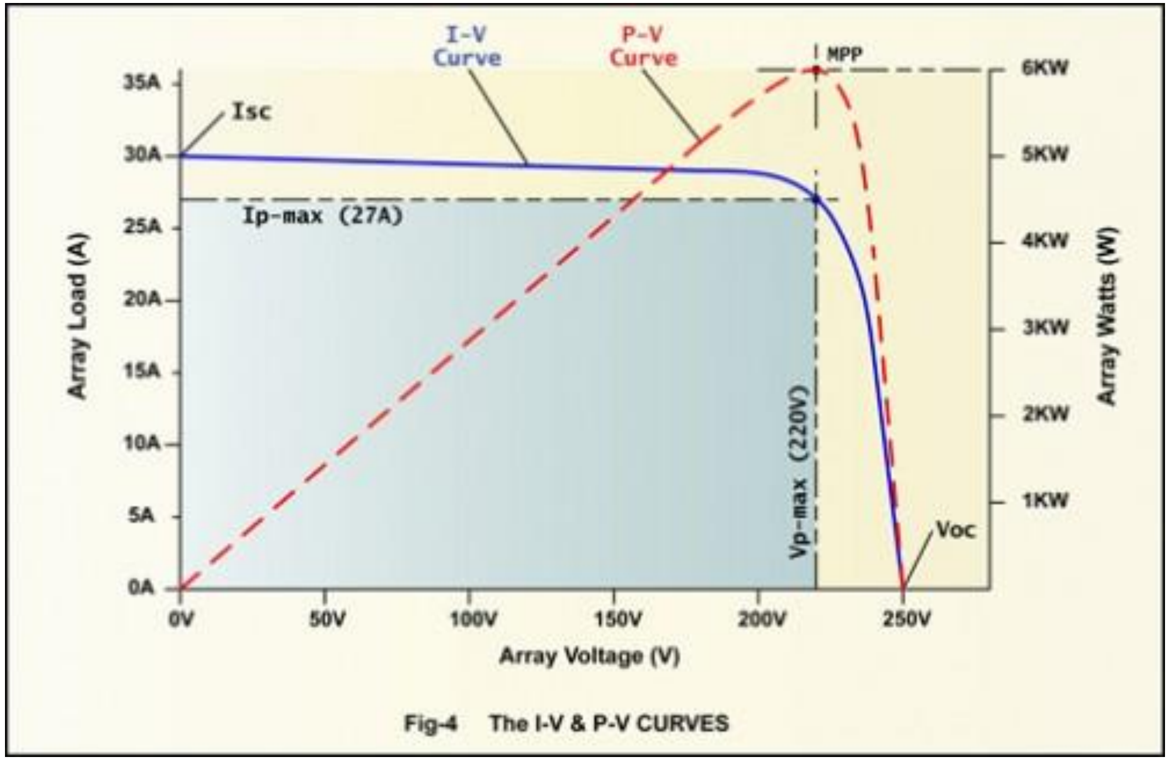
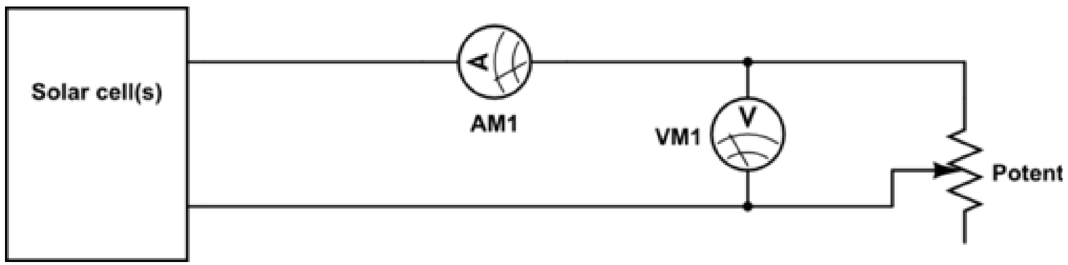


Fig-4 The I-V & P-V CURVES

MPP Testing Techniques



The values in Table 1 were obtained by using a potentiometer to vary the resistance
in the PV circuit, which directly affects the voltage and current in the circuit.
The power calculation shows that the MPP has a voltage of V MPP = 4.934, a current of I MPP
= 0.100 A, with the power, P = 0.491 W.

Trial #	Collected Data		Calculated
	Voltage (V)	Current (A)	Power (W)
1	0.000	0.124	0.000
2	0.624	0.122	0.076
3	1.248	0.120	0.150
4	1.872	0.118	0.222
5	2.497	0.116	0.291
6	3.121	0.114	0.357
7	3.745	0.112	0.421
8	4.369	0.110	0.482
9	4.700	0.103	0.485
10 [MPP]	4.934	0.100	0.491
11	5.165	0.091	0.472
12	5.336	0.085	0.455
13	5.566	0.078	0.432
14	5.927	0.057	0.337
15	6.070	0.045	0.270
16	6.113	0.037	0.225
17	6.137	0.034	0.209
18	6.210	0.025	0.156
19	6.294	0.020	0.123
20	6.373	0.004	0.027
21	6.389	0.002	0.013
22	6.407	0.000	0.000

Data visualization

This data can be visualized more clearly in a graph. Graphing the current and voltage creates a curve that is referred to as an I-V curve. The blue line in the Figure graph is an **I-V curve**. The current is plotted in amps (A) on the left y-axis. The voltage is plotted in volts (V) on the x-axis. On the same graph, the power for each current-voltage combination is plotted in pink. The power is plotted in watts (W) on the right y-axis. This power curve clearly shows the maximum power point. A red line identifies the voltage and current associated with the maximum power point.

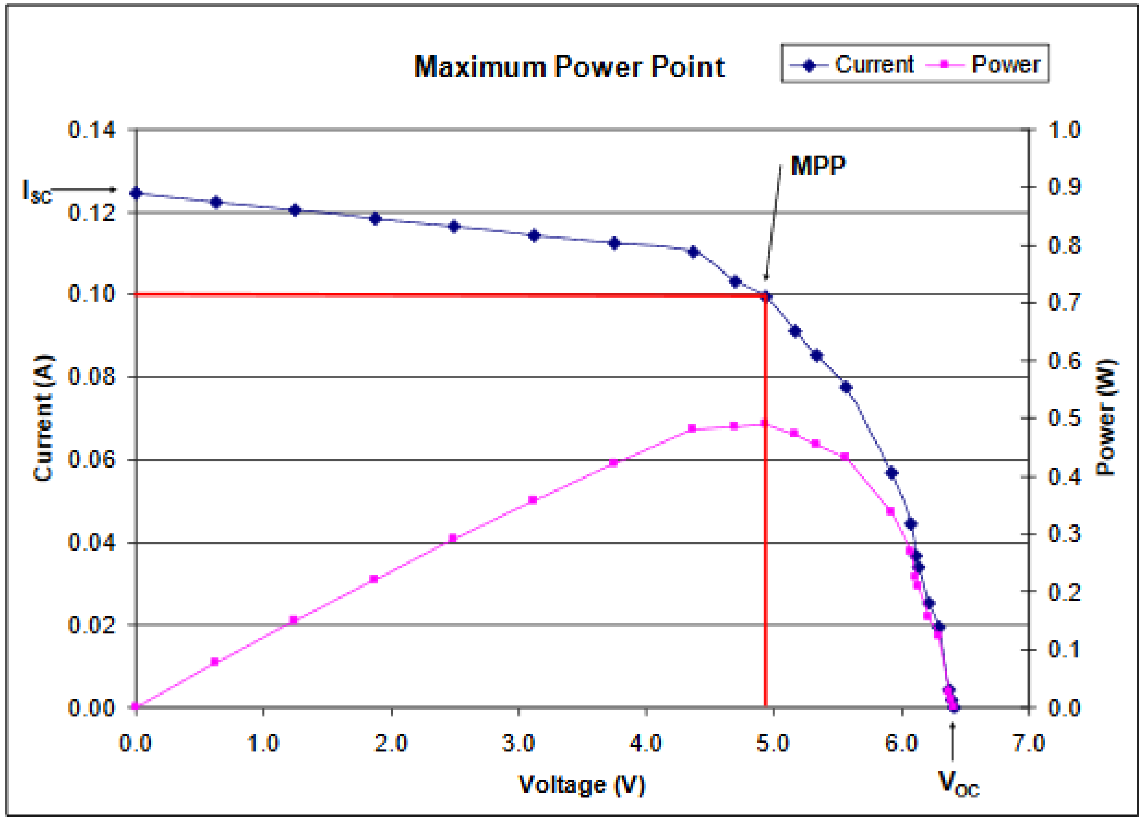


Figure 1: Example I-V (or maximum power point) curve.