NORTHERN TECHNICAL UNIVERSITY

Engineering Technical College /Mosul

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SOLAR PHOTOVOLTAIC CONVERSION

Module-II: Solar Photovoltaic Conversion

- *Basics of Solar Photovoltaics*
- *Solar Photovoltaic Module*
- *Photovoltaic Systems*

Recommended textbooks

- *Yaman Abou Jieb Eklas Hossain. Photovoltaic Systems Fundamentals and Applications. © Springer Nature Switzerland AG 2022.*
- *Al-Waeli, Ali HA, et al. Photovoltaic/thermal (PV/T) systems: principles, design, and applications. Springer Nature, 2019.*

Introduction

1. Photovoltaic PV: The method of producing electricity, using solar cells. A solar cell is a device that /converts solar optical energy (solar radiation) directly into electrical energy.

2. Solar Radiation: Solar radiation: The primary source of the Earth's heat Phenomenon that emanates from the sun towards the Earth, penetrating the gas. The number of solar rays that reach the earth's surface varies according to time and place, does not exceed 5%.

3. Light: The sum of the solar rays emitted by the sun and reaching the Earth's surface. This light consists of a spectrum where throughout the transmission of several including: x-rays, infrared, ultraviolet...etc.

4. Solar reading: Scientists define solar readings as: "***What I see with my eyes and what I feel***", meaning that a person can see the sun's rays, or feel their effect.

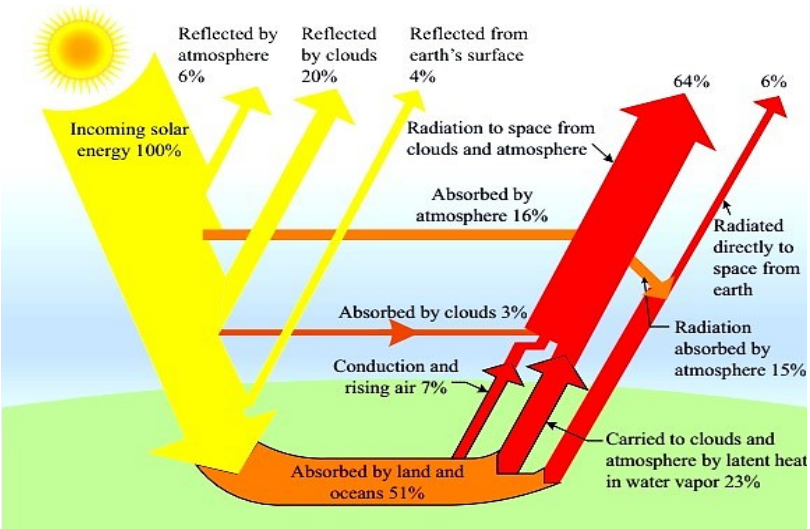
5. Solar constant: The amount of energy received in the form of solar radiation per unit time and unit area. The solar constant is measured in the outer part of the Earth's atmosphere in a plane perpendicular to the rays of the sun and the average value of 1366 W/m^2.

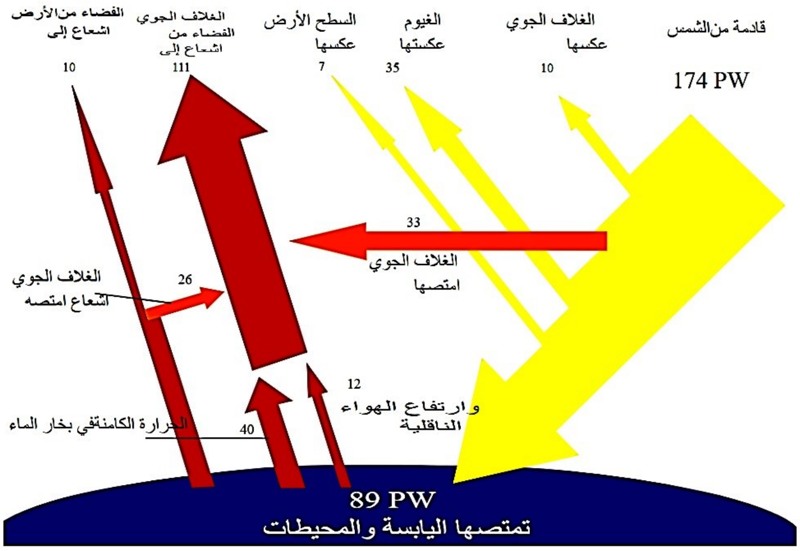
Ex: **What are the components of solar radiation?**

- Solar radiation is the energy that comes from the Sun.
- Radiation is generated from nuclear fusion reactions that occur in the solar nucleus.
- Nuclear radiation produces **electromagnetic radiation** at various frequencies or wavelengths.

The sun's radiation contains three types of rays with ratios:

- 49% are infrared (IR) rays that provide heat.
- 43% are visible rays (VI) that provide light.
- 7% are ultraviolet (UV) rays.
- 1% are other types of lightning.





Principles of a PV cell:

Photovoltaics (PV) or solar cell comprises the convert sunlight directly into electricity.

- The term "photo" means light and "voltaic" electricity, PV cell is a semiconductor device that generates electricity when light falls on it.
- PV energy converters are semiconductor devices that convert part of the incident solar radiation (in form light) into electrical energy. Photons have zero mass with zero charge.
- PV cells when sunlight strikes a PV cell the photons of the absorbed sunlight dislodge the electrons from the atoms of the cell. The free electrons then move through the cell creating and filling in holes in the cell. It is this movement of electrons and holes that generates electricity.
- PV system consists not only of PV modules, also the "**balance of system**" (BOS), the support structures, wiring, storage, conversion devices.

- **Semiconductors** Silicon (Si) and Germanium (Ge) can show both conductive and insulating behavior toward the flow of electrons.
- Temperature rise shifts the semiconductor material behavior toward conductive materials. Moreover, the intentional addition of impurity in materials to improve chemical performance through a process called **doping** is used to increase the material conductivity regardless of the temperature.
- The **doping** process is used in all semiconductor applications, such as in the manufacturing process of electronics (diodes, transistors, thyristors, etc.)

PV Module A single solar cell would generate power in the range of a fraction of (0.1-3 watts). the power requirement by our loads, like fans, TV, and refrigerators is in the range of several 100-1kW. We must generate solar PV power in large amounts MW. In order to fulfill the high-power requirements, a number of cells are connected together to make a Solar PV Module.

The cell has two terminals, a positive terminal, and a negative terminal. The cells are connected in a serial fashion, wherein the positive terminal of one cell is connected to the negative terminal of the next cell and this is repeated to make a string of solar cells. The output of a PV module depends on ambient conditions, temperature, and solar radiation intensity.

The Solar Cell Structure:

- PV take advantage of the photovoltaic effect by which a convert's sunlight to electricity.
- Sunlight contains photons or “packets” of energy sufficient to create electron hole pairs in the **n and p regions.**
- Electrons accumulate in the **n-region and holes accumulate** in the **p-region**, producing a potential difference (voltage) across the cell.
- When an external load is connected, the electrons flow through the semiconductor material and provide current to the external load.

A **silicon solar cell** consists of a thin layer **(wafer)** of silicon that has been doped to create a **p-n** junction.

- The silicon wafer is doped so that the **n** region is much thinner than the **p** region to permit light penetration, as shown in Figure 1(a).
- A grid of very thin conductive contact strips is deposited on top of the wafer by methods such as photoresist shown Figure 1(b). The contact grid must maximize the surface area of the silicon wafer that be exposed to the sunlight in order to collect as much light energy as possible.
- The conductive grid across the top of the cell is necessary so that the electrons have a shorter distance to travel through the silicon when an external load is connected.
- A solid contact covering all of the bottom of the wafer is then added.
- Then an antireflective coating is placed on top the contact grid and **n** region, as shown in Figure 1(c). This allows the solar cell to absorb as much of the sun's energy as possible by reducing the amount of light energy reflected away from the surface of the cell.
- Finally, a glass or transparent plastic layer is attached to the top of the cell with transparent adhesive to protect it from the weather.

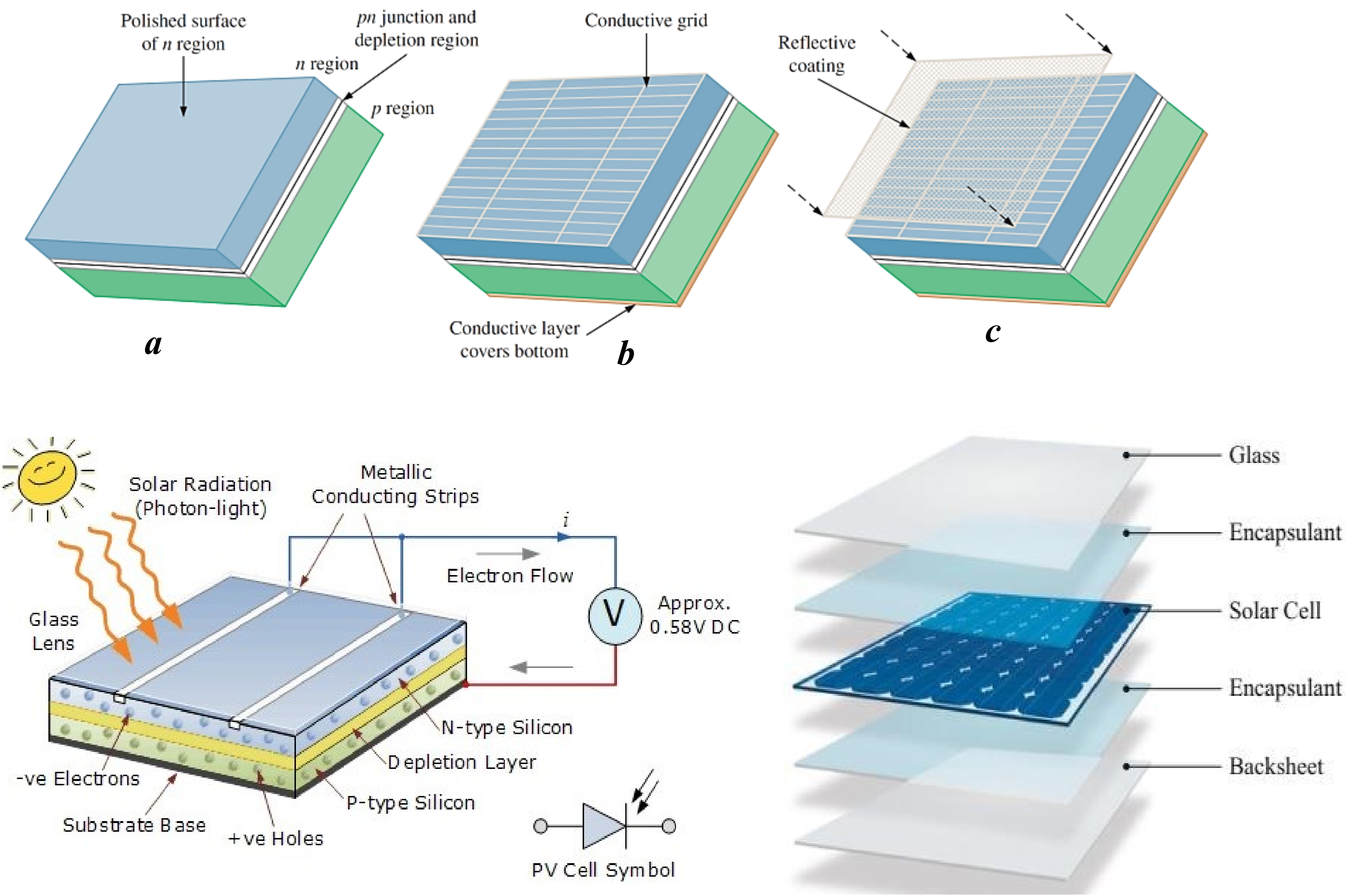


Fig. 1 Solar cell structure

Basic features of solar cells systems:

(a) There are no moving parts so that little maintenance is required.

(b) The cells are reliable and long-lasting, with no harmful waste products.

(c) There is no discernible health hazard.

(d) They have a high power-to-weight ratio, required in aerospace applications.

(e) They utilize an infinitely renewable (compared with the human lifespan) and pollution-free power source.

(f) The cells are usually made of silicon, which is one of earth's most abundant and cheap materials.

(g) The cells can be used on site in remote locations, such as buoys sea, spacecraft.

(h) They are manufactured and researched in a highly developed, scientifically based, well-funded industry.

How solar cell Generates electricity:

A solar cell works in three generalized steps; these steps are the basic way that energy from the sun is converted into usable electricity.

1. Light is absorbed and knocks electrons loose

2. Loose electrons flow, creating an electrical current

3. The electrical current is captured and transferred to wires.

The working of a solar cell can be explained as follows:

a) Photons in the sunlight falling on the solar cell's front face are absorbed by semiconducting materials.

b) Free electron-hole pairs are generated. Electrons are considered as negative charge and holes are considered as positive charge. When solar cell is connected to a load, electron and holes near the junction are separated from each other. The holes are collected at positive terminal (anode) and electrons at negative terminal (cathode). As shown in Fig. 2.

c) Voltage developed at the terminals of a solar cell is used to drive the current in the circuit. The current in the circuit will be direct current or DC current.

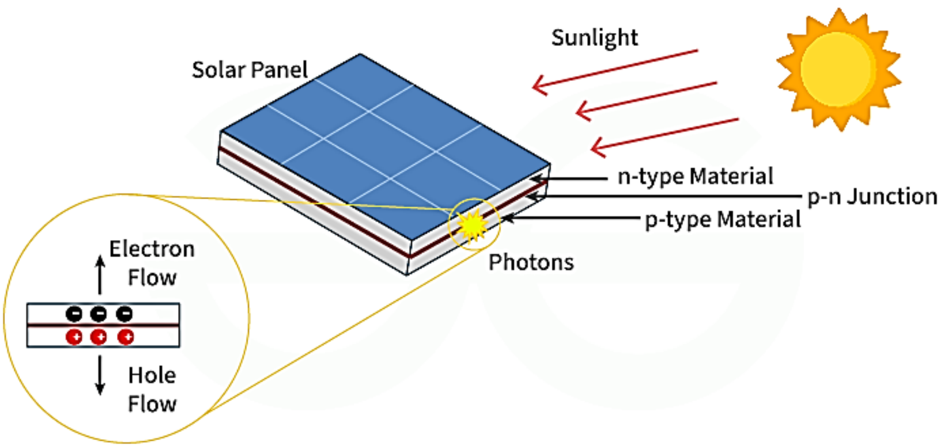
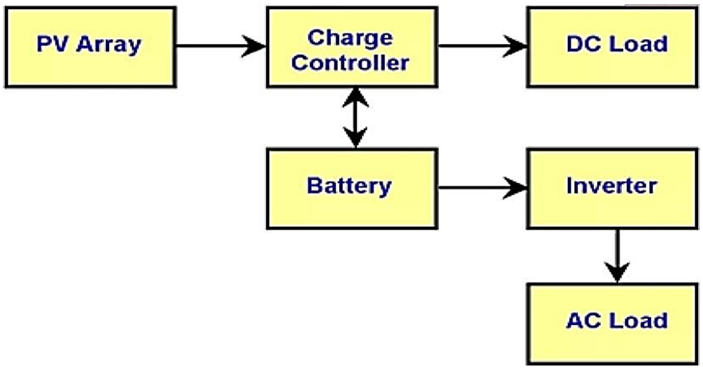


Fig. 2. Convert solar to electricity

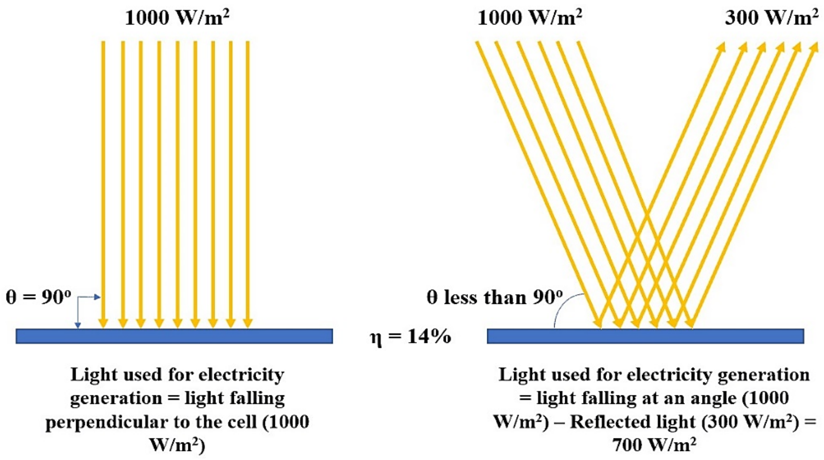
Balance of system (BOS):

Refers to all the components of a solar photovoltaic (PV) system except the solar panels themselves. These include essential elements like racking/mounting systems, inverters, wiring, batteries, charge controllers, and installation labor that are necessary to capture, convert, store, and distribute solar energy. BOS components are crucial for the safe and efficient operation of a solar system and represent a significant portion of the overall project cost.



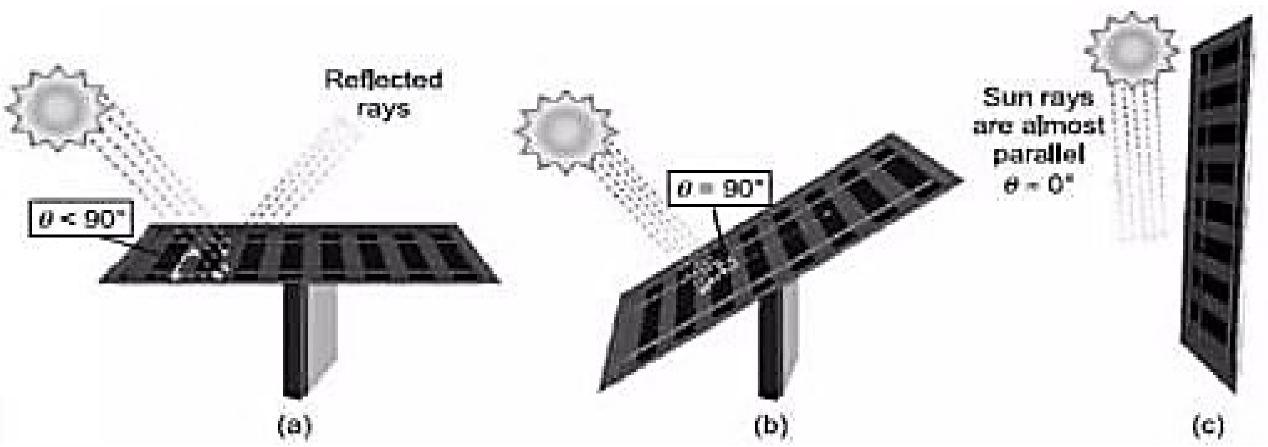
The Angle of Light (θ):

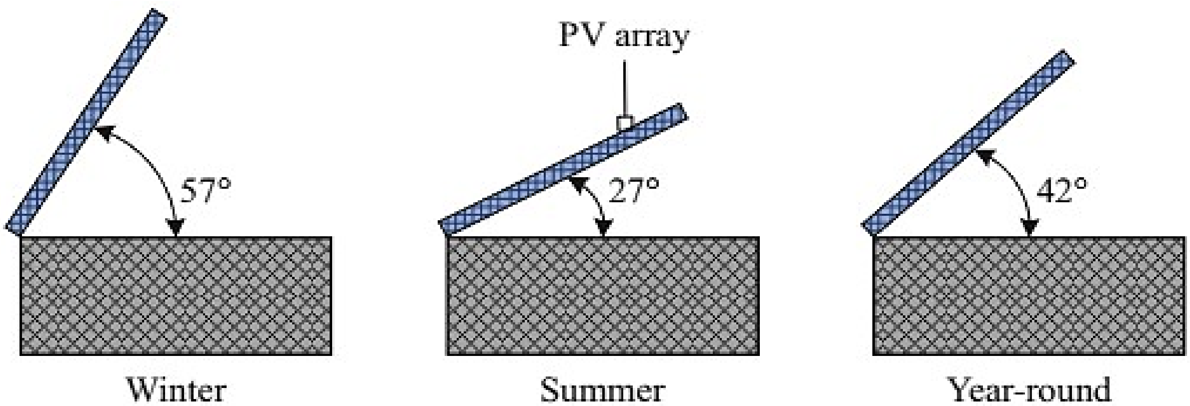
The solar cell produces maximum output power for given sunlight when the angle of the light and the cell are perpendicular to each other 90°. When the angle of the incident of light is less than or greater than 90° than it will produce output power lower than the maximum output power capability of the cell. When the light falls on an angle greater or lesser than 90° some part of the light is reflected, and the light utilized by the cell less than the actual falling on it. This results in a reduction of the output power generated by the cell.



The tilt angle of a solar panel depends on your geographical location and the seasons. For example; The panels should be vertical in the winter and more tilted in the summer to maximize production. The optimal tilt angle is calculated by adding 15° to your latitude during the winter and subtracting 15° during the summer.

Ex: if your latitude is 34 degrees, the optimal tilt angle for solar panels during the winter would be **34 + 15 = 49 degrees.** Conversely, the optimal tilt angle in the summer would be **34 - 15 = 19 degrees.** If the panel angle is constant throughout the year, the average between the two angles (the same latitude value) is calculated.





How to determine the tilt angle of solar panels, either through a program that is installed on the mobile phone as soon as the mobile phone is placed on the iron template.

Structure

Before installation, I mean the program will give the tilt value. In the summer, it should be 20 to 25 degrees, in the spring and autumn, from 30 to 32 degrees, and in the winter, approximately 45 degrees.

There is also an equation that includes

Panel tilt = longitude of the city of Mosul, for example

30.76 degrees ×

Longitude of the city of Mosul

If we apply the equation, it becomes

36.2 30.5 36.2° × 76 + 3 degrees.

degree

Ex: Find the amount of power obtained from a solar containing 500 solar panels, each panel consisting of 100 cells, and calculate the conversion efficiency of the product if you know that the amount of solar energy falling on a single panel is equivalent to 1000W.

Power produced by a single panel - number of cells * voltage per cell * current per cell

2.5 x 0.5 x 100 =

125 watts =

Total power produced = number of panels x power produced by each panel

500 x 125 =

62,500 watts =

62.5 kW =

Conversion efficiency: power out / power in 100%

$$\frac{62{,}000}{1000 * 500} = 12\% \times 100\%$$

<u>Types of Solar cells:</u>

1. Crystalline Materials:

***a)* Single-Crystal Silicon (Mono-crystalline):**

Single-crystal silicon cells are the most common in the PV industry. The main technique for producing it is the **Czochralski (CZ) method**.

- High-purity polycrystalline is melted in a quartz crucible.
- A single-crystal silicon seed is dipped into this molten mass of polycrystalline materials slowly from the melt a single-crystal ingot is formed.
- The ingots are sawed into thin wafers about 200-400 micrometers.
- The thin wafers are polished doped coated interconnected and assembled into modules and arrays.

Characteristics of **SCS** has a uniform molecular structure, high uniformity results in higher energy conversion efficiency are the ratio of electric power produced by the cell to the amount of available sunlight power.

***b)* Poly-crystalline silicon:**

- Consisting of small grains of single-crystal silicon polycrystalline PV cells are less energy efficient than single-crystalline silicon PV cells.
- The grain boundaries in polycrystalline silicon hinder the flow of electrons and reduce the power output of the cell.

- The energy conversion efficiency for a commercial module made of polycrystalline silicon ranges between 10-14%. the cost is lower compared to single-crystalline silicon.
- Polycrystalline silicon material is stronger and can be cut into one-third the thickness of single-crystal material.

c) **Gallium Arsenide (GaAs):**

- A compound semiconductor made of two elements gallium (Ga) and arsenic (As), it has a crystal structure similar to that of silicon.
- An advantage of GaAs is that it has high level of light absorptivity, to absorb the same amount of sunlight.
- GaAs requires only a layer of few micrometers thick while crystalline silicon requires a wafer of about 200-300 micrometers thick.
- It has a much higher energy conversion efficiency than crystal silicon, reaching about 25 to 30%.

2. Thin Film Materials:

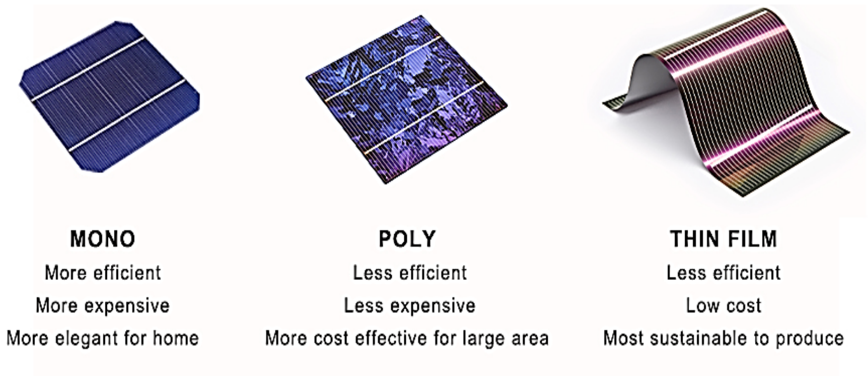
In a thin-film PV cell, a thin semiconductor layer of PV materials is deposited on low-cost supporting layer such as glass, metal or plastic foil. Since thin-film materials have higher light absorptivity than crystalline materials, the deposited layer of PV materials is extremely thin.

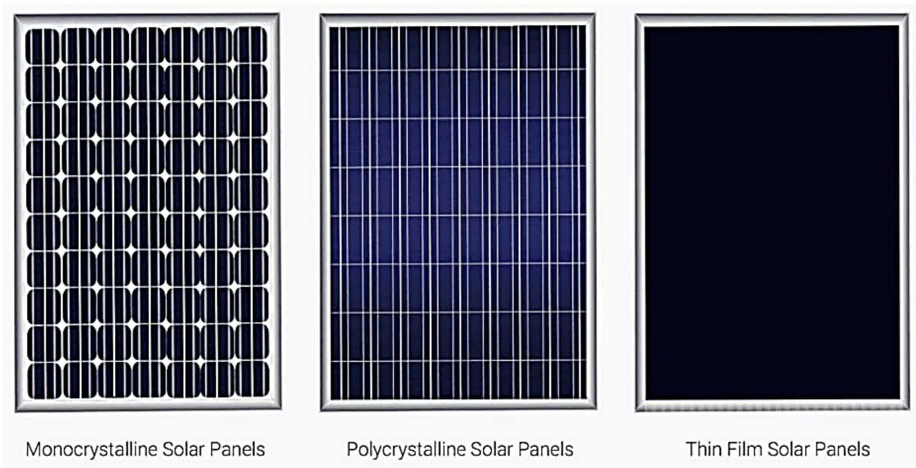
a) Amorphous Silicon (a-Si)

- Used mostly in consumer electronic products which require lower power output and cost of production.
- amorphous silicon has been the dominant thin-film PV material.
- Amorphous silicon is a non-crystalline form of silicon i.e. its silicon atoms are disordered in structure.
- A significant advantage its high light absorptivity, about 40 times higher than that of single-crystal silicon.

b) Cadmium Telluride (CdTe)

- As a polycrystalline semiconductor compound made of cadmium and tellurium.
- It has a high light absorptivity level-only about a micrometer thick can absorb 90% of the solar spectrum.
- Advantage is that it is relatively easy and cheap to manufacture by processes such as high-rate evaporation, spraying or screen printing.





Equivalent circuit of solar cell:

The equivalent circuit of a solar cell consists of an ideal current generator in parallel with a diode in reverse bias, both of which are connected to a load. The generated current is directly proportional to light intensity, shown Figure below.

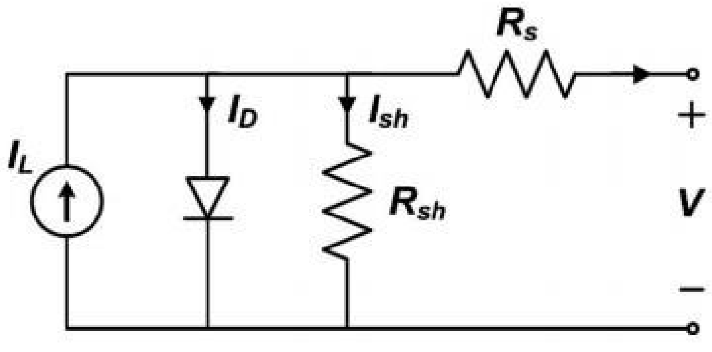


Fig. 3. Equivalent circuit of a photovoltaic solar cell.

I_D = Diode current, *A*. I_{Sh} = Shunt current, *A*. R_S = Series resistance, *Ω*. R_{Sh} = Shunt resistance, *Ω*. I_L= External load current, *A*. V_L= External load voltage, V
The governing equation for this equivalent circuit is formulated using Kirchoff's current law for current I:

$$I = I_L – I_D – I_{sh}$$

Here, I_L represents the light-generated current in the cell, I_D represents the voltage-dependent current lost to recombination, and I_{sh} represents the current lost due to shunt resistances. In this single diode model, I_D is modeled using the Shockley equation for an ideal diode:

$$I_D = I_0\left[\exp\left(\frac{V+IR_s}{nV_T}\right)-1\right]$$

Where n is the diode ideality factor (unitless, usually between 1 and 2 for a single junction cell), I_0 is the saturation current, and V_T is the thermal voltage given by:

$$V_T = \frac{kT_c}{q}$$

Where k is Boltzmann's constant (1.381×10^{-23} J/K) and q is the elementary charge (1.602×10^{-19} C).

Writing the shunt current as $I_{sh}= (V+I_{Rs})/R_{sh}$ and combining this and the above equations results in the complete governing equation for the single diode model:

$$I = I_L - I_0\left[\exp\left(\frac{V+IR_s}{nV_T}\right)-1\right] - \frac{V+IR_s}{R_{sh}}$$

For a photovoltaic module or array comprising Ns cells in series, and assuming all cells are identical and under uniform and equal irradiance and temperature (i.e., generate equal current and voltage), $I_{module} = I_{cell}$ and $V_{module}= Nx \times V_{cell}$ the single diode equation for a module or array becomes.

$$I_M = I_L - I_0\left[\exp\left(\frac{V_M+I_MN_sR_s}{nN_sV_T}\right)-1\right] - \frac{V_M+I_MN_sR_s}{N_sR_{sh}}$$

Care should be taken when implementing model parameters, as they are either applicable to a cell, module, or array. Parameters for modules or arrays are strictly used with the single diode equation for I, which is the more commonly implemented form. In some implementations the thermal voltage V_T, diode ideality factor n, and number of cells in series N_S are combined into a single variable a termed the modified ideality factor:

$$a \equiv \frac{N_snkT_c}{q}$$

Advantages of Solar Photovoltaic:

- **Abundant source:** Solar cell uses solar radiation energy as input, which is a renewable energy source. Solar radiation energy is available in huge quantity as it is abundant. We will not run in the shortage of solar radiation energy in future. On the other hand, the world is already facing the shortage of fossil fuels-based energy sources.
- **Environmentally benign:** The conversion of solar radiation energy into electrical energy does not emit any polluting products and, therefore, it does not cause damage to the environment like the smoke from use of diesel and petrol.

- **Decentralized electricity generation**: Since solar radiation energy is available everywhere, the solar PV electricity can be generated everywhere in decentralized manner in small quantities as per the need, unlike the coal-based power plant where electricity can be generated only in centralized manner in large quantities.
- **Modular implementation:** Implementation of solar PV technology can be modular. In the case of a diesel generator or a coal-based power plant, size once fixed cannot be changed. If we need to increase electricity, we need to buy another diesel generator or set up another coal-based power plant. Solar cell uses sunlight as an input fuel source, which is abundant, sustainable and environmentally friendly energy source.

Challenges/Disadvantages of Solar Photovoltaic:

- **PV electricity cost**: The conventional energy sources have always been the most cost-effective way to supply the large amount of electricity needed for modern life. Producing electricity using solar PV technology is more expensive. However,
- **Energy fluctuation**: In the case of coal-based power plants, companies can easily stockpile coal to meet the ever-changing demand for electricity, especially during peak demand hours. While the solar radiation energy can't be stored to provide energy for future use.
- **Location dependency:** Fossil fuel power plants can be placed almost anywhere, as long as a railroad or pipeline can reach the site for bringing coal and gas. In contrast, solar PV electricity generation depends on the availability of solar radiation.

Factors that affect solar panel efficiency:

- **Temperature**: High temperatures will directly reduce the efficiency of a photovoltaic panel. As the temperature rises, the output voltage of a solar panel decreases, leading to reduced power generation. For every degree Celsius above 25°C, a solar panel's efficiency typically declines by 0.3% to 0.5%.

- **Sunlight**: The amount of direct sunlight a PV panel receives is typically the most significant determiner of how much electricity it can produce. Even the most efficient solar panel can't generate electricity at night, and production is diminished on overcast days.

- **Orientation and Tilt**: Orienting panels towards the sun (facing south if you are in the Northern Hemisphere) to maximize sunlight exposure is best. Depending on your latitude, you can optimize their efficiency by angling them directly toward the sun's path around 30-45 degrees.
- **Dust, Snow, and Debris**: Dirt, leaves, snow, and other debris can block sunlight from the panels. Be sure to clean your solar panels regularly to keep them efficient.

- **Panel Age**: As photovoltaic panels age, their efficiency will slowly decrease year after year. Having said that, high quality solar panels can last 25 years or more longer than an asphalt roof.

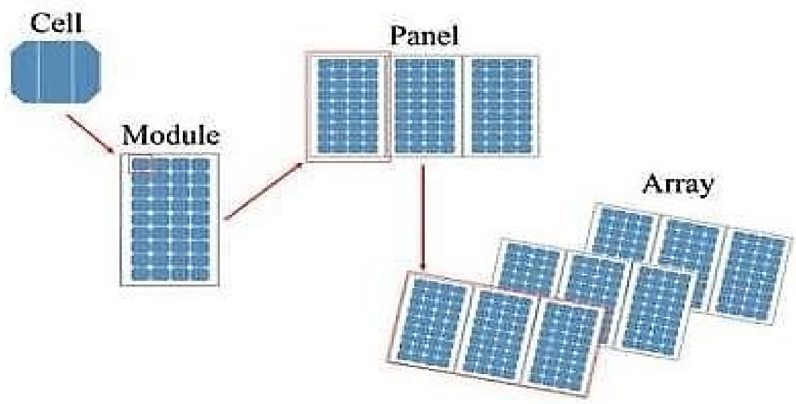
- **Shading**: If shadows from nearby trees or structures block your panels, they won't reach maximum efficiency. This issue also goes for partial shading if one cell in a monocrystalline or polycrystalline PV panel is in the shade.

Components of Solar PV Systems:

Module: It is a group of photovoltaic units that are combined and connected together in series

Panel: It is a group of modules that are combined and connected together in series to obtain the necessary electrical power value.

1. PV module: The solar cell is the basic unit of a PV system. An individual solar cell produces direct current and power typically 2W. For actual usage, the solar cells are interconnected in series/parallel combinations to form a PV module. **The current** output from a PV module directly depends on the solar irradiance and can be increased by connecting solar cells in parallel. **The voltage** of a solar cell does not depend strongly on the solar irradiance but depends primarily on the cell temperature.



Ex: How much solar panel capacity will be suitable for home electrical appliances? 5 lamps of 15 watts are intended to be operated for 4 hours every day.

Sol: Total = 15 x 5 = 75 W. Which gave us 75 watts with 4 hours.
Daily = 75 x 4 = 300 Wh.
300/6 = 50 watts. So, we need a 50W solar panel.

2. Battery (Energy Storage): For storing electrical energy for night time applications and for time when demand of electricity is more than the generation of electricity. Batteries are not required in grid-connected PV systems. **The four** main types of solar batteries are, **lead acid, lithium ion, nickel cadmium, nickel – metal hydride, and flow batteries**. Lead acid batteries have been around for the longest and are known for their low prices and reliability, but they require regular maintenance.

3. Inverter: For converting DC electricity to AC electricity, the DC electricity may either come from PV modules or it can come from batteries.

4. Charge controller (Regulator): For protecting the batteries from over charge and over discharge conditions which reduce the life of batteries.

H.W: Comparison between PWM and MPPT Charge Controller:

Both PWM and MPPT charge controllers are used in solar PV systems. MPPT is known as the advanced version of PWM as it has the ability to vary the PV array voltage from the battery bank voltage.

- **Temperature compensation:** Most of the PWM charge controllers do not have temperature sensors in them, which means the system will lack temperature compensation. Thus, the battery will die out sooner as the change in temperature will affect the output and the system. On the other hand, MPPT charge controllers have temperature sensors in them, which allows compensating the system temperature.
- **Voltage limitation:** There is a voltage limitation in the case of PWM. If the system generates more voltage than its rating, the extra energy will be dissipated as heat, whereas, for MPPT, the voltage rating can be increased.

5. Maximum power point tracker (MPPT): For extracting maximum available power from solar PV modules under given solar radiation input. Many times, charge controller or inverter (in case of grid connection) performs the function of charge controller and MPPT. PV modules together with other components that are put connected with PV modules to supply reliable energy to appliances is referred collectively as ‘solar PV system.

6. Load: The appliances, lights and equipment being powered by a PV solar system constitute electric loads of the PV system. Energy-efficient loads contribute to overall system efficiency and economy.

How calculation load analysis:

Load analysis is calculation for the load used for the evaporative solar cooler system which includes the fan and water pump. In this calculation, it is assumed that the average usage of air-cooling system is 35 hours per week. The power requirement for the load is calculated by using equation:

Power = Voltage x Current

- **Voltage: Electrical pressure**
- **Current: Electrical flow**
- **Power: Rate at which electricity is used**
- **Energy: Amount of electricity used**

Relationships:

- **Power = Voltage × Current**
- **Energy = Power × Time Units:**
- **Voltage is measured in Volts = V**
- **Current is measured in Amps = A**

- **Power is measured in Watts = W**
- **Energy is measured in Wh or more often kWh**

Ex: In table below the specified of load analysis find; **total amp-hours per week and total average ampere hour per day**.

Items	Voltage (V)	Current (I)	Power (P)	Quantities	Total Watt	Hours/Week	Watt-Hour/Week
Fan	12V	0.2A	2.4W	4	9.6W	35	336
Water Pump	12V	0.9A	10.8W	1	10.8W	35	378
Total							714

Sol: Both loads have DC System voltage = 12V.

1. total amp-hours per week used by DC loads.

$$= \frac{714 Watt - hour / Week}{12V}$$

$$= 59.5 \text{ A-h/Week}$$

2. Total average ampere hour per day.

$$= \frac{59.5 A - h / Week}{7 days}$$

$$= 8.5 \text{ A-h/day}$$

Equipment Sizing:

A. PV Array Sizing

From the load analysis calculation, total average ampere-hour per day = 8.5 A-h. It is assumed that the average sun hour per day in Iraq is 5 hours. From the solar panel specification, peak amp of solar module or current at maximum power = 2A Total ampere-hour per day with compensation for loss of battery charge/discharge

= 1.2 × Ampere-hour per day = 1.2 × 8.5 A-h/day = 10.2 A-h/day

Sun hour/day = 10.2 A-h/day 5 hour/day = 2.04 A

amp **required current at maximum power = 2 / 2.04 = 1 module**

B. Battery sizing

From the load analysis calculation, daily amp-hour requirement = 8.5 Ah-hr. maximum number of consecutive cloudy weather days expected in Iraq or number of days of autonomy the system can support is taken to be 2 days

Amount of amp-hour need to store in the battery = Daily amp-hour requirement x **days of autonomy = 10.2 A-h/day × 2 days = 20.4 Ah**
depth of discharge of battery or safety factor = 0.5 (50%)
discharge of battery = 0.5 / 20.4Ah = 40.8 Ah
Total amp-hour rating of battery = 40.8 Ah / 12 Ah = 4
Voltage = 12V/ 12V = 1.
No. of batteries wired in parallel = 4 × 1 = 4 batteries

Ex: A 12V PV system has two DC appliances A and B requiring 15 and 20W respectively. The average operational time per day is 6 hours for device A and 3 hours for device B. Calculate the daily energy requirements of the devices expressed in Ah.

Sol: **Device A:** 15W×6h = 90Wh
Device B: 20W×3h = 60Wh
Total: 90Wh+60Wh = 150Wh 150Wh/12V = **12.5** Ah

Ex: An AC computer (device C) and TV set (device D) 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. Calculate the daily energy requirements of the devices expressed in DC Ah.

- Device C: 40W×2h = 80Wh
- Device D: 60W×3h = 180Wh
- Total: 80Wh+180Wh = 260Wh
- DC requirement: 260Wh/0.85 = 306Wh 306Wh/12V = **25.5** Ah

Ex: A 7kWdc PV system makes 5.5kWac when 1000W per square meter are shining on it. If this is in a location that will get an average of 4.5 peak sun hours (PSH) per day and there are 12% losses from shading, then about how much energy will this system produce in a month?

Sol:
5.5kWac × 4.5PSH × 0.88 derating × 30days = 653kWh

H.W: If a 12V pump drew 5A for 2 hours, how much energy did it use and how many amp hours would it take from a 12V battery? Energy calculation

<u>Standard PV Module Parameters:</u>

The parameters of the solar PV modules (V_{oc}, I_{sc}, W_p), mentioned by the manufacturer are measured under some standard conditions of temperature (25°C) and solar radiation (1000 W/m^2). These test conditions are known as standard test conditions (STC). The testing condition of STC is summarized in Table 4.1.

- **Short circuit current (Isc):**

It is the maximum current that can be produced by a solar cell without affecting its construction. The higher the Isc, better is the cell. It is measured in ampere (A) or (mA). The value of this maximum current depends on the cell technology, cell area, amount of solar radiation failing on the cell, angle of cell.

- **Open circuit voltage (Voc):**

It is the maximum voltage that can be produced by a solar cell when there is no load connected to it. The higher the Voc, the better is the cell. It is measured in volts (V) or sometimes in milli-volts (mV).

- **Maximum power point (Pm):**

It is the maximum power that a solar cell produces under the STC. The higher the P m, the better is the cell. It is given in terms of watt (W). A solar cell can operate at many current and voltage combinations. But it will produce maximum power only when operating at certain current and voltage. This maximum power point is denoted as Pm. Typically, the maximum power point for a I-V curve of solar cells occurs at the 'knee' or 'bend' of the curve.

Pm or Pmax = Im X Vm

- **Current at maximum power point (Im):**

This is the current which solar cell will produce when operating at maximum power point. The Im will always be lower than Isc. It is given in terms of A, mA.

- **Voltage at maximum power point (Vm):**

The voltage which solar cell will produce when operating at maximum power point. It will always be lower than Voc. It is given in terms of V, mV.

- **Fill factor (FF):**

The ratio of the areas covered by Im-Vm rectangle to the area covered by Isc-Voc rectangle whose equation is given below? Typical FF values range from 0.5 to 0.82.

FF = Im × Vm / Isc ×Voc. FF=Pm / Isc × Voc. Pm= Isc × Voc × FF

Efficiency (ŋ):

It is defined as the maximum output power (Pm or Pmax) divided by the input power (Pin). The efficiency of a cell is given in terms of percentage (%), which means that the given percentage of input radiation power is converted into electrical power.

$$\eta = P_m / P_{in}$$

The following graph shows solar cell I-V & P-V curve based on the parameters explained:

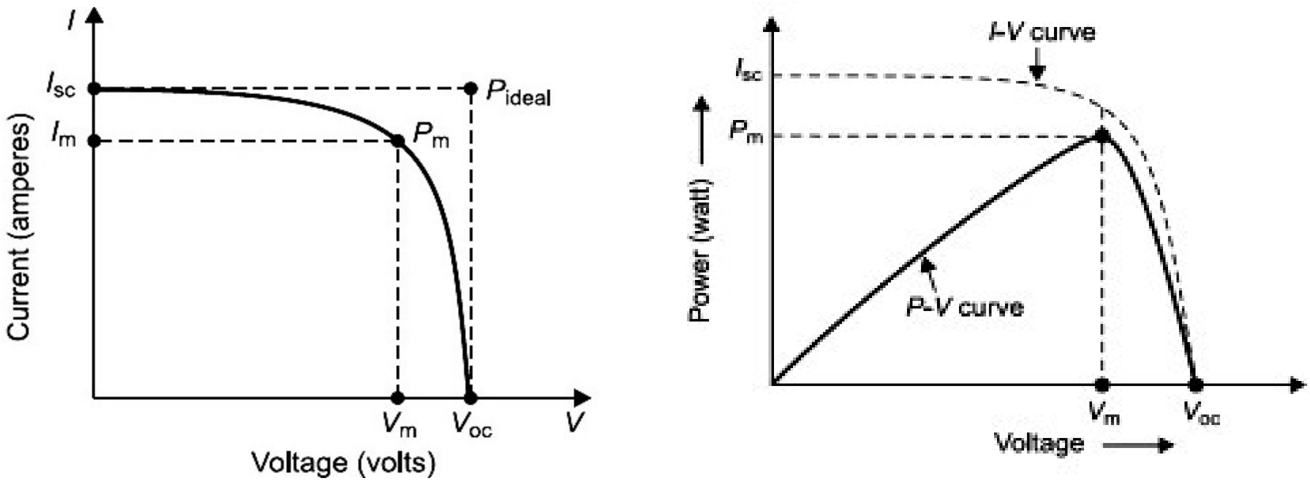


Fig. 4. Solar cell I-V curve

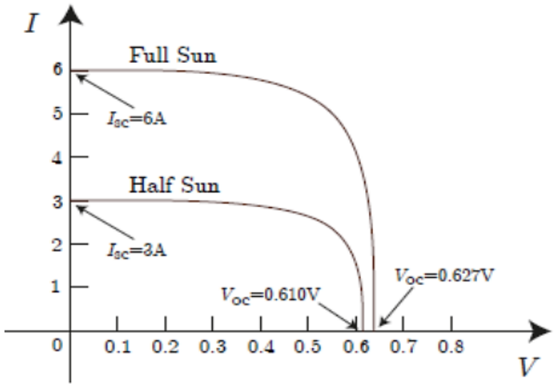
Ex: Consider a 150 cm^2 photovoltaic cell with reverse saturation current I_o is10^{-12} A/cm^2. In full sun, it produces a short-circuit current of 40 mA/cm^2 at 25°C. What would be the short-circuit current and open-circuit voltage in full sun and again for 50% sun. Plot the resulting I-V curves.

Sol: The reverse saturation current $I_0 = 10^{-12}$ A/cm^2 × 150 cm^2 = 1.5×10^{-10} A. At full sun short-circuits current, Isc, is 0.040 A/cm^2 × 150 cm^2 = 6.0 A. Thus, the open circuit voltage for a single cell is:

$$V_{oc,full} = 0.0257\ln\left(\frac{I_{sc}}{I_0}+1\right) = 0.0257\ln\left(\frac{6.0}{1.5\times10^{-10}}+1\right) = 0.627\text{ V}.$$

Since short-circuit current is proportional to solar intensity, at half sun Isc = 3 A and the open-circuit voltage is

$$V_{oc,\ half} = 0.0257\ln\left(\frac{I_{sc}}{I_0}+1\right) = 0.0257\ln\left(\frac{3.0}{1.5\times10^{-10}}+1\right) = 0.610\text{ V}$$



Ex: If the dark saturation current of a solar cell is 1.7×10^{-8} A/m^2, the cell temperature is 27°C, and the short circuit current density is 250A/m^2, find the open circuit voltage V_{oc}, voltage at maximum power V_{max}, current density at maximum power I_{max}, maximum power P_{max}, and maximum efficiency η_{max}. what cell area is required to get an output of 20W when the available solar radiation is 820W/m^2.

Solution

First the value of e/kT_C is evaluated, which is used in many relations:

$$\frac{e}{kT_C} = \frac{1.602\times10^{-19}}{1.381\times10^{-23}\times300} = 38.67\ \text{V}^{-1}$$

Using Eq. (9.9),

$$V_{oc} = \frac{kT_C}{e}\ln\left(\frac{I_{sc}}{I_o}+1\right) = \frac{1}{38.67}\ln\left(\frac{250}{1.7\times10^{-8}}+1\right) = 0.605\ \text{V}$$

Voltage at maximum power can be found from Eq. (9.14) by trial and error:

$$\exp\left(\frac{eV_{max}}{kT_C}\right)\left(1+\frac{eV_{max}}{kT_C}\right) = 1+\frac{I_{sc}}{I_o}$$

or

$$\exp(38.67V_{max})(1+38.67V_{max}) = 1+\frac{250}{1.7\times10^{-8}}$$

which gives $V_{max} = 0.526$ V.

The current density at maximum power point can be estimated from Eq. (9.16):

$$I_{max} = \frac{eV_{max}}{kT_C+eV_{max}}(I_{sc}+I_o)$$

$$= \frac{1.602\times10^{-19}\times0.526}{1.381\times10^{-23}\times300+1.602\times10^{-19}\times0.526}(250+1.7\times10^{-8}) = 238.3\ \text{A/m}^2$$

Maximum power, P_{max}, is obtained from Eq. (9.5):

$$P_{max} = I_{max}V_{max} = 238.3\times0.526 = 125.3\ \ \text{W/m}^2$$

Maximum efficiency, η_{max}, is obtained from Eq. (9.18):

$$\eta_{max} = \frac{P_{max}}{P_{in}} = \frac{125.3}{820} = 15.3\%$$

Finally, the cell area required to get an output of 20 W is:

$$A = \frac{P_{req}}{P_{max}} = \frac{20}{125.3} = 0.16 \text{ m}^2$$

H.W: Calculate the annual energy output of the PV power plant which consist of 30 modules located at site having average daily global radiation of 4.1 kwh/m^2 and average ambient temperature is 35ºC. The specification of A PV module under the stander testing conditions are:

Number of cell	36 series	Short circuit current	9.2 A	NOCT	44 ºC
Max power	150 W	Open circuit voltage	20.1 V		
Max power current	8.8 A	Max power voltage	17.1 V		

Solution :

Annual energy (AE)= ? , 30 modules , daily G = 4.1 [KWh/m²]

Ta =35 Cº

$$G = 4.1\ (\text{KWh/m}^2) = \frac{4.1\ KWh/m^2}{12\ h} = 0.342\ \text{KW/m}^2$$

$$I_{sc}(G) = I_{sc}(\text{at } 1\ \text{Kw/m}^2) \times G\ (\text{in KW/m}^2)$$

$$I_{sc}(G) = 9.2 \times 0.342 = 3.143\ [A]$$

$$Tc = T\alpha + \left(\frac{NocT-20}{0.8}\right) \times G$$

$$Tc = 35 + \left(\frac{44-20}{0.8}\right) \times 0.342 = 45.25\ ^{o}C$$

$$V_{oc}(Tc) = V_{oc} - 0.0023 \times \text{No. of cells} \times (Tc-25)$$

$$V_{oc}(Tc) = 20.1 - 0.0023 \times 36 \times (45.25-25) = 18.423\ [V]$$

$$FF = \frac{Pmax}{Voc \times Isc} = \frac{150}{20.1 \times 9.2} = 0.811$$

$$Pmax\ (G,Tc) = Isc\ (G) \times Voc\ (Tc) \times FF$$

$$Pmax\ (G,Tc) = 3.143 \times 18.423 \times 0.811$$

$$Pmax\ (G,Tc) = 46.975\ [W]$$

$$C_f = \frac{P\ operating\ cond}{Pstc} = \frac{46.975}{150} = 0.313$$

$$AE = \text{No. of modules} \times P\ max \times C_f \times h \text{ in year}$$

$$AE = 30 \times 150 \times 0.313 \times 8760$$

$$AE = 12344985.873\ [Wh/\ year]$$

$$AE = 12.345\ [MWh/\ year]$$

Temperature and irradiance affect I-V curves:

There are various factors that can influence the performance of solar PV modules, **temperature and irradiance**.

- The open circuit voltage of a PV module varies with cell temperature. As the temperature increases due to environmental changes or heat generated by internal power dissipation during energy production the open circuit voltage (Voc) decreases this in turn reduces the power output.
- The design of a solar PV system must take into account the PV module temperature coefficient, comparing the expected average cell temperature in its operational environment.
- irradiance will also affect module performance, with a reduction of sunlight resulting primarily in a reduction in current and consequentially a reduced power output.

- The **I-V characteristics** of a solar PV module is a graph in which different values of current (I) for different voltage (V) is plotted on Y-axis & X-axis respectively. A typical I-V characteristic curve of a solar PV module.

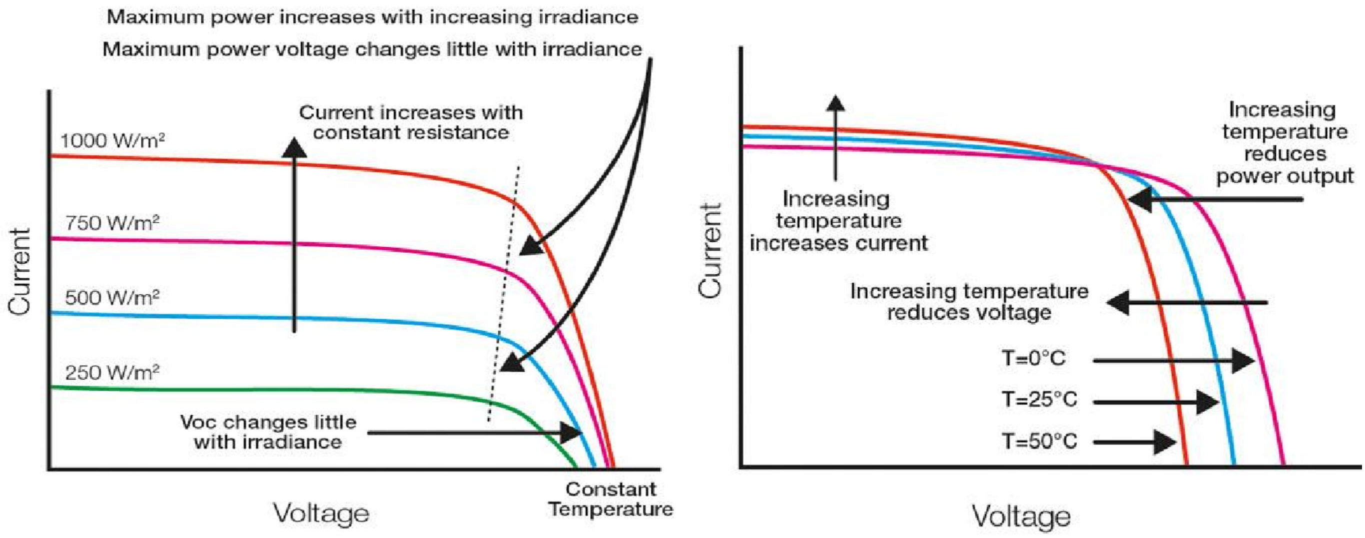


Fig. 5. I-V curve of a solar PV module

• **A P-V curve** is plotted between power of a solar PV module on Y-axis and voltage of a PV module on x-axis. The following figure 6, shows a typical P-V curve of a solar PV module.

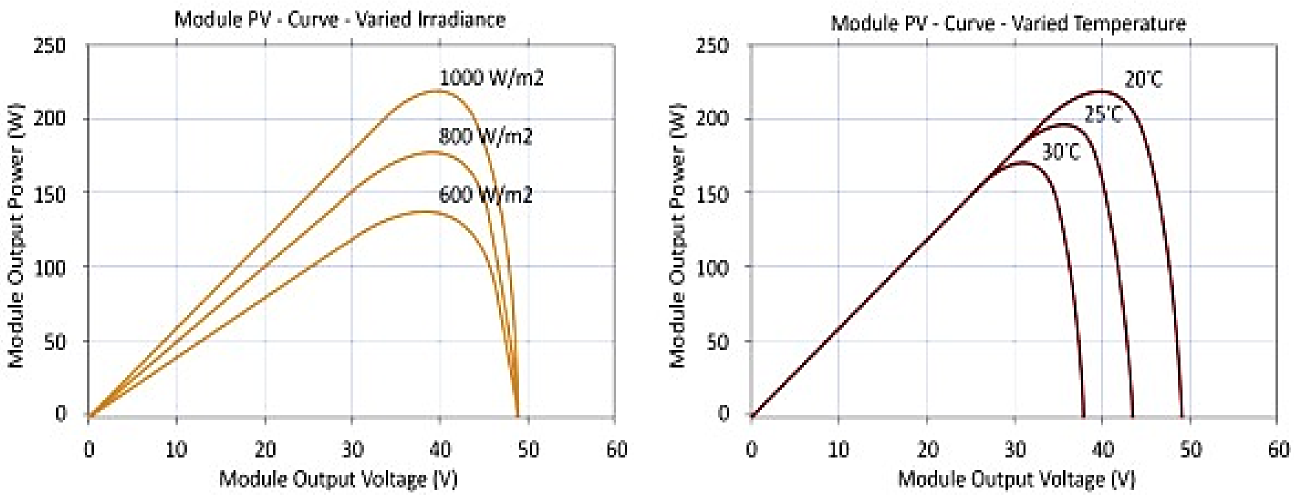


Fig. 6. P-V curve of a solar module

Ex: You have a 12V, 2A light bulb that will run for 3 hours per day. You also have a 100W radio repeater that will be on 100% of the time. How much energy in kWh does the cabin use in a day?

Sol:

12V × 2A = 24W

24W × 3 hours = 72Wh of energy per day for the lights.

100W × 24 hours per day = 2400Wh repeater

Total energy = 2400Wh + 72Wh = 2472Wh/day

EXAMPLE 9.8

A PV system is using 80 W, 12 V panels and 6 V, 155 Ah batteries in a good sunshine area. The battery efficiency is 73% and the depth of discharge is 70%. If, in wintertime, there are 5 h of daylight, estimate the number of PV panels and batteries required for a 24 V application with a load of 2600 Wh.

<u>Calculate the components of a solar energy system</u>

(1) Calculate the amount of energy consumed per day by applying the following equations:

Number × Device capacity × Working hours = Energy consumed by the device per day

4 Lamps × 10 watts × 6 hours = 240 watts. hours

1 TV × 80 watts × 6 hours = 480 watts. hours

1 computer × 80 watts × 4 hours = 320 watts. hours

1 receiver × 20 watts × 6 hours = 120 watts. hours

Total energy consumed per day = <u>1160 watts. Hour</u>

(2) Calculating the number of solar panels:

To know the total capacity, the energy to be generated must be divided by the average solar radiation per day for the area where the system will be built. In Iraq, the average solar arc is between (6 -7) hours, so the total capacity value becomes: **1160 ÷ 6 = 193,333 watts.**
Number of panels = Total capacity ÷ Capacity of one panel
Number of panels = 193,33 ÷ 100 = 1.933 (we need 2 panels).

(3) Calculating the number of batteries: These are the storage units for electrical energy in order to benefit from energy during the night and during periods of weak solar radiation. Energy can be stored sufficient for consumption **from 2-5 days,** depending on the capacity of the battery.
Battery capacity (ampere-hours) = energy to be generated × 1.3
(i.e. it is necessary to keep 30% of the battery capacity to maintain it) ÷ battery voltage.
The number of batteries is calculated as follows: **1160 × 1.3 ÷ 12 = 125.66** ampere-hours. The number of batteries = **125.66 ÷ 100 = 1.25 (need 2 batteries).**

(4) Solar charge controller: Its function is to prevent the battery from continuing to charge after it is full, because overcharging damages the battery. These controllers come in various models and start from 1 to 8 amps for home use, and may reach 30 amps in other models
Number of panels × short circuit current (Isc) **Regulator size = 2×6.35= 12.7A**
It is preferable to double the specified value as a precaution in the future if we want to expand the system and increase the number of panels

(5) Inverter: Converts direct current (DC) to alternating current (AC) as most devices depend on alternating current to operate.
Inverter size = Total power × 30% as an efficiency factor for the inverter performance. **193,333 × 1.3 = 251.33W.**
So, to design a house that runs on solar energy and contains the following loads: lamps, TV, computer and receiver, and according to the operating hours allocated for them above, we need:
2 solar panels with a capacity of (**100W**).
2 batteries with a capacity of (**100 Amp-hours**).
A charge regulator (**20 Amp**.).
An inverter (**300 W**)

Nominal Operating Cell Temperature (NOCT):

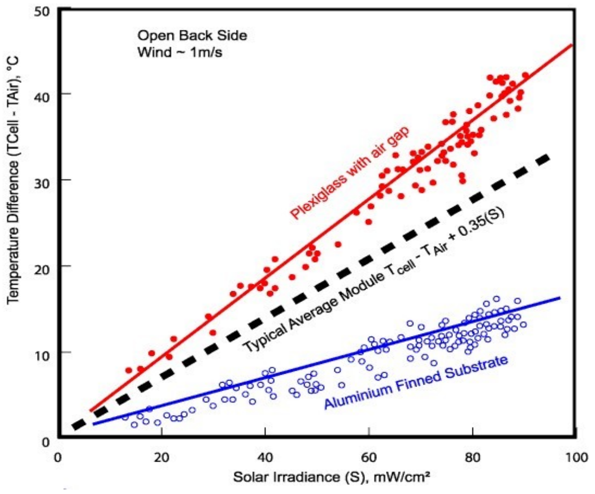
Is defined as the temperature reached by open circuited cells in a module. Test conditions are defined **OR** solar panel temperature based on four main standard reference environments:

- Irradiance on cell surface = 800 W/m^2
- Air Temperature = 20°C
- Wind Velocity = 1 m/s
- Mounting = open back side.

Each type of the solar panels has a different operating temperature, based on two main factors:

- The solar panel designs.
- The mounting conditions.

The NOCT of any Photovoltaic power system increases and decreases regarding the surrounding circumstances. The following graph expresses the heat transfer through conduction & convection between solar panel and the ambient temperature in presence of a certain wind speed. It shows the **best NOCT in blue** and the **worst NOCT in red** and the **moderate one in black.** You can obtain the best NOCT thanks to the aluminum material at the rear of the solar panel that reduces the thermal resistance and increases the surface area for the convection



The formula that shows you how to calculate the nominal operating cell temperature is the following one:

$$T_{solar\ cell} = T_{ambient} + \frac{NOCT - 20}{80} \times S$$

Ta: is the ambient temperature,

T_{NOCT}: is the nominal operating cell temperature in °C which is usually provided by the manufacturer for mPV. (***S or G)*** is the sum of irradiance on both sides. mW/cm^2

<u>Solar Heating and Cooling Technology</u>:

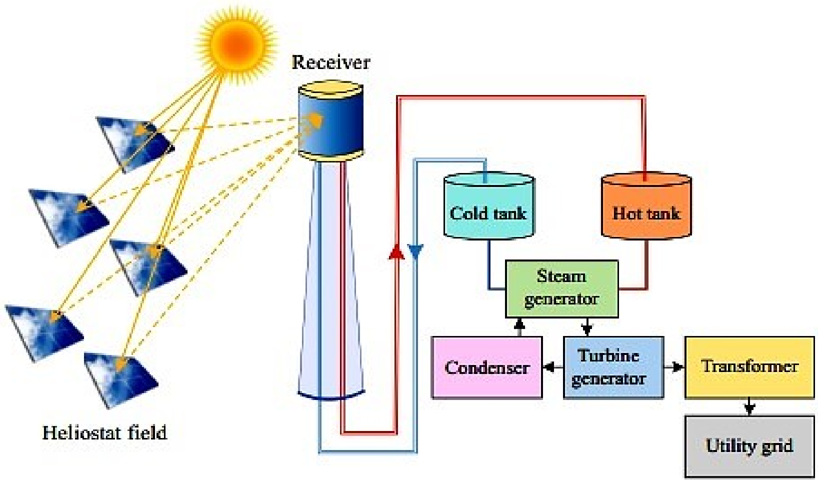
SHC technology is based on concentrating sunlight to use thermal energy from the sun to heat water, swimming pools, and in industries that use hot water in the production process, such as in the food and chemical industries.

Using conventional mechanical principles, users can utilize hot water for space heating or cooling purposes by replacing traditional electrical heating elements or fuel-based heaters with flat or tubular solar collectors. Solar water heaters are efficient and economically feasible. SHC technology is **classified into three main categories:**

1. Solar water heating system (SWHS)
2. Heating, ventilation, and cooling (HVAC)
3. Solar industrial heating process (SIHP).

Passive cooling techniques: such as heat sinks and reflective coatings effectively dissipate excess heat without requiring additional energy input.

Active cooling methods: like water-based cooling or forced air circulation can further enhance heat dissipation but may involve higher costs and energy consumption.



Ex: A PV module is found to operate at 60ºC when ambient temperature = 30ºC and G = 980W/m^2. Determine the NOCT of the module.

Sol:

$$T_c = T_a + G\frac{NOCT - 20}{80}$$

rearranging it:

$$\therefore NOCT = \frac{80}{G}(T_c - T_a) + 20$$

and performing the calculation.

$$T_c = 60°C$$
$$T_a = 30°C$$
$$G = 980\frac{W}{m^2} = 98\frac{mW}{cm^2}$$

$$NOCT = \frac{80}{98\frac{mW}{cm^2}}(60°C - 30°C) + 20$$
$$= 44.5°C$$

Ex: Determination of PV Cell Temperature from NOCT and solar irradiance a solar module is installed in Mosul-Iraq, where the average daytime ambient temperature is 35◦C in June, July, and August. What is the average temperature of the PV cell when the irradiance is 80 mW/cm^2, and the NOCT is 46 °C?

- Ambient temperature, $T_{ambient} = 35\,°C$,
- Irradiance, $S = 80\,mW/cm^2$.

$$T_{solarcell} = 35 + \frac{46-20}{80} \times 80 = 61\,°C.$$

So, the operating temperature of the solar cell is greater than the ambient temperature by 61 − 35 = 26 °C while the PV module is installed on an open backside mounting system.

Ex: A 200-W c-Si PV module has NOCT = 45°C and a temperature coefficient for rated power of -0.5%/°C.

a. At 1-sun of irradiation while the ambient is 25°C, estimate the cell temperature and output power.

SOLN: Using (5.23),

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20°}{0.8}\right) \cdot S = 25 + \left(\frac{45-20}{0.8}\right) \cdot 1 = 56.25°C$$

$$P_{max} = 200W\left[1\text{-}0.5\%/°C(56.25\text{-}25)°C\right] = 168.8\ W \quad \text{... a drop of } 15.6\%$$

b. Suppose the module is rigged with a heat exchanger that can cool the module while simultaneously providing solar water heating. How much power would be delivered if the module temperature is now 35°C? What % improvement is that?

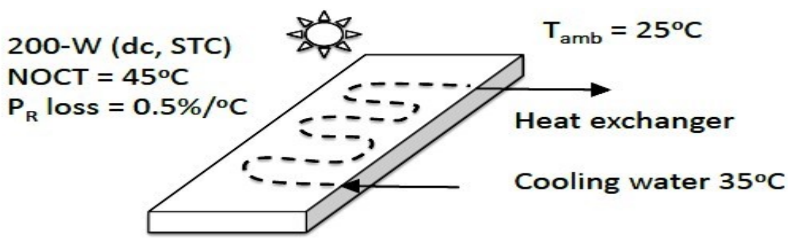


Figure P 5.9

SOLN:

$$P_{max} = 200W\left[1\text{-}0.5\%/°C(35\text{-}25)°C\right] = 190\ W$$

$$\text{Improvement} = \frac{190 - 168.8}{168.8} = 12.56\%$$

H.W: A 1.0 m^2 solar PV module made of silicon is operating at a cell temperature of 38°C and receiving solar irradiance of 900 W/m^2. The short circuit current and reverse saturation current were measured to be 200A & $1.8\text{x}10^{-8}$A, respectively. Estimate

a) The open-circuit voltage. ***Voc*** = **0.647V**

b) The voltage at maximum power point. ***Vmax*** = **0.5385V**

c) The current at maximum power point. ***Imax* = 190.5A**

d) The maximum power generated by the PV module. ***Pmax*** = **102.6W**

e) The maximum efficiency. **0.114 (11.4%)**

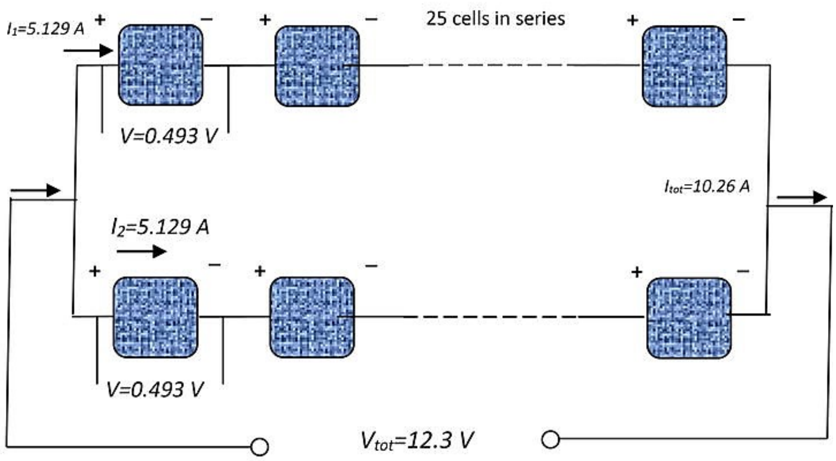
f) The power fill factor. **0.793 (79.3%)**

Ex: Design an arrangement of PV cells to provide an output of 12V & a power of 120W. The maximum power current and voltage per cell are 5.13A & 0.493V, respectively.

P_{max} =5.13 × 0.493 = **2.529W/cell**

The number of PV cells =1202.529 ≈ **48 cells**

The number of PV cells =120.493≈ **25cells**



Two rows in parallel each row has 25 cells in series, total 50 cells with total power = 126.5 *W*

H.W: Consider a stand-alone PV system where it is needed to store and retrieve 10 kWh/day for 4 days with a depth of discharge of 50%. A single battery bank has a charge capacity of 1275Ah. The voltage across the battery terminals is 12V. Estimate how many battery sets would be required to meet the storage specifications. Show the configuration of the battery connection to the PV system.

The total storage = 10 kWh/day × 4 days = 40 *kWh*.

Total energy stored =4050%=80kWh

The energy stored =12V×1275Ah=15.3kWh

The number of batteries =8015.3=5.2≈ 6 battery.

Ex**:** Consider a stand-alone PV system where it is needed to store and retrieve 10 kWh/day for 4 days with a depth of discharge of 50%. A single battery bank has a charge capacity of 1275 Ah. The voltage across the battery terminals is 12 V. Estimate how many battery sets would be required to meet the storage specifications. Show the configuration of the battery connection to the PV system.

Sol: The total storage = 10 kWh/day × 4 days = 40 *kWh.*
total energy stored = 4050% = 80kWh
The energy stored in a single battery set is calculated using
one set=12V×1275Ah=15.3kWh. The number of batteries = 8015.3 =5.2 ≈ 6.

Ex: The 36 cell PV module described has a parallel resistance per cell of Rp is 6.6Ω, and series resistance Rs = 0.005Ω. Under full sun, and under some load, the current is 2.14A and the output voltage is 19.41V. If one cell is fully shaded and this current somehow stays the same, then

- What would be the new module output voltage and power?
- What would be the voltage drop across the shaded cell?
- How much power would be dissipated in the shaded cell?

Sol: Voltage drop = 14.66 V, new voltage = 4.75 V (compared to 19.41 V)
New power = 10.1W (compared to 41.5 W).
Voltage drops across shaded cell = 14.14 V.
Power dissipated in the shaded cell = 30.2W. this will likely cause permanent damage to the cell due to excessive heat

H.W:

If for a PV module operating at NOCT conditions, the cell temperature is 42°C, determine the cell temperature when this module operates at a location where $G_t = 683\ W/m^2$, V = 1 m/s, and 41°C and the module is operating at its maximum power point with an efficiency of 9.5%.

$$T_c = \left(T_{NOCT} - T_{a,NOCT} \right) \left[\frac{G_t}{G_{t,NOCT}} \right] \left[1 - \frac{\eta_e}{(\tau\alpha)} \right] + T_a$$

$$= (42 - 20) \left[\frac{683}{800} \right] \left(1 - \frac{0.095}{0.9} \right) + 41$$

Using empirical

$$T_c = 30 + 0.0175(G_t - 300) + 1.14(T_a - 25)$$

$$T_c = 30 + 0.0175(683 - 300) + 1.14(41 - 25) = 54.9\,^{\circ}C$$

PV Solar Panels Connection:

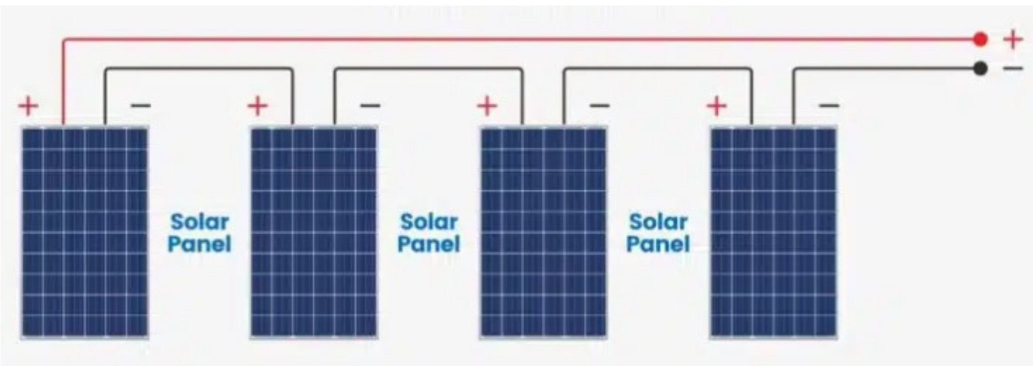
Sometimes, the power requirement is more than the power that a single solar PV panel can produce. For increasing the power generation, panels are connected in any one of the three ways:

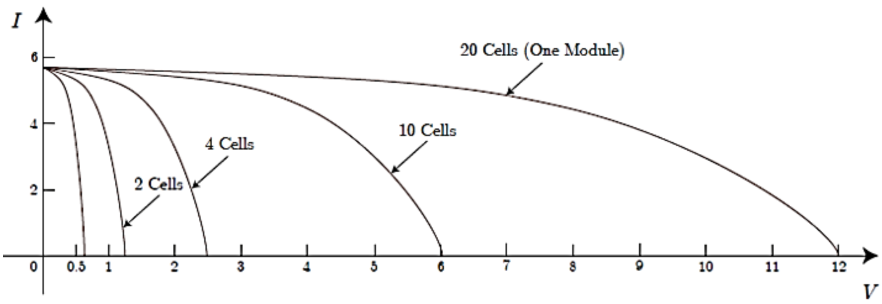
- Series connections
- Parallel connections
- Series-parallel connections

- **Series-Connected Panels**

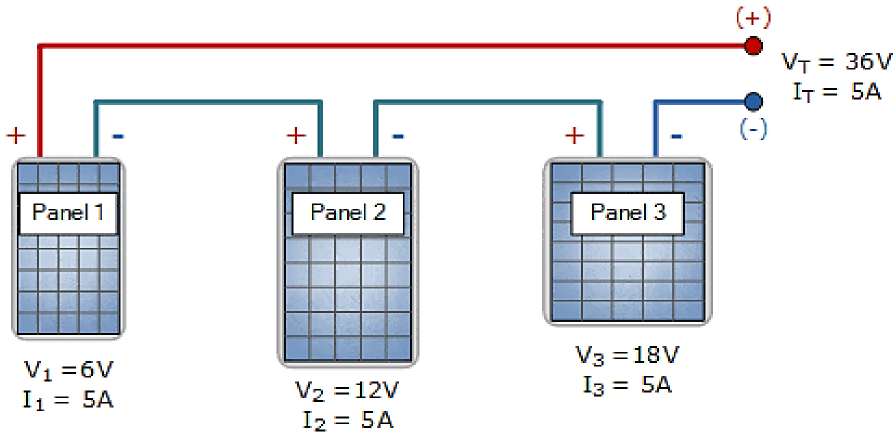
Series connection of photovoltaic devices. A photovoltaic device could be a cell, module, panel, or an array. Photovoltaic devices are connected in series to increase the voltage Two similar photovoltaic devices connected in series The voltage V across two similar series-connected PV devices, A and B, is equal to the sum of the individual device voltages, $V=V_A+V_B$.

The current I, through the two similar series-connected PV devices is equal to the current through either of the individual devices $I=I_A=I_B$.





VT = V(series) = V1 + V2 +V3 = 12+12+12= 36V
IT = I(series) = I1 = I2 = I3 = 5A



VT = V(series) = V1 + V2 +V3 = 6 + 12 + 18 = 36V
IT = I(series) = I1 = I2 = I3 = 5A

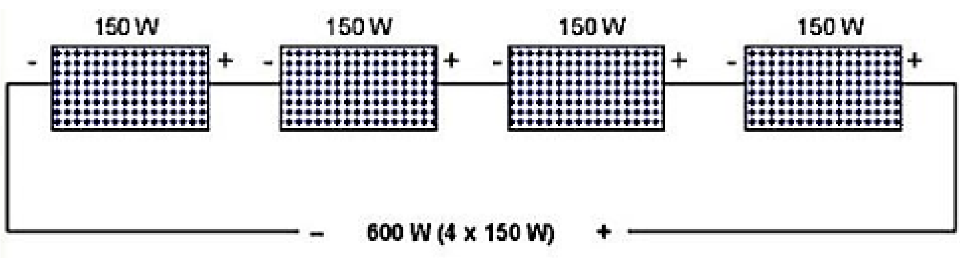
القدرة الكلية يتم حسابها ببساطة عن طريق الجمع الجبري لقدرة كل لوح شمسي، حيث أن جميعها • لها نفس القدرة، كالتالي

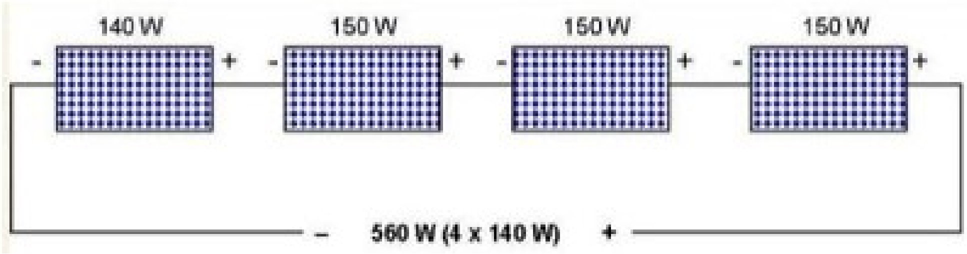
Total power = 150 + 150 +150 + 150 = 600W

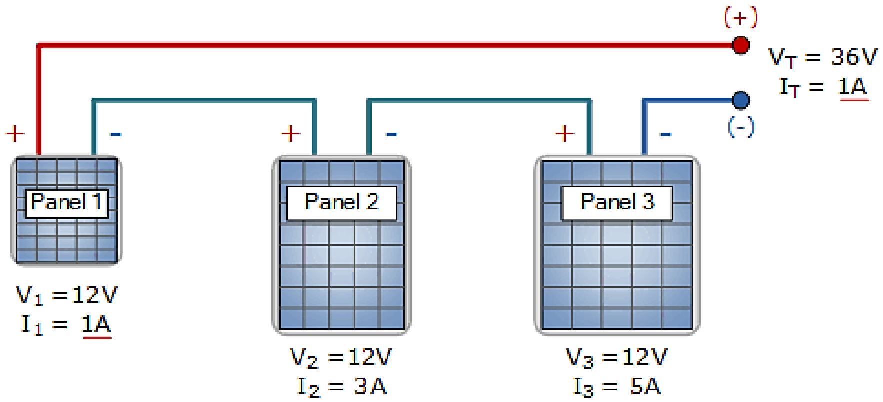
اما في حالة اختلاف القدرة للألواح الشمسية فيتم الحساب على أقل قدره فيهم:

Tot.= 140 x 4 = 560W

هنا يتضح لماذا يفضل عدم توصيل ألواح شمسية ذات مواصفات مختلفة





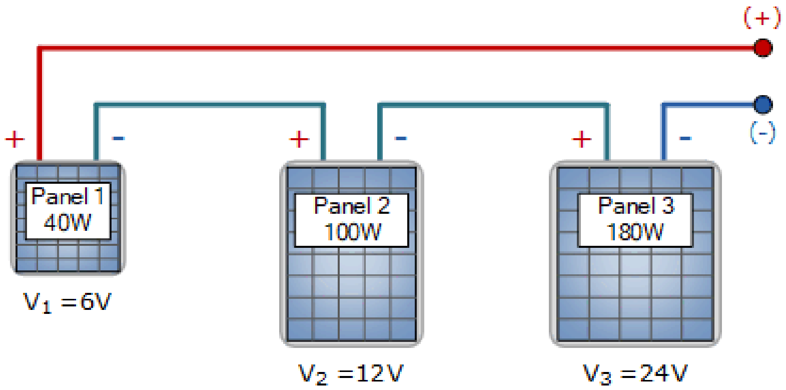


$$P_1 = V_1 \times I_1 = 12 \times 1 = 12 \text{ Watts}$$

$$P_2 = V_2 \times I_2 = 12 \times 3 = 36 \text{ Watts}$$

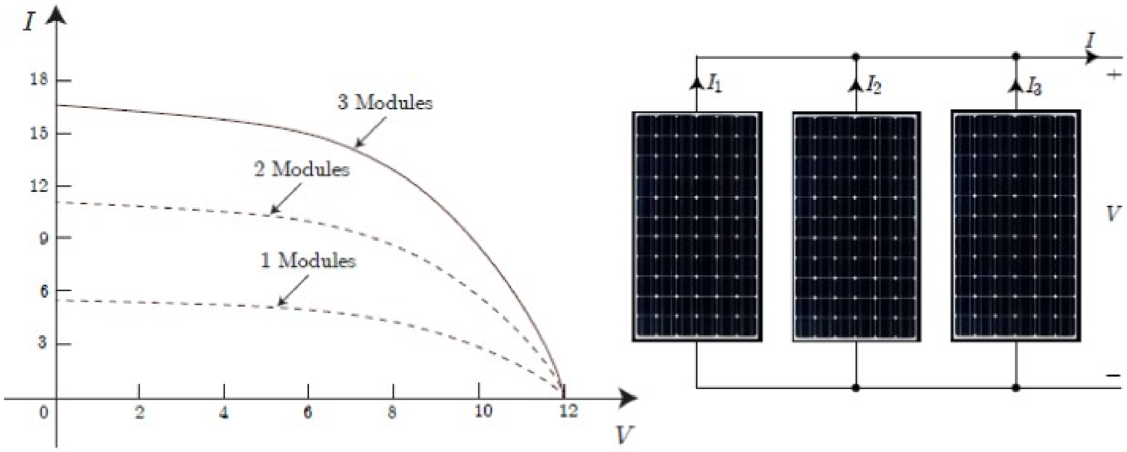
$$P_3 = V_3 \times I_3 = 12 \times 5 = 60 \text{ Watts}$$

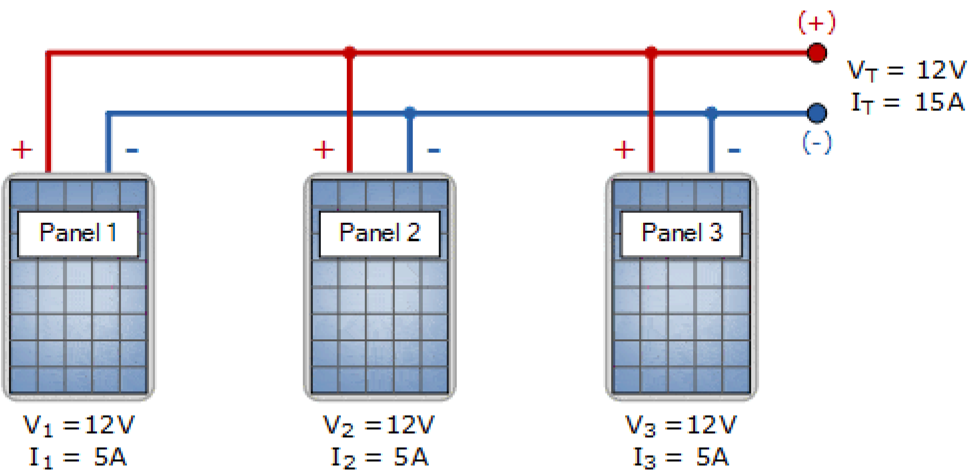
$$P_T = P_1 + P_2 + P_3 = 12 + 36 + 60 = 108 \text{ Watts}$$



- **Parallel-Connected Panels**

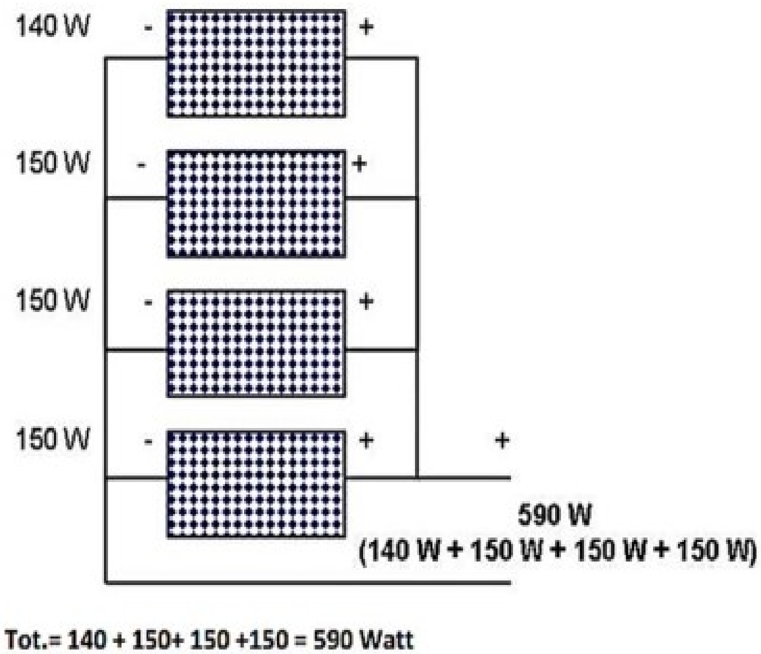
Connecting several modules in parallel creates a panel (array) and results in higher current levels, while the voltage capability of the panel will be the same as a single module.





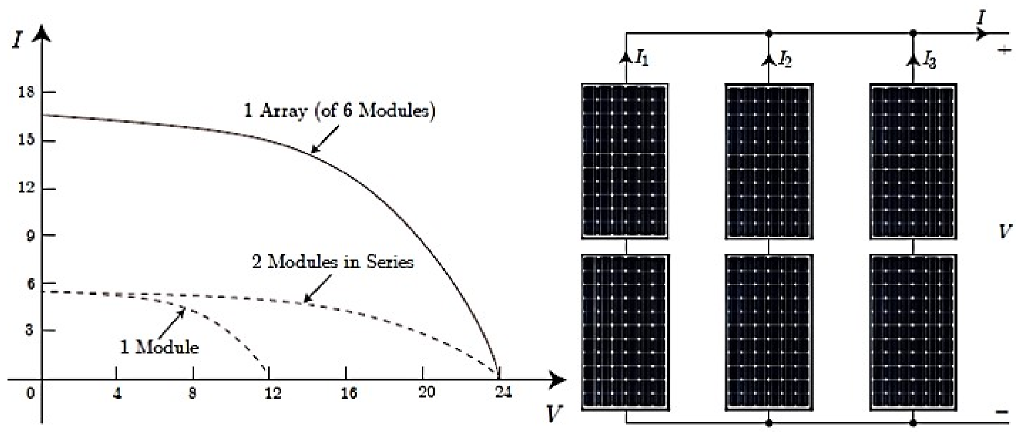
$$I_T = I_{(parallel)} = I_1 + I_2 + I_3 = 5 + 5 + 5 = 15\,\text{Amperes}$$

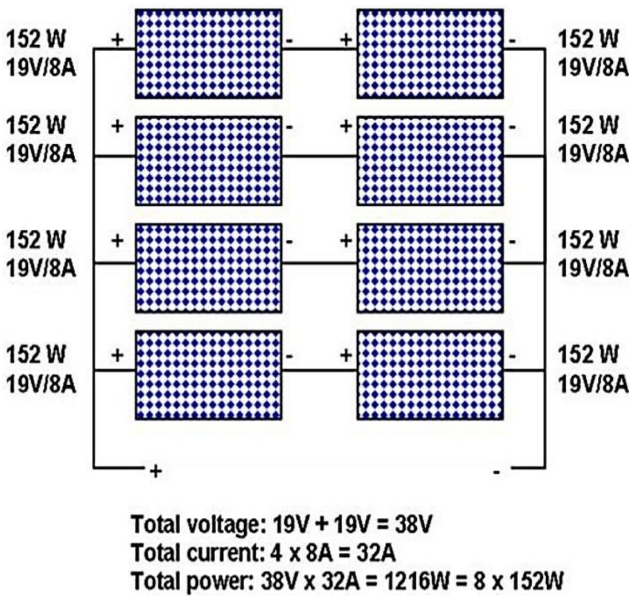
$$V_T = V_{(parallel)} = V_1 = V_2 = V_3 = 12\,\text{Volts}$$

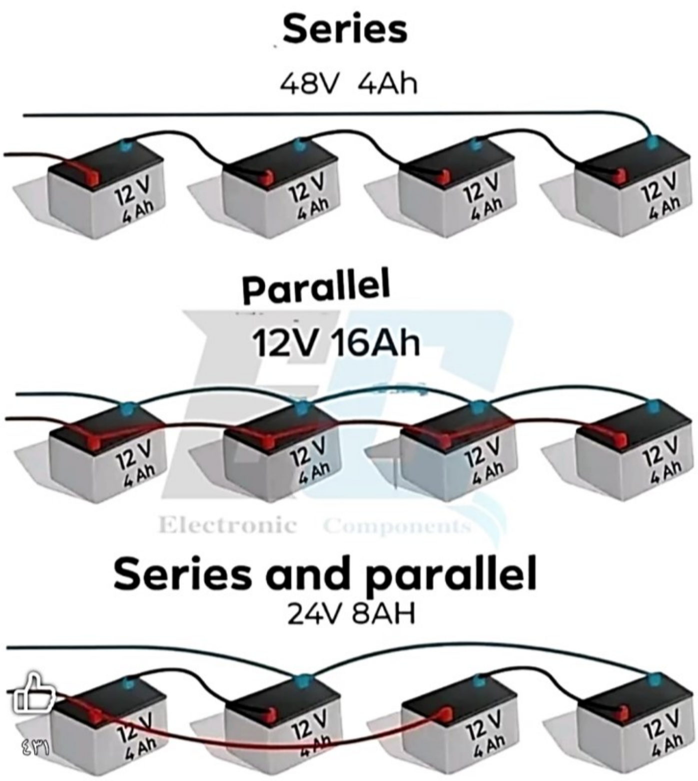


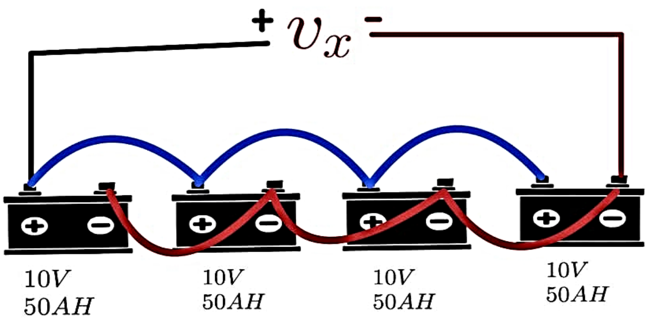
- **Series-parallel connections**:

To further increase the voltage and current levels, we may connect more modules in series and in parallel and form solar arrays.

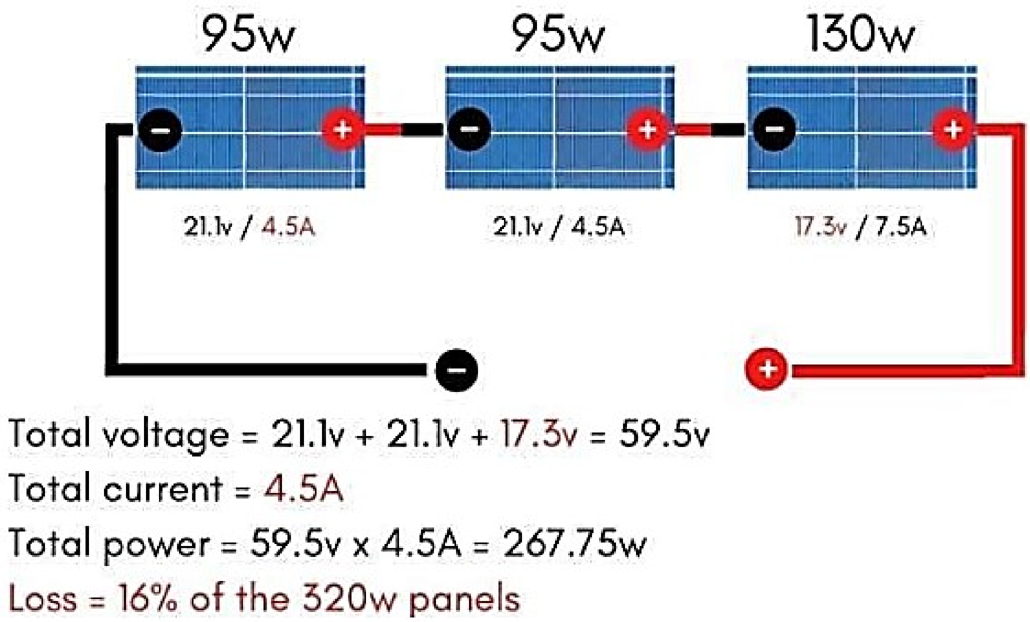



152 W
19V/8A
Total voltage: 19V + 19V = 38V
Total current: 4 x 8A = 32A
Total power: 38V x 32A = 1216W = 8 x 152W


Series
48V 4Ah
Parallel
12V 16Ah
Series and parallel
24V 8AH
12 V
4 Ah


+ v_x -
10V
50AH

$$v_x = ?$$



Example 1

A solar cell gives a current of 0.6 A and voltage of 0.5 V at maximum power point. What is the maximum power point of the solar cell?

Solution

First, we write formula for the maximum power point of a solar cell, given by

$$P_m \text{ or } P_{max} = I_m \times V_m$$

Given that, $I_m = 0.6$ A

$$V_m = 0.5 \text{ V}$$

Therefore, the maximum power point, $P_m = 0.6 \text{ A} \times 0.5 \text{ V} = 0.3 \text{ W}$

Example 2

A solar cell having an area of 100 cm^2 gives 3.1 A current at maximum power point and 0.5 V at maximum power point at STC. The cell gives 3.5 A short circuit current and 0.6 V open circuit voltage. What is the maximum power point of the solar cell? Also, find out the efficiency of the cell.

Sol:

We know, P_m = 1.55 W and at STC, P_{in} = 1000 W/m^2

First, we convert the unit of area from square centimetre (cm^2) to square metre (m^2) by dividing area in cm^2 by 10000.

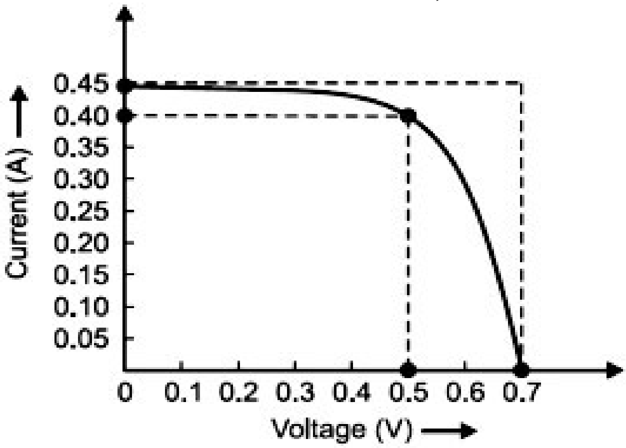
Here, $A = 100 \text{ cm}^2 = 100 \times 10^{-4} \text{ m}^2 = 0.01 \text{ m}^2$

Now, putting the number we can calculate the efficiency of the cell.

$$\eta = \frac{P_{max}}{P_{in} \times A} = \frac{1.55 \text{ watt}}{1000 \text{ W/m}^2 \times 0.01 \text{ m}^2} \times 100 = 15.5\%$$

Thus, efficiency of the solar cell is 15.5%.

Ex: From an **I-V** curve of a solar cell, all solar cell parameters can be derived. Find FF.



Short cir

Open circuit voltage (V_{oc}) = 0.7 V

Current at maximum power point (I_m) = 0.40 A

Voltage at maximum power point (V_m) = 0.5 V

Now,

$$\text{Maximum power point, } P_m \text{ or } P_{max} = I_m \times V_m = 0.40 \times 0.5 = 0.2 \text{ W}$$

$$\text{Fill Factor, FF} = \frac{I_m \times V_m}{I_{sc} \times V_{oc}}$$

or

$$\text{FF} = \frac{P_m}{I_{sc} \times V_{oc}} = \frac{0.2}{0.45 \times 0.7} \times 100 = 63.49\%$$

Note: In order to represent the FF value in 'percentage', multiply by 100.

Example

Determine the parameters of a module formed by 34 solar cells in series, under the operating conditions G=700 W/m^2, and T_a=34ºC. The manufacturers values under standard conditions are: I_{sc} = 3A; V_{oc} = 20.4V; P_{max} = 45.9 W; NOCT = 43ºC.

Solution

1. Short-circuit current

   I_{sc} (700 W/m^2) =3 x 0.7 = 2.1 A.

2. Solar cell temperature
   T_c = 34 + 0.7 x (43-20)/80 = 54.12ºC

3. Open-circuit voltage
   V_{oc} (54.12ºC) = 20.4 – 0.0023 x 34 x (54.12 – 25) = 18.1 V

4. Maximum power point
   FF= 45.9/ (3 x 20.4) = 0.75
   P_{max} (G, T_c) = 2.1 x 18.1 x 0.75 = 28.5 W

Thus, noting the manufacturers value of Pmax we see that the module will operate at about 62% of its nominal rating.

Example 7

A solar cell has maximum power point of 0.3 W. The cell voltage at maximum power point at STC is 0.65 V. What is the current at maximum power point of the solar cell?

Solution

Given that,

$P_m = 0.3$ W

$I_m = ?$

$V_m = 0.65$ V

First, we write the formula for maximum power point P_m or P_{max} of a solar cell given by

$$\text{Maximum power point } (P_m) = I_m \times V_m$$

where,

P_m = Maximum power point (W)

I_m = Current at maximum power point (A)

V_m = Open circuit voltage (V)

Now, we rewrite formula for maximum power point P_m of a solar cell to get the value of I_m given by expression below.

$$\text{Current at maximum power point, } I_m = \frac{P_m}{V_m}$$

Putting the value, we can calculate the current at maximum power point.

$$I_m = \frac{P_m}{V_m} = \frac{0.3}{0.65} = 0.46 \text{ A}$$

Thus, the current at maximum power point is 0.46 A.

Example : A solar cell (0.9 cm^2) receives solar radiation with photons of 1..8 eV energy having an intensity of 0.9 mW/cm^2. Measurements show open-circuit voltage of 0.6 V/cm^2, short-circuit current of 10 mA,/cm^2, and the maximum current ts 50% of the short-circuit current. The efficiency of cell is 25%. Calculate the maximum voltage that the cel1 can give and find the fill factor.

Types of solar PV systems:

A solar PV system can be of several types depending on the way the energy is generated and used. Broadly, PV system is divided in three categories.

1. **Stand-alone solar PV systems.**
2. **Grid-connected solar PV system.**
3. **Hybrid solar PV system.**

1. Stand-alone PV systems (Off-Grid system):

- These systems are self-sufficient in themselves they do not depend on any other source of energy to supply electricity to planned appliances or load.
- The example of standalone solar PV systems includes a solar lantern, a solar PV home lighting system, a solar PV water pumping system.
- They invariably use means to store energy, typically in the form of batteries.
- Because batteries are used, it is important to use to protect electronics. Also, for conversion of DC electricity from PV modules and from battery, inverter will have to be used.
- A standalone PV system stores energy in batteries for night time application when there is no sunlight.

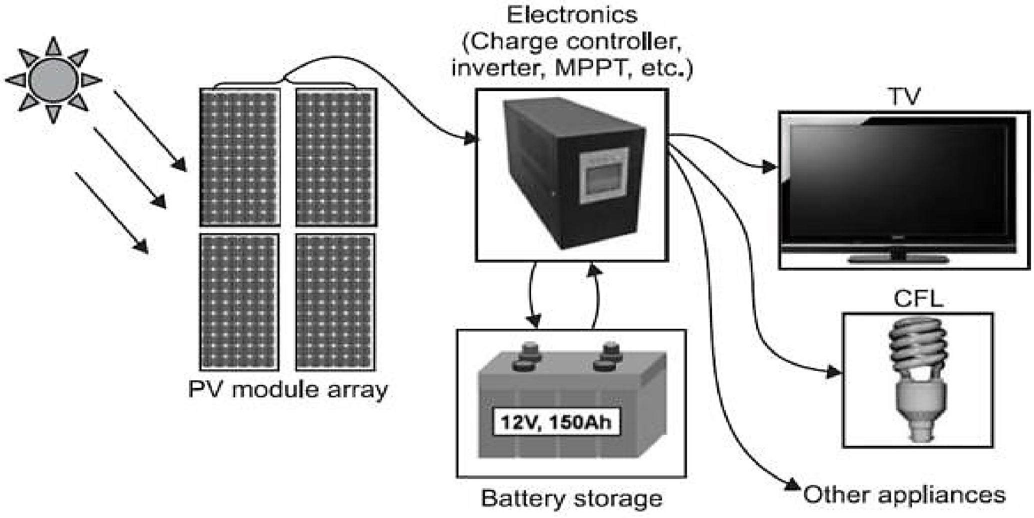


Fig.7. Stand-alone solar PV system

2. Grid-connected solar PV systems:

- A grid-connected solar PV system is connected with nearby available electricity grid.
- The generated electricity is feed into the grid no battery storage is used in this case. But conversion of DC electricity generated by solar PV modules into AC electricity is required before feeding to the grid.
- This type of PV system configuration is used in India for large scale (MW level) solar PV power plants.
- Electricity grid voltage and frequency are well defined and, therefore, the PV electricity can be fed to electricity grid only after proper power conditioning, converting PV generated electricity to appropriate voltage and frequency level.
- Grid-connected solar PV system, the inverter not only performs the function of DC to AC conversion but also performs the function of grid synchronization which is related to bringing generated PV energy to appropriate voltage and frequency level.
- A grid connected PV system does not store energy in battery; it takes energy from the grid when there is no sunlight.

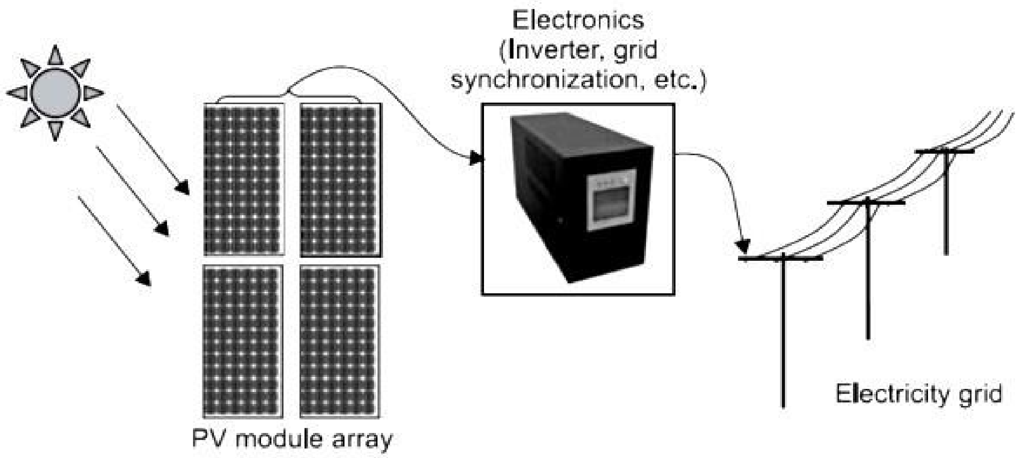


Fig 8. Grid connected solar PV system.

3. Hybrid solar PV system:

- In some cases, an auxiliary source of energy like diesel generator is used in addition to solar PV modules and/or grid.
- This need to be done when solar PV modules are not designed to supply the full required energy by the load (may be due to cost reason). In such case of use of auxiliary source, a solar PV system is called hybrid solar PV system, shown figure below.

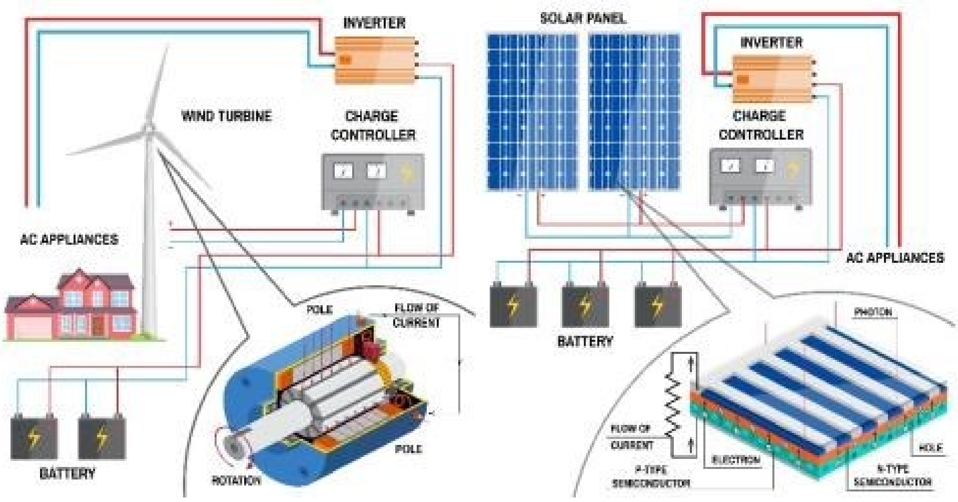


Fig. 9. Hybrid solar PV.

Blocking Diode and Bypass Diode of solar:

Shading is a problem in PV modules since shading just one cell in the module can reduce the power output to zero.

1. Shading one cell reduces the output of the whole string of cells or modules.
2. Excess power from the unshaded cells is dissipated in the shaded cell.
3. Bypass diodes isolate the shaded cell.

Shading of a single cell the output of a cell declines when shaded by a tree branch, building or module dust. The output declines proportionally to the amount of shading. For completely opaque objects such as a leaf, the decline in current output of the cell is proportional to the amount of the cell that is obscured.

Physics of shading

- The voltage of the module with one shaded cell:

$$V_{SH} = V_{n-1} - I(R_P + R_S)$$

$$V_{SH} = \left(\frac{n-1}{n}\right) V - I(R_P + R_S)$$

- The drop-in voltage caused by the shaded cell:

$$\Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right) V + I(R_P + R_S)$$

$$\Delta V = \frac{V}{n} + I(R_P + R_S)$$

$$\Delta V \cong \frac{V}{n} + I R_P$$

Ex: The 36-cell PV module described has a shunt (parallel) resistance per cell of Rsh = 6.6 Ω, and series resistance RS = 0.005 Ω. Under full sun, and under some load, the current I = 2.14 The output voltage V = 19.41 V. If one cell is fully shaded and this current somehow stays the same, then – What would be the new module output voltage and power?

– Find the voltage drop across the shaded cell?
– How much power would be dissipated in the shaded cell?

Ans:

- *(a) voltage drop = 14.66 V, new voltage = 4.75 V (compared to 19.41 V), new power = 10.1 W (compared to 41.5 W),*
- *(b) voltage drop across shaded cell = 14.14 V,*
- *(c) power dissipated in the shaded cell = 30.2 W – this will likely cause permanent damage to the cell due to excessive heat!*

A diode is a specialized electronic component with two terminals known as the anode and the cathode. It has asymmetric conductance, which means that it conducts mainly in one direction. It has very less resistance, ideally zero, to the flow of current in one direction whereas it has high resistance, ideally infinite, in the other direction. Diodes are usually made up of semiconductor materials such as germanium, silicon or selenium. Diodes may have same characteristics, but their functionalities depend on the way they are used. The diodes which play important roles in the functioning of solar panels are:

1. Blocking diode. **2. By-Pass diode.**

1. Blocking diode:

The following diagram shows a simple setup, with two panels wired in series charging a battery (for simplicity no controller is shown) and a blocking diode connected in series with the two panels:

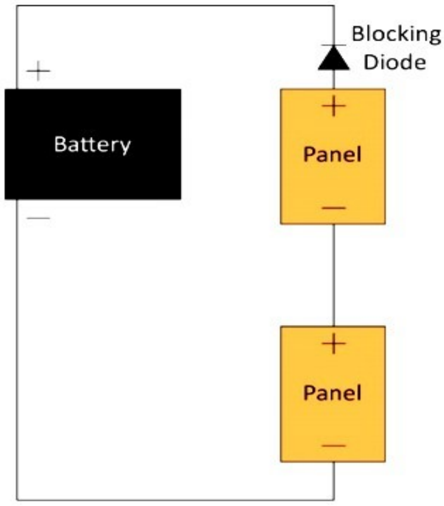


Fig. 11. Blocking diode

During sunshine hours, battery is charged as long as the voltage generated by the two solar panels is greater than the specified voltage of the battery. However, in the absence of sunshine, while no voltage is being generated by the panels, a flow of current is caused through the panels by the voltage of the battery in the opposite direction. This would result in the discharge of the battery, if there is no blocking diode in the circuit. Blocking diodes are useful for a system that uses solar panels for charging the battery. They are generally used in the construction of solar panels.

2. By-Pass Diodes

If one of the solar panels in the preceding diagram is shaded, the panel will not be able to produce significant power and it will also possess a high resistance which will block the flow of power generated by the un-shaded panel. The following diagram shows working of by-pass diodes:

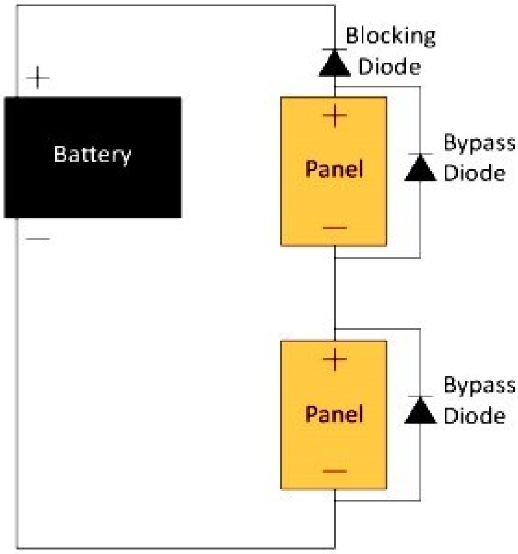


Fig. 10. By-pass diode

In this case, when one panel is shaded, the current generated by the un-shaded panel will flow through the by-pass diode so that it can avoid the high resistance of the shaded panel. If the panels are not connected in series that will allow production of high voltage, by-pass diodes will not be of any use. They are most efficient whereas string inverter or a maximum power point tracking (MPPT) controller involves series connected panels for producing voltages that are greater than the minimum input voltage. Some solar panels are formed with cells grouped together, each group consisting of a built-in by-pass diode. Shading of a panel may be caused by a branch of a tree, debris or snow.