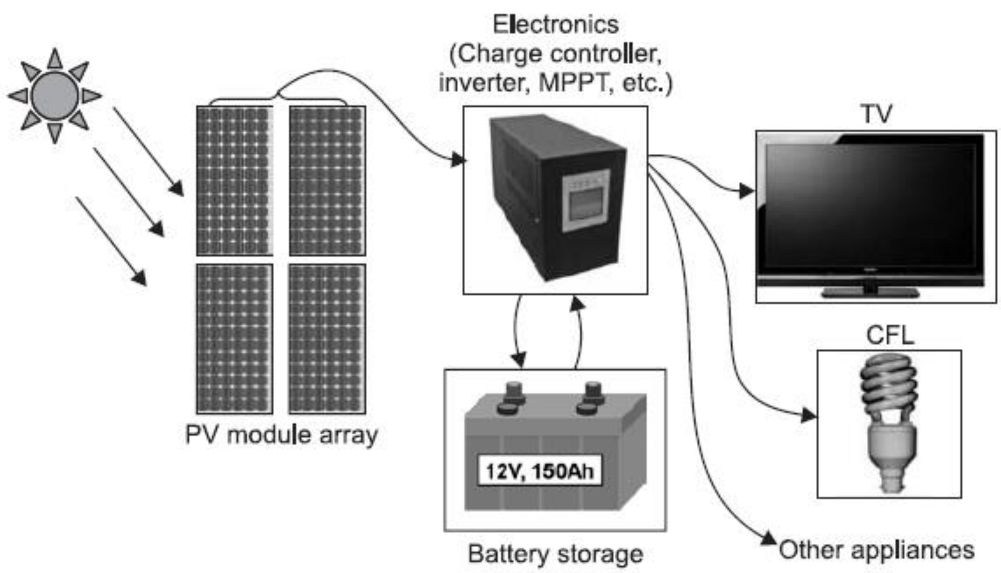
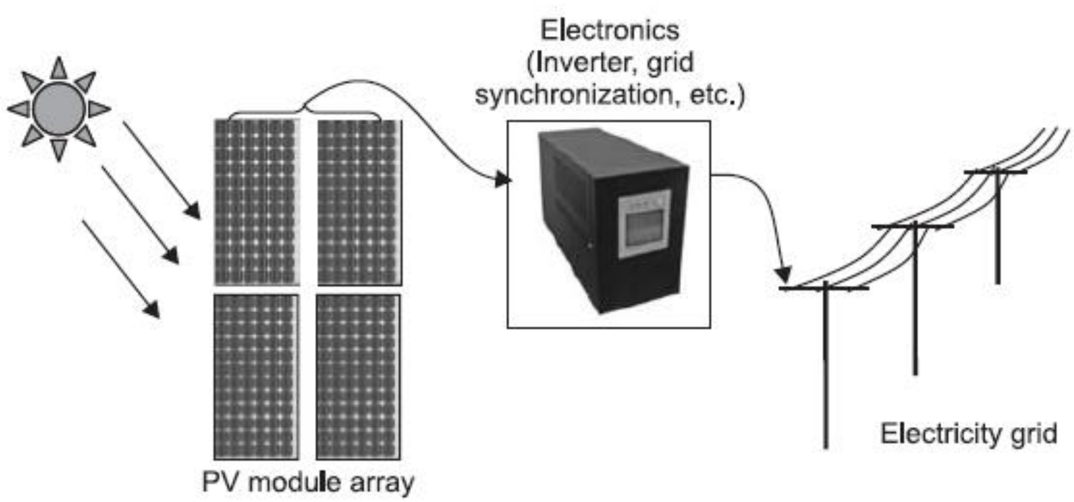
Stand alone system :



Grid connected system:



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 systems is called '**hybrid solar PV system**'.

Advantages of PV:

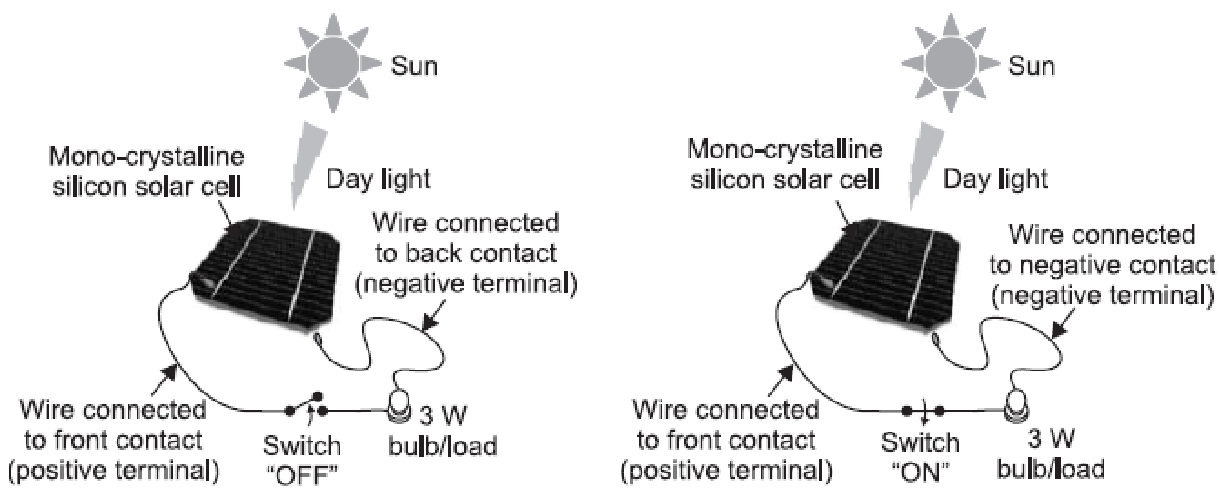
- Abundant source: Like fossil fuels the solar radiations never become deplete.
- Environmentally benign.
- Decentralized electricity generation.
- Modular implementation.

Dis adv

- PV electricity cost.
- Energy fluctuation.
- Location dependency.

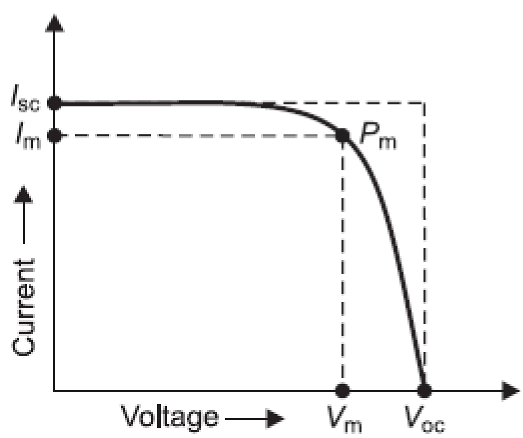
What is a Solar Cell?

A solar cell converts sunlight into electricity directly, without any intermediate conversion steps.



Working of solar cell:

1. Photons in the sunlight falling on the solar cell's front face are absorbed by semiconducting materials.
2. 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). Electric potential is built at the terminals due to the separation of negative and positive charges. Due to the difference between the electric potentials at the terminals we get voltage across the terminals.
3. 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.



- *Short circuit current* (I_{sc}): It is the maximum current a solar cell can produce. The higher the I_{sc}, better is the cell. It is measured in Ampere (A) or milli-ampere (mA). The value of this maximum current depends on cell technology, cell area, amount of solar radiation falling on cell, angle of cell, etc. Many times, people are given current density rather than current. The current density is obtained by dividing I_{sc} by the area of solar cell (A). The current density is normally referred by symbol, 'J', therefore, the short circuit current density, J_{sc} is given by I_{sc}/A.
- *Open circuit voltage* (V_{oc}): It is the maximum voltage that a solar cell produce. The higher the V_{oc}, the better is the cell. It is measured in volts (V) or sometimes milli-volts (mV). The value of this maximum open circuit voltage mainly depends on cell technology and operating temperature.
- *Maximum power point* (P_m or P_{max}): It is the maximum power that a solar cell produces under STC. The higher the P_m, the better is the cell. It is given in terms of watt (W). Since it is maximum power or peak power, it is sometimes also referred as W_{peak} or W_p. A solar cell can operate at many current and voltage combinations. But a solar cell will produce maximum power only when operating at certain current and voltage. This maximum power point is denoted in Figure 3.4 as P_m. Normally, the maximum power point for a *I-V* curve of solar cells occurs at the 'knee' or 'bend' of the curve. In terms of expression P_m is given as:

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

- *Current at maximum power point* (I_m)*:* This is the current which solar cell will produce when operating at maximum power point. The I_m will always be lower than I_{sc}. It is given in terms of ampere (A) or milli-ampere (mA).
- *Voltage at maximum power point* (V_m)*:* This is the voltage which solar cell will produce when operating at maximum power point. The V_m will always be lower than V_{oc}. It is given in terms of volt (V) or milli-volt (mV).
- *Fill factor* (FF)*:* As the name suggests, FF is the ratio of the areas covered by I_m-V_m rectangle with the area covered by I_{sc}-V_{oc} rectangle (both shown by dotted line in Figure 3.4), whose equation is given below. It indicates the square-ness of *I-V* curve. The higher the FF, the better is the cell. The FF of a cell is given in terms of percentage (%). Cell with squarer *I-V* curve is a better cell.

$$\mathrm{FF} = \frac{I_m \times V_m}{I_{sc} \times V_{oc}}$$

or

$$\mathrm{FF} = \frac{P_m}{I_{sc} \times V_{oc}}$$

Here the expression for P_{max} or P_m can alternatively be written in terms of I_{sc}, V_{oc} and FF as:

$$P_m = I_{sc} \times V_{oc} \times \mathrm{FF}$$

- Efficiency (η): The efficiency of a solar cell is defined as the maximum output power (P_m or P_{max}) divided by the input power (P_{in}). The efficiency of a cell is given in terms of percentage (%), which means that this percentage of radiation input power is converted into electrical power. P_{in} for STC is considered as 1000 W/m^2. This input power is power density (power divided by area), therefore, in order to calculate the efficiency using P_{in} at STC, we must multiply by solar cell area. Thus, efficiency can be written as:

$$\eta = \frac{P_m}{P_{in}} = \frac{I_{sc} \times V_{oc} \times \mathrm{FF}}{P_{in} \times A}$$

Let us now see what the possible values of solar cell parameters and how the values that depend on the various solar cell technologies.

Q1.

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.

First, we write the 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,

$I_{sc} = 3.5$ A
$I_m = 3.1$ A
$V_{oc} = 0.6$ V
$V_m = 0.5$ V

Maximum power point, $P_m = 3.1 \text{ A} \times 0.5 \text{ V} = 1.55 \text{ W}$

Now, we write the formula for efficiency of a solar cell given by

$$\eta = \frac{P_{max}}{P_{in} \times A}$$

where,

η = Efficiency in per cent (%)
P_{max} = Output power in watt (W)
P_{in} = Light input power per unit area in watt/square meter (W/m^2)
A = Solar cell area in square meter (m^2)
η = ?

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.

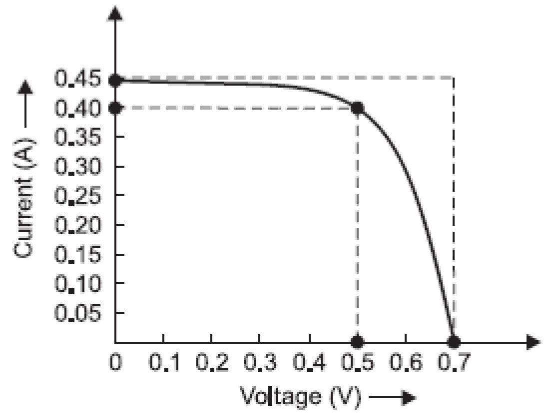
$$\eta = \frac{P_{max}}{P_{in} \times A} = \frac{1.55 \text{ watt}}{1000 \text{ W/m}^2 \times 0.01 \text{ m}^2} \times 100 = 15.5\%$$

cell, all derived.

Thus, efficiency of the solar cell is 15.5%.

Q2.

Refer the characteristic curve (Figure 3.5) and find out the Fill Factor for the solar cell.



Short circuit current (I_{sc}) = 0.45 A
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,

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

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

or

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

Q3.

A solar cell having an area of 25 cm^2 gives a current of 0.85 A and voltage 0.55 V at maximum power point. The short circuit current is 0.9 A and open circuit voltage is 0.65 V. What is the Fill Factor, maximum power point and efficiency of the solar cell? Consider STC.

Given, Short circuit current (I_{sc}) = 0.9 A
Open circuit voltage (V_{oc}) = 0.65 V
Current at max power point (I_m) = 0.85 A
Voltage at maximum power point (V_m) = 0.55 V
Light input power (W/m^2) = 1000 W/m^2

$$\text{Area} = A = 25\ \text{cm}^2 = 25 \times 10^{-4}\ \text{m}^2 = 0.0025\ \text{m}^2$$

Now,
Maximum power point, P_m or $P_{max} = I_m \times V_m = 0.85 \times 0.55 = 0.4675$ W

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

or

$$\text{FF} = \frac{P_m}{I_{sc} \times V_{oc}} = \frac{0.4675}{0.9 \times 0.65} \times 100 = 79.91\%$$

$$\text{Efficiency } (\eta) = \frac{P_{max}}{P_{in} \times A} = \frac{0.4675}{1000 \times 0.0025} \times 100 = 18.7\%$$

Q4.

A solar cell having Fill Factor (FF) 60% gives 2.5 A current at maximum power point at STC. The cell gives 3 A short circuit current and 0.5 V open circuit voltage. What is the voltage at maximum power point of the solar cell?

Given that,

$I_{sc} = 3$ A

$I_m = 2.5$ A

$V_{oc} = 0.5$ V

$V_m = ?$

FF = 60%

First, we write formula for Fill Factor of a solar cell given by

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

where,

I_{sc} = Short circuit current (A)

I_m = Current at maximum power point (A)

V_{oc} = Open circuit voltage (V)

V_m = Voltage at maximum power point (V)

FF = Fill Factor (%)

We know, FF = 60%

First, we convert Fill Factor (FF) from per cent to decimal by dividing it by 100.

Therefore,
$$\text{FF} = \frac{60}{100} = 0.6$$

Now, we rewrite the formula for Fill Factor of a solar cell to get the value of V_m given by expression below.

$$\text{Voltage at maximum power point, } V_m = \text{FF} \times \frac{I_{sc} \times V_{oc}}{I_m}$$

Now, putting the value, we can calculate the voltage at maximum power point.

$$V_m = \text{FF} \times \frac{I_{sc} \times V_{oc}}{I_m} = 0.6 \times \frac{3 \times 0.5}{2.5} = 0.36 \text{ V}$$

Thus, the voltage at maximum power point is 0.36 V.

Q5.

A solar cell having Fill Factor (FF) 68% gives 0.6 V voltage at maximum power point at STC. The cell gives 3 A short circuit current and 0.7 V open circuit voltage. What is the current at maximum power point of the solar cell?

Given that,

$I_{sc} = 3$ A
$I_m = ?$
$V_{oc} = 0.7$ V
$V_m = 0.6$ V
FF = 68%

First we write formula for Fill Factor of a solar cell given by expression below

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

where,

I_{sc} = Short circuit current (A)
I_m = Current at maximum power point (A)
V_{oc} = Open circuit voltage (V)
V_m = Voltage at maximum power point (V)
FF = Fill Factor (%)

We know, FF = 68%

First, we convert Fill Factor (FF) from per cent to decimal by dividing it by 100.

$$\text{FF} = \frac{68}{100} = 0.68$$

Now, we rewrite formula for Fill Factor of a solar cell to get the value of I_m given by expression below.

$$\text{Current at maximum power point, } I_m = \text{FF} \times \frac{I_{sc} \times V_{oc}}{V_m}$$

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

$$I_m = \text{FF} \times \frac{I_{sc} \times V_{oc}}{V_m} = 0.68 \times \frac{3 \times 0.7}{0.6} = 2.38 \text{ A}$$

Thus, current at maximum power point is 2.38 A.

Q6.

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?

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.

Solar photovoltaic technologies	*Solar cell type*	*Materials used*	*Efficiency (η in per cent)*
Crystalline Silicon (c-Si) solar cell	Mono-crystalline silicon	Mono-crystalline silicon	14–16
	Poly or multicrystalline Si (mc-Si)	Multi-crystalline silicon	14–16
Thin film solar cell	Amorphous Si (a-Si)	Amorphous silicon	6–9
	Cadmium telluride (CdTe)	Cadmium and tellurium	8–11
	Copper-Indium-Gallium-Selenide (CIGS)	Copper, Indium, Gallium, Selenium	8–11
Multi-junction solar cell	GaInP/GaAs/Ge Gallium indium phosphide/Gallium arsenide/ Germanium	Gallium (Ga), Arsenic (Ar), Indium (In), Phosphorus (P), Germanium (Ge)	30–35

There are many commercially available solar cell technologies. The name of technology comes from the materials used in making solar cells.

TABLE 3.6 Typical Solar Cell Parameters (η, J_{sc}, V_{oc} and FF) of Commercial Solar Cells with Available Cell Areas

Solar cell type	*Efficiency (η) (in %)*	*Cell area (A) (in cm^2)*	*Output voltage (V_{oc}) (in V)*	*Output current (J_{sc}) (in mA/cm^2)*	*Fill factor (FF) (in %)*
Mono-crystalline silicon	14–17	5–156	0.55–0.68 V	30–38	70–78
Poly or multi-crystalline Si (mc-Si)	14–16	5–156	0.55–0.65 V	30–35	70–76
Amorphous Si (a-Si)	6–9	5–200	0.70–1.1 V	8–15	60–70
Cadmium telluride (CdTe)	8–11	5–200	0.80–1.0 V	15–25	60–70
Copper-Indium-Gallium-Selenide (CIGS)	8–11	5–200	0.50–0.7 V	20–30	60–70
Gallium indium phosphide/Gallium arsenide/Germanium (GaInP/ GaAs/Ge)	30–35	1–4	1.0–2.5 V	15–35	70–85

There are five common factors that affect the power generated by solar cells. They are as follows:

1. The conversion efficiency (η),
2. The amount of light (P_{in}),
3. The solar cell area (A),
4. The angle at which day light falls (θ), and
5. The operating temperature (T)

Large amount of light falling means high generated power, less amount of light falling means low generated power.

Q7.

Calculate the output power for solar cells of efficiencies 16%. When the input power is say, 1000, 800, 600 and 400 W/m^2 and area of solar cell is 100 cm^2.

First we write formula for efficiency of a solar cell given by

$$\eta = \frac{P_{max}}{P_{in} \times A}$$

where,

η = Efficiency in per cent (%)

P_{max} = Output power in watt (W)

P_{in} = Light input power per unit area in watt/meter (W/m^2)

A = Solar cell area in square metre (m^2)

η = 16%

P_{in} = 1000, 800, 400 W/m^2

P_{max} = ?

It is given that cell efficiency is 16% and cell area is A = 100 cm^2.

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

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

Now, we solve for light input power = 1000 W/m^2

Above equation can be written as:

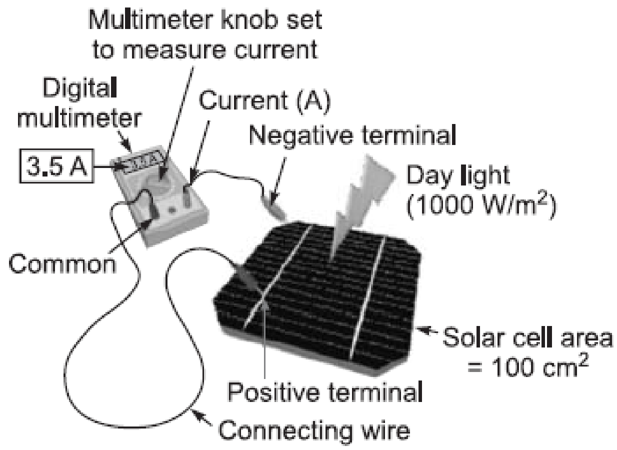
$$P_{max} = \eta \times P_{in} \times A$$

We put the respective terms values and we get,

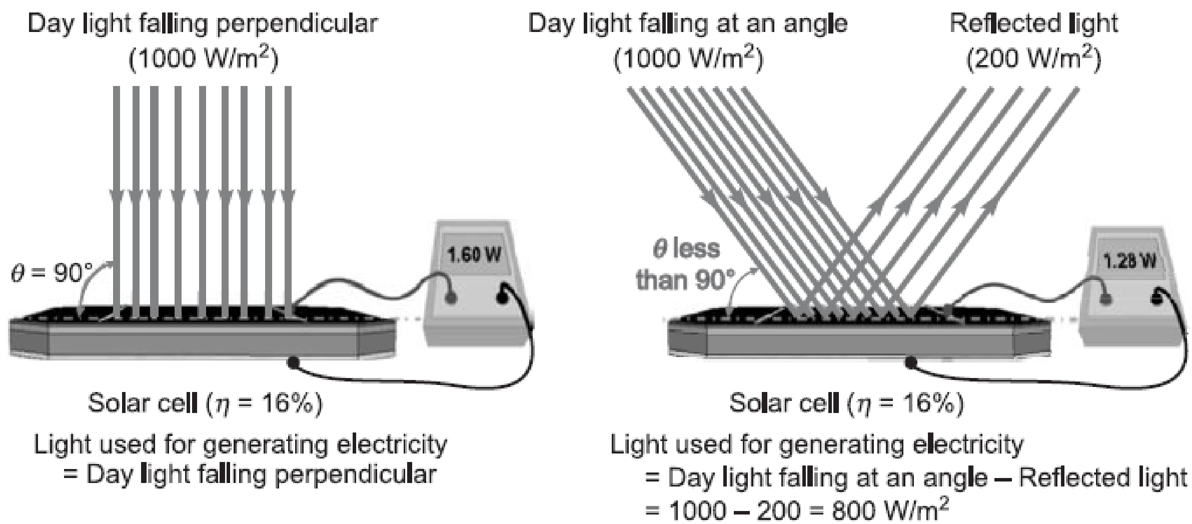
$$P_{max} = \left(\frac{16}{100}\right) \times 1000 \times 100 \times 10^{-4} = 1.6 \text{ W}$$

For other values of efficiency you can calculate in the same way.

For half of the area the current delivery will be half

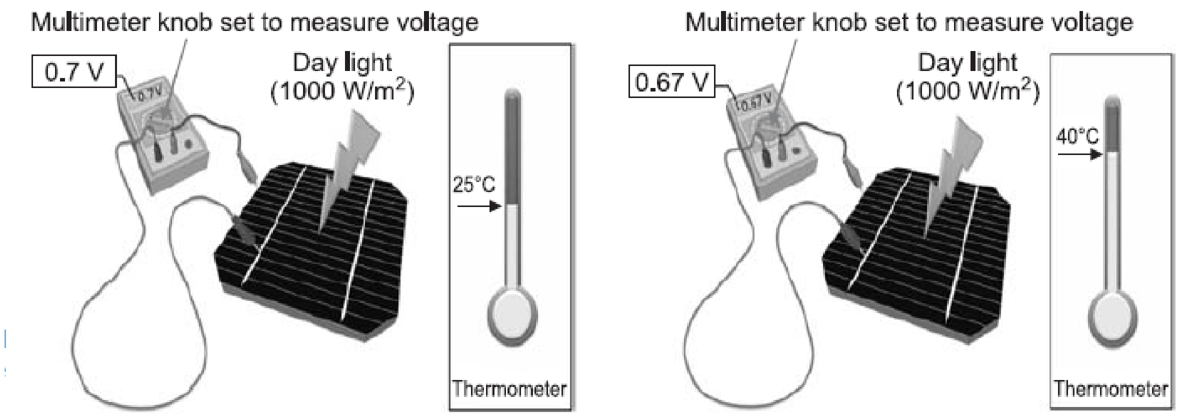


Light falling perpendicular to solar cell gives maximum output power.



Effect of temperature on solar cell:

Parameter of crystalline silicon solar cells	*Decrease per °C rise in cell temperature from standard test condition (STC) value of 25°C*
Voltage	–0.0023 V or –2.3 mV
Power	–0.45%
Efficiency	–0.45%



Q8.

If the actual operating temperature of the solar cell is 40 °C. The output voltage of a solar cell at standard operating temperature is, say 0.7 V. The output voltage decreases by 2.3 mV/°C. Calculate the new value of output voltage?

Let us consider, actual operating temperature = T_{actual} = 40 °C

Standard operating temperature = $T_{standard}$ = 25 °C

Output voltage decrease per degree Celsius = $V_{decrease}$ = 2.3 mV/°C

Output voltage at 25 °C = V_{oc} (25 °C) = 0.7 V

Output voltage at 40 °C = V_{oc} (40 °C) = ?

We know the solar cells output voltage reduces by some value when the temperature is above 25 °C.

So, the reduced output voltage = $V_{oc}(40\,°C) = V_{oc}(25\,°C) - (V_{decrease} \times \Delta T)$

$$\Delta T = T_{actual} - T_{standard}$$
$$= 40 - 25 = 15\,°C$$

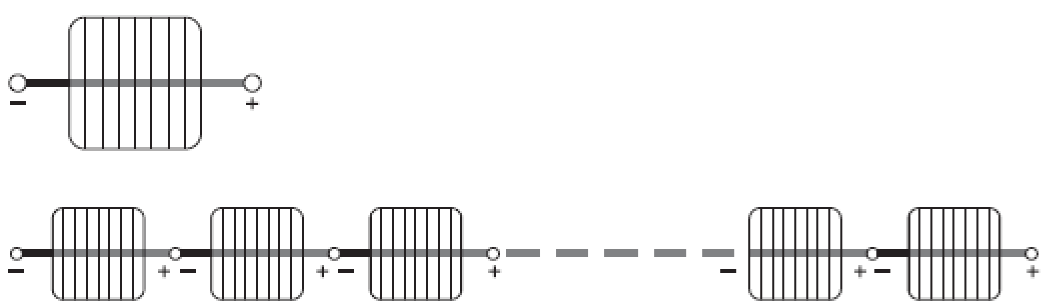
Now, $0.7\text{ V} - (2.3 \times 10^{-3}\text{ V/°C} \times 15\,°C) = 0.7\text{ V} - 0.0345\text{ V}$

$$= 0.67\text{ V}$$

So, from the above result, is clear that the solar cells output voltage decreases if operating temperature is above 25 °C. Figure 3.10 shows the change in the output voltage with the change in the operating temperature of a solar cell.

PV Module :

Many number of cells connected together to form a solar PV panel:



Test parameters	Values	Remarks
Solar input radiation	1000 W/m^2	This solar radiation is corresponding to the condition when solar radiation travels 1.5 times the thickness of the earth's atmosphere. Therefore, this radiation value is called Air Mass 1.5, and also referred as AM1.5 global solar radiation.
Temperature	25 °C	This is cell temperature in the PV modules and not the PV module surface temperature. Normally, cell's temperature in a PV module is much higher than PV module's surface temperature.
Wind speed	1 m/s	The flow of winds cools the PV module and that is why sometimes wind speed is also specified.

Q9.

A small PV module having an area of 0.094 m^2 gives a current of 0.71 A and voltage of 16.5 V at maximum power point under STC. What is the maximum power point of the SPV module? Also, find out the efficiency.

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

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

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

Given that, $I_m = 0.71$ A

$$V_m = 16.5 \text{ V}$$

Therefore, maximum power point, $P_m = 0.71 \text{ A} \times 16.5 \text{ V} = 11.71 \text{ W}$

Now, we write formula for efficiency of a solar cell given by the expression

$$\eta = \frac{P_{max}}{P_{in} \times A}$$

where,

η = Efficiency in per cent (%)

P_{max} = Output power in watt (W)

P_{in} = Light input power per unit area in watt/square metre (W/m^2)

A = Solar cell area in square meter (m^2)

η = ?

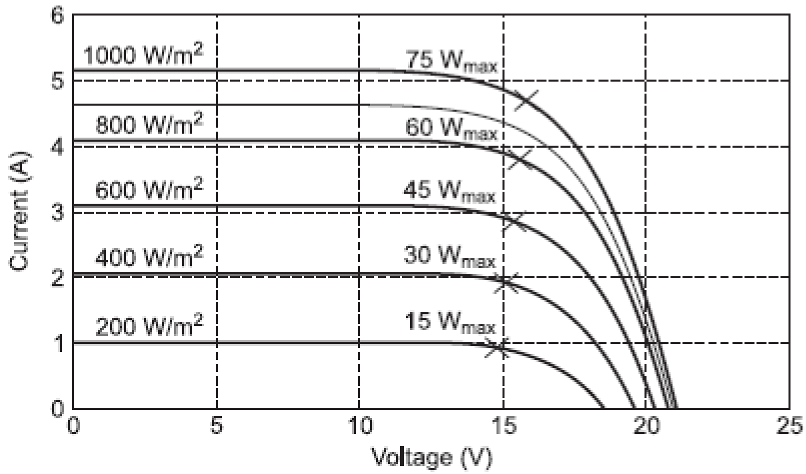
We know, $P_m = 10.06$ W and at STC, $P_{in} = 1000$ W/m^2

Now, we solve for efficiency,

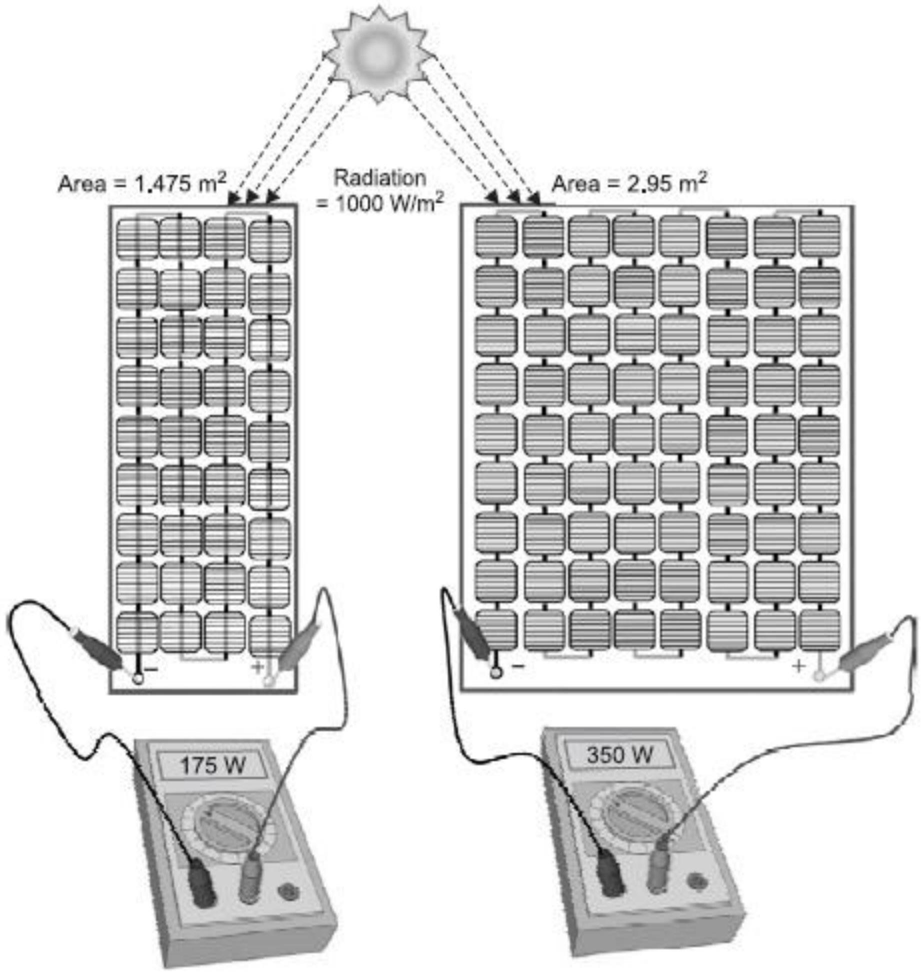
$$\eta = \frac{P_{max}}{P_{in} \times A}$$

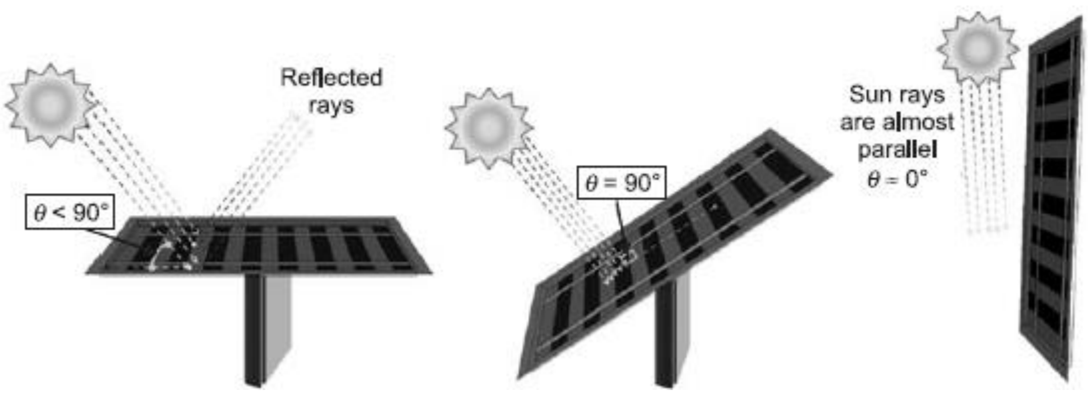
$$\eta = \left(\frac{11.71}{1000 \times 0.0945}\right) \times 100 = 12.39\%$$

Q10.



PV Technology name	*Typical value of change in parameter value per °C rise in cell temperature from standard test condition (STC) value of 25 °C (+ indicates increase, – indicates decrease)*			
	Temperature coefficient of current (I_{sc})	*Temperature coefficient of voltage* (V_{oc})	*Temperature coefficient of fill factor* (FF)	*Temperature coefficient of power* (P_m)
Crystalline silicon	+0.08%/°C	−0.35%/°C	−0.15%/°C	−0.45%/°C
Cadmium telluride	+0.04%/°C	−0.25%/°C	−0.035%/°C	−0.25%/°C
Double junction amorphous silicon	+0.07%/°C	−0.3%/°C	−0.095%/°C	−0.25%/°C

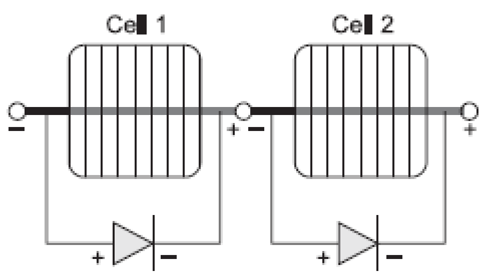




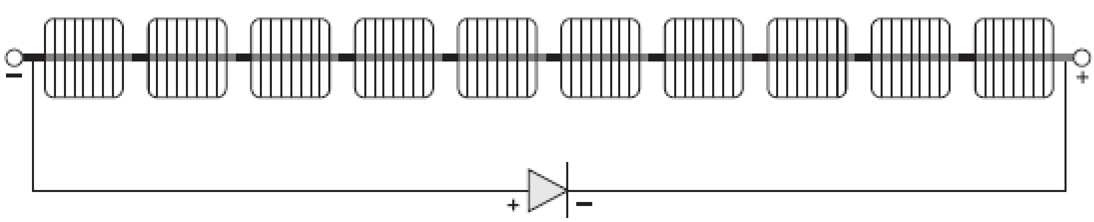
Bypass diode:

In solar PV modules, in almost all cases, all the solar cells, identical in nature, are connected in series. When light falls on a PV module, same current is generated in all solar cells which flow through PV module. Now, due to some reason, if one of the solar cells gets shaded (no light falling on one cell), then the current generated by that cell will be lower than the rest of the solar cells. Since the cells are connected in series, the shaded solar cell (generating low or no current) will resist the current flow generated by non-shaded solar cells generating full current. In this case, the shaded solar cell becomes a load for the other cells, and the power generated by other solar cells may get dissipated in the shaded solar cells. Due to this, the shaded solar cell can become very hot, forming hot spots in the PV module. The hot spots sometimes can give rise to breaking of glass cover in PV module or in a worst case, it can cause fire. Therefore, local heating of solar cells in a PV module due to shading should be avoided.

Bypass diode is used to avoid the destructive effect of hot spots or local heating in series connected cells in PV modules. A diode, called bypass diode, is connected in parallel with solar cells with opposite polarity to that of a solar cell as shown in Figure 4.21. Thus, in normal condition (no shading), the bypass diode is operated in reverse bias condition, effectively in open circuit. But if a series connected cell is shaded, reverse bias will appear across it. This reverse bias will act as a forward bias voltage for bypass diode since it is connected with opposite polarity. In this way, the bypass diode will carry the current, rather than shaded cell (meaning bypassing the current from shaded cell). By bypassing the current, the solar cell gets protected by heating and causing permanent damage to the PV module.

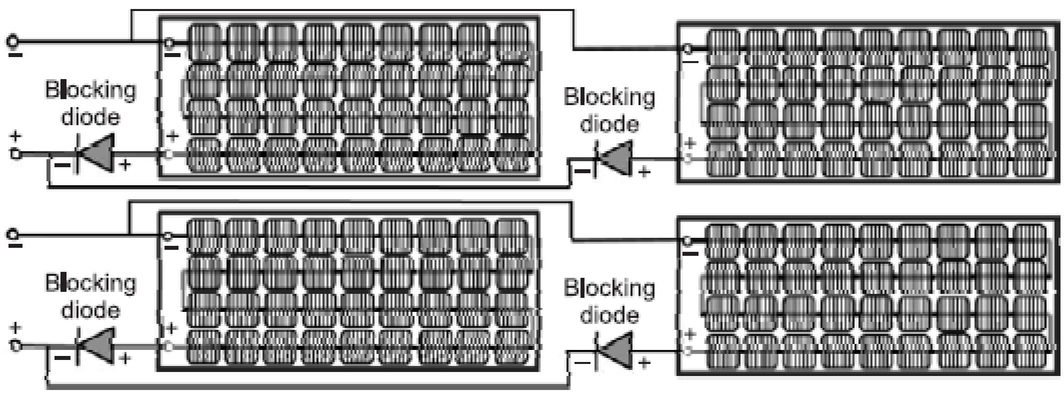


Due to cost reason , one diode or a series of string :

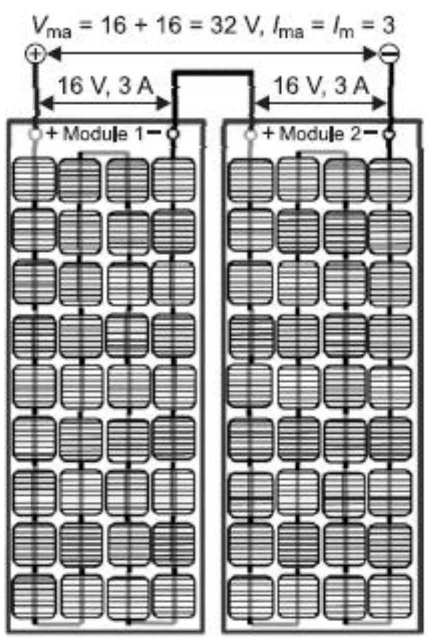


Blocking diodes:

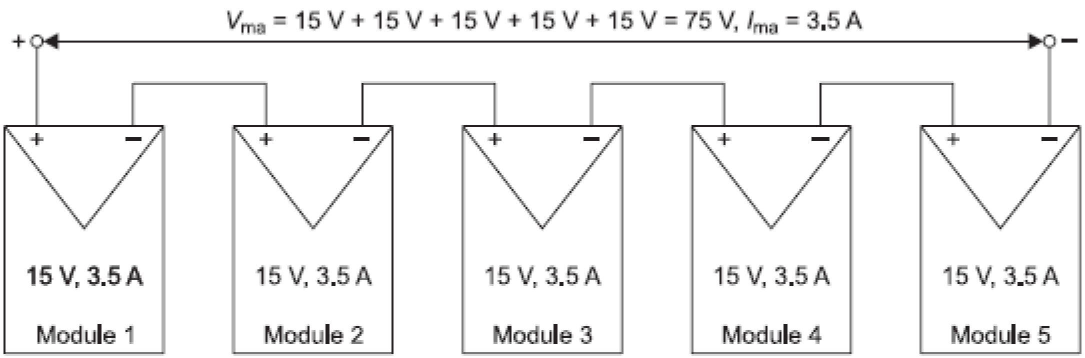
In standalone PV systems, PV modules are used to either supply the load during day time or to charge a battery. In day time, energy is generated by PV module and supplied to battery. When there is no sunlight, like in the night, the SPV modules stop producing the energy and become idle. During night, charged batteries start supplying energy to the SPV modules. This is loss of energy and should be avoided. In order to avoid the flow of current from battery to solar PV modules, a diode, called blocking diode is used to block the current flow. Thus, the blocking diode prevents the discharging of battery into the SPV module. The connection of blocking diode with a solar PV module is shown in Figure 4.23.



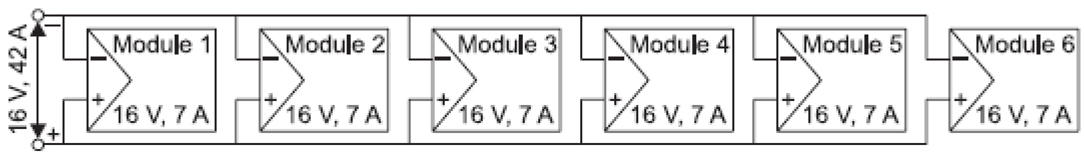
shows two modules connected in series to make array.



Modules are in series : (To add the voltages)



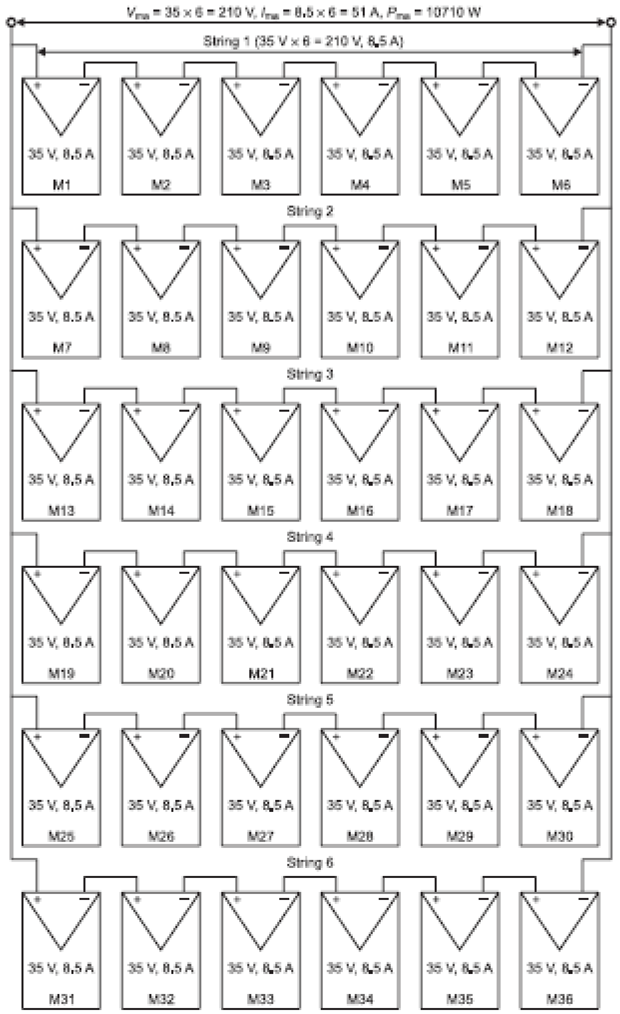
Modules are in paraller (To add the current)



To enhance voltage and current:

ch

ny
'V
gs



Vma = 35 × 6 = 210 V, Ima = 8.5 × 6 = 51 A, Pma = 10710 W
String 1 (35 V × 6 = 210 V, 8.5 A)
35 V, 8.5 A
M1
M2
M3
M4
M5
M6
String 2
M7
M8
M9
M10
M11
M12
String 3
M13
M14
M15
M16
M17
M18
String 4
M19
M20
M21
M22
M23
M24
String 5
M25
M26
M27
M28
M29
M30
String 6
M31
M32
M33
M34
M35
M36