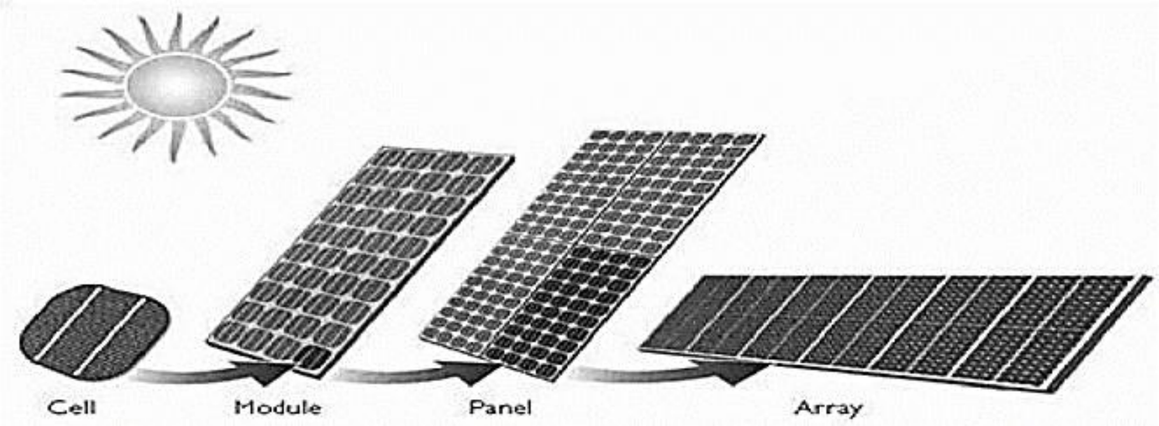
Solar Panels
Principles and Sizing

PV System Basics

- ***Solar cell***. The PV cell is the component responsible for converting light to electricity. Some materials (silicon is the most common) produce a PV effect, when the sunlight strikes the silicon material, electrons become free flowing through an external circuit, thus generating current. Solar cells are designed to absorb as much light as possible (are interconnected in series and parallel electrical connections) to produce desired voltages and currents.
- ***PV module***. A PV module is composed of interconnected solar cells that are encapsulated between a glass cover and weatherproof backing. The modules are typically framed in aluminum frames suitable for mounting.
- ***PV Panel***: PV panels include one or more PV modules assembled as a prewired, field installable unit.

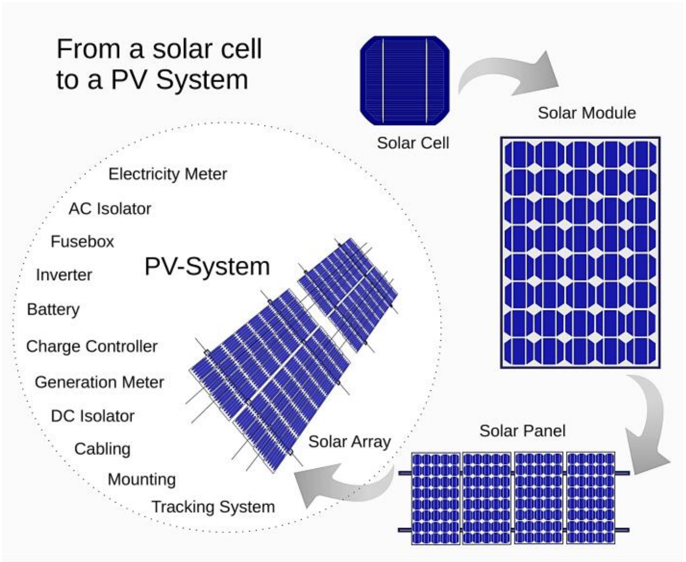


PV System Basics ...

- PV modules are connected together in series or parallel electrical arrangements to provide the required current or voltage to operate electrical loads.

- The module has a frame (usually aluminum) that gives it rigidity and allows for ease of handling and installation. Junction boxes (found on the backs of the PV modules) where conductor connections are made to transfer power from the modules to loads.

- Figure: 100W, 12VDC, Polycrystalline



PV System Basics ...

- ***PV array***. The PV modules are connected in series and parallel to form an array of modules, thus increasing total available power output to the needed voltage and current for a particular application.

- ***Peak Watt (W_p)***. PV modules are rated by their total power output, or peak Watts. A peak Watt is the amount of power output a PV module produces at Standard Test Condition (STC) [i.e., STC means a module receives a full noontime irradiance of 1000W/m^2 where their cells have operating temperature of 25°C, and a standardized solar spectrum referred to as an air mass (m) = 1.5].

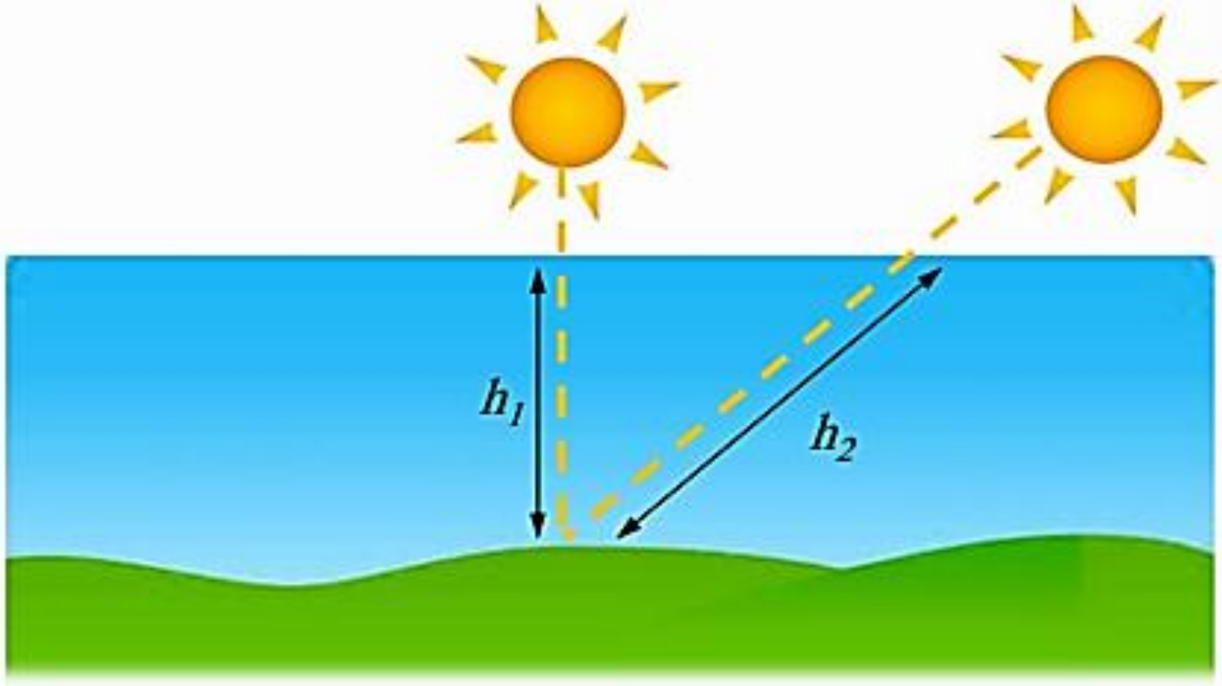
- Keep in mind that modules often operate at much hotter temperatures than 25°C (power reduces by about 0.5% for every 1°C hotter). Therefore, a 100W module operating at 45°C (20° hotter than STC, yielding a 10% power drop) would actually produce about 90 W. *Amorphous PV modules do not have this effect.*

PV System Basics …

- ***Air mass*** **(*m*)**: is an indication of the length of the path that solar radiation travels through the atmosphere up to reach the sea level.

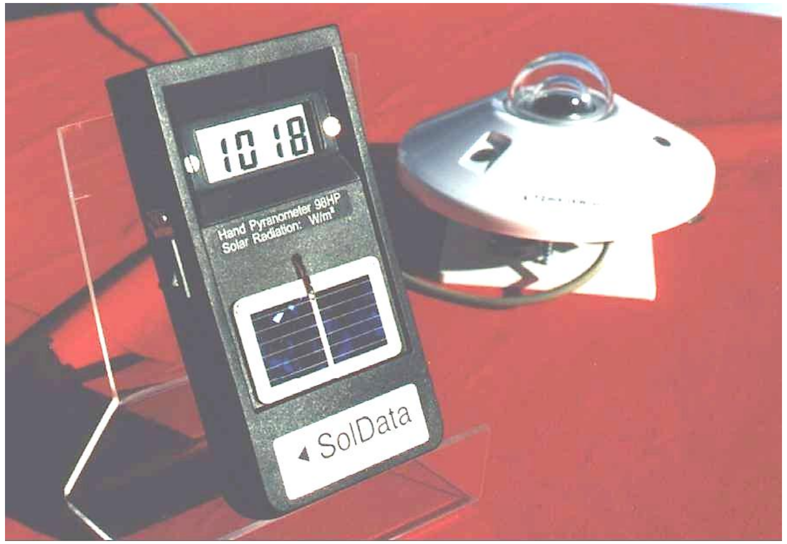
➢ The air mass ratio is given by:

$$m = \frac{h_2}{h_1}$$

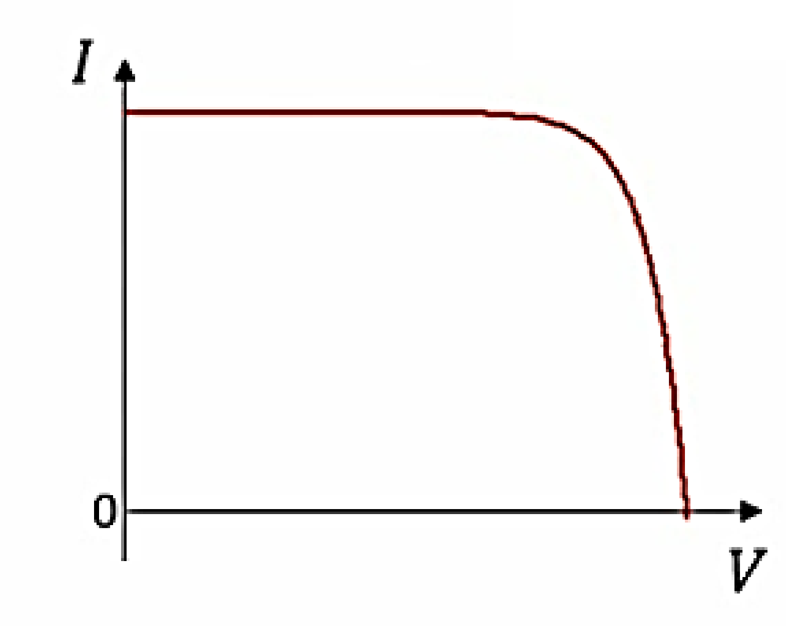


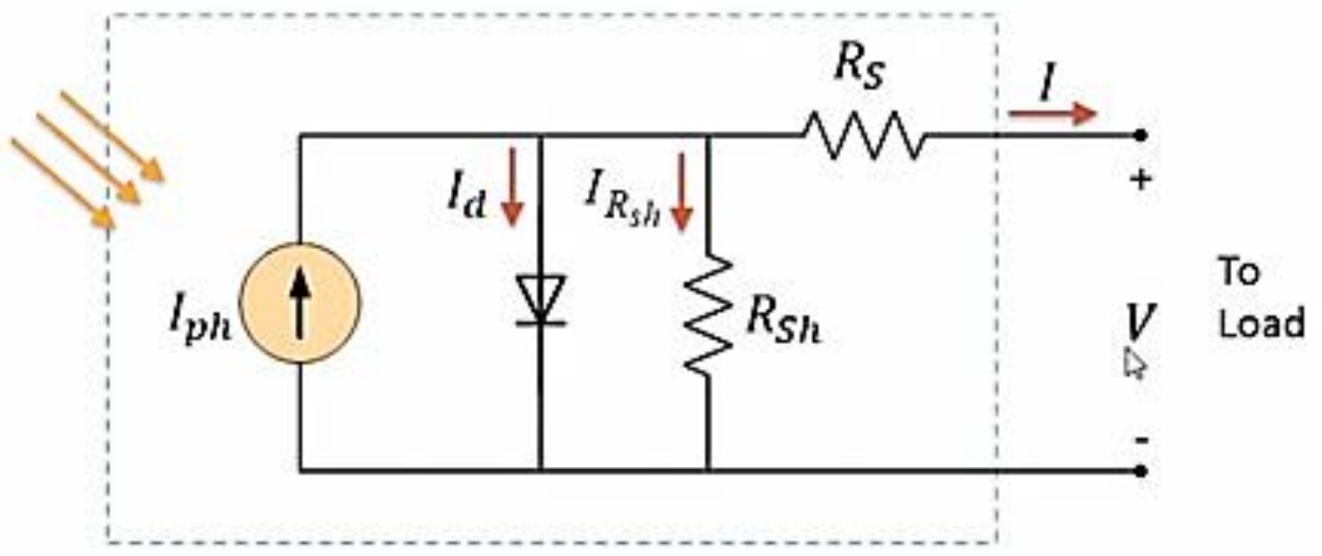
PV System Basics ...

- ***Solar Insolation*** or ***Solar Irradiance*** or ***Solar Energy***: is the number of hours of sunlight strength that you can get at your PV site. It is measured in (W/m^2) or ($kWhr/m^2/day$). It is measured using a pyranometer. See Figure.
- *This **solar irradiance** varies depending on the time of the year and where you live.*
- The more powerful the sun's energy, the more power you get, *although solar panels continue to generate small amounts of electricity in the shade.*



Modelling of PV Cell

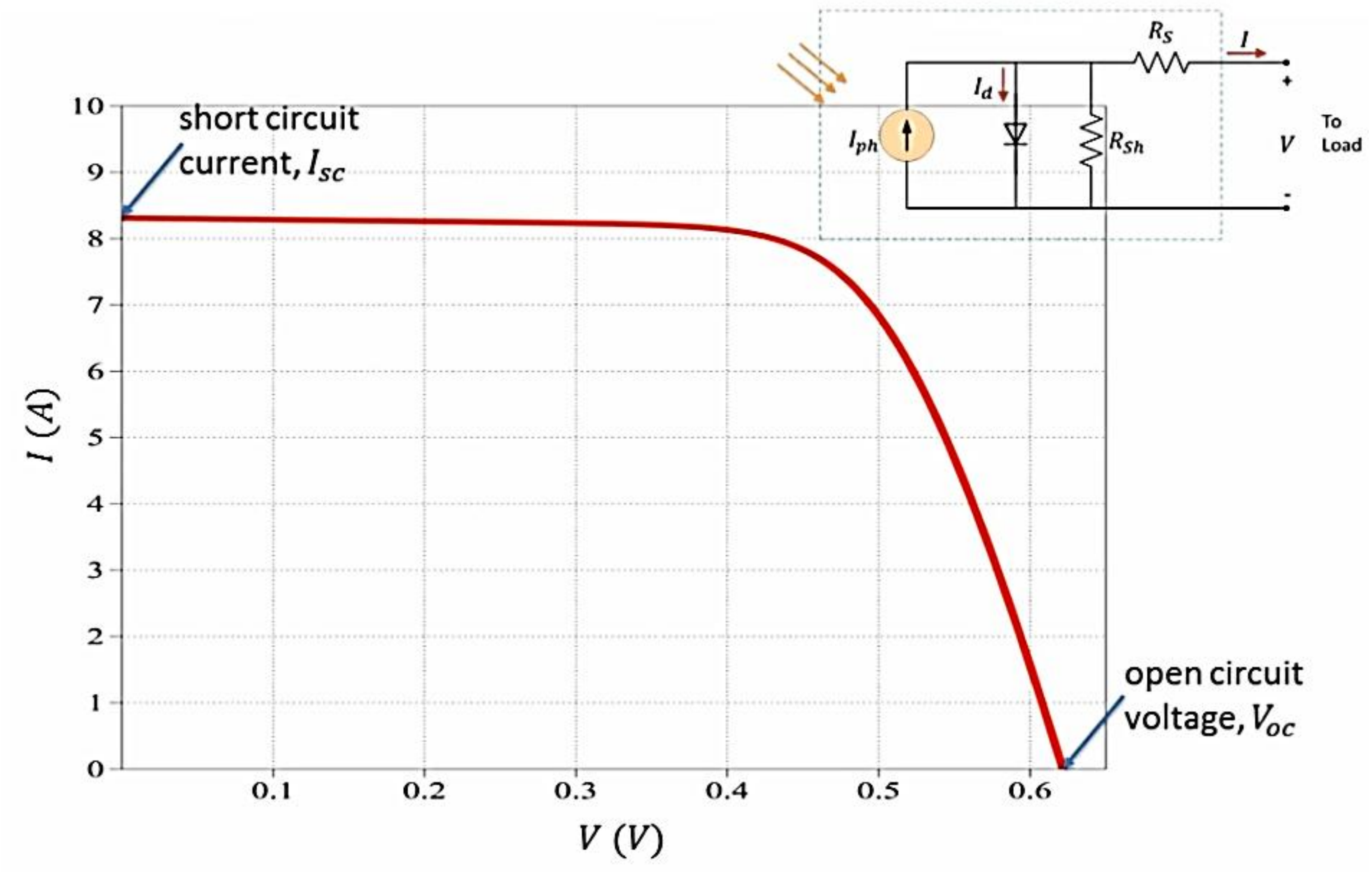




https://www.youtube.com/watch?v=uuKOu7vpteo

- The I-V curve is obtained experimentally by exposing the PV cell or module to a constant level of irradiance while maintaining a constant cell temperature. (i.e., The PV module operated over a wide range of voltages and currents by varying a load resistance from zero (a short circuit) to infinity (an open circuit).

I-V Characteristics (I-V Curve) of a Single PV Cell



I-V Curve & Power Curve of PV Module

TABLE 6.2
Example Manufacturer's Specifications for a 53-Wp PV Module

Operating point	Model BP VLX-53
P_{mp}	53 W_p (peak Watts)
V_{mp}	17.2 V
I_{mp}	3.08 A
V_{oc}	21.5 V
I_{sc}	3.5 A
Standard test conditions (STCs)	1,000 W/m², 25°C

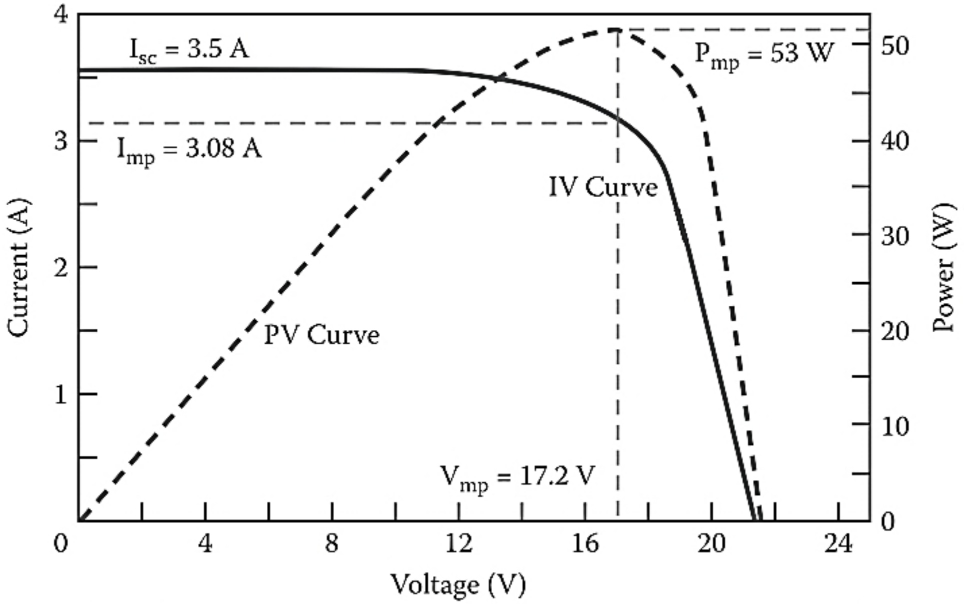


FIGURE 6.1 Typical I-V and power curves for a crystalline PV module operating at 1,000 W/m² (STC).

- **I-V curve** is obtained experimentally by putting a load resistance (i.e., at PV module terminals) vary from zero (short circuit) to infinity (open circuit) during the PV module is exposed to a constant level of irradiance while maintaining a constant cell temperature.
- **A power curve** is generated by multiplying current and voltage at each point on the *I-V curve*. However, the only point desired to operate on this curve is the maximum power point. Figure shows the I-V and PV power curves of a typical PV module.

I-V Curve & Power Curve of PV Module ...

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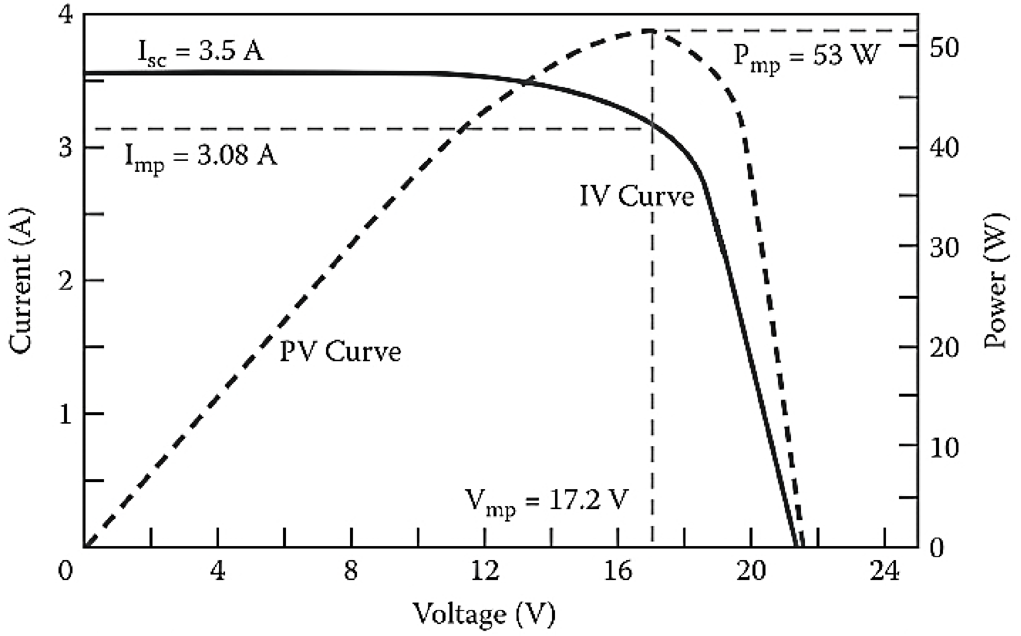

FIGURE 6.1 Typical I-V and power curves for a crystalline PV module operating at 1,000 W/m² (STC).

at V_{oc} = 0V → I_{sc} = 3.5A   at I_{sc} = 0A → V_{oc} = 21.5V

I_{mp} : current at maximum power V_{mp} : voltage at maximum power

P_{mp} : maximum power

- *I-V curves* can show the peak power point located on the farthest upper right corner of where *the rectangular area is greatest under the curve.*

I-V Curve & Power Curve of PV Module ...

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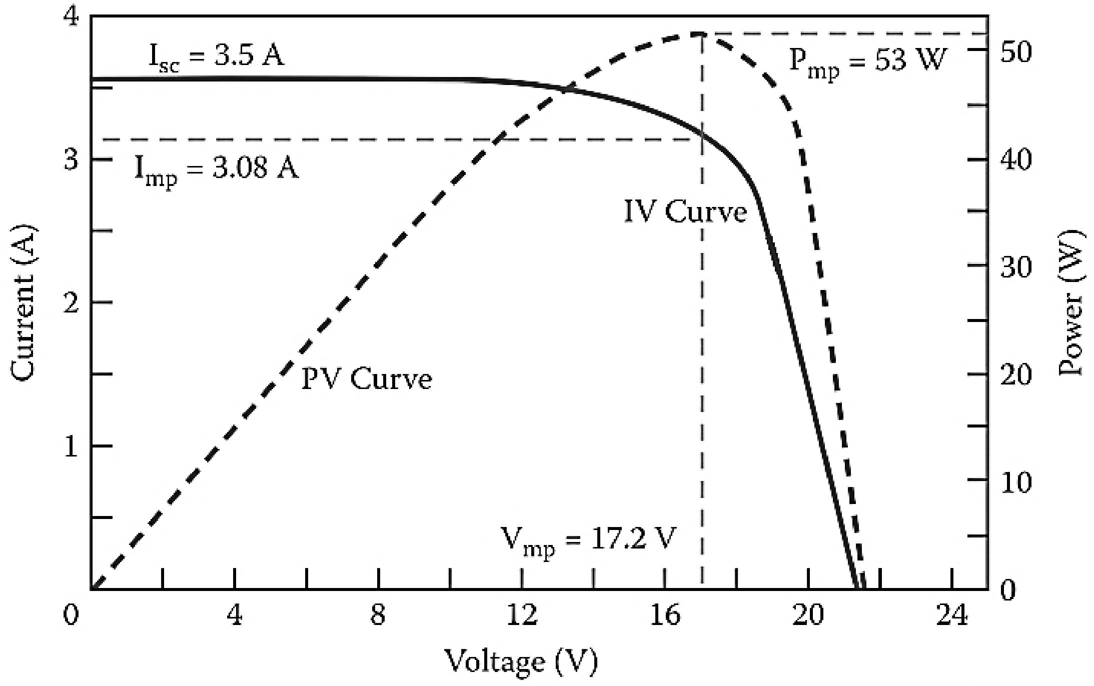


FIGURE 6.1 Typical I-V and power curves for a crystalline PV module operating at 1,000 W/m² (STC).

- No power is produced at the short-circuit current with no voltage (or at open-circuit voltage with no current).
- Maximum power is generated at only one point on the power curve; this occurs at the knee of the I-V curve. This point represents the maximum efficiency of the device in converting sunlight into electricity.

What does mean: PV panel has 53W_p

- It means that: solar panel can produce 53Watt when the PV panel exposed to a solar irradiance of 1000Watt/m^2 when PV cells of the panel has a temperature of 25^{o}C.

Effect of Solar Irradiance on I-V Curve

- The power produced by a crystalline PV module is affected by two key factors: *solar irradiance* and *module temperature*.
- **Figure 6.2** : I-V curve at different irradiance levels. The lower the solar irradiance is, the lower is the current output and thus the lower is the peak power point. The amount of current produced is directly proportional to increases in solar radiation intensity.

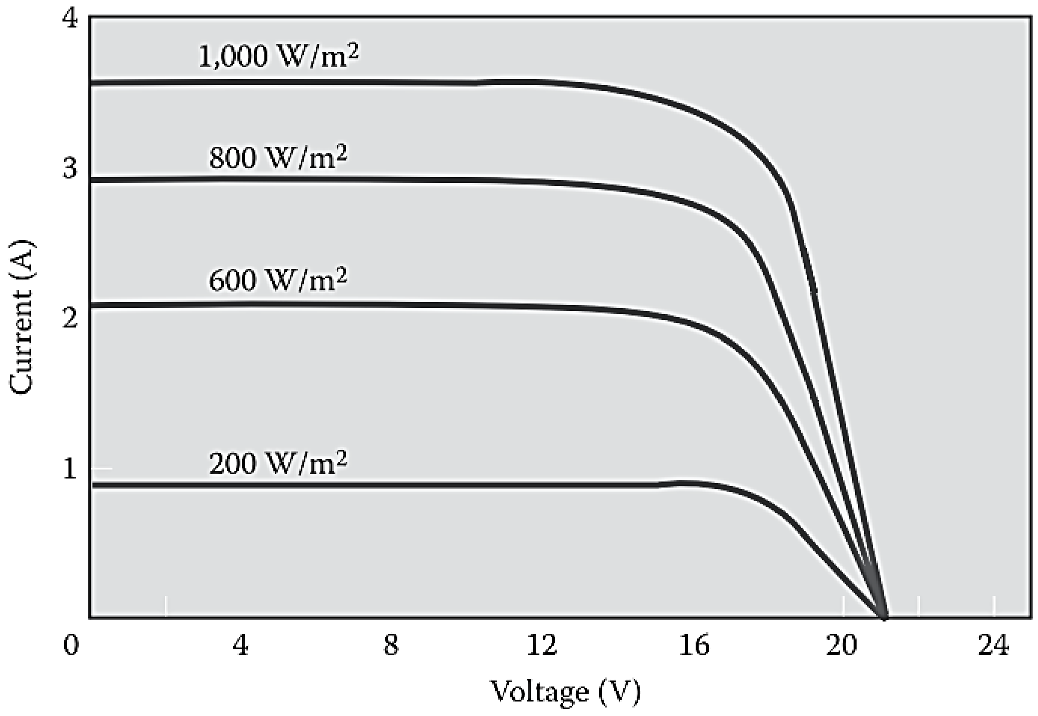


FIGURE 6.2 PV module current diminishes with decreasing solar irradiance.

- **Figure 6.2** : Voltage essentially remains constant. Basically, V_{oc} does not change; its behavior is essentially constant even as solar irradiance intensity is changing.

Effect of Module Temperature on I-V Curve

- **Figure 6.3** : Effect of temperature on Module's output power. As module operating temperature increases, module voltage drops while current essentially holds steady. PV module operating voltage is reduced on average for crystalline modules approximately 0.5% for every degree Celsius above 25° of STC.

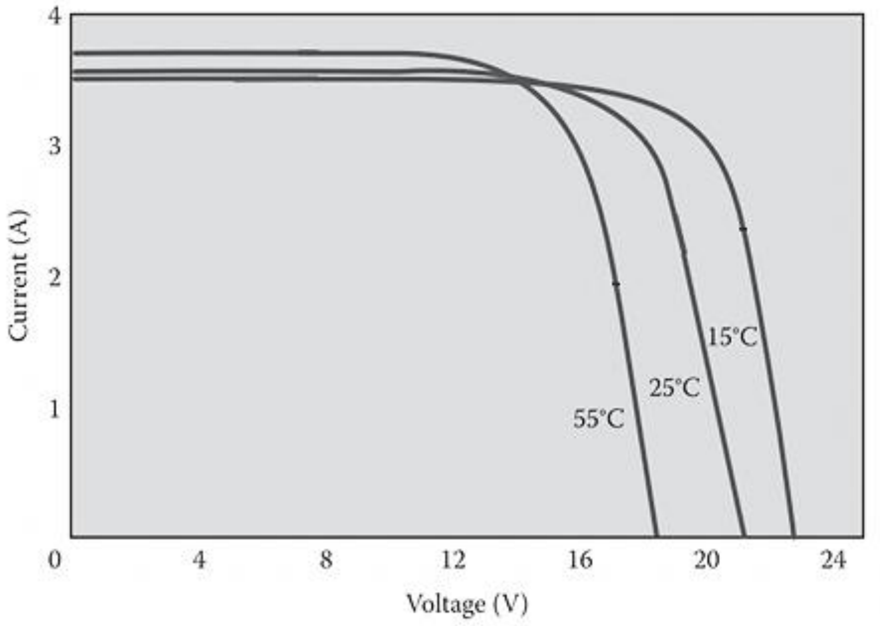


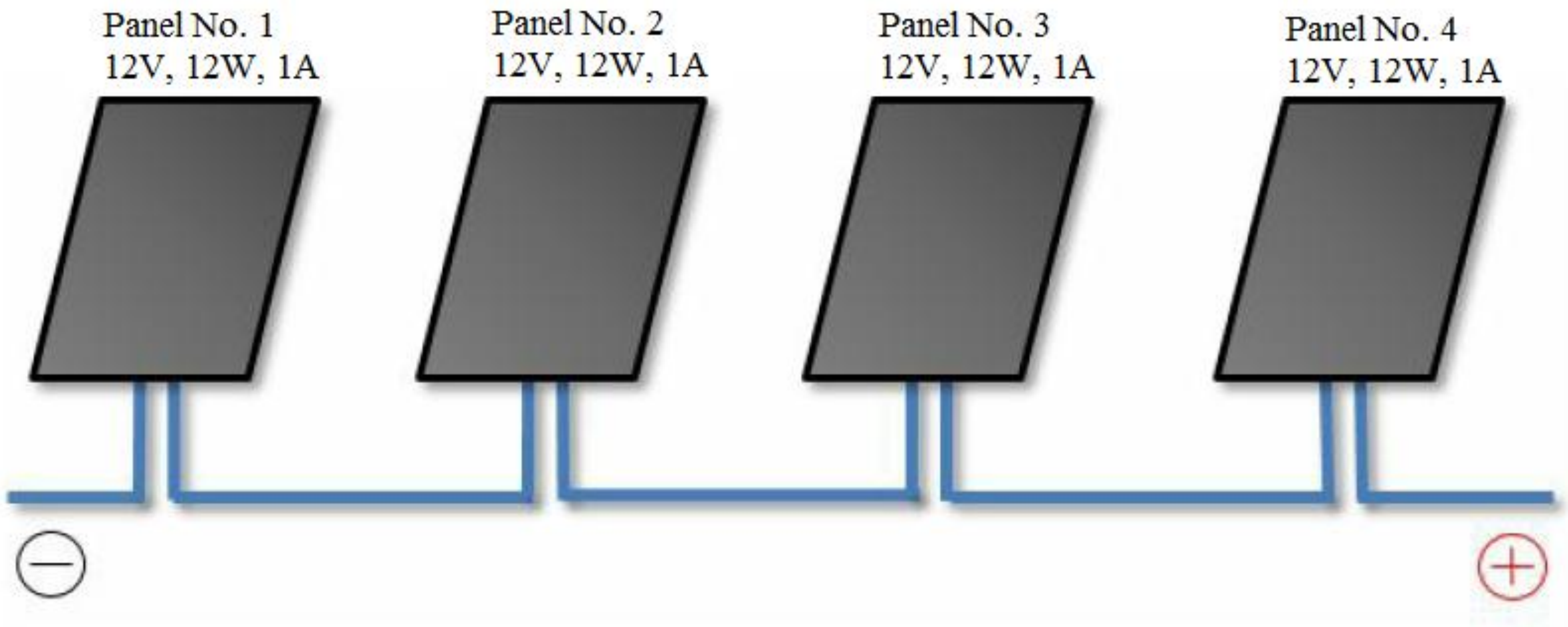
FIGURE 6.3 PV module voltage drops with temperature, as does power.

- Thus, a $100W_p$ crystalline module under STC now operating at 55°C with no change in solar irradiance will lose about 15% of its power rating and provide about 85 W of useful power.
- In general, when sizing terrestrial PV systems, one should expect a 15–20% drop in module power from STC. This is important to remember when calculating daily actual energy production.

Effect of Module Temperature on I-V Curve …

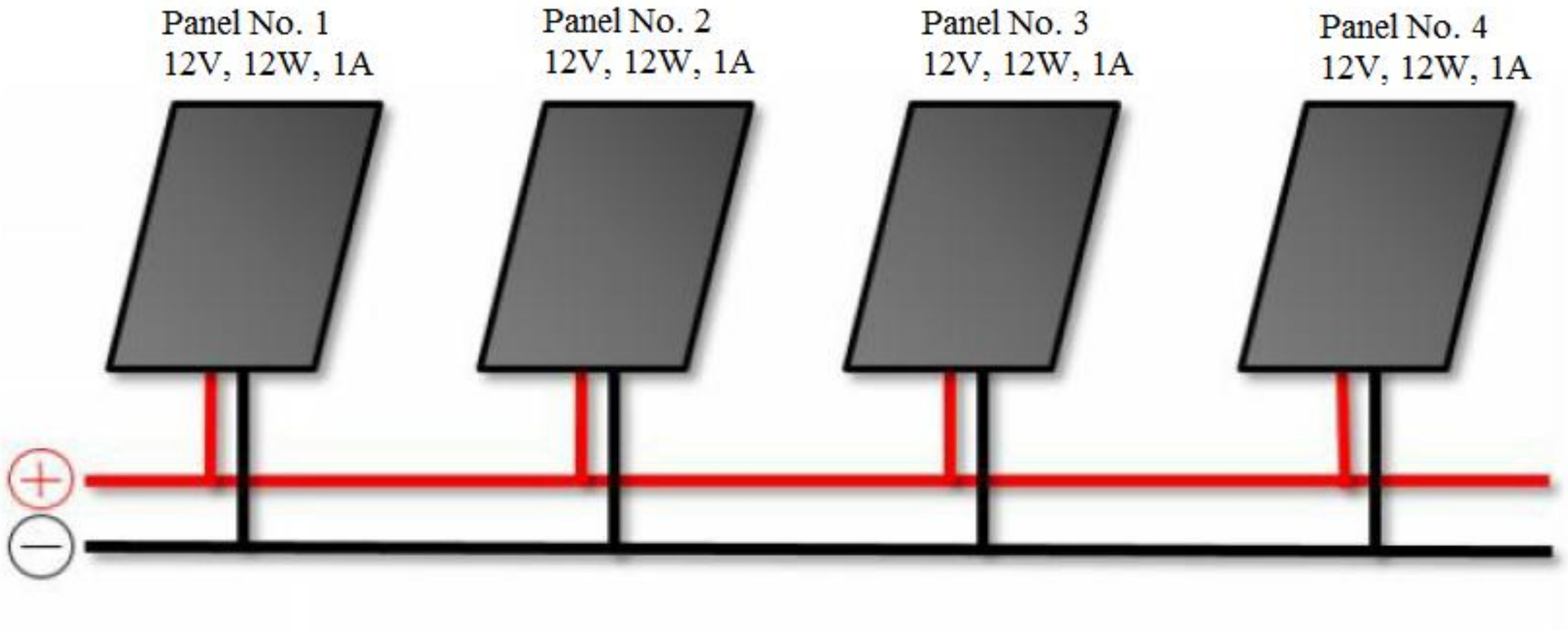
- Just remember that real-world operating conditions will see a derating in module performance due to the temperature effect for crystalline modules. Conversely, in very cold climes, a module operating under 25°C will produce more power than rated.
- This means that: module output power decreases as module's temp higher than 25^{o}C. Also, module output power increases as module's temp less than 25^{o}C.

Series Connection of PV modules (increasing PV system total voltage)



A solar array made of four solar panels connected in series. If each individual panel is rated as a 12-volt, 12-watt panel, this solar array would be rated as a 48-volt, 48-watt array with a 1 amp current.

Parallel Connection of PV modules (increasing PV system total current)



A solar array made of four solar panels connected in parallel. With each panel rated as a 12-volt, 12-watt panel, this solar array would be rated as a 12-volt, 48-watt array with a 4 amp current.

Example 1

- Sixteen PV modules like the one shown in Table 6.2 have been interconnected to operate a water pumping system. The array consists of two parallel panels. Each panel consists of eight series modules. The I-V and PV curves that describe the behavior of the array will have the same shape as those shown in Figure 6.2.
- Determine:

(a) Peak current of the array, I_p. [6.16A]

(b) Peak voltage of the array, V_p. [137.6V]

(c) Peak power of the array, P_p. [848Watt]

(d) Maximum array current, I_{sc}. [7A]

(e) Maximum array Voltage, V_{oc}. [172V]

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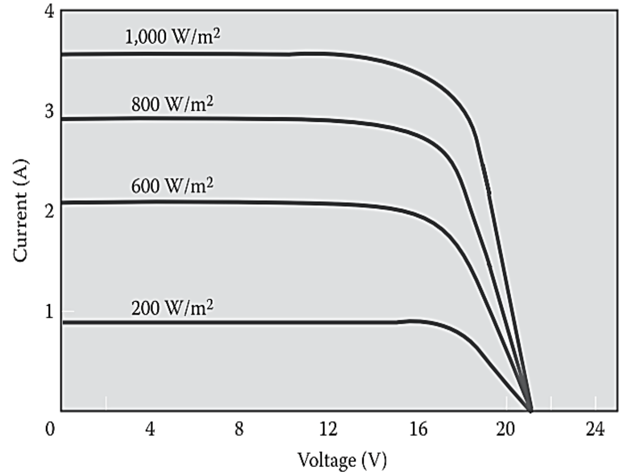


FIGURE 6.2 PV module current diminishes with decreasing solar irradiance.

Calculating Solar Irradiance

- Thanks to NASA, calculating your own solar irradiance is simple. NASA's network of weather satellites has been monitoring the solar irradiance across the surface of the earth for many decades. Their figures have taken into account the upper atmospheric conditions, average cloud cover and surface temperature, and are based on sample readings every three hours for the past quarter of a decade. They cover the entire globe.

Calculating Solar Irradiance …

- The Solar Electricity Handbook website has incorporated this information across the entire world. Simply select your current location and you can view the irradiance figures for your exact area. You can access this solar irradiance information by visiting:
- **http://www.SolarElectricityHandbook.com** and following the links to calculators and resources.

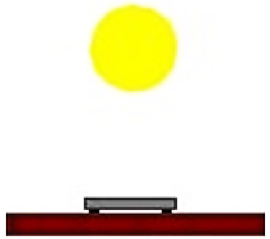
- Using the information from the website (follow links: **Online Calculators** > **Solar Irradiance Tables**) here are the solar irradiance figures for Cairo in Egypt, shown on a month-by-month basis. They show the average daily irradiance, based on mounting the solar array flat on the ground:

Solar Irradiance figures

Select Country: Egypt

Select Town/City: Cairo

Solar Panel direction: Facing directly East



Cairo
Average Solar Insolation figures

Measured in $kWh/m^2/day$ onto a horizontal surface:

Jan	Feb	Mar	Apr	May	Jun
3.16	3.88	5.05	6.14	6.96	7.65

Jul	Aug	Sep	Oct	Nov	Dec
7.30	6.82	5.77	4.44	3.36	2.95

Calculating Solar Irradiance …

- From the shown Figure: What Does Mean Dec 2.95kWh/m²/day?
- Answer:

$$\frac{Solar\ Irradiance\ of\ Your\ Location}{Standard\ Solar\ Irradiance} = \frac{2.95\frac{kWh}{m^2.day}}{1\frac{kW}{m^2}} = 2.95\ h/day$$

2.95 h/day (i.e., 2 hours and 57 minutes per the day) your PV site in Cairo in Egypt, will expose to solar irradiance of 1000W/m² in December month when the PV panels are Flat on the ground as shown in the figure.

Solar Irradiance figures

Select Country: Egypt

Select Town/City: Cairo

Solar Panel direction: Facing directly East

Cairo
Average Solar Insolation figures

Measured in kWh/m²/day onto a horizontal surface:

Jan	Feb	Mar	Apr	May	Jun
3.16	3.88	5.05	6.14	6.96	7.65

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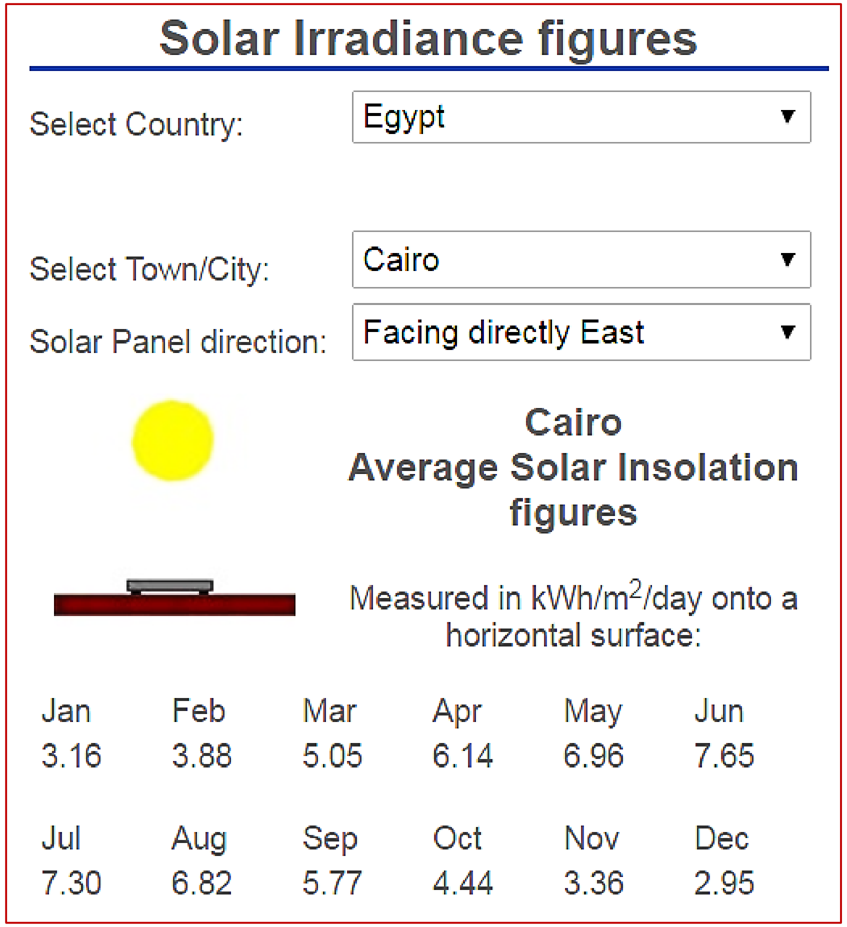
7.30	6.82	5.77	4.44	3.36	2.95

Capturing more of the Sun's energy

- The tilt of a solar panel has an impact on how much sunlight you capture: mount the solar panel flat against a wall or flat on the ground and you will capture less sunlight throughout the day than if you tilt the solar panels to face the sun. Note the difference in the figures:



Solar Irradiance figures

Select Country: Egypt

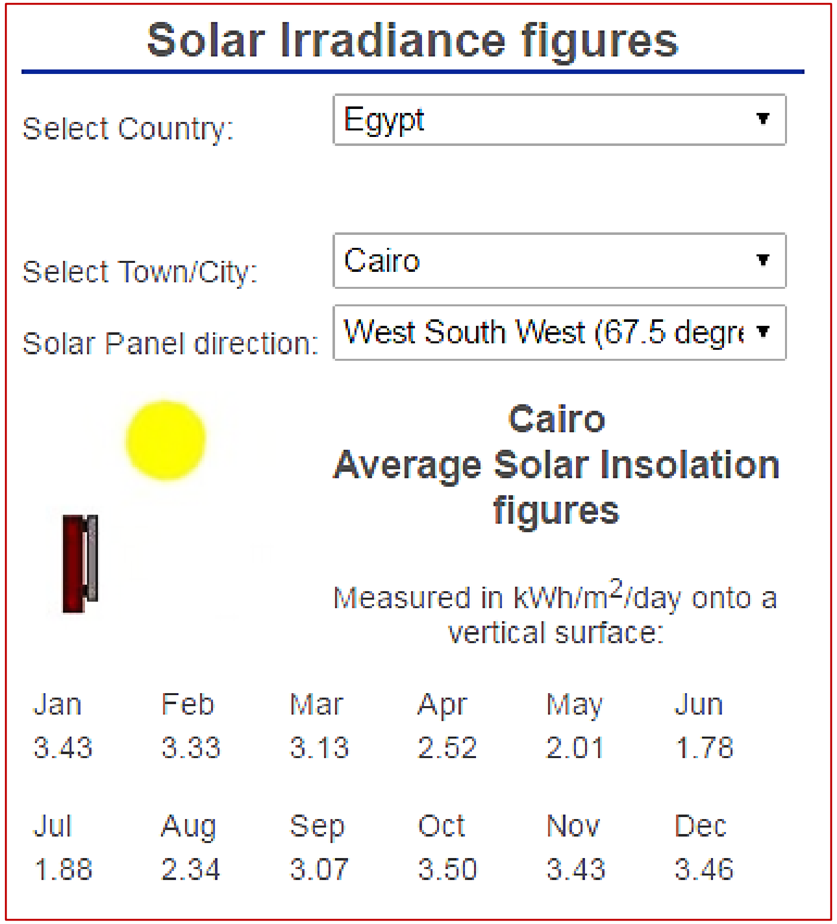
Select Town/City: Cairo

Solar Panel direction: Facing directly East

Cairo
Average Solar Insolation figures

Measured in $kWh/m^2/day$ onto a horizontal surface:

Jan	Feb	Mar	Apr	May	Jun
3.16	3.88	5.05	6.14	6.96	7.65
Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
7.30	6.82	5.77	4.44	3.36	2.95



Solar Irradiance figures

Select Country: Egypt

Select Town/City: Cairo

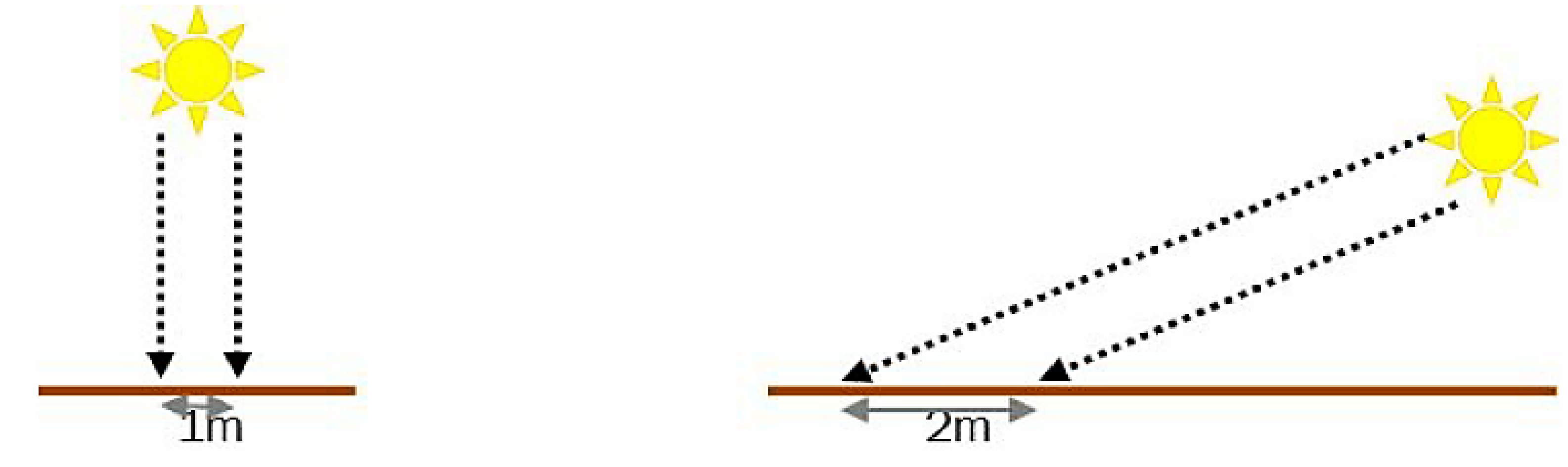
Solar Panel direction: West South West (67.5 degre

Cairo
Average Solar Insolation figures

Measured in $kWh/m^2/day$ onto a vertical surface:

Jan	Feb	Mar	Apr	May	Jun
3.43	3.33	3.13	2.52	2.01	1.78
Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1.88	2.34	3.07	3.50	3.43	3.46

Capturing more of the Sun's energy ...



This diagram shows the different intensity of light depending on the angle of sun in the sky. When the sun is directly overhead, a 1m-wide shaft of sunlight will cover a 1m-wide area on the ground. When the sun is low in the sky – in this example, I am using an angle of 30° towards the sun – a 1m-wide shaft of sunlight will cover a 2m-wide area on the ground. This means the intensity of the sunlight is half as much when the sun is at an angle of 30° compared to the intensity of the sunlight when the sun is directly overhead.

- The reason for this is the intensity of the sunlight. When the sun is high in position in the sky the intensity of sunlight is high. When the sun is low in position in the sky the sunlight is spread over a greater surface area

The Impact of Tilting Solar Panels on Solar Irradiance

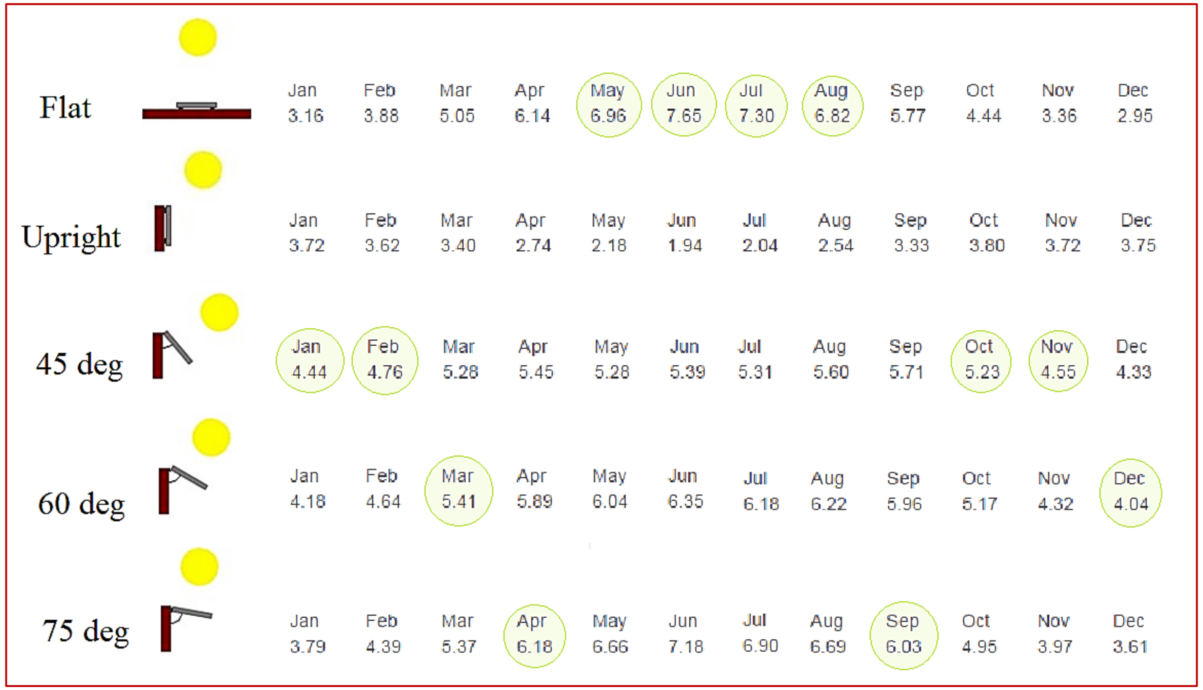
- If we tilt our solar panels towards the sun, it means we can capture more of the sun's energy to convert into electricity. Often the angle of this tilt is determined for you by the angle of an existing roof. However, for every location there are optimal angles at which to mount your solar array, in order to capture as much solar energy as possible. Figures for Cairo in Egypt. For each month in the year we highlight on the best position.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flat	3.16	3.88	5.05	6.14	**6.96**	**7.65**	**7.30**	**6.82**	5.77	4.44	3.36	2.95
Upright	3.72	3.62	3.40	2.74	2.18	1.94	2.04	2.54	3.33	3.80	3.72	3.75
45 deg	**4.44**	**4.76**	5.28	5.45	5.28	5.39	5.31	5.60	5.71	**5.23**	**4.55**	4.33
60 deg	4.18	4.64	**5.41**	5.89	6.04	6.35	6.18	6.22	5.96	5.17	4.32	**4.04**
75 deg	3.79	4.39	5.37	**6.18**	6.66	7.18	6.90	6.69	**6.03**	4.95	3.97	3.61

Optimum Fixed Year-round Setting For PV Panels

- To calculate the optimum tilt of your solar panels all-year, you can use the relation:

Optimum Fixed Year-round Setting = 90° – (your latitude خط العرض)



	Jan	Feb	March	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Average Irradiance
Flat	3.16	3.88	5.05	6.14	6.96	7.65	7.3	6.82	5.77	4.44	3.36	2.95	**5.29**
Upright	3.72	3.62	3.4	2.74	2.18	1.94	2.04	2.54	3.33	3.8	3.72	3.75	**3.07**
45 deg	4.44	4.76	5.28	5.45	5.28	5.39	5.31	5.6	5.71	5.23	4.55	4.33	**5.11**
60 deg	4.18	4.64	5.41	5.89	6.04	6.35	6.18	6.22	5.96	5.17	4.32	4.04	**5.37**
75 deg	3.79	4.39	5.37	6.18	6.66	7.18	6.9	6.69	6.03	4.95	3.97	3.61	**5.48**

- **Cairo in Egypt** has a latitude of 30.2°: Optimum Year Setting = 90° – 30.2° = 59.8° ≈ 60°
- This does not mean that you will get the maximum power output every single month, instead it means that across the whole year, this tilt will give you the best compromise, generating electricity all the year round.