4.7 MEASUREMENTS OF SOLAR RADIATION

Solar radiation data are measured mainly by the following instruments:

(i) Pyranometer A pyranometer is designed to measure global radiation, usually on a horizontal surface, but can also be used on an inclined surface. When shaded from beam radiation by using a shading ring, a pyranometer measures diffused radiation.

(ii) Pyrheliometer An instrument that measures beam radiation by using a long narrow tube to collect only beam radiation from the sun at normal incidence.

(iii) Sunshine Recorder It measures the sunshine hours in a day.

4.7.1 Pyranometer

A precision pyranometer is designed to respond to radiation of all wavelengths and hence measures accurately the total power in the incident spectrum. It contains a thermopile whose sensitive surface consists of circular, blackened, hot junctions, exposed to the sun, the cold junctions being completely shaded. The temperature difference between the hot and cold junctions is the function of radiation falling on the sensitive surface. The sensing element is covered by two concentric hemispherical glass domes to shield it from wind and rain. This also reduces the convection currents. A radiation shield surrounding the outer dome and coplanar with the sensing element, prevents direct solar radiation from heating the base of the instrument. The instrument has a voltage output of approximately $9 \mu V/W/m^2$ and has an output impedance of 650 Ω. A precision spectral pyranometer (model: PSP) of Eppley Laboratory is shown in Fig. 4.6. The pyranometer, when provided with a shadow band (or occulting disc), to prevent beam radiation from reaching the sensing element, measures the diffused radiation only. Such an arrangement of shadow band stand (model: SBS) is shown in Fig. 4.7.

Fig. 4.6 *Pyranometer (Courtesy: Eppley Laboratory)*

Fig. 4.7 *A pyranometer with shadow band (courtesy: Eppley Laboratory)*

Many inexpensive instruments are also available for measuring light intensity, including instruments based on cadmium-sulphide photocells and silicon photodiodes. These instruments give good indication of relative intensity but their spectral response is not linear, and thus they cannot be accurately calibrated.

4.7.2 Pyrheliometer

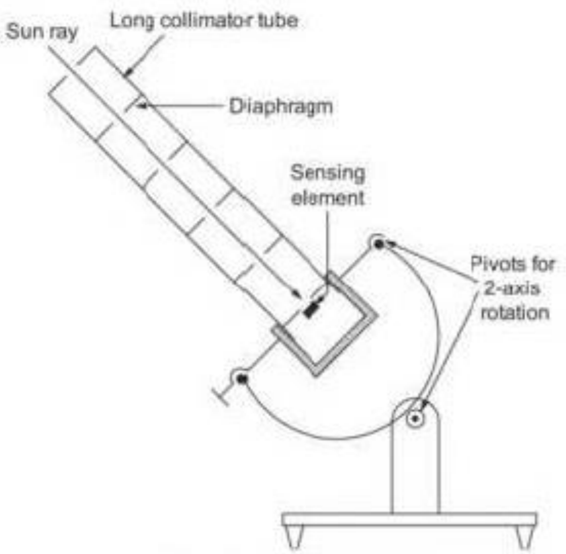


Fig. 4.8 *Pytheliometer*

The normal incidence pyranometer, shown in Fig. 4.8 uses a long collimator tube to collect beam radiation whose field of view is limited to a solid angle of 5.5° (generally) by appropriate diaphragms inside the tube. The inside of the tube is blackened to absorb any radiation incident at angles outside the collection solid angle. At the base of the tube a wire wound thermopile having a sensitivity of approximately 8 $\mu V/W/m^2$ and an output impedance of approximately 200 Ω is provided. The tube is sealed with dry air to eliminate absorption of beam radiation within the tube by water vapour. A tracker is needed if continuous readings are desired.

4.7.3 Sunshine Recorder

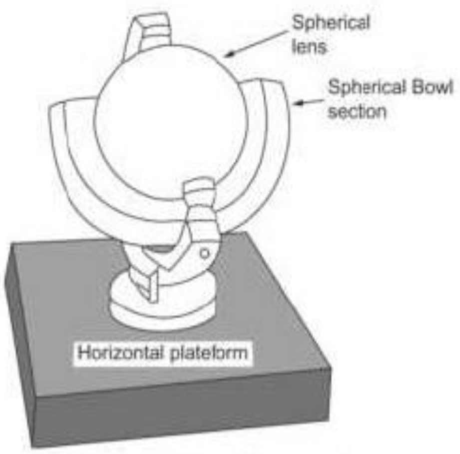


Fig. 4.9 *Sunshine recorder*

This instrument measures the duration in hours of bright sunshine during the course of a day. It essentially consists of a glass sphere (about 10 cm in diameter) mounted on its axis parallel to that of the earth, within a spherical section (bowl), as shown in Fig. 4.9. The bowl and glass sphere are arranged in such a way that the sun's rays are focused sharply at a spot on a card held in a groove in the bowl. The card is prepared from a special paper bearing a time scale. As the sun moves, the focused bright sunshine burns a path along this paper. The length of the trace thus obtained on the paper is the measure of the duration of the bright sunshine. Three overlapping pairs of grooves are provided in the spherical segment to take care of the different seasons of the year.

SOLAR CELL CHARACTERISATION

A solar cell can be operated at any point along its characteristic current–voltage curve, as shown in Fig. 3. Two important points on this curve are the open circuit voltage (V_{oc}) and short-circuit current (I_{sc}). The open-circuit voltage is the maximum voltage at zero current, whereas the short circuit current is the maximum current at zero voltage. For a silicon solar cell under standard test conditions, V_{oc} is typically 0.6–0.7 V, and I_{sc} is typically 20–40mA for every square centimeter of the cell area. To a good approximation, I_{sc} is proportional to the illumination level, whereas V_{oc} is proportional to the logarithm of the illumination level.

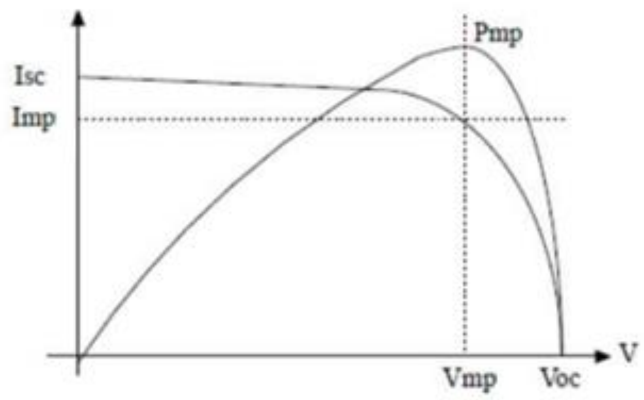


Figure 3: I vs. V characteristics of a solar cell

A plot of power (P) against voltage (V) for this device (Fig. 3) shows that there is a unique point on the I-V curve at which the solar cell will generate maximum power. This is known as the maximum power point (V_{mp}, I_{mp}). To maximize the cell parameters: open-circuit voltage, short-circuit current, and fill factor (FF)—a term describing how ''square'' the I-V curve is, given by

$$Fill\ Factor = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}}$$

For a silicon solar cell, FF is typically 0.6–0.8.

Because silicon solar cells typically produce only about 0.5 V, a number of cells are connected in series in a PV module. A panel is a collection of modules physically and electrically grouped together on a support structure. An array is a collection of panels (see Fig. 4).

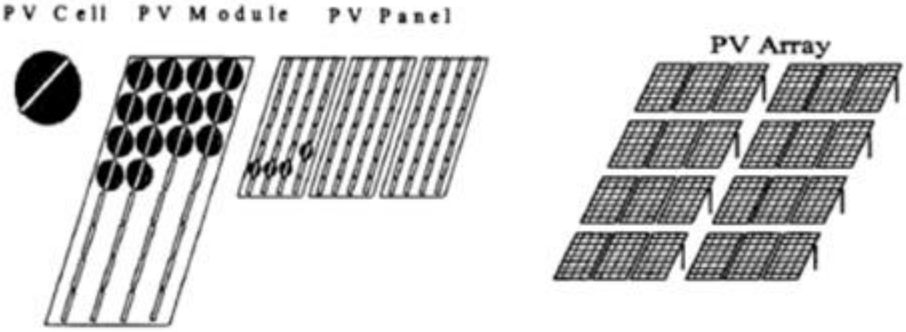


Figure 4: Elements of SPV system

The effect of temperature on the performance of a silicon solar module is illustrated in Fig. 6.5.

Note that I_{sc} slightly increases linearly with temperature, but V_{oc} and the maximum power P_m decrease with temperature.

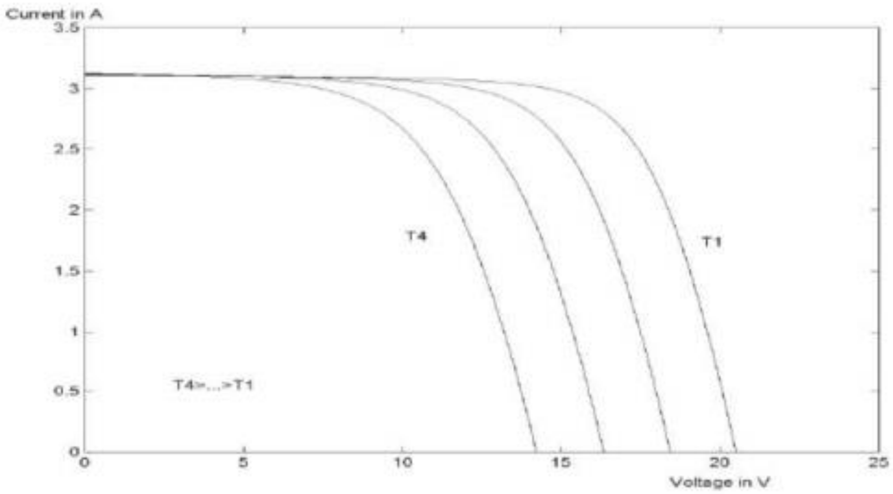


Figure 5: Effect of temperature on the performance of Silicon solar module

Figure 6 shows the variation of PV current and voltages at different insolation levels. From Figs. 5 and 6, it can be seen that the I V characteristics of solar cells at a given insolation and temperature consist of a constant-voltage segment and a constant-current segment. The current is limited, as the cell is short-circuited. The maximum power condition occurs at the knee of the characteristic where the two segments meet.

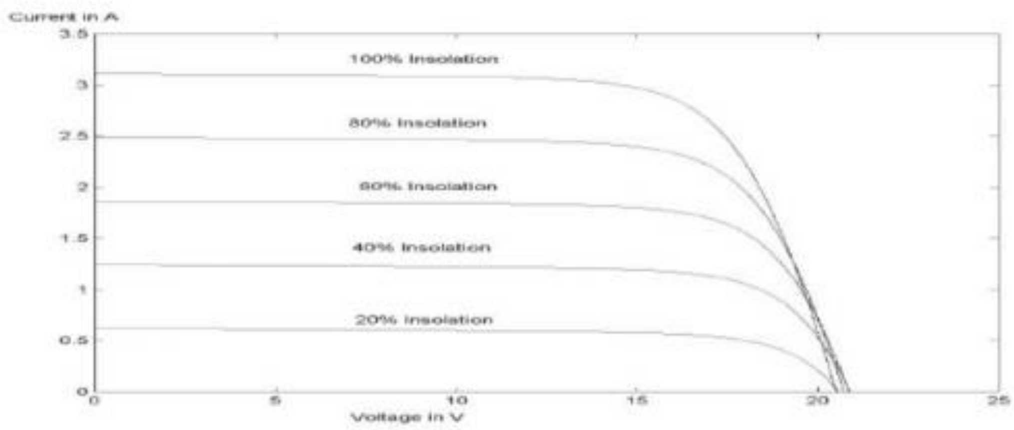


Figure 6: I-V characteristics for different insolation levels

TYPES OF SOLAR CELLS

Based on the types of crystal used, solar cells can be classified as,

1. Monocrystalline silicon cells

2. Polycrystalline silicon cells

3. Amorphous silicon cells

1. The Monocrystalline silicon cell is produced from pure silicon (single crystal). Since the Monocrystalline silicon is pure and defect free, the efficiency of cell will be higher.
2. In polycrystalline solar cell, liquid silicon is used as raw material and polycrystalline silicon was obtained followed by solidification process. The materials contain various crystalline sizes. Hence, the efficiency of this type of cell is less than Monocrystalline cell.
3. Amorphous silicon was obtained by depositing silicon film on the substrate like glass plate.

- The layer thickness amounts to less than 1µm – the thickness of a human hair for comparison is 50-100 µm.
- The efficiency of amorphous cells is much lower than that of the other two cell types.
- As a result, they are used mainly in low power equipment, such as watches and pocket calculators, or as facade elements.

Material	Efficiency (%)
Monocrystalline silicon	14-17
Polycrystalline silicon	13-15
Amorphous silicon	5-7

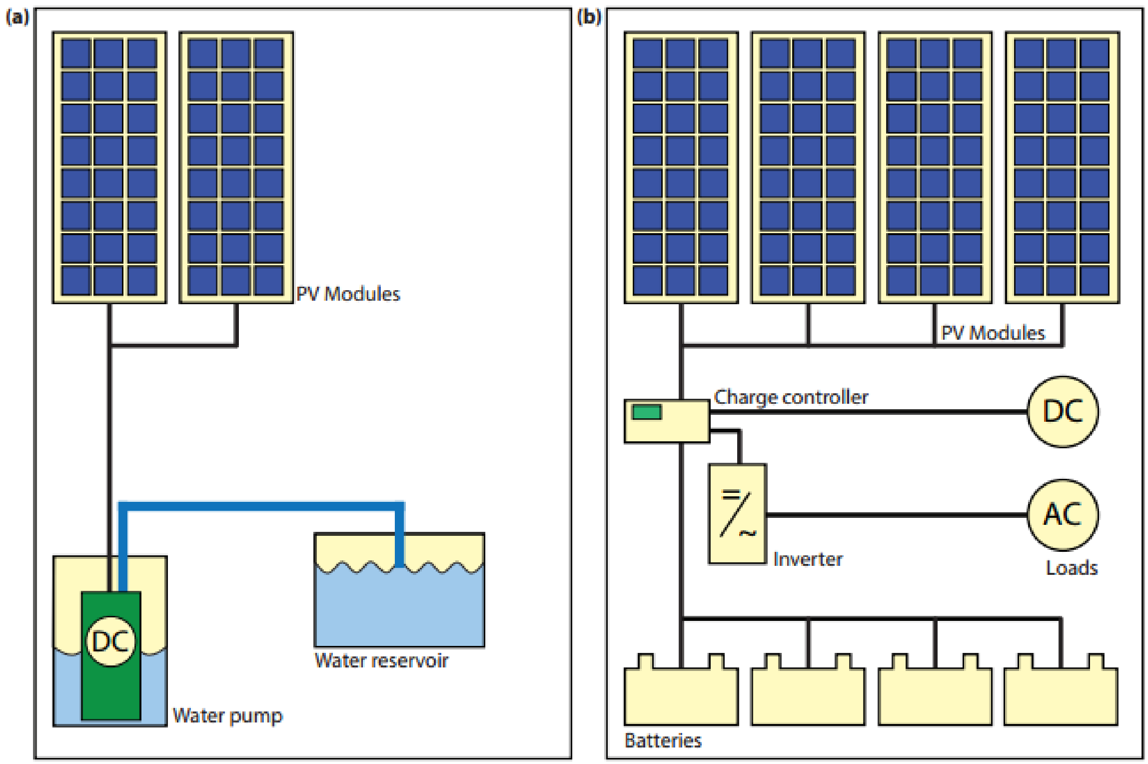
Introduction to PV systems

Introduction

After we have discussed the fundamental scientific theories required for solar cells in Part II and have taken a look at modern PV technology in Part III, we now will use the gained knowledge to discuss complete PV systems. A PV system contains many different components besides the PV modules. For successfully planning a PV system it is crucial to understand the function of the different components and to know their major specifications. Further, it is important to know the effect on the location of the (expected) performance of a PV system.

Types of PV systems

PV systems can be very simple, consisting of just a PV module and load, as in the direct powering of a water pump motor, which only needs to operate when the sun shines. However, when for example a whole house should be powered, the system must be operational day and night. It also may have to feed both AC and DC loads, have reserve power and may even include a back-up generator. Depending on the system configuration, we can distinguish three main types of PV systems: stand-alone, grid-connected, and hybrid. The basic PV system principles and elements remain the same. Systems are adapted to meet particular requirements by varying the type and quantity of the basic elements. A



Schematic representation of (a) a simple DC PV system to power a water pump with no energy storage and (b) a complex PV system including batteries, power conditioners, and both DC and AC loads.

modular system design allows easy expansion, when power demands change.

Stand-alone systems

Stand-alone systems rely on solar power only. These systems can consist of the PV modules and a load only or they can include batteries for energy storage. When using batteries charge regulators are included, which switch off the PV modules when batteries are fully charged, and may switch off the load to prevent the batteries from being discharged below a certain limit. The batteries must have enough capacity to store the energy produced during the day to be used at night and during periods of poor weather. Figure 15.1 shows schematically examples of stand-alone systems; (a) a simple DC PV system without a battery and (b) a large PV system with both DC and AC loads.

Grid-connected systems

Grid-connected PV systems have become increasingly popular for building integrated applications. As illustrated in Fig. 15.2, they are connected to the grid via inverters, which convert the DC power into AC electricity. In small systems as they are installed in residential homes. the inverter is connected to the distribution board, from where the PV-generated power is transferred into the electricity grid or to AC appliances in the house. These systems do not require batteries, since they are connected to the grid, which acts as a buffer into that an oversupply of PV electricity is transported while the grid also supplies the house with electricity in times of insufficient PV power generation.

Large PV fields act as power stations from that all the generated PV electricity is directly transported to the electricity grid. They can reach peak powers of up to several hundreds of MW_p. Figure 15.3 shows a 25.7 MW_p system installed in Germany.

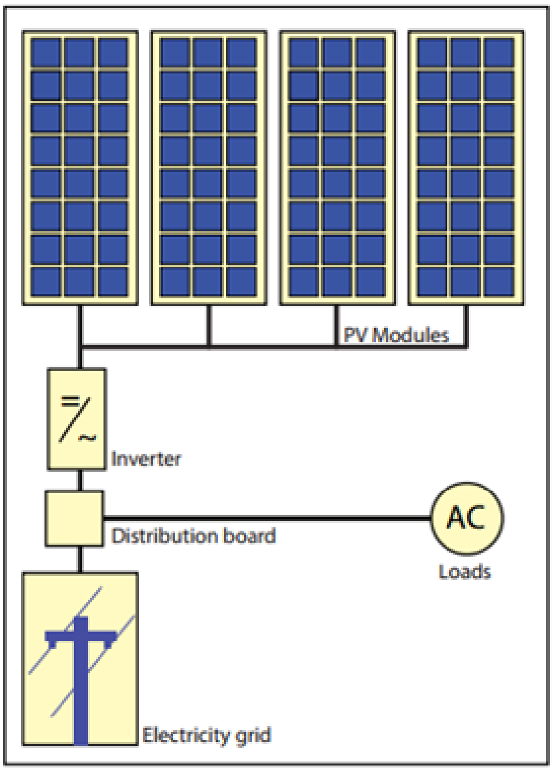


Figure 15.2: Schematic representation of a grid-connected PV system.

Figure 15.3: The 25.7 MW_p Lauingen Energy Park in Bavarian Swabia, Germany [82].

15.2.3 Hybrid systems

Hybrid systems consist of combination of PV modules and a complementary method of electricity generation such as a diesel, gas or wind generator. A schematic of an hybrid system shown in Fig. 15.4. In order to optimise the different methods of electricity generation, hybrid systems typically require more sophisticated controls than stand-alone or grid-connected PV systems. For example, in the case of an PV/diesel system, the diesel engine must be started when the battery reaches a given discharge level and stopped again when battery reaches an adequate state of charge. The back-up generator can be used to recharge batteries only or to supply the load as well.

15.3 Components of a PV system

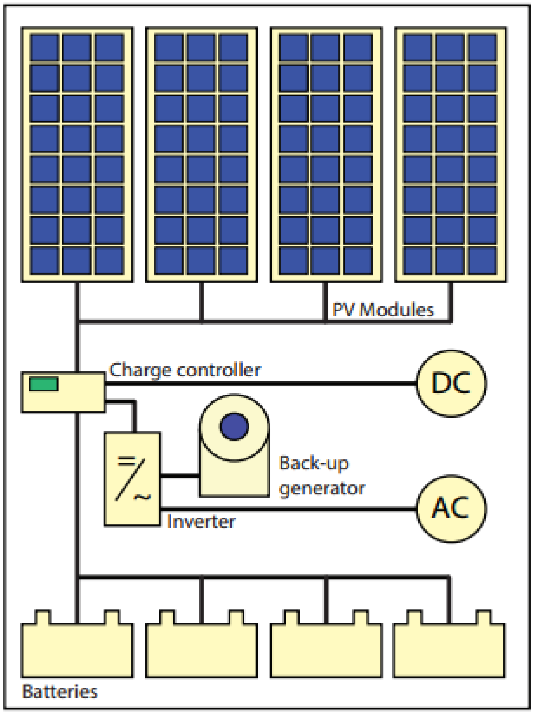


Figure 15.4: Schematic representation of a hybrid PV system that has a diesel generator as alternative electricity source..

As we have seen earlier in this book, a solar cell can convert the energy contained in the solar radiation into electrical energy. Due to the limited size of the solar cell it only delivers a limited amount of power under fixed current-voltage conditions that are not practical for most applications. In order to use solar electricity for practical devices, which require a particular voltage and/or current for their operation, a number of solar cells have to be connected together to form a *solar panel*, also called a *PV module*. For large-scale generation of solar electricity solar panels are connected together into a *solar array*.

Although, the solar panels are the heart of a *PV system*, many other components are required for a working system, that we already discussed very briefly above. Together, these components are called the *Balance of System* (BOS). Which components are required depends on whether the system is connected to the electricity grid or whether it is designed as a stand-alone system. The most important components belonging to the BOS are:

- A *mounting structure* is used to fix the modules and to direct them towards the sun.
- *Energy storage* is a vital part of stand-alone systems because it assures that the system can deliver electricity during the night and in periods of bad wheather. Usually, *batteries* are used as energy-storage units.
- *DC-DC converters* are used to convert the module output, which will have a variable voltage depending on the time of the day and the weather conditions, to a fixed voltage output that *e. g.* can be used to charge a battery or that is used as input for an inverter in a grid-connected system.
- *Inverters* or *DC-AC converters* are used in grid-connected systems to convert the DC electricity originating from the PV modules into AC electricity that can be fed into the electricity grid.
- *Cables* are used to connect the different components of the PV system with each other and to the electrical load. It is important to choose cables of sufficient thickness in order to minimise resistive losses.

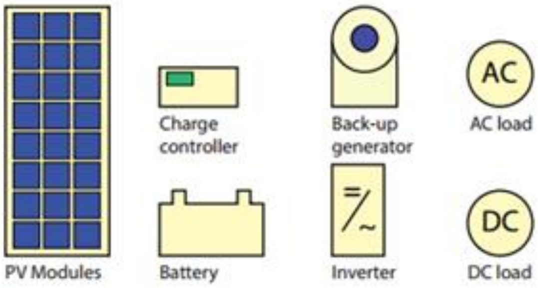


Figure 15.5: A schematic of the different components of a PV system.

Even though not a part of the PV system itself, the *electric load*, *i.e.* all the electric appliances that are connected to it have to be taken into account during the planning phase. Further, it has to be considered whether the loads are AC or DC loads.

The different compontents of a PV system are schematically presented in Fig. 15.5 and will be discussed in detail in Chapter 17.

Components of PV Systems

PV modules

In this section we will discuss *PV modules* (or solar modules), their fabrication and how to to determine their performance.

Before we start with the actual treatment of PV modules, we briefly want to introduce different terms. Figure 17.1 (a) shows a crystalline *solar cell*, which we discussed in Chapter 12. For the moment we will consider only modules that are made from this type of solar cells. A *PV module*, is a larger device in which many solar cells are connected, as illustrated in Fig. 17.1 (b). The names PV module and solar module are often used interchangeably. A *solar panel*, as illustrated in Fig. 17.1 (c), consists of several PV modules that are electrically connected and mounted on a supporting structure. Finally, a *PV array* consists of several solar panels. An example of such an array is shown in Fig. 17.1 (d). This array consists of two strings of two solar panels each, where *string* means that these panels are connected *in series*.

Series and parallel connections in PV modules

If we make a solar module out of an ensemble of solar cells, we can connect the solar cells in different ways: first, we can connect them in a *series connec-*

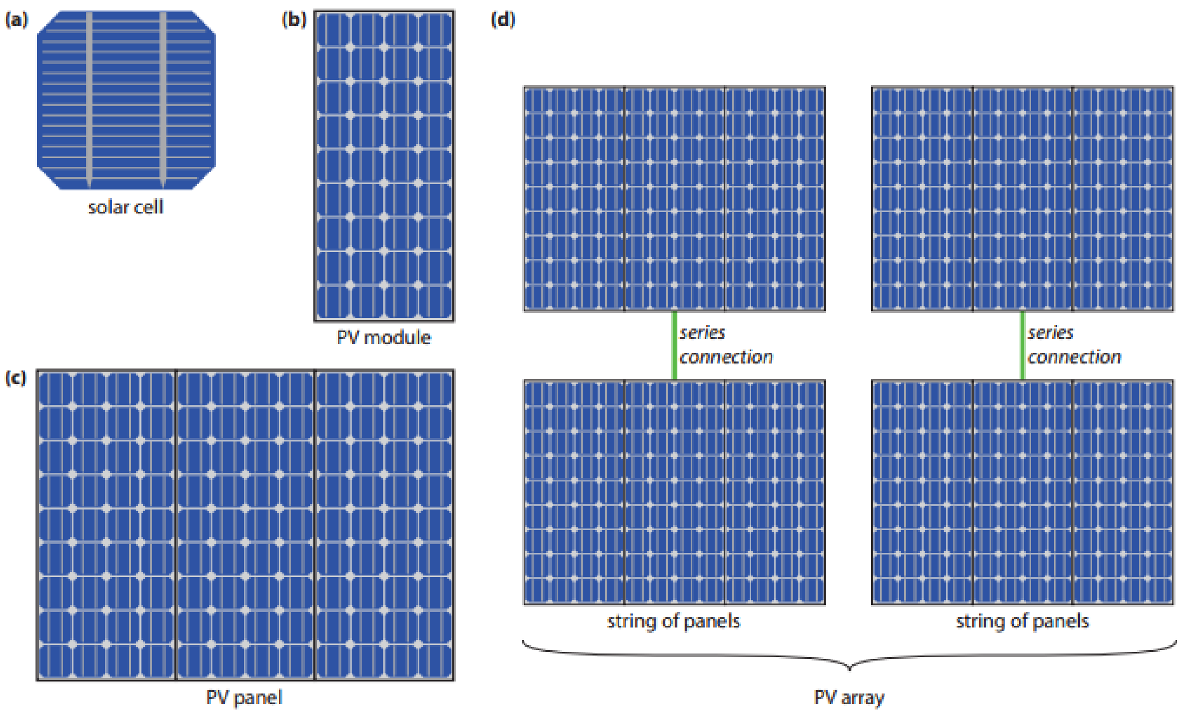


Figure 17.1: Illustrating (a) a solar cell, (b) a PV module, (c) a solar panel, and (d) a PV array.

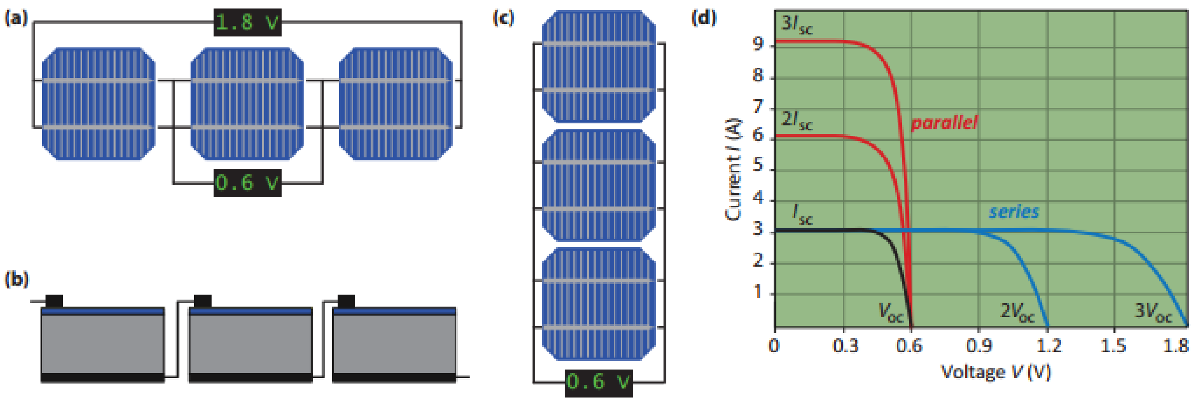


Figure 17.2: Illustrating (a) a series connection of three solar cells and (b) realisation of such a series connection for cells with a classical front metal grid. (c) Illustrating a parallel connection of three solar cells. (d) *I*-*V* curves of solar cells connected in series and parallel.

tion as shown in Fig. 17.2 (a). In a series connection the voltages add up. For example, if the open circuit voltage of one cell is equal to 0.6 V, a string of three cells will deliver an open circuit voltage of 1.8 V. For solar cells with a classical front metal grid, a series connection can be established by connecting the bus bars at the front side with the back contact of the neighbouring cell, as illustrated in Fig. 17.2 (b). For series connected cells, the current does not add up but is determined by the photocurrent in each solar cell. Hence, the total current in a string of solar cells is equal to the current generated by one single solar cell.

Figure Fig. 17.2 (d) shows the *I*-*V* curve of solar cells connected in series. If we connect two solar cells in series, the voltages add up while the current stays the same. The resulting open circuit voltage is two times that of the single cell. If we connect three solar cells in series, the open circuit voltage becomes three times as large, whereas the current still is that of one single solar cell.

Secondly, we can connect solar cells in *parallel* as illustrated in Fig. 17.2 (c), which shows three solar cells connected in parallel. If cells are connected in parallel, the voltage is the same over all solar cells, while the currents of the solar cells add up. If we connect *e.g.* three cells in parallel, the current becomes three times as large, while the voltage is the same as for a single cell, as illustrated in Fig. 17.2 (d).

The reader may have noticed that we used *I*-*V* curves, *i.e.* the *current-voltage* characteristics, in the previous paragraphs. This is different to Parts II and III, where we used *I*-*V* curves instead, *i.e.* the *current density - voltage* characteristics. The reason for this switch from *J* to *I* is that on module level, the total current that the module can generate is of higher interest than the current density. As the area of a module is a constant, the shapes of the *I*-*V* and *J*-*V* curves of a module are similar.

For a total module, therefore the voltage and current output can be partially tuned via the arrangements of the solar cell connections. Figure 17.3 (a) shows a typical PV module that contains 36 solar cells connected in series. If a single junction solar cell would have a short circuit current of 5 A, and an open circuit voltage of 0.6 V, the total module would have an output of $V_{oc} = 36 \cdot 0.6\,\mathrm{V} = 21.6\,\mathrm{V}$ and $I_{sc} = 5\,\mathrm{A}$. However, if two strings of 18 series-connected cells are connected in parallel, as illustrated in Fig. 17.3 (b), the output of the module will be $V_{oc} = 18 \cdot 0.6\,\mathrm{V} = 10.8\,\mathrm{V}$ and $I_{sc} = 2 \times 5\,\mathrm{A} = 10\,\mathrm{A}$. In general, for the *I*-*V* characteristics of a module consisting of m identical cells in series and n identical cells in parallel the voltage multiplies by a factor m while the current multiplies by a factor n. Modern PV modules often contain 60 (10×6), 72 (9×8) or 96 (12×8) solar cells that are usually all connected in series in order to minimise resistive losses.

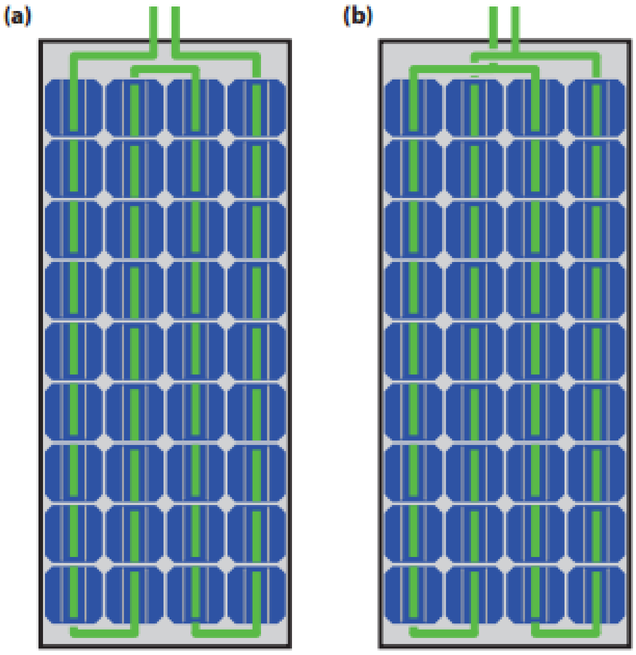


Figure 17.3: Illustrating a PV module consisting (a) of a string of 36 solar cells connected in series and (b) of two strings of 18 solar cells each that are connected in parallel.

MAXIMUM POWER POINT TRACKING

Maximum power point tracking (MPPT) concept is very unique to the field of PV Systems, and hence brings a very special application of power electronics to the field of photovoltaics. The concepts discussed in this section are equally valid for cells, modules, and arrays, although MPPT usually is employed at PV module/array level. As discussed earlier, the behaviour of an illuminated solar cell can be characterised by an I-V curve. Interconnecting several solar cells in series or in parallel merely increases the overall voltage and/or current, but does not change the shape of the I-V curve. Therefore, for understanding the concept of MPPT, it is sufficient to consider the I-V curve of a solar cell. The I-V curve is dependent on the module temperature on the irradiance. For example, an increasing irradiance leads to an increased current and slightly increased voltage, as illustrated in Fig. 17.7. The same figure shows that an increasing temperature has a detrimental effect on the voltage.

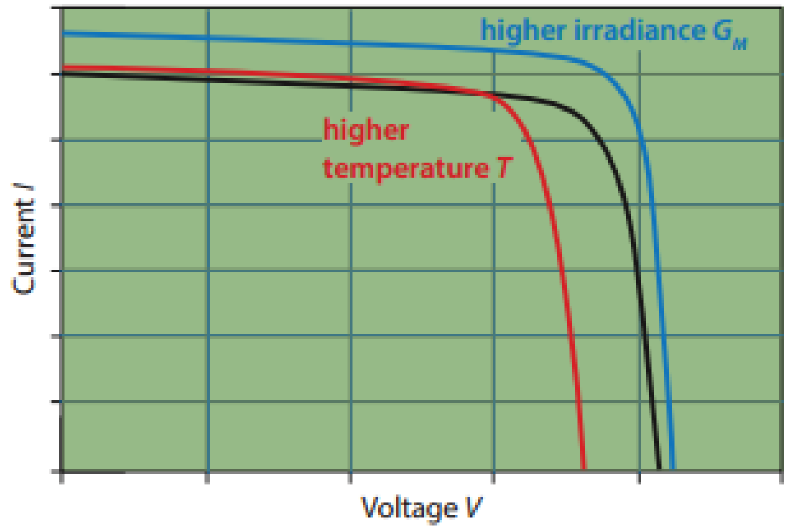


Figure 17.7: Effect of increased temperature T or irradiance G_M on the I-V curve.

Now we take a look at the concept of the operating point, which is the defined as the particular voltage and current, at that the PV module operates at any given point in time. For a given irradiance and temperature, the operating point corresponds to a unique (I, V) pair which lies onto the I-V curve. The power output at this operating point is given by

$$P = I \cdot V. \tag{17.1}$$

The operating point (I, V) corresponds to a point on the power-voltage (P-V) curve, shown in Fig. 17.8. For generating the highest power output at a given irradiance and temperature, the operating point should such correspond to the maximum of the (P-V) curve, which is called the maximum power point (MPP). If a PV module (or array) is directly connected to an electrical load, the operating point is dictated by that load. For getting the maximal power out of the module, it thus is imperative to force the module to operate at the maximum power point. The simplest way of forcing the module to operate at the MPP, is either to force the voltage of the PV module to be that at the MPP (called V_{mpp}) or to regulate the current to be that of the MPP (called I_{mpp}). However, the MPP is dependent on the ambient conditions. If the irradiance or temperature change, the IV and the P-V characteristics will change as well and hence the position of the MPP will shift. Therefore, changes in the I-V curve have to be tracked continuously such that the operating point can be adjusted to be at the MPP after changes of the ambient conditions. This process is called Maximum Power Point Tracking or MPPT. The devices that perform this process are called MPP trackers. We can distinguish between two categories of MPP tracking:

• Indirect MPP tracking, for example performed with the Fractional Open Circuit Voltage method.

• Direct MPP tracking, for example performed with the Perturb and Observe method or the the Incremental Conductance method.

All the MPPT algorithms that we discuss in this section are based on finding the and tuning the voltage until V_{MPP} is found. Other algorithms, which are not discussed in this section, work with the power instead and aim to find IMPP.

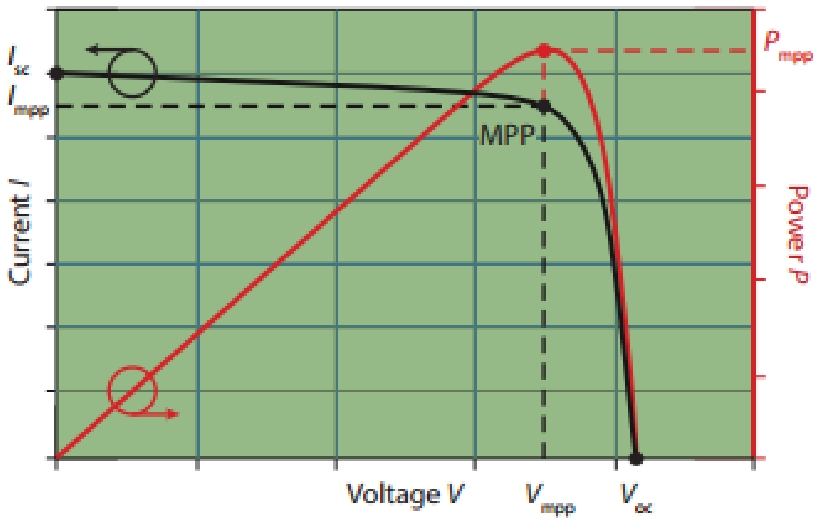


Figure 17.8: A generic *I*-*V* curve and the associated *P*-*V* curve. The maximum power point (MPP) is indicated.