15
PV modules

In this chapter we will discuss the most important issues concerning *PV modules*. Before starting with the actual discussion, we have to introduce some important terms. Figure 15.1 (a) shows a crystalline silicon (c-Si) *solar cell*, which were discussed in Chapter 12. Until Section 15.6 we will consider only modules made from c-Si solar cells. In a *PV module* many solar cells are connected, as illustrated in Fig. 15.1 (b). The names PV module and solar module are often used interchangeably. As illustrated in Fig. 15.1 (c), a *solar panel* consists of several PV modules that are electrically connected and mounted on *one* supporting structure. Finally, a *PV array* consists of several solar panels. An example of such an array is shown in Fig. 15.1 (d). This array consists of two strings of two solar panels each, where *string* means that these panels are connected *in series*.

15.1 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 connection* as shown in Fig. 15.2 (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 produce 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 busbars at the front side with the back contact of the neighbouring cell, as illustrated in Fig. 15.2 (b). For series connected cells, the currents do not add up. In contrast, the current of the whole string is determined by the cell that delivers the smallest current. Hence, the total current in a string of solar cells is equal to the smallest current generated by one single solar cell.

Figure Fig. 15.2 (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

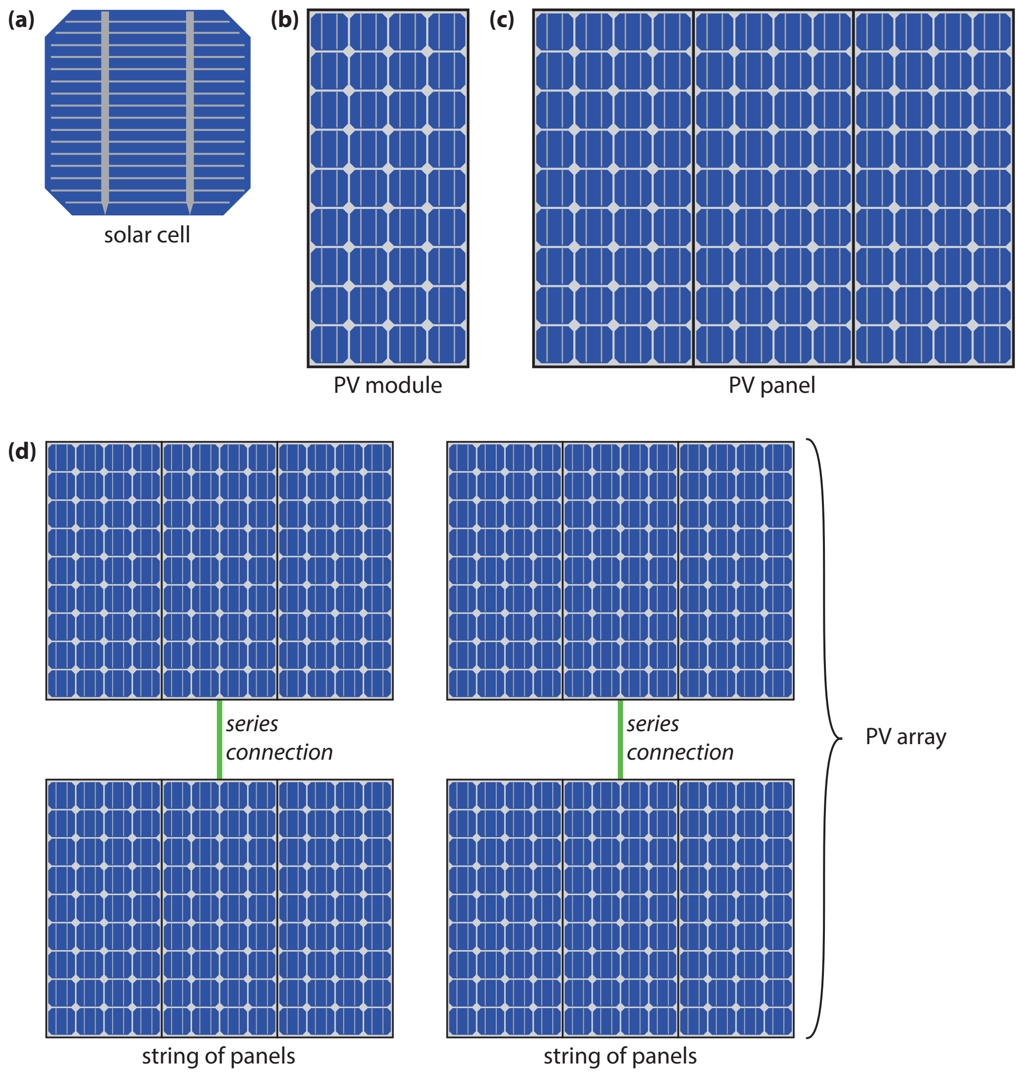

Figure 15.1: Illustrating (a) a solar cell, (b) a PV module, (c) a solar panel, and (d) a PV array.

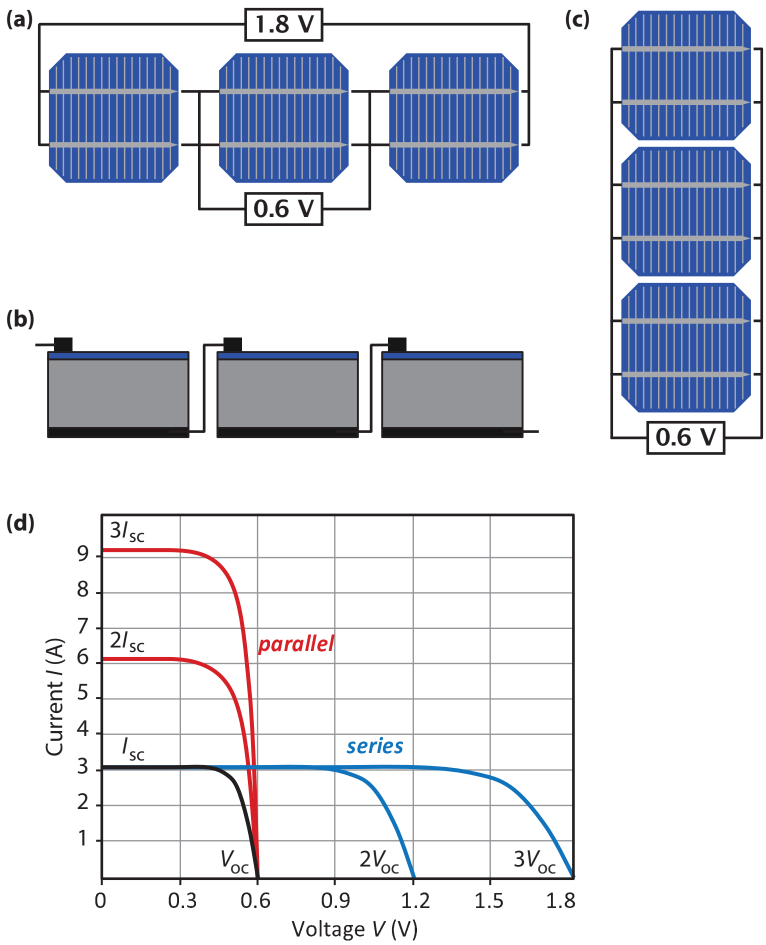

Figure 15.2: Illustrating (a) a series connection of three solar cells and (b) realisation of such a series connection for cells with a classical front metal grid. (c) Illustrating a parallel connection of three solar cells. (d) *I*-*V* curves of solar cells connected in series and parallel.

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 solar cell.

Secondly, we can connect solar cells in *parallel* as illustrated in Fig. 15.2 (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 with the same *I*-*V* characteristics in parallel, the current becomes three times as large, while the voltage is the same as for a single cell, as illustrated in Fig. 15.2 (d).

Several strings of series-connected solar cells can be connected in parallel, which is sometimes done in PV modules for rural applications. In principle, also several groups of parallel-connected cells can be connected in series. However, this is usually not done in reality as cells connected in parallel, the currents become higher which increases resistivity losses in the cables.

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 the previous chapters, 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 PV modules usually are characterised by short-circuit and maximum-power-point currents instead of current densities. 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 15.3 (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 $V_{oc} = 36 \cdot 0.6\,\text{V} = 21.6\,\text{V}$ and $I_{sc} = 5\,\text{A}$.

However, if two strings of 18 series-connected cells are connected in parallel, as illustrated in Fig. 15.3 (b), the output of the module will be $V_{oc} = 18 \cdot 0.6\,\text{V} = 10.8\,\text{V}$ and $I_{sc} = 2 \times 5\,\text{A} = 10\,\text{A}$. In general, for the *I*-*V* characteristics of a module consisting of m identical cells in series and n identical strings in parallel the voltage multiplies by a factor m while the current multiplies by a factor n. Modern PV modules often contain 60, 72 or even 96 solar cells that are usually all connected in series in order to minimise resistive losses and to enable high voltages that are required for an efficient operation of the inverter, which we will discuss in Section 19.2.

15.2 PV module parameters

Like for solar cells, for a PV module a set of parameters can be defined to characterise the module. The most common parameters are the *open circuit voltage* V_{oc}, the *short circuit current* I_{sc} and the *module fill factor* FF_M. On module level, we have to distinguish between the *aperture area efficiency* and the *module efficiency*. The *aperture area*, also known as *active area* is defined as the area of the PV-active parts only. The total module area is given as the aperture area plus the dead area consisting of the interconnections and the edges of the module. Clearly, the aperture area efficiency is larger than the module efficiency.

Characterising the the efficiency and the fill factor of a PV module is less straightforward than measuring voltage and current. In an ideal world with perfectly matched solar cells and no losses, one would expect that the efficiency and fill factor at both module

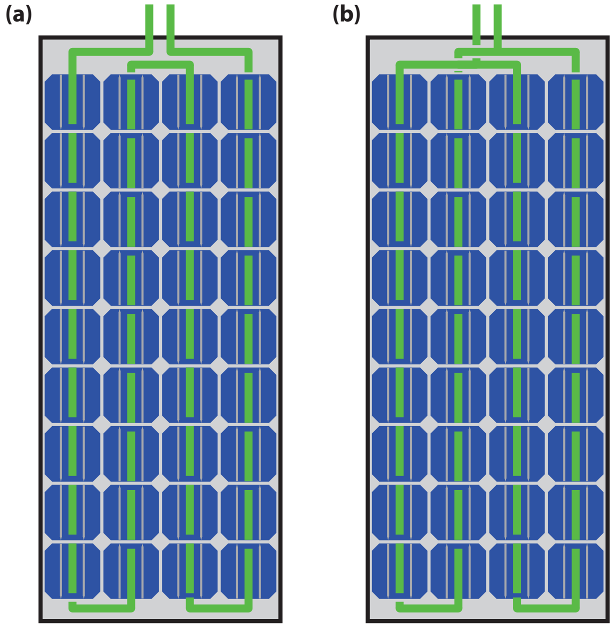

Figure 15.3: Illustrating a PV module consisting (a) of a string of 36 solar cells connected in series and (b) of two strings of 18 solar cells each that are connected in parallel.

and cell levels to be the same. This is not the case in real life. As mentioned above, the cells are connected with each other using interconnects that induce resistive losses. Further, there might be small mismatches between the cells interconnected cells. When $m \times n$ cells are interconnected, the cell with the lowest current in a string of m cells in series determines the module current.

The reason for mismatch between individual cells are inhomogeneities that occur during the production process. Hence, in practice PV modules perform a little less than one would expect from ideally matched and interconnected solar cells. This loss in performance translates to a lower efficiency at module level. If the illumination across the module is not constant or if the module heats up non-uniformly, the module performance reduces even further. Often, differences between cell and module performance are mentioned in datasheets that are provide by the module manufacturers. For example, the datasheet of a Sanyo HIT-N240SE10 module gives a cell level efficiency of 21.6%, but a module level efficiency of only 19%.

15.3 Bypass diodes

PV modules have so-called *bypass diodes* integrated. This diodes are necessary, because in real-life conditions, PV modules can be *partially shaded*, as illustrated in Fig. 15.4 (a). The shade can be from an object nearby, like a tree, a chimney or a neighbouring building. It also can be caused by a leaf that has fallen onto the module. Partial shading can have sig-

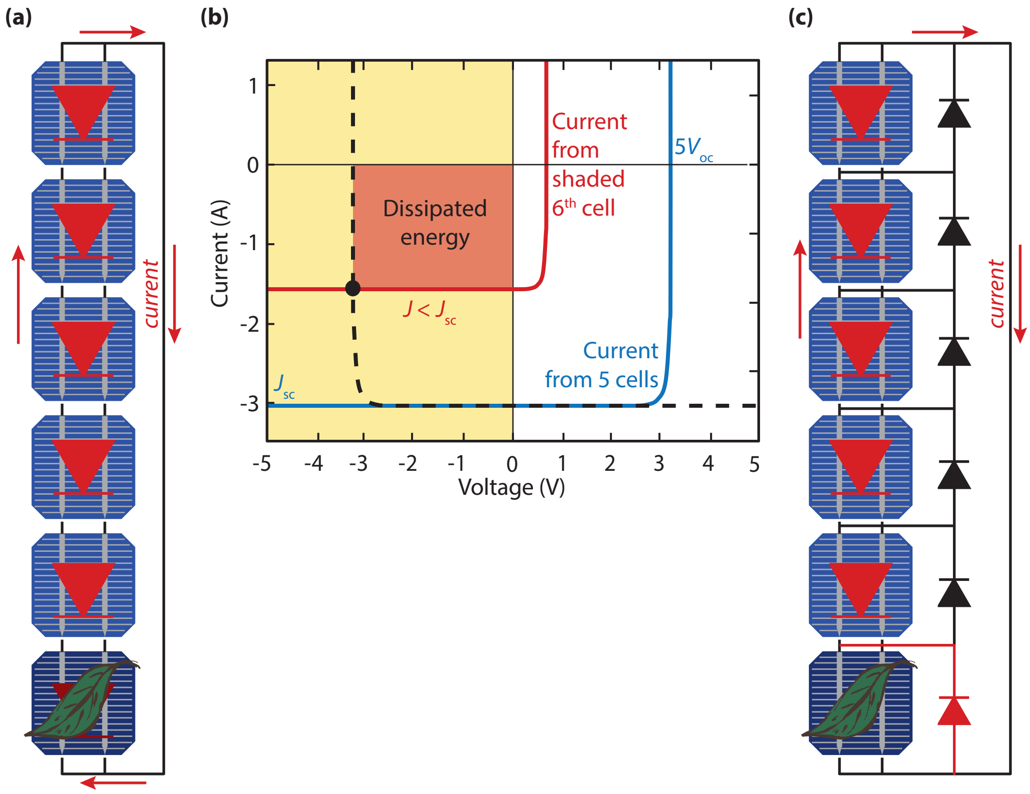

Figure 15.4: Illustrating (a) string of six (short-circuited) solar cells of which one is partially shaded. (b) This has dramatic effects on the *I*-*V* curve of this string. (c) Bypass diodes can solve the problem of partial shading.

nificant consequences for the output of the solar module. To understand this, we consider the situation in which one solar cell in the module shaded for a large part shaded. For simplicity, we assume that all six cells are connected in series. This means that the current generated in the shaded cell is significantly reduced. In a series connection the current is limited by the cell that generates the lowest current; this cell thus dictates the maximum current flowing through the module.

In Fig. 15.4 (b) the theoretical *I*-*V* curve of the five unshaded solar cells and the shaded solar cell is shown. The five unshaded solar cells act like a reverse bias source on the shaded solar cell, which can be graphically represented by reflecting their IV curve through the $V = 0$ axis (see dashed line in Fig. 15.4 (b)). Hence, the shaded solar cell is operated at the intersection of its *I*-*V* curve and the reflected curve. As this operating point is in its reverse-bias area, it does not generate energy, but starts to dissipate energy and heats up. The temperature can increase to such a critical level, that the encapsulation material cracks, or other materials wear out. Further, high temperatures generally lead to a decrease of the PV output as well. In addition, a large reverse bias applied to the cell may induce *junction breakdown*, which potentially can damage the cell.

These problems occurring from partial shading can be prevented by including bypass diodes in the module, as illustrated in 15.4 (c). As discussed in Chapter 8, a diode blocks the current when it is under negative voltage, but conducts a current when it is under positive voltage. If no cell is shaded, no current is flowing through the bypass diodes. However, if one cell is (partially) shaded, the bypass diode starts to pass current through because of the biasing from the other cells. As a result current can flow around the shaded cell and the module can still produce the current equal to that of a unshaded single solar cell. In real PV modules, not every solar cell is equipped with a bypass diode, but groups of cells share one diode. For example, a module of 60 cells, that are all connected in series forming one string, can contain three bypass diodes, where each diode is shared by a group of 20 cells.

15.4 Fabrication of PV modules

As we discuss in Section 15.5, a PV module must withstand various influences in order to survive a lifetime of 25 years or even longer. To ensure such a long lifetime, the PV module must be built of well-chosen components. Fig. 15.5 shows the typical components of a crystalline silicon PV module. For real PV modules, the layer stack may consist of different materials depending on the manufacturer. The major components are [105]:

- *Soda-lime* glass with a thickness of several millimetres, which provides mechanical stability while being transparent for the incident light. It is important that the glass has a low iron content as iron leads to absorption of light, which can lead to losses. Further, the glass must be *tempered* in order to increase its resistance to impacts.
- The solar cells are sandwiched in between two layers of *encapsulants*. The most common material is *ethylene-vinyl-acetate* (EVA), which is a thermoplastic polymer (plastic). This means that it goes into shape when it is heated but that these changes are reversible.
- The *back layer* acts as a barrier against humidity and other stresses. Depending on the manufacturer, it can be another glass plate or a composite polymer sheet. A material