Part III

Renewable Energy Technologies

Renewable energy is revolutionising energy availability. Climate change motivates the search for energy sources that do not generate a carbon footprint. It must be recognised that traditional energy sources require water for primary fuel extraction, refining, transportation and electricity generation. Solar PV and wind energy can decouple the dependency between water and energy with much smaller carbon and water footprints. The other crucial property is the scalability of solar PV and wind, from stand-alone household production to villages and regions. However, the sun does not shine all the time and the wind is sometimes too calm. Therefore, the intermittent generation of energy from solar and wind has to be managed. Stored energy must be available when the primary sources are not available.

Solar PV is the topic of Chapter 8 and wind energy is briefly discussed in Chapter 9. Various ways to handle the intermittent nature of these energy sources are described in Chapter 10. Some issues of energy management are discussed in Chapter 11. The coordination of different production units and different loads is critical. The use of energy storage capacity makes it necessary to carefully plan the energy flow in the stand-alone system.

Chapter 8

Solar PV

> "Solar power is a safe form of nuclear energy. We are using fusion reactions that are 150 million *km* away to make light that we then convert to electricity with photovoltaic modules."
>
> **Professor Sean White (2016).**

The end user of a solar photovoltaic (PV) system does not need to know any details of the technology to convert sunlight to electric power. It is sufficient to know that a certain number of solar cells will produce a certain amount of electric power. However, it may be useful to have some background knowledge about the solar technology to estimate what can be expected in terms of both productivity and potential problems.

In Chapter 8.1 the fundamental properties of sunlight and its influence on solar panels are described. Characteristic parameters of solar cells are explained in 8.2. Solar cell technology – how sunlight is converted to electricity – is briefly explained in 8.3. It is important to realise the importance of solar cell efficiency. Solar cell temperature is a key parameter determining efficiency. Solar cells are combined into systems, as described in 8.4. The solar PV energy potential for various

doi: 10.2166/9781780409443_0095

water operations is illustrated in 8.5. Economic aspects of solar PV operations are further reviewed in Chapter 12.

8.1 UTILISING THE SUN

The solar radiation that reaches the outer atmospheric layers of the Earth has a particular spectral profile. Its intensity is highest between the wavelengths 0.3 and 4 μm. About 7% of the extra-terrestrial spectrum energy intensity is at ultraviolet wavelengths, 47% in the visible range and 46% infrared.

8.1.1 Irradiance

Irradiance is the measure of solar *power* at a certain geographical location and is measured in W/m^2 (see also 3.5). A significant amount of solar radiation is attenuated as it travels through the atmosphere. This attenuation is due to:

- Absorption of solar radiation by different particles in the atmosphere,
- Backward scattering and reflection of solar radiation by air particles, water vapour, dust etc.

On a *clear* day some 80% of the radiation reaches the ground and is absorbed. Around 5% is scattered and reflected into space. 10–15% can be absorbed by particles in the atmosphere and typically 2% is reflected from the ground.

On a *cloudy* day 30–60% of the radiation can be reflected and 5–20% absorbed by the clouds. There is a diffuse radiation from the clouds, which reaches the ground, so the total irradiation at ground level may be 0–50% of the radiance. A solar irradiance of 1,000 W/m^2 is known in the PV community as *one equivalent sun.*

8.1.2 Global horizontal irradiance

A solar cell will absorb a combination of several parts:

- Direct radiation comes as a direct beam from the sun to the solar cell;
- Ground-reflected radiation is the part of the radiation that is first reflected on the ground and then reaches the solar cell.

The irradiance is quantified as *Global Horizontal Irradiance* (GHI) and is the total amount of solar energy incident on a horizontal surface, coming from both direct and scattered sunlight. GHI is a key parameter for solar PV applications. The GHI varies quite a lot depending on the geographical location: see Table 8.1. For most of the off-grid locations that we are focusing on – rural areas in Africa and developing Asia – the GHI is high. There are several sources of information of the solar irradiance around the world, for example the Global Solar Atlas, published by the World Bank Group (http://globalsolaratlas.info).

Table 8.1 Annual Global Horizontal Irradiance (GHI) in various regions of the world.

Region	**GHI Range** *kWh/m*^{2} **Per Year**
Africa	1,600–2,700+
Middle East & North Africa	1,700–2,700+
Latin America & Caribbean	1,000–2,700+
North America	<700–2,600+
Europe	<700–2,100
South and Central Asia	1,400–2,400
East Asia	1,000–2,300
South-East Asia & Pacific	900–2,600

Source: Data from WEC (2016, Chapter 8).

The irradiation depends on the elevation angle α of the sun. For low elevation angles the direct solar radiation needs to cross a larger section of the atmosphere to reach any point on the ground, so the attenuation factor is larger. The length of the solar radiation path through the atmosphere compared to the shortest path is indicated as air mass (AM). $AM1$, i.e. one air mass, indicates a vertical path from sea level to the outer atmospheric layer at standard barometric pressure with the sun directly overhead. The AM is defined to be zero outside the atmosphere. A simplified, and widely reported, relationship links AM to the solar elevation α: $AM = 1/\sin\alpha$. This equation does not hold for very low values of the solar elevation α. Conventionally, AM is given a value of 38 for $\alpha \approx 0$.

The most widely used solar PV systems are flat panels. The useful power amount of a solar beam striking a plane surface is its normal component with respect to the plane. The solar power absorbed by the surface depends on the beam's angle of incidence θ with the normal direction from the plane. The maximum power transfer (h_0) is reached when the incident beam is perpendicular to the surface: that is $\theta = 0$. For angles different from zero, the share of useful power collected on the plane (h) is $h(\theta) = h_0 \cdot \cos\theta$.

8.2 SOLAR PV CHARACTERISTIC PARAMETERS

Solar PV cells generate DC power in rough proportion to the total incident solar irradiation. The PV power output also depends on the PV cells' operating temperature. As the temperature increases the output power will decrease, as shown in 8.3.

Solar electricity systems are given a rating in kilowatts peak (kW_p). This is essentially the rate at which it generates energy at peak performance, for example at noon on a sunny day. Obviously, the true electricity generation rate will depend on the system's orientation, shading and how sunny the location is. Solar irradiation of 1 kW/m^2 is used to define standard testing conditions (STC). To give an order of magnitude: for each m^2 of commercial solar cells there is about 140–200 W of electric power produced. In other words: the solar cell will have an efficiency of the order 14–20% (see also 8.3.2).

When sunlight hits a solar cell, it will show a typical characteristic relation between output current and voltage. Four parameters characterise the solar cell:

- The short circuit current I_{SC},
- The open circuit voltage V_{OC},
- The peak power $P_{\max}$, and
- The fill factor FF.

These parameters will determine the efficiency of the cell.

If the module were to be short-circuited then the current I_{SC} would flow through the circuit, at least in theory. The short circuit current represents the upper limit of the current that is generated by the solar cell. It is proportional to the irradiation and the cell area. Commercial silicon solar cells can deliver a high current. For a cell of $150 \cdot 150$

mm^2 it typically reaches almost nine amps under standard conditions of 1 kW/m^2.

If the cell electrodes are disconnected, then there is no current flowing through the external circuit. The voltage under this condition is called the open circuit voltage (V_{OC}) and is the maximum voltage that a solar cell can deliver. Typically, the value for commercial solar cells is of the order 0.4–0.6 *V*. The relation between the short circuit current and the open circuit voltage is illustrated by Figure 8.1.

Solar cells can deliver between 35 and 200 W/m^2.

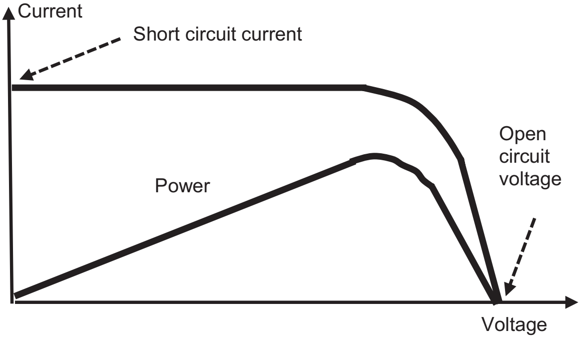

Figure 8.1 Principal relation between the current and voltage in a solar cell. The short circuit current I_{SC} is obtained by zero voltage and the open circuit voltage V_{OC} is reached by zero current (=open circuit). The maximum output power is reached by a certain combination of current and voltage.

The maximum power – called the peak power $P_{\max}$ (indicated as W_p or kW_p) – from a cell can be delivered at specific values of the output voltage and the corresponding current. This is illustrated in Figure 8.1. Naturally the electric circuitry should be designed so that the cell can deliver peak power under the given external conditions. Typically, a solar cell of $150 \cdot 150$ mm^2 can deliver a maximum power exceeding 5 *W* or of the order 200 W/m^2.

The ratio between the theoretical maximum power generated by a solar cell ($P_{\max}$) and the product of the open circuit voltage and the short circuit current is called the fill factor, FF:

$$FF = \frac{P_{\max}}{V_{OC} \cdot I_{SC}}$$

The fill factor is typically around 0.75–0.8.

Based on the four characteristic parameters, the conversion efficiency can be calculated and is defined at the ratio between the maximum generated power $P_{\max}$ and the incident power (P_{in}) under standard testing conditions (STC):

$$\eta = \frac{P_{\max}}{P_{in}} = \frac{V_{OC} \cdot I_{SC} \cdot FF}{P_{in}}$$

The efficiency is further examined in Chapter 8.3 and has typical values between 0.14 and 0.2.

8.3 CONVERSION OF SUNLIGHT TO ELECTRICITY

Solar PV technology uses a semiconductor material to directly convert sunlight to electricity. In such a material the absorption of the light raises an electron to a higher energy state. This electron will then move from the solar cell into an external circuit. The electron delivers its energy in the external circuit and then returns to the solar cell. Almost all PV energy conversion uses semiconductor materials, where a *p-n* junction has been created, to allow this to happen.

8.3.1 Photovoltaic technologies

There have been various photovoltaic technologies for solar cells developed to date:

- Crystalline silicon technology, either monocrystalline or polycrystalline,
- Thin-film, such as amorphous silicon, and
- Organic cells.

The dominating technology is based on either monocrystalline or polycrystalline silicon (c-Si) technology. Monocrystalline cells are produced by slicing wafers (up to 150 *mm* diameter and 200 microns thick) from a high-purity single crystal boule. Four sides of the silicon ingots are cut off to make high-purity silicon wafers. As a result, a large part of the original silicon becomes waste, which adds to the production cost.

Polycrystalline cells are manufactured by sawing a cast block of silicon first into bars, and then into wafers. The process is simpler than the process to make monocrystalline since less silicon waste is produced. The main trend in crystalline silicon cell manufacturing involves a move toward polycrystalline technology. There is an intense effort to reduce the costs to produce monocrystalline cells, so they might be more competitive with polycrystalline in the future. According to Fraunhofer (2016) silicon-based PV technology accounted for about 94% of the total production in 2016. The share of polycrystalline technology is now about 70% of total production.

Thin-film cells are constructed by depositing extremely thin layers of photosensitive materials onto a backing such as glass, stainless steel or plastic. Thin-film manufacturing processes result in lower production costs compared to crystalline technology. The most popular thin-film technology is amorphous (uncrystallised) silicon (a-Si). In amorphous silicon solar cells there is much less silicon used (about 1%) compared to crystalline silicon cells. The cells can be grown in any shape or size and can be produced in an economical way. Amorphous silicon cells have been used for a long time in non-critical outdoor applications and consumer products such as watches and calculators. They are now being adopted by other larger-scale applications. In 2016, the market share of all thin-film technologies amounted to about 6% of total annual production (Fraunhofer, 2016). Mass production costs of thin-film modules are lower than for crystalline silicon modules. They also have a higher heat tolerance.

The drawback of the thin-film technology is its lower efficiency, due to the active material used. Commercially interesting materials are cadmium telluride (CdTe) and copper-indium/gallium-diselenide/disulphide (CIS/CIGS).

There are several technologies based on organic cells. This includes dye-sensitised solar cells, antenna cells, molecular organic solar cells and completely polymeric devices. The dye cell is the closest to commercialisation; the other organic cells are still in their development phase.

In addition to thin-film and organic solar cells, compounds such as perovskite are being used in developing the next generation of solar PV cells. This is a mineral ($CaTiO_3$) that was discovered in the Ural mountains in Russia in 1839 and is named after the Russian mineralogist Lev Perovski (1792–1856). Efficiencies of perovskite cells have jumped from 3.8% in 2011 to over 20% by 2014. While perovskite solar cell technology is yet to be consolidated for commercial use, cells can be very cheap as they are made from relatively abundant elements such as ammonia, iodine and lead. However, there are severe doubts in terms of environmental safeguarding over the use of lead. Moreover, perovskite cells are unstable and deteriorate significantly when exposed to the environment. The replacement of lead with a more environmentally friendly element and the improvement of stability will be important objectives for researchers in this field. Developing a tandem solar cell with correct matching of the top perovskite and bottom silicon cell is expected to increase the conversion efficiency of the solar cells well beyond 25%, while keeping manufacturing costs low.

8.3.2 Efficiency of PV modules

A major concern about photovoltaic technologies is their efficiency, life and performance over time. Commercial PV modules convert around or less than 20% of the solar energy irradiation to electricity. The efficiencies of PV panels also have a temperature coefficient, and generally degrade in rising temperatures.

Efficiencies of solar PV modules are typically of the order 14–21%. Table 8.2 shows that monocrystalline panels have the highest efficiency. They also have the longest expected lifetime. Polycrystalline and thin-film solar modules have a lower cost but are less efficient. Therefore, there is a trade-off between production cost and efficiency to find the best choice of panel type.

Efficiencies of solar PV modules are of the order 14–21%.

Table 8.2 Efficiencies of commercial solar PV modules.

Type of Panel	Efficiency (Commercial) %	Efficiency (Best Lab) %
Monocrystalline	17–21	24.4–26.7
Polycrystalline	14–16	19.9–22.3
Thin-film CIGS	14–16	19.2–21.7
Thin-film CdTe	14–16	18.6–21.0
Thin-film a-Si	13.8–15.5*	11–14

Source: Data from Fraunhofer (2015, 2016).
*Based on modules with highest efficiency of their class.

Research on solar cells is making an impressive improvement to available efficiencies. With a combination of concentrated solar PV and new semiconductor technologies (III–V multijunction concentrator solar cells) the achievable efficiency reached 46% in 2017 (Fraunhofer, 2016).

Solar panels have a relatively long lifetime and often have a 25-year performance guarantee. This is of course an unusually long time, so the solar panels are considered to be the most reliable parts of a solar system. There is still, however, a degradation in performance and power output decreases about 1% in the first ten years.

Solar panels have a commonly guaranteed lifetime of 25 years.

Another problem of efficiency loss is caused by what is called mismatch. One would assume that the cells in the sun would deliver their power to the load. Instead the shaded cells may absorb the power and significantly reduce the total efficiency of the module. If a single cell gets no light, then the current in all the series-connected cells will be reduced to the same current level as the shaded cell. So, one poorly performing cell (in the shade) can cause the total power output to be reduced to zero. More seriously, there may be a local heating of the module that will damage some cells. This local heating, however, can be avoided by using protective electronics – so-called bypass diodes – around the cell.

Energy is needed to produce solar cells. One way to express the energy requirement is to calculate how much time is needed for the solar PV system to produce as much energy as was required to manufacture the panels. The payback time naturally depends on the geographical location.

The payback time is displayed as function of the irradiation (in kWh/m^2/year) in Fraunhofer (2016). The energy payback time (EPBT) for 1,000 kWh/m^2/year (typically for northern Europe) is found to be 2.1 years, and for 1,700 kWh/m^2/year (typically for southern Europe) is 1.2 years. In comparison to the highest irradiation in Africa, which is more than 2,700 kWh/m^2/year (Table 8.1), the EPBT can be as short as 0.7 years. Assuming the solar panels have a 25-year lifetime, this means that a solar PV system in Africa can produce as much as 35 times the energy that was needed to produce it.

Example 8.1: *Power Density of a Large-Scale Solar PV*

A large solar PV array located in the Mojave Desert, California is documented in Rever (2017). The huge plant of 550 MW covers an area of 16 km^2. Assuming that all the area is covered with solar panels it means that the power production from the solar modules is 34 W/m^2.

8.3.3 Temperature dependence

As well as the irradiation the solar module output is dependent on the temperature. Under standard testing conditions the module temperature is assumed to be the same as the ambient temperature. However, under normal conditions the solar cells are heated and will give out a lower voltage output when they are subjected to heating. A typical PV module will convert only 14–20% of the sunlight into electric power; the rest of the sunlight is converted into heat. The resulting operating temperature will be at a point between the heat loss to the surroundings and the heat generated in the module.

Heating of the solar panel can result in a power loss of around 8% in a year. This of course means that less energy will be produced by the PV system. It can also reduce the PV system's lifespan. The temperature dependence is expressed as the relationship between the short circuit current and the open circuit voltage versus the temperature, respectively. The temperature coefficients indicate how much the voltage and current change for each degree increase from the standard 25°C reference.

The open circuit voltage will typically *decrease* by 0.4% for every degree K deviation from the reference, while the short circuit current will *increase* by 0.05% for every degree increase. Since the voltage depends more on temperature than the current, the power will decrease as the temperature increases.

Solar power output decreases with increasing temperature.

Example 8.2: *Power Requirement for Irrigation Pumping*

Temperature will influence the required solar power for pumping. The required hydraulic energy is multiplied by a temperature factor

$$\frac{1}{1-\alpha(T_{\text{cell}}-T_0)}$$

where α is the PV module temperature coefficient, which is of the order 0.45%/°C (Campana *et al.*, 2016). T_{cell} is the solar cell temperature and T_0 a reference temperature of 25°C. So, with a cell temperature of 50°C the required power will increase with around 13%.

Global warming because of climate change may increase the risk of lower efficiency, since the PV cells operate best at around 25°C.

Efficiency loss caused by increasing temperature has been studied in Saudi Arabia (Adinoyi & Said, 2013). A module temperature increase from 38°C to 48°C resulted in 10.3% losses in efficiency. This corresponds to a temperature coefficient $\alpha = 0.9\%/°\text{C}$ (now based on the reference temperature 38°C). The annual loss of energy due to high temperature was estimated at around 10%.

8.3.4 Floating PV systems

In some areas of the world, notably in China, Japan, South Korea, India, the UK, France, Italy, Brazil, Portugal and the U.S., there has been a move towards floating solar panel technology, in which the panels float on the surface of water. This will have some appealing consequences including that the panels do not take up valuable space on land. Japan has implemented more than 55 MW_p of floating solar across 45 plants. This includes the floating solar panels on the

Yamakura Dam, the world's largest floating PV project (see Chapter 13). The water cools the panels, which will make them perform more efficiently. Since elevated temperatures can reduce the lifespan of the panels, they have a longer lifespan than ground-mounted panels. Another important secondary effect is that the panels prevent evaporation from the water surface. Since evaporation is a major problem in many water reservoirs (Olsson, 2015, Chapter 10) in water-scarce areas, it has been suggested that covering the dam with solar panels partially solves this problem.

8.3.5 Technology development

As indicated, in coming years there will almost surely be an emphasis on developing solar cells with higher efficiency, improved thermal stability and a longer PV module lifetime. There is also an interesting move towards raising the energy efficiency by capturing the light from the rear side of the solar cell, and to capture diffused light. As indicated, the conversion efficiency will exceed 20% within a few years and the degradation will be as low as <0.3%/year (WEC, 2016, Chapter 8).

8.4 SYSTEMS OF SOLAR CELLS

A single PV cell is usually quite small and may typically produce 1–2 *W* of power. By connecting solar cells in series and parallel large *modules* are formed that can produce a higher power output. Typically, 36 cells are connected in series to form a module. There are many different types of PV modules and their structure depends on the type of application. Then the modules can be further connected to larger units called arrays. Therefore, typical solar PV systems are built up from a number of modules and arrays.

A single solar cell provides a voltage of around 0.6 *V*. By connecting several cells in series, a higher voltage will be produced. It is common that modules are designed to be able to charge a 12 *V* battery. Thirty-six cells in series provides an open circuit voltage of 21 *V*. Depending on temperature reductions and best operating conditions the module may produce 17–18 *V*. Since it will only require around 15 *V* to charge a 12 *V* battery, this will be sufficient. The voltage may well drop due to less light or further voltage reduction in parts of the system. More on batteries can be found in Chapter 10.3.

The current from a module is a function of the size of the solar cells and their efficiency. A single solar cell has an area of typically 100 cm^2. As a rule of thumb, the current from a module will be of the order 3.5–4 A. Having 36 cells in the module means that the area is 3,600 cm^2, or a square of $60 \cdot 60$ cm^2.

The most common PV system consists of flat-plate cells. Another more advanced category is systems where the sunlight is concentrated. Concentrating optics are used to focus the light on small solar cells. This increases the power output and decreases the number of required cells.

A complete solar PV system needs more than the solar cells to provide the output electric power. It includes a charge controller, an inverter (see 4.5) and batteries that provide adequate electric power. Pumps are usually powered by alternating current (AC) motors, which are typically more robust and cheaper than direct current (DC) motors. Since the solar panels produce DC currents a DC/AC converter is required for the AC pumps.

Energy storage is a concern (further examined in Chapter 10) and batteries are used to store the PV output in order to smooth or sustain the system operation when the solar irradiation is insufficient. Control system aspects are illustrated in Chapter 11.

8.5 ENERGY REQUIREMENTS FOR WATER OPERATIONS

Example 8.3: *Solar PV Output for Pumping, Eastern India*

The actual power production of a solar array over a day for different months in eastern India has been measured by Rahman and Bhatt (2014). Since the solar irradiance varies with the length of the day, the DC power output from a 3 kW_p solar array in the Patna region was measured every 15 minutes on bright sunshine days in different months of the year. The array tracked the sun with a manual mechanism. From 9:00 to 14:30 in almost all months, except November to January, the power rating of the array was within the interval range 1.9–2.4 *kW*. As a result, a 2.2 *kW* (3 *hp*) pump could be operated at close to rated power for six hours daily. So, a rule of thumb for eastern India is that a solar array of 1 kW_p can provide sufficient power for a 1 *hp* (0.74 *kW*) solar pump.

Example 8.4: *Small-Scale Solar PV for Desalination, Jordan*

This solar PV desalination plant is in Jordan and is designed to produce fresh water from brackish water, as reported by Hoffman (2017a). The plant delivers 95 *kWh* per day to produce 22 m^3 of fresh water from 37 m^3 of brackish water. This gives an energy requirement of $95/22 = 4.3$ kWh/m^3 to produce fresh water (compare 5.3.5).

8.6 FURTHER READING

Varadi *et al.* (2018), Chapter 2, present a pedagogic introduction to solar power technologies. An easy-reading introduction to the various technologies is also found in WEC (2016, Chapter 8). Goswani (2015) contains a comprehensive description of major developments in solar energy. A case study on rural electrification in Papua New Guinea is presented by Kaur and Segal (2017).

White (2014) is an easy-read introduction into solar PV, while White (2016) is a comprehensive text on solar PV and installation.

ABB has published an ambitious technical application paper on solar PV systems (ABB, 2018) that explains their principles, connection, mounting and economy.

SAM (System Advisor Model) is a detailed performance and financial modelling tool for solar and wind energy applications (https://sam.nrel.gov/). SAM is based on computer models developed at NREL, Sandia National Laboratories, the University of Wisconsin and other organisations. SAM bases its calculations on an extensive and freely available database of meteorological and climate data for several locations worldwide. It provides the dynamic operation profile, on an hourly basis, of solar thermal generation, solar PV generation and wind energy and can therefore support the simulation of load performance of e.g. desalination systems. SAM contains online databases for both solar PV and wind: the NREL National Solar Radiation Database for solar resource data and ambient weather conditions as well as the NREL WIND Toolkit for wind resource data.

The site PV Education Network (http://pveducation.org), developed by Christiana Honsberg and Stuart Bowden at Solar Power Labs at Arizona State University (ASU) (http://pv.asu.edu/), contains a wealth of good illustrations and practical examples of PV generation and solar energy. Parida *et al.* (2011) present an overview of solar PV technologies.

The basic calculation for the dynamic energy yield of solar flat panels is presented in the form of Python code by Piani (2017).