

Chapter 2

Photovoltaic Technologies

Any economic analysis of solar PV generation should start with a description of its technical aspects. The aim is not to address the technical details which are rather the work of thousands of researchers and engineers around the world over since several decades ago but to address those technical attributes which are likely to have economic effects, either because they affect key variables such as the cost of equipment or because they are drivers of the perspectives of this energy source for electricity.

Cells represent the most essential part of a photovoltaic system. These devices are able to generate a continuous electricity current from the solar radiation being captured. A cell is made up of two layers, termed p and n , which are made up of a semiconductor material, silicon in general, with a contact zone between them. Both layers are doped with small quantities of boron (semiconductor type p) and phosphorous. The former creates a deficit of free electrons (i.e. it has a positive polarity), whereas the later has a surplus of free electrons (or negative polarity). When solar radiation (which has a spectrum of 200–2600 nm) impacts, then the photons with a wavelength equal or above 1110 nm are absorbed by the p/n region of contact.¹ Most of these photons only produce heat, but others lead to other electrons acquiring the necessary energy to freely move, leading to a flow which is deviated to an external circuit.² In order to increase the performance of the cells, some technologies have been developed to concentrate the phosphorous near the conductors and also to facilitate the movement of electrons towards the posterior side of the cell, from where they will be evacuated.

¹The absorption value is the one for silicon. There are other semiconductor elements with different bands of absorption, although all of them are between 1000 and 1800 nm.

²As a general rule, between 10 and 20 % of the incidental sunlight is transformed into electricity. See Boyle (2004: 68–74), Kaltschmitt and Rau (2007: 229–238), Sauer et al. (2007: 238–244), Andrews and Jelley (2007: 135–140), Randolph and Masters (2008: 436–440), Liu et al. (2009) and Prentiss (2015: 147–151).

Silicon, which is the main material in the cells, undergoes an intense physical and chemical transformation from its raw state to its conversion in ingots which are previous to the production of the cells.³ This material has several purity degrees. Those ingots will have a diameter of between 10 and 15 cm and a length of a metre. They are cut in wafers, which are thin platelets. This is a very delicate task, in which a lot of material was lost a few years ago. Currently, the precision of the cutting operation allows obtaining commercial cells with a square form and a width of 1/4 mm or less.

Given that a typical cell produces on average a continuous current of 3 A to 0.5 V (i.e. a power capacity of 1.5 W), the cells are currently put together in groups of 60 or 96. They are connected between each other through electric circuits, leading to photovoltaic panels or modules, whose dimensions are $1 \times 1.5 \times 0.04$ m. The surface was about 1 m² years ago, but today, it can reach 1.5 m², which leads to a power capacity of between 260 and 320 W (MIT 2015: 21). The cells are encapsulated in order to protect them from humidity and weather. For this, EVA (ethylene-vinyl acetate) and Tedlar (polyvinyl fluoride) films are used. In addition, in order to increase the absorption of photons, the glass (with a low iron content) is impregnated with an antireflective coating substance. This substance determines the colour of the module: in the case of c-Si, any colour but blue would involve a loss in performance. The modules are usually framed in aluminium, or between glasses in case they are integrated in places where the light has to pass through.

The modules, which are equipped with a connection box in their back, are connected among each other. They are definitely the most visible elements of a solar PV farm. If the modules are ground-mounted installations, they usually are arranged according to the following three possibilities:

- Long rows of fixed panels in an inclined position which stand up against metallic structures above the ground.
- Long rows of modules in an inclined position which stand up against a metallic reticulate pegged on the ground.
- Arrays or set of panels which stand up against solid metallic pillars making up huge sails. These structures usually have gears which track the sun. Tracking systems increase the performance of the system by an additional $\sim 15\%$, although they also increase the cost of the plant.

A specific type of modules is concentration modules. They aim to focus the rays from the sun with optical systems in order for the radiation to impact on the cell with the greatest possible intensity. A Fresnel lens (from Augustin Jean Fresnel, its creator in 1822) is used to concentrate the light. It is made up of methacrylate and

³This is a long process, with some highly sophisticated stages, which is quite energy-intensive. More details on the manufacturing process for the different types of cells are provided in Boyle (2004: 75–78) and Sauer et al. (2007: 245–251).

has a square form, with a side of 120 mm long and a width of 3 mm. The lens concentrates the image of the sun on a prism which, in turn, homogenizes the flow impacting on the cell (Xie et al. 2011). The particular optics of the lens determines the degree of concentration of the rays. A common classification divides panels into 2–5 suns, 5–300 suns and more than 300 suns, although they can reach a thousand suns (Jäger-Waldau 2011: 25; SunShot 2012: 72).

Concentration modules are more expensive, given their complex design. However, they also have a greater performance in order to host the so-called multijunction cells, i.e. cells made up of very thin films of different semiconductor elements. They are piled-up structures which are equivalent to the union of several cells, which increases the absorption of the width of solar radiation and, thus, the conversion rate of light into electricity. The mass manufacturing of multijunction cells continues to be a challenge, given its complex architecture, as well as the fact that it uses relatively expensive materials (see below).

The concentration modules made up of multijunction cells always include mechanical systems for a strict tracking of the sunrays.⁴ Since the cells are subject to high temperatures, their cooling is recommendable. It is, thus, a photovoltaic technology for large solar PV farms, placed in sites with strong and continuous direct solar radiation, i.e. without clouds (Sauer et al. 2007: 245).

The bifacial modules (with two surfaces) are another particular type of modules. They are able to capture the frontal incident sunlight and the one being reflected on the back (Fraunhofer ISE 2015: 68). In order to achieve this, the reflexivity of the land on which the panels are placed should be increased. If this is a flat roof, it can be covered with appropriate patina. If they are on the ground, foil or similar materials can be used. The global increase in the performance of the solar farm means that the land cannot be used for other purposes (see below).

All the solar PV installations have a wide panoply of auxiliary devices, jointly called balance of system (BoS), including the monitor systems for the farm, its protection elements (such as diodes, fuses, and switches), the meter measuring the energy generated and fed into the grid, the wires corresponding to the converter which increases the intensity of the current to high voltage and the sensors to detect possible intruders. All in all, the inverter is the most prominent auxiliary component. Its mission is to transform the continuous current from the panels into alternate current.⁵

⁴Only an exact adjustment guarantees using the maximum of the normal direct irradiance, i.e., the rays which run parallel to the imaginary line from the sun to the receptor and which, under clear-sky conditions, represent between 60 and 80 % of the solar radiation impacting the Earth crust (Drury et al. 2012: 10-1 and 10-3). However, the most common panels operate with both direct and indirect sunlight, although this entails a penalty in terms of performance.

⁵It should be pointed out that the commercialization of modules with alternate current started in 1998. The reason was that they incorporated a small device for the conversion of the electricity flow (Perlin 1999: 196).

2.1 Cells: Types and Efficiency

Taking a very general perspective, two types of photovoltaic cells can be distinguished: silicon and the rest. Regarding the former, silicon has very different properties depending on the size and regularity (shape) of its crystals. There is a trade-off between its capacity to absorb the photons (which is greater the more amorphous the material is) and the capacity to transmit the generated electric current, which is better the more crystalline it is. This dilemma has considerable economic implications: the amorphous alternative is the cheapest, but also the least efficient and vice versa. Regarding the rest of the cells, they are made up of semiconducting substances which are close to silicon in the periodic table of elements. Therefore, they have similar photoelectric properties. Unfortunately, most of them are rather scarce materials. For some authors, this scarcity generates doubts about their role in the future development of the sector, an issue addressed in the last section of this chapter.

In order to concretize the different types of cells and panels, the following distinction is deemed appropriate:

1. Cells made up of crystalline silicon (c-Si). A further distinction between mono-crystalline and multi- or poly-crystalline cells can be made. The former are more efficient, show a better performance but are also more expensive. Crystalline cells usually have a width of $<200\text{ }\mu\text{m}$ (micron). Their manufacturing is divided into six stages (silicon production, silicon purification, silicon crystal growth, wafer slicing, cell fabrication and module assembly) during which large amounts of material and energy are consumed. They are the most widespread alternative, after their price experienced a significant reduction between 2009 and 2012.
2. Gallium arsenide (GaAs) and GaInP (with indium and phosphorous) cells. They both had initially high-performance rates: cells with a performance of 28.8 % in the laboratory and panels with a 24.1 % performance rate (MIT 2015: 25). Their performance is even higher in the concentration modules. They are expensive cells due to, both, the price of materials and their manufacturing costs. They are usually placed on flexible ground, in order to reduce their cost. They have been used in panels feeding spatial devices and in concentration modules with Fresnel lens.
3. Thin-film cells are formed by the deposition of semiconductor materials above a substrate (glass, plastic, etc.) using photolithographic methods in order to fix the circuits. Their width is only between 0.3 and $3\text{ }\mu\text{m}$.⁶ On the one hand, there are amorphous silicon cells (a-Si) isolated or forming tandem cells, in which a microcrystalline silicon layer ($\mu\text{c-Si}$) is added to the a-Si layer (MIT 2015: 24). There are also thin films made up of very thin silicon crystals, i.e. thin-film c-Si

⁶For comparative purposes, a human hair has a width of about $100\text{ }\mu\text{m}$ and a red blood cell of about $7\text{ }\mu\text{m}$.

cells. The production of all these cells requires much less material and energy than the massive disc crystalline cells. Therefore, they are usually cheap, although their performance sharply degrades in the initial days of its performance (between 10 and 20 %). This is the long ago known Staebler–Wronski effect. Such degradation can be mitigated if the formation of the microstructure in the receiving layer is controlled, although its performance is still limited (Arvizu et al. 2011: 352). On the other hand, there are cells which combine materials in the columns III-V of the periodic table, including cadmium tellurium (CdTe), copper indium selenide (CuInSe₂, more commonly denominated CIS) and copper indium gallium selenide (CIGS). These compounds make up the multijunction cells with 2 or more layers of materials which can thus capture the maximum part of the solar width.⁷ Their performance is closer to c-Si, especially in the case of CIGS. If they are placed in concentration modules, then their performance increases substantially (Andrews and Jelley 2007: 148–153; Ullal and von Roedern 2007; Boyle 2010: 42; Hansen and Percebois 2010: 562; MIT 2015: 25). Within the large family of multijunction cells, those based on kesterite crystals (with copper, zinc, selenium, etc.) should also be mentioned. Although they have reached performances of 12.6 %, they should reach 15 % in order to improve their commercial possibilities, as well as developing appropriate mass-manufacturing methods (Siebentritt and Schorr 2012; MIT 2015: 30).

4. There are several types of cells in an experimental stage. They can be classified into emerging (when the concept is settled) and new ideas and developments which can potentially lead to technological breakthroughs (EUPVTP 2007: 41–48, 2011: 43; El Chaar et al. 2011). Among the former, we should mention those cells whose active layer is made up of organic molecules or dye-sensitized cells. They were initially known as Grätzell cells to honour one of his inventors, together with O'Regan, in 1991 (Andrews and Jelley 2007: 155; Arvizu et al. 2011: 353). There are several modalities of this alternative, with the photo-electrochemical cell of titanium dioxide (TiO₂) being the most promising one. These cells combine solid and liquid parts (liquid or gel electrolyte), with a performance of 11.1 % Standard Test Conditions (STC),⁸ which could raise to 15 % in a decade. Their functioning is currently being exhaustively investigated. However, they have a serious stability problem over time due to the well-known degradation of organic compounds when they are exposed to solar radiation

⁷Within the different alternatives for multijunction cells, those made up of two layers, i.e., the inferior one from Si and the superior one from a high-performance semiconductor material, have the greatest commercial possibilities (Fraunhofer ISE 2015: 33).

⁸It is defined as the energy generated by cells if they are exposed to lamps designed to reproduce an spectral distribution AM 1.5 and an energy density of 1000 W/m², i.e., the power of the solar radiation received by the Earth crust on a clear day, with an ambient temperature of 25 °C. The term AM 1.5 (Air Mass 1.5) refers to the attenuation of the solar radiation by the atmosphere. In other words, STC refers to laboratory optimal functioning conditions, which are closer to the ones existing in the cold but sunny winter mornings of temperate zones.

(Boyle 2004: 81–82). Their elaboration is expected to be simple and cheap, and a suitable solid substitute of its watery fraction (Sauer et al. 2007: 257–258). Within the radical recent developments, there are numerous alternatives of organic cells which combine different materials, such as indium tin oxide (ITO) with polymers. They use nanotechnologies, as it is the case of the colloidal quantum dots, that is, collections of some thousand atoms which have physical properties similar to both bulk semiconductor material and discrete molecules (Jourde 2005: 356; Allhoff et al. 2010: 44–53; García-Valverde et al. 2010; SunShot 2012: 72). The aim is to circumvent the aforementioned trade-off. Its commercial possibilities depend on the achievement of performances between 8 and 10 % and between 5 and 10 years of useful lifetime (currently about 2 years). This, together with a lower manufacturing cost, could lead to a generation cost below €cents 10/kWh (Kumar and Chand 2012: 377). Recently, cells made from perovskite have raised great expectations. It is a calcium titanium oxide mineral composed of calcium titanate, which was already identified in the XIX century. The first design of cells using this material achieved a performance of 3.8 % in 2009, increasing fast to 20.1 % in 2014 (both STC). It is expected that its theoretical limit (31 %) will be reached shortly. In addition to its high efficiency, the manufacturing of these thin-film cells through deposition of materials will be cheap (Sivaran et al. 2015). Finally, there are high expectations about the fully integration of graphene and related two-dimensional crystals with the materials used today in organic (and inorganic) cells in order to increase their conversion efficiency (Bonaccorso et al. 2015). However, most of these emerging technologies have serious problems of stability, due to oxygen and humidity (MIT 2015: 30, 241). As of today, none of the designs have left the laboratory. The construction of pilot plants is not expected in the near future. There is also the suspicion that its diffusion would require the revision of parts of the BoS. All in all, a lot of basic and applied research still needs to be carried out.

Once the typology of cells has been described, an indicator of efficiency should be defined. The operative capacity of the cells is measured through the relationship between the useful energy being recovered (watts) (E_{out}) and the total sunlight impacting the collector surface (watts) (E_{in}), per cm^2 exposed, expressed in percentage terms:

$$\eta = \frac{E_{out}}{E_{in}}$$

The efficiency (η) ratio of a cell can also be used with respect to the modules, especially for thin-film ones. Its value, for the same type of cell or panel, changes according to the conditions under which it operates. Among these, three stand out: the angles of orientation with respect to the sun, the possibility to track the sun and the environmental conditions under which it was calculated (Tester et al. 2012: 651–656). In the case of newly commercialized modules, the maximum performance

Table 2.1 Efficiencies of cells and modules in different situations

%	Type	Max. theoretical (approx.) ^a	Cell under standard test conditions	Module efficiency
Crystalline silicon	Mono	30	23/25	16/18
	Poly	26	17/21	12/15
Thin film (simple and x-junction)	a-Si/ μ c-Si	20	12/14	≤ 10
	CIS	26	16/18	
	CdTe	29	16/18	10/12
	CIGS	29	20	≥ 16
Concentration	Multijunction	50	32/45	≤ 31
Organic	–	15	10	–

^aThe maximum theoretical performance of a single-junction solar cell made up of a semiconductor material of optimal absorption (bandgap of 1.34 eV), without concentrating solar rays, is 33 % (or Shockley–Queisser limit). In the case of a multijunction dual cell, this limit raises up to 46 % and reaches 52 % for a triple-junction cell. The values shown in the column are slightly below, because the absorption capacity of materials is never exactly the optimal one

is called rated (or nominal) power. Once installed and active, its performance is usually lower. Table 2.1 shows the current values for the performance of crystalline cells and modules in different situations. It can be observed that there is a huge distance (around 30 %) between the performance of the cells under ideal conditions in the laboratory and the real performance of the most commonly commercialized modules. The maximum theoretical performance is also included. It is particularly high in the case of multijunction cells placed in concentration modules.

The performances rates shown in the table are the result of a long history of research efforts. Figure 2.1 shows the evolution of the performance rates of the c-Si cells, be them mono- or poly-crystalline, both under STC conditions, from 1952 to 2014 (elaborated using the data from Green 2009a; Green et al. 2008, 2009, 2010, 2011, 2012a, 2012b, 2013, 2014).

The figure covers all the modern history of the solar PV sector. The criteria for calculation of the performance have undergone some changes during those 60 years. This has led to adjustments in order to homogenize the data, including the following:

- We have taken into account the changes in the definition of the standard conditions. A standardized procedure to measure the performance was non-existent in the 1940s–1960s, although the performance rates were very low. In the 1970s and 1980s, the measure of performance followed the criteria set by NASA, both for the cells in the space as well as in Earth. In the early 1980s, quite a lot of research was done in order to achieve more efficient cells. This led to the publication of the ASTM standard in 1985 with AM 1.5 and 25 °C. The International Electrotechnical Commission (IEC) adopted it in 1989 as IEC 60904-3 Ed. 1. Finally, in April 2008, the IEC voted to accept the new global range, the IEC 60904-3 Ed. 2, which started to be applied since that year.

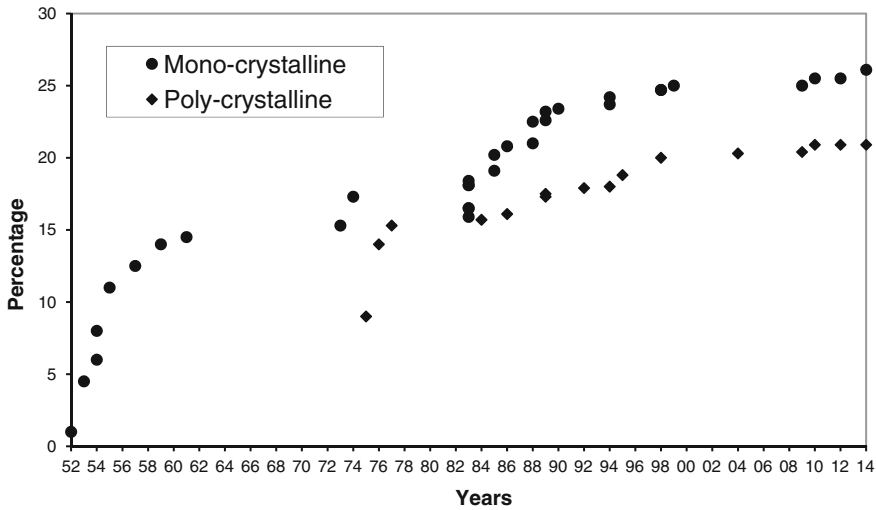


Fig. 2.1 Historical evolution of the STC performance of cells

- The proxies for the numerical values before 1974, especially for the Si mono-c case, have been ignored. There were negligible deviations.
- The historical data set of the performance of the Si mono- and multicrystalline cells from 1983 to 1999 has been recalculated using the last indicated standard. As explained by Green (2009a), the differences with the values which were declared at the moment and those being recalculated are only ± 0.005 or ± 0.01 %.
- Throughout these years, an important issue has been the impact of the surface of the material exposed to the light on the calculation of performance rates. The total, opening and lightened areas have been used in the past. In recent times, the last option has been used whereas, before 1985, the first one was more common.
- Both in the case of mono- and multicrystalline Si, the cells considered have a surface above 1 cm^2 operating in STC.

As observed in the figure, four periods can be distinguished regarding the performance of Si mono-c:

1. Performance rates were extremely low until the end of the 1950s. Solar PV generation was a little bit more than a scientific curiosity. In that decade, some research programmes were implemented with an aim to increase the performance. Diffused junctions were developed, the process of control of silicon crystall growth was improved, and doping with boron was introduced. The performance increased quickly, reaching 14.5 % in 1961.
2. The performance reached in the early 1960s was not clearly improved until 25 years later, although with some rather isolated cases such as a cell from Comsat Laboratories. Notwithstanding, the introduction of photolithography in

order to fix the links, the change in the texture of the cell surface and the improvements in the antireflective coating set the basis for the jump in performance rates in the 1980s.

3. In the mid-1980s, performance reached 18 %, which led to the current stage of the development of photovoltaic cells. Performance increased systematically to reach 25 % by the end of the 1990s. Some improvements were introduced, including light trapping and surface passivation.
4. During the XXI century, the performance under STC conditions has remained stagnant at 25 %.

Regarding the evolution of multi-c-Si cells, this has run in parallel with the mono-c Si, although at systematically lower levels. From the 1970s, the performance of best multicrystalline cells has been about 5 % points below the mono-crystalline ones. It should be remembered that the first attempts to use multicrystalline Si (instead of the more expensive mono-crystalline) by the pioneer researcher Darryl Chapin were a failure: the performance did not reach 1 %. The limit of 6 % was not exceeded until the mid-1970s. The change in the manufacturing process consisting of the slow cooling of the ingots ensured crystals of a satisfactory size and, thus, higher performance levels (Perlin 1999: 167).

It is very important to take into account that the slowing down of the performance of cells does not imply that the cost per kWh has also been stagnant. The processes and the p-Si (poly-silicon) manufacturing equipment have improved; the cells and modules have drastically reduced their costs; and the modules have improved their nominal performance (Montgomery 2010: 170). Focusing on performance, it should be mentioned that the commercial Si panels have experienced an average annual efficiency of 0.3 % in the last 10 years, reaching 16 % in 2013. In the case of the high-quality modules, the evolution of the maximum performance has been as follows: those of the SunPower X-series are expected to reach an efficiency of 26 % in 2015 (from 23 % in 2012); the heterojunction intrinsic thin-layer Sanyo/Panasonic (HIT S/P) reached 19 % in 2012 (from less than 14 % in 1997); the CdTe modules of First Solar are expected to reach 15 % in 2015, from 10 % in 2006; the thin-film module CIGS of Solar Frontier, whose efficiency was 12 % in 2011, will increase to 14 % in 2015; and the efficiency of the a-Si/ μ c-Si module of Oerlikon will go from 7.5 % in 2009 to 12 % in 2015 (IEA 2014: 12 and 27). It is noted in IRENA (2014: 35) that the performance of modules has improved by 3–4.5 % annually in the last 10 years.⁹ In addition, there have been some improvements in the BoS and a better knowledge of the distribution of the solar radiation as well as a greater experience in the construction and management of solar PV plants.

⁹Another aspect worth emphasizing is that the difference between the nominal performance and the real one is lower (3–5 %) for the best modules and much higher (6–8 %) for the lower-quality ones. Solar PV panels are not always commodities, but more sophisticated articles whose quality is a relevant attribute.

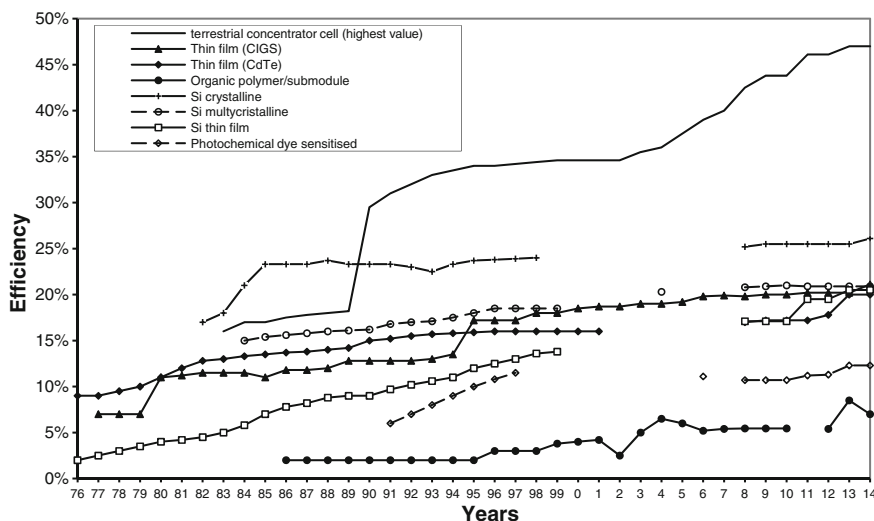


Fig. 2.2 Evolution of the STC performance of the different types of cells. *Source* Own elaboration combining data from Green et al. (2008, 2009, 2010, 2011, 2012a, 2012b, 2013, 2014), Kurtz (2012: 4–5) and GEA (2012: 828)

Figure 2.2 shows the different performance levels for the different types of existing cells, although for a shorter period than in the figure above. Four situations can be distinguished. Multijunction cells operating in concentration modules rank highest. Mono-crystalline silicon cells follow behind. These are slightly above the multicrystalline cells and other thin-film cells. At a long distance, we find the organic cells.

It should be stressed that the performance rate runs in parallel with the relative prices of the commercialized cells. Thus, their cost per watt is closer than suggested in the figure.

Regarding the trade-off between performance and costs, some observations are worth making. Si mono-c cells have a greater performance due to their better electrical connectivity, in spite of their limited capacity to attract photons. A-Si thin-film cells, in contrast, benefit from the fact that the more amorphous the material, the greater the capacity to absorb photons, although the lower its electrical conductivity. In addition, its material is less stable. Behind this result is the degree of crystallization of the Si being used, an attribute which is difficult to attain. This leads to mono-c cells being expensive but more efficient, whereas a-Si cells are cheap but their performance is worse. This is why efforts have focused on the design of thin-film cells with different microstructures: Si microcrystalline ($\mu\text{-Si}$), poly-crystalline (pc-Si) and nanocrystalline (nc-Si). The Si proto-crystalline and the Si poly-amorphous are also available (Sauer et al. 2007: 254). All these materials are made up of crystals of different sizes within an amorphous matrix. The aim is to each an intermediate technical position between the good electrical properties of c-Si and the favourable optical features of the amorphous one, taking into account

the economic implications at stake. This trade-off and the efforts to circumvent it would not be relevant if the kWh of electricity being generated was competitive in the electricity market.

The most relevant information shown by the previous figures is the stagnancy of the performance of the cells in the last 15 years. The persistence of this bad data explains that the experts coincide in that the manufacturing cost, from refining silicon to the assembly of the module, has been the key factor in the reduction of the cost of solar PV generation (kWh). The next chapter analyses the technoeconomic factors related to the manufacturing processes of cells and modules which have led to an enormous reduction of the cost of solar PV generation in the last years.

2.2 The Performance Under Real Operation Conditions

The performance of the cells under optimal conditions is, *grosso modo*, between 35 and 45 % above the performance of a plant under real operation conditions. The performance of the modules is slightly below its peak power capacity (or peak watt, W_p). In addition, the rest of devices of the system show losses and, above all, the overall installation is subject to weathering. All this negatively affects the energy performance of the plants, as explained in this section. The treatment is general, since each installation represents a particular case which deserves a specific treatment.

The performance of solar PV devices has been analysed following two different approaches:

- Estimating the energy balance of the useful life cycle of the cells and, thus, the modules.
- Quantifying the impact of all those circumstances which reduce the final electricity output, i.e. kWh of AC, with respect to the nominal performance of the different devices which make up the plant.

The first approach leads to indicators of general energy performance of solar PV. A common opinion some time ago was that the manufacturing of cells and modules required more energy than the one being generated by those systems throughout their lifetime. Thus, solar PV generation did not provide net energy to society, and supporting this technology was an environmental nonsense and economic wasteful. Although this argument held when the technology was in an initial stage, it has been contradicted by several studies being carried out since the 1980s, which show that the energy balance is positive. Two indicators are used in this type of investigations. The most common is the energy yield ratio (EYR), also known as the energy payback time (EPBT), and the energy productivity factor. The EYR measures the number of years which are needed for a module to generate the same amount of energy which was required in its manufacture, given the performance of the electricity system in which it operates (Raugei 2013). In the mid-1990s, this indicator was between 3 and 5 years for standard c-Si modules (Knapp and Jester

2000), with an average useful lifetime of 15–20 years. The EYR has currently been halved in the best locations, i.e. those with a high radiation. In addition, the useful lifetime of panels has increased to 30 years. For thin-film modules, this ratio would be even better. The second indicator, which is reciprocal to the first one, shows the number of times that the amount of energy being consumed in the manufacturing and installation of a solar PV system is generated by this system during its lifetime. Obviously, the extension of the lifetime of the module has been a key factor leading to a better score in those indicators.

The different types of losses which occur during the process of normal operation of a solar PV installation can be classified in five main categories:

- Those caused by weather and the incidences due to outdoor operation. Its effect is different in each moment.
- Those related to the quality of the main equipments and their installation and the technical limitations of the auxiliary devices.
- The care put in the maintenance activities.
- The impact of unexpected events.
- The impact of the degradation of the panel over the years.

Table 2.2 includes the first four factors. Among the climatic circumstances, technical limits, maintenance and unexpected events, the following are worth mentioning:

1. Excessive temperature. The modules made from crystalline stuff lose performance when the temperature is above 25 °C. A degree above such limit reduces the energy generated by 0.45–0.5 % (Barbose et al. 2006; Borenstein 2008: 7; Arvizu et al. 2011: 351). In the case of thin films, once the modules have been

Table 2.2 Impact on the performance of a solar PV installation

Performance factors	Solar energy available	Affecting the performance	Affecting functioning time
Geographical location	Latitude, clouds, fogs, snow and ice	Temperature, environment, angle, incidence of the rays, wind speed	Damages caused by storms
Design of the system	Correct orientation of the module	Dimensioning, inverters, shadows, incorrect solar tracking, transformer	Shadows, incorrect solar tracking
Quality of the equipment	–	Inaccurate technical specifications	Durability and reliability of components
Quality of the installation	–	Quality of connections, quality of assembly	Failure of system due to a defective installation
Maintenance	–	Cleaning of modules	Breakdowns
Unexpected events	–	Failure of the systems	Outrages, theft

stabilized, this reduction is lower (0.2 %). At the time of the maximum isolation in the summer in the Mediterranean latitudes, the temperatures of the modules may reach 70 °C and, on the other hand, the panels placed on roofs usually operate at higher temperatures compared to those placed on the ground.

2. Dust and droppings from birds bring dirt to the surface of the modules and may lead to a 4 % loss. Regular cleaning once every several weeks solves the problem. This process is not as easy as simply spraying jets of water over the panels. It is better to use steam and wipers.
3. The losses due to the fact that the solar rays do not impact perpendicularly on the surface of the solar PV module. This may lead to a reduction of 3–5 % of energy generation compared to the optimal conditions.
4. The range of solar radiation is not always uniform. The capacity of the cells may change by 1 % due to small changes in the range.
5. Given that the modules have different rated powers, there might be losses when connecting them between each other. This mismatch may lead to losses of between 1 and 4 %.
6. The presence of shadows during dawn and sunset. These shadows are caused by the arrays, buildings nearby, trees, etc. This problem, which affects both fixed as well as tracking systems, may lead to losses of 1–10 %. If the cells are constantly in a shadow area, the so-called hot spot problem may be caused, whereby there is a serious alteration of their behaviour, which leads to their destruction.
7. The functioning of the inverter. With an operating regime of 80–90 % of its rated power, the losses caused by the process of transformation of DC/AC can amount to 4–5 %.
8. The inexactitudes in the tracking system are another technical cause of energy loss. Notwithstanding, a strict computer control can minimize them.
9. Losses due to the resistance of the wires of the installation (between 1.5 % regarding the wires for DC and 2 % with respect to AC wires).
10. Some losses are related to special configurations of the solar PV systems. For example, their integration in the roof of buildings leads to losses of 4–5 % with respect to another which is separated from the building. The reason is the lack of ventilation. If they are integrated on the façade, the losses are between 7 and 10 % (Sauer et al. 2007: 270).

The deterioration of the modules due to the fact that they are subject to the weather conditions should be added to those specific causes of losses. Among the factors leading to the gradual deterioration ($\ddot{u}$) of the initial maximum power of the modules, the ultraviolet rays, the humidity of the environment, and the particulates and pollutants in the air (sand, salt, ashes and aerosols) are worth mentioning. After years of continuous outdoor exposure, the panels end up showing a poor image (Skoczec et al. 2008: 239): the encapsulating material is darkened (browning) and separated from the cells (delamination), the surface exposed to the sun has dirt which is impossible to remove, the external glass has cracked, the connection box suffers corrosion, and so forth.

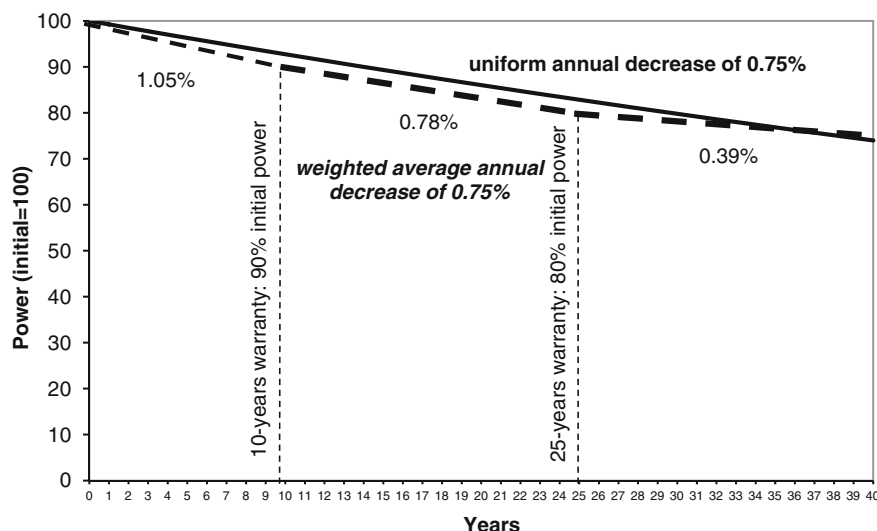


Fig. 2.3 Loss of the performance of the modules

Figure 2.3 shows an empirical pattern of the decline of the performance of c-Si modules. It has been built from the results of two decades of research on modules.¹⁰

The continuous line of the figure reflects the power provided by a given module at the start of each year, if its deterioration followed a uniform annual rate of 0.75 %.¹¹ Therefore, the initial 100 % value goes down to 74 % after 40 years. Thus, given that many manufacturers guarantee 90 % of the initial maximum power after 10 years, the rate of reduction in the performance cannot exceed 1.05%/year. If the 80 % of power is guaranteed for the 25th year, the rate of reduction should be a maximum of 0.78 %/year. Therefore, from the year 25–40, the pace of reduction should be adjusted to 0.39 %/year in order to maintain the uniform annual rate of 0.75 % for the whole life cycle. However, this rate, which is the lowest of the ones being mentioned above, is probably too optimistic for panels with lifetimes close to 40 years.¹²

¹⁰The work by Skoczec et al. (2008) is one of the first ones to cover a wide period with a high rigour. The sample does not contain thin-film panels. The later do appear in the review of Jordan and Kurtz (2013).

¹¹The 0.75 % annual rate corresponds to 70 % of the modules in the sample (which includes 204 mono- and poly-c Si modules). The deterioration was very high in only 17.6 % of the cases (eventually leading to their loss).

¹²If those values are accepted, the final power of a module is 75.4 %, around 1.5 % above the value of the uniform rate. The expression being used for the calculation of the annual average reduction (weighted by the rated power) has been the following:

Other authors propose values which are slightly different regarding the deterioration rate of the initial maximum power of the modules. This is the case of Branker et al. (2011: 4476–4477) who indicate that, although an annual rate of 0.5–1 % is assumed, the current rate for c-Si modules would be between 0.2 and 0.5 %/year. This is a purely indicative value, since no empirical evidence is provided. The work of Jordan and Kurtz (2013) is more interesting in this regard. The authors compare tens of measures carried out in the last 40 years. The conclusion is that the average annual deterioration rate is 0.8 %, whereas the median rate is 0.5 %.

Regarding the useful lifetime of the thin-film modules, the experience is still limited: the oldest plants are from 1988. The accumulated evidence, however, indicates that there would not be major problems beyond the initial reduction of performance.¹³

The joint performance of a plant in each year is measured by the capacity factor (L). This compares its output in kWh_{AC} with the one that could be expected from a plant with a similar nameplate capacity but operating under a so-called constant solar radiation, i.e. 1120 W/m² (MIT 2015: 41). Formally,

$$L = \frac{q_{AC_{year}}}{kW_p \cdot H}$$

with $H = 8760$ h. The value of L usually falls between 15 and 25 %. This is a lower value compared to thermal plants (~ 45 % for combined cycle gas plants, 60–70 % for coal plants and 90 % or more for nuclear plants).

Another option is the performance ratio (π_t) (or quality factor), which takes as reference another system which would be operating under optimal conditions in the same location. The following is the expression of the performance ratio (adapted from Oozeki et al. 2010: 597):

$$\pi_t = \frac{q_{AC_t} \cdot S_c}{\psi_t \cdot kW_p}$$

where q_{AC_t} refers to the energy generated by the plant per unit of time (year), expressed in kWh of AC; S_c represents the solar constant; ψ_t is the average solar radiation in the location being analysed, measured in kWh/year per m² (which

(Footnote 12 continued)

$$\tilde{u}^* = \frac{T_1 \cdot \tilde{u}_1 + T_2 \cdot \tilde{u}_2 + T_3 \cdot \tilde{u}_3}{T_1 + T_2 + T_3}$$

where $\tilde{u}^* = 0.75$ %/year, T_i is the duration of each period, and $\tilde{u}_i$ is its rate.

¹³However, the modules subject to very high solar radiation, such as the one in desert areas (>3500 kWh/m²/year), may have a short useful life (perhaps between 15 and 20 years). If this was the case, specific designs for modules located in those environments should be developed.

changes with the latitude, the climatic conditions, etc.); and kW_p refers to the nameplate capacity of the modules.

The value π_i is expressed as a percentage. The ratio compares the energy (kWh_{AC}) generated for a plant in a specific place, with the quantity which could be expected as suggested by the nominal efficiency (η) of the modules.¹⁴ It is an ex post measurement relating the real quantity of kWh_{AC} being produced to the potential generation of the kW_p being installed. Therefore, the performance ratio indicates the annual energy efficiency of a solar PV system, including all possible losses affecting it. Due to changes in solar radiation during the daylight and the conditions of the weather, solar PV generation usually has performance ratios between 80 and 90 %, despite its capacity to operate with diffuse radiation.

There are other criteria to assess the performance of a solar PV installation. For example, the amount of kWh_{AC} per kW_p installed which can be denoted by π^* (since it is a simplified version of the performance ratio) or the annual fraction of the number of annual hours which are needed to generate the energy produced in a solar PV farm if this had been operating at the nominal rated power of the modules. This indicator should not be confused with the technical availability of the plant, that is, the number of annual hours which a plant is active, once the time periods due to breakdowns, revision and maintenance have been removed. The technical availability of solar PV modules is closer to 100 % (taking into account daylight only). This is higher than for thermal plants. Most of the (unusual) failures which totally interrupt solar PV generation occur in the BoS devices.

To sum up, the different factors which lead to losses in the operative capacity of a solar PV installation have a relevant share: around 1/6 of the rated power of the modules and around 40 % of the STC of a cell.¹⁵ This value may increase if the quality of the equipment is poor.

2.3 Scarce Materials for Photovoltaic Generation

The solar PV sector requires a large amount of silicon, since this is the main material for the manufacturing of most cells. As it is well-known, silicon is a widespread element in the Earth crust. Therefore, its availability at reasonable prices is not a source of concern.¹⁶

¹⁴Manufacturers do not only identify the panels by their rated nameplate power, but they also indicate the nominal operating cell temperature (NOCT) or temperature reached by the cells when the panel receives a radiation of 800 W/m^2 with an spectral distribution AM 1.5, an ambient temperature of 20°C and a wind speed of 1 m/s .

¹⁵This threshold fits the results of studies such as Mau and Jahn (2006).

¹⁶The world Si production in 2012 was 7.8 million MT. Silicon is about 300 million times more abundant than Te and 20 mil and 20 thousand more abundant than Ga (MIT 2015: 132, 134). The abundance of Si exceeds by far the amount of materials cited in this section.

However, scarce materials are used in the multijunction cells and some types of thin-film modules. These materials include tellurium (Te), cadmium (Cd), indium (In), gallium (Ga), selenium (Se) and germanium (Ge).¹⁷ Although the so-called CdTe, GaAs/Ge, CIS and CIGS cells and modules raise great expectations, there are doubts about their large-scale diffusion in the future, taking into account the limited availability of the semiconductors metals that are part of them.¹⁸

A brief description of the mining of these elements starts with the already well-studied case of tellurium.¹⁹ Its abundance in the Earth crust is derisory: between 0.36 and 5 ppb (parts per billion). This makes it more scarce than platinum and gold (Green 2009b: 348; Zweibel 2010: 700). Tellurium has never been extracted directly, and it can be doubted that mines of this material are to be discovered. There are only two places in the world where they have an exceptional concentration: the deposit Dashiugou in Chendgu (China) where it reaches between 0.2 and 25 %, with total reserves of 1000 MT and the old deposits in the Moctezuma district (Mexico), with a concentration of 0.25 and reserves around 1700 MT (Green 2006b: 749). There are other deposits in countries such as USA (Deer Trail Mine), Russia, Uzbekistan, Australia and the Fiji islands (Green 2009b: 351), and bismuth telluride deposits in Kankberg and Bjorkdal in Sweden (Zweibel 2010: 700; Woodhouse et al. 2013: 208).²⁰ Te has been a scorned by-product of gold extraction, with a price much lower than this one. However, with attractive prices, Te could also be obtained from lead and nickel mining. All these sources can provide between 100 and 120 MT per year, perhaps during 10–15 years. This could cover a production of 7 GW/year of CdTe modules (Woodhouse et al. 2013: 208).

The rarity of Te under natural conditions explains that its production is tributary of the electrolytic refining of copper. Even so, although the copper rock can contain only between 1 and 3 ppm (parts per million) of Te, in the highly pure copper anodes the average concentration of Te goes up to 105 ppm, with their highest

¹⁷Silver (Ag) and ruthenium (Ru) should be added to this list. The first is used in the electricity connections of cells and modules. Between 50 and 120 mg/W are required, with a central value of 80–90 mg/W, which implies a cost of €6–14/W. Solar PV consumed about 1000 MT in 2010 (7 % of world consumption). Their total reserves are estimated at 570 thousand metric tonnes (MT) (Feltrin and Freundlich 2008: 182; MIT 2015: 144). Current efforts are directed at finding a good substitute for it, with copper nitrate mixed with some other substances being the best candidate (EUPVTP 2007: 19, 2011: 27; Green 2011b; IEA 2014: 28). The second one is used in very small quantities in dye-sensitized cells, which are still in an experimental stage (Green 2006b: 743). Its total amount of reserves has been estimated at 10 thousand MT (Feltrin and Freundlich 2008: 183).

¹⁸Compounds such as FeS₂, Cu₂S or Zn₃P₂ also show high performance rates and their availability is greater. They are part of the above-mentioned kesterites (Wadia et al. 2009; Wadia 2010: 109).

¹⁹This and the following paragraph has been written based on the information obtained in Green (2009b), Ejaz (2010) and <http://www.minormetals.com>, <http://minerals.usgs.gov/minerals/pubs/commodity>, www.metal-pages.com and www.metalprices.com, as well as the references being cited in the text.

²⁰Additionally, up to 60 % of the primary tellurium could be within manganese nodules scattered in the ocean depths (Andersson 2000: 70).

presence in the anode slimes (around 2 %)(Green 2006b: 744). In 2006, the electrolytic mud of copper refining provided about 430 MT in 2006, 550 MT in 2011 and, perhaps, 880 MT in 2020 and 1200 MT/year in 2030.²¹ Te is also extracted from the mud of lead and bismuth refining processes in much lower quantities (Houari et al. 2014: 131). Extracting it from the solid sulphur residues from oil refining has also been proposed, although this is unlikely, given its very low concentration (below 1 ppm) (Green 2011a).

Adding direct mining and Te refining, the current decade started with a world supply of Te of about 630 MT (Drury et al. 2012: 10–49). This annual amount is expected to increase gradually. Most of it will end up in the production of solar PV cells in association with cadmium (CdTe), although Te is also used in some steel alloys and in products for the electronic industry. On the other hand, the global reserves are estimated at 47 thousand MT (Morgan et al. 2007: 14; Feltrin and Freundlich 2008: 183). The production of CdTe could reach 70 GW/year in 2030, under the best expectations of mining and refining and a clear reduction of the quantity of Te needed per W (Woodhouse et al. 2013: 208).

The demand for Te (for solar PV uses) mostly comes from the company First Solar, which is a pioneer in the manufacturing of CdTe cells. This firm has accumulated stocks of this material and has a long-term contract signed with the company exploiting the Chendgu deposit. It has a subsidiary firm working on the aforementioned Moctezuma district.

The fact that the world supply has always been concentrated in a very few hands has not prevented the price of Te from being very low. It was around \$25/kg in the 1950s and about \$40/kg in 1980. It then went down, but increased considerably between 1987 and 1992 to reach \$70/kg. At the beginning of this century, those prices were reduced to a very low \$10/kg. Then, increased again to reach \$200/kg (€160/kg) in 2006 and a maximum of \$308/kg (€198/kg) in 2008, which was also the maximum reached in 2005 (Candelise et al. 2011: 3).²² The average price in 2010 had been reduced to \$210/kg (€167/kg), increasing again 2011 (\$349/kg, €251/kg). The price went down in 2012 and 2013 to \$112/kg (€84/kg). In short, Te has shown a highly volatile price.

However, the price may increase in a sustainable manner. This has fed a debate on what would be the price negatively affecting the commercialization of CdTe cells: the most optimists expect it reaching \$3500/kg (Houari et al. 2014: 131), whereas a few years ago others expected prices at levels three times below (Green 2006b: 749). All in all, the quantity of Te in CdTe cells is negligible and has gone

²¹Those predictions are based on a 55 % recovery rate. However, if non-electrolytic copper purification methods were abandoned and the performance of the electrolytic methods was increased, the recovery rate would increase by 50 %, although this depends on the price of Te. For example, the concentration of gold is 10 times lower than Te. It is recovered due to its high price. In 2011, the price of gold was 130 times higher than the price of Te (Woodhouse et al. 2013: 209).

²²The oscillations in the previous decade are a reflection of the speculative movements with respect to the demand in the solar PV sector as well as the policy followed by First Solar. A manager from this firm claims that \$100/kg was a reasonable price (as cited in Ejaz 2010: 19).

down: 0.27 g/W (with 0.23 g/W of Cd) in the middle of the past decade, according to Green (2006a: 388), being halved a year later (Zweibel 2010: 700; Drury et al. 2012: 10–49).²³ These quantities are so low that each additional \$100/kg increase in the price of Te only adds a cent per watt to the cost of the module. The direct manufacturing cost of CdTe cells/modules has been reduced from \$2/W in 2004 to \$0.84/W in 2010 and \$0.74/W in 2011, or 2013 depending on the source (Ejaz 2010: 20; Zweibel 2010: 699; Woodhouse et al. 2013: 201; Houari et al. 2014: 130). This last figure involves a final price of $\sim$ \$1.07/W.²⁴

Regarding cadmium, it is not present in any mineral with a high degree of concentration. This metal is obtained as a by-product of rock, whose extraction and processing are economically justified due to the zinc, copper or lead that they contain.²⁵ The concentration of Cd in those rocks is usually around 0.1 ppm. It can also be obtained from the phosphate rock and from the recycling of final products (Andersson 2000: 65). The main producers are China, South Korea and Japan.

Demand for cadmium stems from the manufacturers of batteries (nickel–cadmium batteries). It is also used in some pigments and enamels. The current Cd demand by the solar PV sector is below 1 % of the total (Raugei and Fthenakis 2010: 5224).

In 2013, the average price for cadmium with a 99.99 % purity level reached €1.5/kg. This price has been volatile throughout the years. In 2010, it was around €3/kg, whereas it was only 1€ at the start of the century. It increased in 2005 to €8/kg and reached a maximum of €9.4/kg in 2007. Cadmium has been traditionally and comparatively low due to its toxicity, which makes it recommendable to separate it from zinc. The risk that it may cause cancer makes its manipulation at industrial scale a complicated task.²⁶ However, the manufacturing and use of CdTe modules prevents the cadmium it contains (about 60 MT/GW) from being scattered in the environment or being used in short-life applications, i.e. integrated in products which end up in the landfill very soon (Raugei and Fthenakis 2010: 5227).

²³More specifically, one of the first authors being cited (Green 2006a) estimated that the quantity necessary of Te per GW was 266 MT, whereas the second authors claimed (5 years later) 91 MT/GW and even 60 MT/GW. These last figures are clearly below 106 MT/GW, which the former envisaged for 2020 and they are below 0.4 g of Te/W under current manufacturing conditions (Ejaz 2010: 32). Anyway, these values, which are very small, may lead to a wrong impression. In order to obtain 1 TW of CdTe panels, 100 thousand MT would be required, an exorbitant number.

²⁴The most optimistic predictions point out to direct manufacturing costs in 2030 of \$0.47/W, and 10 cents higher than the sale price, for a performance of 18 % and a minimum width of the active layer of 1 μ m (Woodhouse et al. 2013: 202–204, 208).

²⁵Whereas zinc extraction has gone from 5.5 million MT/year in the early 1970s to twice that amount at present, Cd demand has remained stable at 20,000 MT/year.

²⁶Managing it safely was an important reason, although not the only reason for some firms to abandon CdTe module manufacturing. In 2002, BP closed its Fairfield (CA) plant and Matsushita abandoned this line of products. However, this was not the case of the US company First Solar, founded in 1984 (Boyle 2004: 79; Braun and Skinner 2007; Johnstone 2011: 297–299).

Indium (In) can be found in nature with different although always low concentration levels, commonly lower than 100 g/MT. This is a similar proportion to silver and mercury (Green 2009b: 348). Its dispersion is behind the fact that it is not exploited as a specific mineral, but it is rather isolated from zinc rocks (where its concentration is about 0.05 ppm), copper, sulphur, iron and tin. It can also be recovered from tailings and from recycling. All in all, its price should be similar to gold or platinum in order to make its systematic recovery an economically justified activity (Andersson 2000: 68 and 70).

Canada is the largest producer of In. The Mount Pleasant mines (with a concentration of 280 g/MT, and estimated reserves of 480 MT) and other mines are located in this country: Kidd Creek, Heath Seele and Brunswick. Its presence could be larger in the Toyoha mine in Japan. Its production capacity could be as high as 130 MT/year, with reserves of 5000 MT. The mine was closed in 2006 due to the exhaustion of zinc and lead, despite the high (but insufficient) price of In (Green 2009b: 355). China has greater reserves: more than 11 thousand MT in the mines of Dajing, Dachang and Dulong. The direct exploitation of the former, located in the north of the country, would be possible at a price of between \$600 and \$1000/kg. The other mines, located in the south, would require prices of more than \$2000/kg. It should be mentioned that the Chinese government imposes quotas on its exports since 2007 (slightly above 200 MT/year). This restriction has not prevented this country from capturing an increasing share of the world supply of In. This could also be explained by concerns about the environmental impact of the mining of In and its by-products (Green 2009b: 356). Finally, other countries follow suit, such as Namibia, USA, Bolivia and South Africa.

In was used in very small amounts for experimentation for years although, from the mid-1980s, the semiconductors industry started to buy it in considerable quantities, displacing the nuclear plants as the main demand players. Consequently, the price of Indium with 99.97 % purity levels, which had remained stable around \$200/kg between 1988 and 1994, suddenly increased up to \$600/kg in the mid-1990s due to the demand of laptop manufacturers. It then went down to around \$100/kg (€88/kg) in 2003, increased to \$1140/kg (€855/kg) in 2005 from \$800/kg in 2004 (Ejaz 2010: 20). The demand of the manufacturers of LCD screens is behind this fast increase, since they consume more than 50 % of the available In, compared to <2 % of solar PV panel manufacturers (Candelise et al. 2011: 18). However, it had already gone down to \$820/kg (€664/kg) in September of that year. Four years later, the average price had decreased to \$382/kg (€275/kg). Its average value in 2010 was around \$552/kg (€417/kg), increasing up to \$770/kg (€585/kg) by the end of 2011. In 2013, the price reached \$570/kg (429 €/kg). In these last years, In has featured relatively high prices, leading to an increased recycling effort. For example, of the 1250 MT of indium supplied in 2007, about 700 MT came from recycling.

Gallium is also not present in any particular rock. It has to be obtained from bauxite (15 ppm), zinc, etc. Paradoxically, gallium is as abundant as copper, although the later can be found in concentrations between 200 and 800 ppm (Andersson 2000: 65). 380 MT were extracted in 2012. Its price has remained low and stable from the early 1980s. Since it is a by-product of aluminium processing, it

has been relatively abundant, although it has never had a relevant commercial use, except for the very small quantities required in the displays in watches, calculators, etc. The average price of high-purity gallium has fluctuated between \$538 and \$640/kg between 2001 and 2005, going down to \$443/kg (€353/kg) in 2006. It then went up to \$579/kg (€395/kg) in 2008. The average price reached its maximum value in 2011 at \$688/kg (€495/kg). Two years later, it went down to \$511/kg (€395/kg). In spite of the continuous oscillations, the average price is about \$500/kg.

Selenium was quite abundant in nature, since it operates in several biochemical processes. Thus, in spite of being toxic at high concentration levels, selenium is a micronutrient of plants and animals. Its extraction occurs as a by-product of copper mining (its rock contains 0.12 ppm of Se, the electrolytic anodes have 400 ppm, and the anode slimes have a 7.8 % concentration level, according to Green 2006b: 744), silver, zinc and lead. One of the few deposits with a relatively high concentration is in Wolverine (Alaska). This could contain as much as 2800 MT of commercially recoverable selenium. The main source of Se is the electrolytic copper process. It can also be obtained in sulphur acid plants and could be extracted from coal if it was profitable to do so. The world reserves are estimated at around 170 thousand MT (Morgan et al. 2007: 16). Selenium has been used as pigment in glass manufacturing, as an alloy for some types of steel and in the elaboration of pharmaceutical products. Since the end of the 1960s, its photoreceptor capability led to its widespread use in photocopiers. It started to be used in solar PV some years later. World production in 2003 was 1673 MT (primary selenium) and 252 MT of recovered and recycled selenium. Japan, Canada and Belgium are the largest selenium producers. The price of refined selenium has always been low: its average value was \$4.4/kg in 1998, going up to \$8.3/kg in 2002, which are values below their extraction costs (Green 2006b: 747). However, in April 2005, it reached €115/kg. Its price was around €36/kg in 2009 and €60/kg in 2010 and €105/kg in 2011 and went down to half this value in 2013. This volatility reflects its demand for the production of steel, glass, fertilizers, etc.

Another very uncommon metal used in the solar PV sector is germanium. Being discovered by Dmitri Ivanovich Mendeleiev, it was not isolated until 1886. Germanium is highly dispersed, and its total reserves are estimated at 10 thousand MT (Feltrin and Freundlich 2008: 183). It is only present in concentrations from trace elements in some minerals such as zinc and copper. Some deposits of the later exist in Zaire and Namibia, and these are also the most abundant deposits of germanium.

However, it is estimated that about 75 % of Ge total reserves are in coal mines. This is the reason that between 25 and 35 % of the total is being recovered from the ashes in thermal plants. This share could increase due to price pressures. Its world annual consumption is about 100 MT. The price in 2008 was close to \$1500/kg, although it was 75 % lower five years earlier. It went down and increased later to reach \$1650/kg (€1186/kg) in 2011 and \$1950/kg (€1430/kg) in 2014. Both USA and the USSR/Russia considered it as an strategic metal and, thus, accumulated large stocks.

The use of the semiconductor qualities of Ge started with the radar. Also, as it is well-known, the first transistor being built was from germanium. Its market significantly increased in the 1950s and 1960s with the birth of the electronic sector. Silicon, which was more abundant and cheaper, started to replace it in the mid-1970s. As a result, both its demand and its price were reduced, but they increased in the second half of the 1990s with the boom of optical fibre. It has also been used in night vision systems and in some electronic circuits. In the solar PV sector, germanium is, above all, a substrate of some high-performance multijunction cells, which are used in the concentration modules. Its extreme rarity is behind its replacement by gallium.

The description of the extraction, use and prices of the considered elements suggests that the analysis of its medium- and long-term availability is quite a complex issue. It requires collecting a lot of information and integrating highly uncertain and different technical and economic factors. Thus, in the next pages, the elements to be considered will be discussed. This analysis could be useful in case the reader was interested in the assessment of its future availability for the solar PV sector.

To start with, any estimation of the future availability of these minerals is subject to two types of restrictions (adapted from Andersson 2001: 9–10; Candelise et al. 2011: 4):

- Its absolute availability (or total reserves) which sets an upper limit on the overall photovoltaic capacity of the considered technology. Given that those materials are usually in multijunction cells, the scarcest is the one that will determine the limit in its installation.
- The current capacity of extraction, refining, recovery and recycling operations. This sets a limit on the annual growth of the sector, and it can block its growth for some time.

Taking into account the first restriction, the following ratio can be written as follows,

$$S_i = R_i / f_i^{W_p}$$

whereby the solar PV capacity associated with the stock of metal i (S_i) depends on R_i (or the total available volume of the metal) and f_i , which is the quantity consumed per W_p (or another unit of capacity). This ratio is different for each type of cell and metal.

The choice of the unit in f_i does not have to refer to capacity, since it can also be a unit of use of this rated power, such as kWh (in a year). The relationship between both options can be expressed as follows:

$$S_i^{\text{kWh}} = R_i / f_i^{\text{kWh}} = R_i / f_i^{W_p} \cdot E$$

In other words, the quantity of kWh which allows the production of metal i is the ratio between its available volume and the necessary quantity to generate a kWh.

This value is equal to the ratio S_i multiplied by the factor E relative to the transformation kWh/ W_p (or quantity of service -energy- per unit of generation capacity), under the assumption that E does not change over time.

Its annual availability rate can be written as follows:

$$G_i^{W_p}(t) = \frac{r(t) - l(t)}{f_i^{W_p}(t)}$$

$$G_i^{kWh}(t) = \frac{r(t) - l(t)}{f_i^{kWh}(t)}$$

where $r(t)$ is the quantity extracted and refined, together with the one recovered and recycled from the metal i in year t , measured in metric tons or kg; $l(t)$ represents the mineral discarded or annually lost in the transformation and recycling processes; and $f_i^{W_p}(t)$ and $f_i^{kWh}(t)$ are the annual net quantities required by W_p or kWh, respectively. Those ratios allow an assessment of the specific availability of a metal year after year, i.e. the volume at the disposal of the sector so that it can increase one more year, following an expansive trajectory.

The terms in these expressions implicitly include many variables. Simplifying somehow, the wide array of existing circumstances has been grouped in three types of categories:

- The volume of the material put at the disposal of the sector.
- The requirements per unit of product (or service).
- The reaction of markets.

These issues are briefly addressed in the following paragraphs.

The first factor refers to reserves, both regarding the amount existing in the Earth crust as well as the speed at which they are extracted. The figure for global reserves is never exact due to the lack of sufficient geological information. However, all these materials seem to be present in the Earth crust in a quantity much higher than any future need of the solar PV sector (MIT 2015: 133–134). The real problem is to find them with a degree of concentration which allows their extraction (technical perspective) and justifies it (economic criterion). Those metals are usually obtained as a by-product of minerals such as copper and/or zinc (Te, Se, In, Ge, Cd) or aluminium (Ga). This is quite a stable association: the variation in the quantity of the main mineral being extracted usually leads to a proportional change in the same direction in the volume of the semiconductor metal being obtained, although the quantity obtained per unit of land being removed could differ.

The quantity of extracted mineral would be altered by improvements in the methods and the extraction technologies as well as by changes in prices, both of the main mineral and the accompanying elements. In this later case, the price increase would induce a higher rate of recovery in the extraction and refining processes as well as higher recycling rates. Thus, the price has a direct effect on the vicissitudes

of the life cycle of the mineral already extracted, especially when its degree of concentration is so low that mining it is only economically justified at very high prices.²⁷

However, it is most likely that its recovery and recycling intensifies before its direct extraction increases. This would be a historical novelty. Its very low concentration together with very low prices has led to very low recovery rates. There is the suspicion that the tellurium and the indium contained in mineral ores could be as much as 10 times larger the quantities being produced so far. In the case of Te, a moderate increase of the prices could lead to higher recovery rates (of 2–3 orders of magnitude). Regarding both gallium and germanium, the current quantities in the residues of mineral extraction would be above the quantity being refined by various orders of magnitude (Andersson 2000: 67–8; 2001: 19).

The needs for the material per unit of product (or service) represent a second very relevant aspect. In the case of solar PV, this refers to the quantity required per W (or per kWh). This ratio can be modified due to technical changes such as the improvement in the deposition process of the photoreceptor films. For example, in the case of CdTe cells, the thickness of the active layer could be reduced in a few years to 0.2 μm from a value of 3–8 μm (Zweibel 2010: 700; Candelise et al. 2011: 16).

Therefore, the projections of the installed capacity of CdTe modules, combined with the forecasts of such unitary consumptions, have a key role to play in the future material needs. In general, once the final-generation capacity target is set, the average annual growth rate of material needs as well as the rate at which those materials should be obtained is also set. This growth rate results from the combination of extraction, refining, recovery and recycling and is also affected by the consumption in other sectors as well as its time profile (Andersson 2000: 73).

A deeper analysis of the information provided in the previous paragraph reveals the relevance of five factors:

- The quantity of semiconductor per W, which depends on the width of the wafer/layer of the module, allows to proxy the rated power which could be installed, given a specific supply of metal. It is more logical, however, to make predictions in terms of the kWh generated, which entails making assumptions on its performance, the efficiency of BoS and the features of the site for future solar PV farms (latitude, weather, etc.). Different technical innovations will need to be considered (which should respect the physical restrictions). Geographical assumptions will need to be made. Furthermore, it should be assessed how the improvements expected in the performance of cells/modules will affect their useful life or how their design and manufacturing is made more complicated.

²⁷Long-term expectations on the mining of the main elements should not be disregarded. Thus, although copper and zinc are minerals whose markets grow due to the demand from emerging countries, a slowdown will likely occur in the XXI century. This circumstance will affect the supply of the related semiconductor metals. Gallium could be an exception since the demand for aluminium could be high for decades without leading to a considerable reduction in the very abundant bauxite reserves. The availability of germanium would be affected by the drastic reduction of coal consumption.

- The degree of recovery of the material from the decommissioned electricity generation plants should be assessed, as well as the recycling from other uses. In this last case, we should point out that the separation of the material to be recycled is very difficult for paintings, additives, etc. The manipulation of the recycled equipments may involve some risks. Finally, the quality of some of the material being recovered may be poor.
- Another factor that should be considered is the possibility to reintegrate the discarded material (in the form of shavings) to the manufacturing process of cells/panels. Given that the lifetime of solar PV farms extends for a few decades, the recovery of the residues of the manufacturing process will exceed the quantity of material obtained from the modules being withdrawn.
- The duration of the useful lifetime of the cells/modules. The projections will need to take into account that, at a certain moment, the manufacturing of the cells will lead to an increase in the generation capacity, but will also lead to a replacement of the obsolete/old solar PV farms.
- The substitution between these metals. This is feasible in many cases, but it can affect the performance of the cell or module.

The third aspect to be considered is the reaction of the markets to the global scarcity and the restrictions which could eventually appear. The market for these rare metals is quite special. On the one hand, only one or a few firms control the world supply (under the close look of the respective governments); on the other hand, their price is usually low when their uses are unclear; and they go up fast when their demand is activated. Although these materials are only a minuscule fraction of the total costs of a module (less than 1 %), this market is prone to speculation. The increase in prices can be disproportionate and takes place before the appearance of real quantitative restrictions. Every tension in the markets feeds a negative public perception about the feasibility of the affected technology. This impression may last beyond the substantive reasons which originated it, pushing down the expectations of the sector. This situation can be aggravated by the opaque character of the firms which trade with these metals: they are not transparent neither with respect to the reserves susceptible of being exploited nor with respect to their consumption dynamics. And, finally, the production of some of these minerals is concentrated in a few countries. This is why strictly geopolitical considerations are an inextricable part of the mechanics of these markets.

So far, it should have been clear that there are many complexities and uncertainties which make any prediction of the evolution of the photovoltaic technologies which require scarce semiconductors a difficult task (Houari et al. 2014: 132–137). Thus, the conclusions of those predictions will have a mere indicative character. But it is still worth taking a look at the main results from those studies carried out in this context.

For the next decades, the focus should be on the relationship between the annual rates of supply of the mineral and the increase in the manufacturing capacity of the modules. In Andersson (2000: 72, 2001), the conclusion was reached that the maximum production until 2020 without supply restrictions would be around

20 GW/year for CdTe cells, 70 GE/year for CIGS and 200 GW/year for the case of a-Si doped with germanium. This was a coherent estimation taking into account the expansion of the solar PV sector at an annual 20–30 %, which was the case in those years, assuming incremental improvements in thin-film modules.

However, there are less optimistic predictions: the economically exploitable indium reserves are around 6 thousand MT, and thus, with the current rate of growth in consumption, it would no longer be available in 2020 (<http://minerals.usgs.gov>). There are doubts that the recovery and recycling of In can be increased, either in the medium or long term. Moreover, EUPVTP (2007:53) recommends the replacement of germanium in the medium term.

Green (2009b: 356) argues that new sources of supply for Te and In are required if CdTe and CIGS techniques want to keep on growing at the rates of the last years (around 40 % annual). In the case of Te, there are modest possibilities for direct extraction. The best Te mines could provide about 30 GW of metal. Since the production of CdTe cells was estimated at 1 GW in 2009, those mines will be exhausted in 2016 if the annual growth rate was 40 %. From then on, the supply of Te will need to be based on a recovery of all the possible mineral ores and on recycling. Exploiting deposits with a degree of concentration below 0.02 % (or 200 ppm) is unlikely to maintain Te prices below \$800/kg. This is the limit in order to keep the cost of cells below \$0.2/W in 2020. All in all, this expert does not believe that the production of CdTe cells will exceed 10 GW/year. Thus, projections above such level of annual manufacturing are not realistic. He also does not see that the Te could be replaced. On the contrary, he notes that In could be partly replaced in CIGS cells using elements such as ZnSn. There could also be technical improvements which would reduce the current 0.075 g/W of In contained in the CIGS modules to 0.04 g/W by the end of the current decade or even to 0.025 g/W according to Drury et al. (2012: 10–49). Only a concentration above 85 ppm would justify mining activities. In this case, its price could stay below \$1600/kg.

The exhaustion of the global reserves of the considered metals and, to a lesser extent, its systematic recovery and recycling strategies are the decisive factors for projections for 2050 and beyond. If the price of those metals was so high that it could justify their direct extraction, the solar PV sector would be the “coal industry of the XXI century” (Andersson 2000: 73). Their very low concentration levels would require the deployment of operations at an unimaginable scale, with a huge environmental impact.

The possibility that the demand for these metals ends up dominating the mining of zinc, copper, etc., can be discarded.²⁸ Therefore, other alternatives have to be

²⁸It is not clear that this would be a satisfactory situation from an energy point of view. For example, a CdTe module of a micron width which contains 3.2 g of tellurium (obtained in the refining of two MT of copper), with a 10 % performance rate, included in a solar PV system with an 80 % performance ratio and a solar radiation of 2000 kWh/m²/year, generates about 150 kWh/year. Therefore, 40 years would be needed in order to obtain as much as the electricity produced by the combustion of a single ton of coal, i.e., 3 MWh in a plant with a 35 % efficiency rate (Andersson 2001: 26, n. 24).

searched for. Long-term predictions have been clearly pessimistic in the past (Anderson 2001: 3) but are now quite optimistic (see Candelise et al. 2011: 6, 13–16). The first ones assumed that only 5 % of the total supply of energy in 2100 would come from thin-film modules elaborated with materials belonging to III-V of the periodic table. This implies a maximum of 10 thousand TWh/year and, thus, an installed capacity of less than 6 TW. Reaching this capacity involves an average growth of 60 GW/year for a century. This is a colossal effort which could be considered unfeasible given the available reserves and the fraction that can be recovered and recycled. However, recent studies estimate that materials will be sufficiently available in 2050 to produce 211 GW/year of CdTe panels and 152 GW/year for CIGS. The reason is twofold: (1) the recycling capacity of Te or In has not been taken into account. This could reach 90–95 %, both for old panels and for other sources, such as LCD screens; (2) the reduction of wastage and the recovery of material dispersed during the deposition process (exceeding 75 % for Te and 90 % for In) (Candelise et al. 2011: 13 and 16). However, whether the CdTe manufacturing sector can produce more than 100 GW/year is unclear (Woodhouse et al. 2013: 210).

To sum up, despite the enormous difficulties to make medium- and long-term predictions, the different studies share a similar generic conclusion: the large-scale expansion of the solar PV sector will hardly be based on the thin-film variants CdTe, CIS or CIGS. Beyond this extreme diagnostic, however, their specific share is being debated. The prospects of a-Si thin-film technologies are brighter. In particular, this is the case for structures halfway between amorphous and micro-crystalline whose performance/cost ratios are quite satisfactory and do not show problems in terms of raw material supply.²⁹

References

- Allhoff F, Lin P, Moore D (2010) What is nanotechnology and why does it matter? From science to ethics. Wiley-Blackwell, Chichester
- Andersson BA (2000) Material availability for large-scale thin-film photovoltaics. *Prog Photovoltaics Res Appl* 8(61):71–76
- Andersson BA (2001) Material constraints on technology evolution: the case of scarce materials and emerging energy technologies. Department of Physical Resource Theory, Chalmers University of Technology and Göteborg University. Available at http://frt.fy.chalmers.se/PDF-docs/BA_thesisWoP.pdf. Accessed June 2011
- Andrews J, Jelley N (2007) Energy science. Principles, technologies, and impacts. Oxford university Press, Oxford
- Arvizu D et al (2011) Direct solar energy. In: Edenhofer O et al (eds) IPCC special report on renewable energy sources and climate change mitigation. Cambridge University Press, Cambridge, pp 333–400

²⁹The availability of materials for batteries is addressed in MIT (2015: 136). Problems in this context are unlikely.

- Barbose G, Wiser R, Bolinger M (2006) Designing PV incentive programs to promote performance: a review of current practice. Paper of the Ernest Orlando Lawrence Berkeley National Laboratory 61643. Available at <http://eetd.lbl.gov/EA/EMP>. Accessed May 2010
- Bonaccorso F et al (2015) Graphene, related two-dimensional crystals, and hybrid systems for energy conversion and storage. *Science* 347(6217):1246501-1/9
- Borenstein S (2008) The market value and cost of solar photovoltaic electricity production. Working paper series, 176. Center for the Study of Energy Markets, Berkeley. Available at <http://www.ucei.org>. Accessed January 2012
- Boyle G (2004) Solar photovoltaics. In: Boyle G (ed) *Renewable energy. Power for a sustainable future*, 2nd ed. Oxford University Press, Oxford, pp 65–104
- Boyle G (2010) Tecnologías de energía renovable para la generación de electricidad. In: Moselle B, Padilla J, Schmalensee R (eds) *Electricidad verde. Energías renovables y sistema eléctrico*. Marcial Pons, Madrid, pp 31–68
- Branker K et al (2011) A review of solar photovoltaic levelized cost of electricity. *Renew Sustain Energy Rev* 15:4470–4482
- Braun GW, Skinner DE (2007) Experience scaling-up manufacturing of emerging photovoltaic technologies. SR-640-3965. Golden (Co), NREL. Available at <http://www.nrel.gov>. Accessed October 2010
- Candelise C et al (2011) Materials availability for thin film (TF) PV technologies development: a real concern? IECPT working paper 001. London, Imperial College Centre for Energy Policy and Technology. Available at <https://workspace.imperial.ac.uk>. Accessed February 2013
- Drury E et al (2012) Chapter 10. Solar Energy Technologies. In: Hand MM et al (eds) *Renewable electricity futures study. Volume 2: renewable electricity generation and storage technologies*, pp 10-1–10-60. Report NREL/TP-6A20-52409. NREL, Golden. Available at http://www.nrel.gov/analysis/re_futures. Accessed July 2014
- Ejaz Q (2010) Rapporteur's report. In: APS/MRS/MITEL critical elements for new energy technologies. An MIT energy initiative workshop report. MIT, Cambridge, pp 13–59. Available at www.mit.edu/mitei. Accessed August 2012
- El Chaar L et al (2011) Review of photovoltaic technologies. *Renew Sustain Energy Rev* 15:2165–2175
- EUPVTP (2007) A strategic research agenda for photovoltaic solar energy technology. The European photovoltaic technology platform. Luxembourg, Office for Official Publications of the European Communities. Available at <http://www.eupvplatform.org>. Accessed June 2010
- EUPVTP (2011) A strategic research agenda for photovoltaic solar technology. Photovoltaic technology platform, 2nd edn. Office for Official Publications of the European Communities, Luxembourg. Available at <http://www.eupvplatform.org>. Accessed June 2014
- Feltrin A, Freundlich A (2008) Material considerations for terawatt level deployment of photovoltaics. *Renewable Energy* 33:180–185
- Fraunhofer ISE (2015) Current and future cost of photovoltaics. Long-term scenarios for market development, system prices and LCOE of utility-scale PV systems. Study on behalf of Agora Energiewende, Freiburg. Available at <http://agora-energiewende.de>. Accessed in February 2015
- García-Valverde R et al (2010) Life cycle analysis of organic photovoltaic technologies. *Prog Photovoltaics Res Appl* 18:535–558
- GEA (2012) Global energy assessment. Toward a sustainable future. Cambridge University Press/International Institute for Applied System Analysis, Cambridge/Laxenburg
- Green MA (2006a) Consolidation of thin-film photovoltaic technology: the coming decade of opportunity. *Prog Photovoltaics Res Appl* 14:383–392
- Green MA (2006b) Improved estimates for Te and Se availability from Cu anode slimes and recent price trends. *Prog Photovoltaics Res Appl* 14:743–751
- Green MA (2009a) The path to 25 % silicon solar cell efficiency: history of silicon cell evolution. *Prog Photovoltaics Res Appl* 17:183–189
- Green MA (2009b) Estimates of Te and In prices from direct mining of known ores. *Prog Photovoltaics Res Appl* 17:347–359

- Green MA (2011a) Is sour crude or sour gas a potential source of Se and Te? *Prog Photovoltaics Res Appl*. Accessed online in www.wileyonlinelibrary.com. Accessed July 2011
- Green MA (2011b) Ag requirements for silicon wafer-based solar cells. *Prog Photovoltaics Res Appl* 19:911–916
- Green MA et al (2008) Solar cell efficiency tables (version 32). *Prog Photovoltaics Res Appl* 16:435–440
- Green MA et al (2009) Solar cell efficiency tables (version 34). *Prog Photovoltaics Res Appl* 17:320–326
- Green MA et al (2010) Solar cell efficiency tables (version 36). *Prog Photovoltaics Res Appl* 18:346–352
- Green MA et al (2011) Solar cell efficiency tables (version 37). *Prog Photovoltaics Res Appl* 19:84–92
- Green MA et al (2012a) Solar cell efficiency tables (version 39). *Prog Photovoltaics Res Appl* 20:12–20
- Green MA et al (2012b) Solar cell efficiency tables (version 40). *Prog Photovoltaics Res Appl* 20:606–614
- Green MA et al (2013) Solar cell efficiency tables (version 42). *Prog Photovoltaics Res Appl* 21:827–837
- Green MA et al (2014) Solar cell efficiency tables (version 44). *Prog Photovoltaics Res Appl* 22:701–710
- Hansen JP, Percebois J (2010) *Énergie. Économie et politiques*. Éditions de Boeck Université, Bruxelles
- Houari Y et al (2014) A system dynamics model of tellurium availability for CdTe PV. *Prog Photovoltaics Res Appl* 22:129–146
- IEA (2014) *Tecnology roadmap. Solar photovoltaic energy*. OECD/IEA, Paris. Available at <http://www.iea.org>. Accessed September 2014
- IRENA (2014) *REthinking energy 2014: toward a new power system*. International Renewable Energy Agency. Available at <http://www.irena.org/publications>. Accessed October 2014
- Jäger-Waldau (2011) *PV status report 2011. Research, solar cell production and market implementation of photovoltaics*. JRC scientific and technical reports, EUR 24807 EN. Institute for Energy/Joint Research Centre/European Commission. Luxembourg, Office for Official Publications of the European Communities. Available at <http://ie.jrc.ec.europa.eu>. Accessed March 2012
- Johnstone B (2011) *Switching to solar. What we can learn from Germany's success in harnessing clean energy*. Prometheus Books, New York
- Jordan DC, Kurtz SR (2013) Photovoltaic degradation rates—an analytical review. *Prog Photovoltaics Res Appl* 21:12–29
- Jourde P (2005) *Le photovoltaïque: Les filières, les marchés, les perspectives*. In: Bobin JL et al (eds) *L'énergie de demain. Techniques, Environnement, Économie*. EDP, Grenoble, pp 351–370
- Kaltschmitt M, Rau U (2007) *Principles [photovoltaic power generation]*. In: Kaltschmitt M, Streicher W, Wiese A (eds) *Renewable energy. Technology, economics and environment*. Springer, Heidelberg, pp 229–236
- Knapp KE, Jester TL (2000) An empirical perspective on the energy payback time for photovoltaic modules. In: *Solar 2000 conference, Madison (Wisconsin)*
- Kumar P, Chand S (2012) Recent progress and future aspects of organic solar cells. *Prog Photovoltaics Res Appl* 20:377–415
- Kurtz S (2012) *Opportunities and challenges for development of a mature concentrating photovoltaic power industry*. Revised version. NREL/TP-520-43208, NREL, Golden (Co). Available at <http://www.nrel.gov>. Accessed February 2013
- Liu Q et al (2009) Solar and wind energy resources and prediction. *J Renew Sustain Energy* 1:1–12
- Mau S, Jahn U (2006) *Performance analysis of grid-connected PV systems*. Available at <http://www.arsenal.ac.at/downloads>. Accessed March 2009

- MIT (2015) The future of solar energy. An interdisciplinary MIT study. Energy Initiative Massachusetts Institute of Technology, Cambridge. Available at <http://mitei.mit.edu>. Accessed May 2015
- Montgomery SL (2010) The powers that Be. Global energy for the twenty-first century and beyond. The University of Chicago Press, Chicago
- Morgan M et al (2007) Future state of the PV industry. Trends and technologies. Available at <http://socrates.berkeley.edu>. Accessed March 2009
- Oozeki T et al (2010) Performance trends in grid-connected photovoltaic systems for public and industrial use in Japan. *Prog Photovoltaics Res Appl* 18:596–602
- Perlin J (1999) From space to earth. The story of solar electricity. Aatec Publications, Ann Arbor
- Prentiss M (2015) Energy revolution. The physics and the promise of efficient technology. The Belknap Press of Harvard University Press, Cambridge
- Randolph J, Masters GM (2008) Energy for sustainability. Technology, planning, policy. Island Press, Washington
- Raugei M (2013) Energy pay-back time: methodological caveats and future scenarios. *Prog Photovoltaics Res Appl* 21:797–801
- Raugei M, Fthenakis V (2010) Cadmium flows and emissions from CdTe: future expectation. *Energy Policy* 38:5223–5228
- Sauer DU, Rau U, Kaltschmitt M (2007) Technical description [photovoltaic power generation]. In: Kaltschmitt M, Streicher W, Wiese A (eds) Renewable energy. Technology, economics and environment. Springer, Heidelberg, pp 238–286
- Siebentritt S, Schorr S (2012) Kesterites—a challenging material for solar cells. *Prog Photovoltaics Res Appl* 20:512–519
- Sivaran V et al (2015) Outshining silicon. *Sci Am* 313(1):54–59
- Skoczed A, Sample T, Dunlop ED (2008) The results of performance measurements of field-aged crystalline silicon photovoltaic modules. *Prog Photovoltaics Res Appl* 17:227–240
- SunShot (2012) SunShot vision study. Sunshot Initiative US Department of Energy. Available at <http://energy.gov>. Accessed September 2012
- Tester JW et al (2012) Sustainable energy. Choosing among options, 2nd ed. MIT, Cambridge
- Ullal HS, von Roedern B (2007) Thin film CIGS and CdTe photovoltaic technologies: commercialization, critical issues, and applications. In: Conference paper preprint NREL, CP-520-42058). NREL, Golden. Available at <http://www.nrel.gov>. Accessed July 2010
- Wadia C (2010) Mined resource constraints on solar energy and battery storage potential. In: APS/MRS/MITEI, critical elements for new energy technologies. An MIT energy initiative workshop report, pp 105–110. MIT, Cambridge. Available at www.mit.edu/mitei. Accessed August 2012
- Wadia C et al (2009) Materials availability expands the opportunity for large-scale photovoltaics deployment. *Environ Sci Technol* 43(6):2072–2077
- Woodhouse M et al (2013) Perspectives on the pathways for cadmium and telluride photovoltaic module manufacturers to address expected increases in the price for tellurium. *Sol Energy Mater Sol Cells* 115:199–212
- Xie WT et al (2011) Concentrated solar energy applications using Fresnel lenses: a review. *Renew Sustain Energy Rev* 15:2588–2606
- Zweibel K (2010) The impact of tellurium supply on cadmium telluride photovoltaics. *Science* 328:699–700. Available at <http://www.sciencemag.org>. Accessed in April 2013

The Economics and Policy of Solar Photovoltaic
Generation

Mir-Artigues, P.; del Rio, P.

2016, XX, 346 p. 56 illus. in color., Hardcover

ISBN: 978-3-319-29651-7