CHAPTER 8

Solar photovoltaics (PV)

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Contents

8.1 Basic theory of semiconductors. Photovoltaic effect

The photovoltaic conversion is based on the photovoltaic effect, that is, on the conversion of the light energy coming from the sun into electrical energy. To carry out this conversion, devices called solar cells are used, constituted by semiconductor materials in which a constant electric field has been created artificially (by means of a pn junction).

Next, we will try to understand in a qualitative way how light is converted into electricity. This requires remembering some concepts of physics and chemistry.

The semiconductor material par excellence is Silicon given its extraordinary abundance, 60% of the earth's crust is composed of silica that has a high content of it, in addition to its interesting electronic properties. 90% of the current solar cells are made of silicon, and the others are governed by the same physics, so we are going to study silicon.

However, other materials are also used. It is worth mentioning the Gallium Arsenide (AsGa) with better qualities than Silicon for the production of electrical energy, but its scarcity in nature makes it so expensive that it is only used in applications where costs are not relevant as is the case with spatial applications in which it is usually the use of solar cells manufactured with AsGa for its high efficiency.

Other materials are selenium (Se), germanium (Ge), cadmium telluride (CdTe) diselenide, and copper Indium (commonly called CIS), Indium Antimonide (SbIn), etc. In the periodic table (the part of interest is shown below) these elements and compounds of interest for the photovoltaic industry can be located. Silicon is in the fourth column of the periodic table, called Group IV (Fig. 8.1).

Fig. 8.1 Portion of the periodic table of interest in photovoltaic applications.

The chemical properties of the elements are largely related to the number of electrons that have the materials in their outer layer, and how many electrons are missing to complete it. A silicon atom has 14 electrons. In the outer layer (3) it has four electrons, and another four are missing to complete it. Those four electrons of its outer layer (of valence) are available to associate with other atoms.

Silicon crystallizes in a network similar to that of a diamond. Through covalent bonds, very stable and strong, each silicon atom shares one of its four valence electrons with four other atoms (thus remaining in a stable structure, with its outer layer full, with 8 electrons). Since electrons tend to occupy the lowest energy levels, most of them are linked, and at absolute zero temperature, all of them. At room temperature, some acquire enough energy to escape the bond and can then move through the material (conduction). This behavior is not exclusive of semiconductors but is manifested in all materials; what is peculiar is the amount of energy needed to release an electron from the link.

The quantum theory describes the differences between conductors (metals) and semiconductors using energy band diagrams. The electrons present in an isolated atom can occupy only allowed energy levels; there are other levels that cannot be occupied and that are called forbidden levels. When an isolated atom becomes part of a determined crystalline structure, it interacts with other nearby atoms of the crystal and the energy levels are affected producing a splitting of the same that gives rise to bands of energy. Electrons have energies that lie in bands. In the same way that the electrons in an atom cannot have any energy, the electrons in a crystal cannot take any energy either. And just as the last energy levels in an atom define the chemical properties of the atom, the last bands of energy define the electronic properties of a crystal (Fig. 8.2).

In the outermost energy band, the electrons are free to move between the different atoms. This most energetic band is called the conduction band. The electrons that are in this conduction band are those that contribute to the flow of current. In metals, this band is partially full, but for semiconductors at absolute zero temperature, it is completely empty. At room temperature, only one in 10^{10} electrons is in the conduction band.
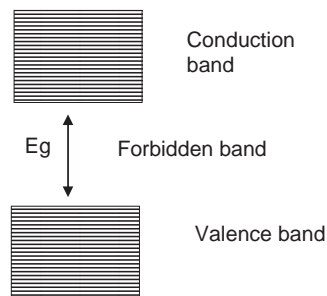

Fig. 8.2 Band scheme.

The electrons of the outermost layers that intervene in the chemical bonds, called valence electrons, occupy an energy band (valence band, the one before conduction in terms of energy levels) that can overlap with the conduction band or remain separated from her.

The spaces between allowed bands are forbidden bands. The most important one is the one that separates the conduction band from the outer energy band full. The energy that an electron must acquire to jump that forbidden band is called gap energy, for example. The unit that is usually used is the electron–Volt (eV), which is the energy that an electron acquires when its voltage increases by $1\,V$ ($1\,eV = 1.6 \times 10^{-19}\,J$).

Depending on the width (energy) of the bandgap (gap width), the materials exhibit different electrical behavior, resulting in Conductive materials (the permitted band overlaps the conduction band), Insulating materials (the forbidden band is wide, of the order of $10\,eV$), and semiconductor materials (the bandgap is of the order of $1\,eV$).

In short, the amount of energy needed to release an electron from the link is a value of each material and is called the energy of the bandgap because between the energy level occupied by the bound electron and the free electron there is no energy value allowed.

In the case of metals, this energy is zero, that is, all the electrons are free to move through the material. In insulating materials, the energy required is so high that the number of free electrons is negligible, even at high temperatures. The amount of energy needed, in the case of semiconductors ($1.12\,eV$ for silicon to 25°C), allows an effective control of the flow of charges and is what makes these materials so suitable for electronics and for the generation of electrical energy when the semiconductor receives solar radiation. Where can that amount of energy that can release an electron come from? Thermally, or in the case of the photovoltaic effect, of the energy of the Sun's rays, of the photons.

As an example of interest to us, consider that in a silicon crystal at $0\,K$, the atoms have four valence electrons (and are represented by an ionic core with electric charge $4+$) and four electrons that form bonds with neighboring atoms. At absolute zero temperature, silicon is a perfect insulator. There are no free electrons to move as in the case of metals. As the temperature increases (the atoms receive a contribution of external energy), some electrons have enough energy to free themselves from their nucleus and can reach the conduction band leaving the corresponding gap in the valence band, making possible a flow like an electric current. Both the electrons in the conduction band and the gaps in the valence band are able to move under the action of an electric field, due in the latter case to the gaps that can be occupied by valence electrons of the adjacent atoms, producing the movement of the hole as if it were a positive charge. The number of electron–hole pairs thus created is relatively low at room temperature and depends exponentially on— E_{gap}/KT, where k is the Boltzman constant and T is the temperature expressed in degrees Kelvin.

The higher the temperature, the more electrons can constitute the current, so that the conductivity increases with temperature (in contrast to metals in which the conductivity decreases). The conductivity of Silicon at room temperature is very low (it is a semiconductor material), but by adding minute amounts of other materials (doped), the conductivity can be strongly increased.

Suppose that a luminous radiation affects the crystalline network, which in an atomic analysis of behavior is characterized by quanta of energy: photons, in the case of light, with an energy determined by its wavelength.

The solar radiation that reaches the earth, which is distributed from a range of wavelengths ranging from 300 nm to approximately 4 μm, is partially reflected by the atmosphere and partly transmitted to the earth's surface. The photovoltaic applications used in space, in satellites or spacecraft, have available solar radiation different from that of terrestrial photovoltaic applications. Radiation outside the atmosphere is distributed along different wavelengths in a manner similar to the radiation of a "black body," according to Planck's law, while at the surface of the earth the atmosphere selectively absorbs the radiation of certain wavelengths.

It is called spectral Irradiance to the power (light) received by a unit surface area at a wavelength difference dλ. The units are $W/m^2 μm$. (The integral of the spectral irradiance along all the wavelengths of interest is called Irradiance.) (Fig. 8.3).
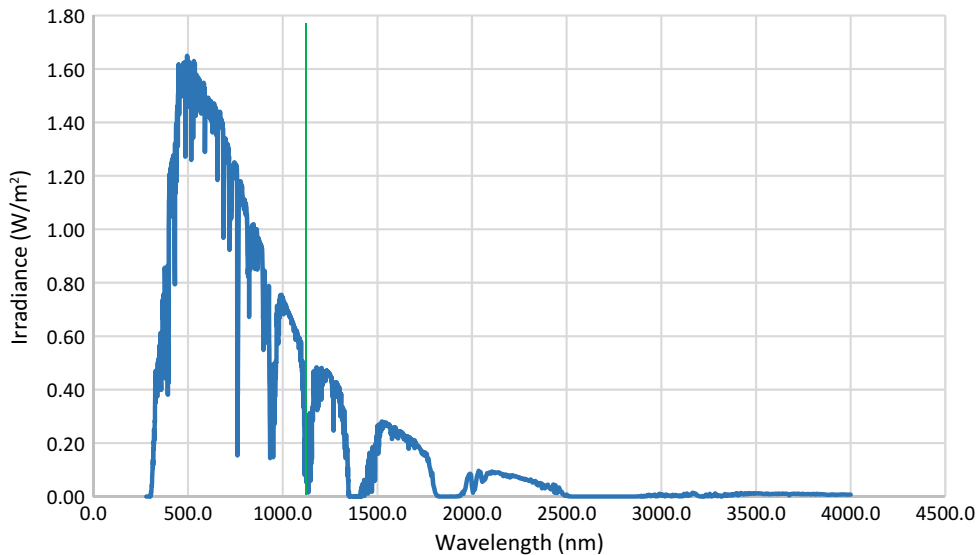

Fig. 8.3 Irradiance vs wavelength (the *green line* [light gray in print version] corresponds to 1.1 eV), Spectrum AM 1.5.

Photons are characterized by their frequency or by their wavelength, as well as by their energy. These three parameters are related.

$$c = \lambda v$$

where c is the speed of light (3×10^8 m/s), v is the frequency in Hz and λ is the wavelength, in meters. On the other hand,

$$E = h v = hc/\lambda$$

where E is the energy of a photon (in Joule, J) h is Planck's constant (6.626×10^{-34} Js).

The same equation can be expressed in a simplified form if the constants are replaced by their value,

$$E_{photon} (eV) = 1240/\lambda (nm)$$

The probability of photons interacting with the crystal lattice is very high, especially considering that a silicon wafer, a sheet of thickness $< 500 \mu m$, is opaque to solar radiation. When a photon interacts with a link, it transfers its energy to it. If the amount of energy is equal to or greater than the gap energy, the electron is released from the bond and becomes a free-charge carrier to travel through the crystal.

Making the simple calculation we can deduce that the minimum wavelength for the photon can communicate energy to an electron to create an electron–hole pair in silicon (bandgap of 1.1 eV) is 1.12×10^{-6} m $= 1.12 \mu m$.

Photons with higher wavelengths do not have enough energy to excite the electron, creating electron-hole pairs that contribute to create current, so all energy is lost. On the other hand, photons with lower wavelengths create the electron-hole pair but all the excess energy is lost in heat. Table 8.1 shows the gap width values for other materials.

Another parameter of interest, especially to describe the operation of solar cells, and which we have already mentioned when discussing the radiative generation-recombination mechanisms, is the absorption coefficient (α).

This parameter describes how easily the semiconductor absorbs a photon and creates an electron–hole pair, eh. It depends on the value of the semiconductor and nature, indirectly or directly from the bandgap.

We can say that at the moment when absorption occurs, the conversion of light into electricity has potentially started. It is only necessary that these pairs can be removed from the cell and circulate through an external circuit in the form of electric current.

There are semiconductors in which the absorption process is easier. They are the so-called direct gap semiconductors like the GaAs. These are very absorbent materials and cause the active layers that make up the cell to be very thin (few microns) because with little material all the light can be absorbed.

In short, in a crystal of pure silicon, each atom shares its valence electrons with four neighboring atoms in covalent bonds. This very strong bond between an electron and the

Table 8.1 Gap energy of materials for photovoltaic cells

Material	Bandgap (eV)
Si	1.11
SiC	2.60
$CdAs_2$	1.00
CdTe	1.44
CdSe	1.74
CdS	2.42
$CdSnO_4$	2.90
GaAs	1.40
GaP	2.24
Cu_2S	1.80
CuO	2.00
Cu_2Se	1.40
$CuInS_2$	1.50
$CuInSe_2$	1.01
$CuInTe_2$	0.90
InP	1.27
In_2Te_3	1.20
In_2O_3	2.80
Zn_3P_2	1.60
ZnTe	2.20
ZnSe	2.60
AlP	2.43
AlSb	1.63
As_2Se_3	1.60
Sb_2Se_3	1.20
Ge	0.67
Se	1.60

The materials indicated in bold are the most used in photovoltaic
cells.

two atoms that it helps to join can be broken by communicating enough energy: 1.1 eV
or more. This corresponds to a photon of light of a wavelength of 1.12 μm or less (all
colors of the visible spectrum and enough in the infrared). These released electrons move
through the crystal in the same way that they move freely in a metal, not bound to any
atom. It is free to accelerate in the presence of an electric field, that is, it takes part in the
conduction of electricity.

In this transition, it leaves behind a "hole," a place where an electron is missing. The
neighboring electrons can leave their bonds to fill the gap, essentially changing the posi-
tion. Therefore, both the electrons and the holes can move through the crystal. This is
called a photoconductive effect.

If nothing is done, at a certain time, t (calling the average life of the minority
carriers), the electron will find another position where there is a gap, so it will be linked.

The electron will no longer move through the material, and neither will that gap that it has filled. This process is called recombination and producing another photon (heat).

The process of increasing the energy of an electron from the one in the bond to the one that allows it to move freely through the crystal is called generation and the reverse process recombination, which occurs when a free electron becomes part of a link and releases the energy in the form of heat.

From a silicon crystal, as described so far, you cannot extract electrical energy when exposed to solar radiation. The reason is that the electric charges generated by the light radiation do not follow any preferential direction of movement. They move erratically through the crystal and are quickly caught by unsatisfied links, that is, they recombine.

What is needed is a way to separate electrons and holes so that they do not recombine in the crystal, and a trajectory to drive these electrons out to perform work on a charge. The first is achieved by a union between two semiconductors with different electrostatic charges. The second, simply by means of metallic contacts on each side of the union. Next, we will analyze the first point.

8.1.1 Doping

In order to build an effective solar cell, it is necessary to contaminate the silicon crystal in a controlled manner. Two types of impurities are introduced in a very small amount with respect to the total number of silicon atoms so that they do not substantially modify the crystal lattice.

When in the crystalline structure of a pure (intrinsic) semiconductor impurities are introduced from another element with a different number of valence electrons, another type of semiconductor called extrinsic semiconductor is found.

If we add a small amount (of the order of a part per million) of phosphorus in the silicon crystal, so that the phosphorus atoms occupy a position in the structure of the silicon crystal, it is said that we have doped the crystal with phosphorus.

Phosphorus is from group V of the periodic system since it has five valence electrons (one more than Si). The nuclei and inner electrons of the P atoms are established at the positions of the crystal, and four of the five electrons participate in covalent bonds with electrons from the four neighboring Si atoms. The fifth electron is very weakly bound to the phosphorus atom, so much so that in fact at room temperature it is thermally excited and released.

Doping with elements such as phosphorus, with a valence electron more than the crystal atoms, is called doping of type n (n of negative), and the dopant is called a donor because it provides electrons easily.

Doping the Si with Boro, the exact opposite effect is achieved. Boron belongs to group III, that is, it has three valence electrons (one less than Si). It is situated in the structure of the crystal of Si (one for each 10 million atoms of Si) but it only has electrons to

form three covalent bonds with the neighboring atoms, leaving a gap. This gap, identical to the photogenerated gap explained above, moves through the crystal structure easily at room temperature.

For silicon, boron is a type p (positive) dopant, called an acceptor because it provides a gap that easily captures free electrons.

The two elements that are used to contaminate silicon have 3 and 5 valence electrons, respectively; it is usual to use boron and phosphorus for each case because their atoms are similar in size to silicon. The doping procedure is carried out on a glass that in its manufacture was already contaminated with one of the two elements. The other is added so that each side of the wafer-shaped glass contains a kind of impurity, finally. In the region with phosphorus, zone n, there are many electrons that are not linked and, consequently, the phosphorus atoms are easily ionized, that is, the unbonded electrons, one for each phosphorus atom, require very little energy to be mobile charges; the room temperature is sufficient. In the region with boron, zone p, what are missing are complete links and that facilitates the displacement of electrons that occupy a link to unsatisfied links. This behavior is characterized by the use of a fictitious particle, the hole, which has a positive charge and allows a mathematical–physical analysis much simpler than that required to represent large packages of electrons in motion. What is easier, to analyze the movement of an air bubble in a glass with sparkling water or that of the water molecules around the bubble?

8.1.2 Diodes

Photovoltaic cells are diodes with a large surface exposed to the sun. A diode is an n–type layer attached to a p–layer. The space where the two layers meet is called junction. Each region has moving particles of different charge. At the instant the diode is formed, the trillions of free electrons near the junction in the n–type material immediately rush to fill the voids of the p–type material, leaving the n–side (which was electrostatically neutral) with a net positive charge. In the same way, the gaps on the p–side migrate to the material of type n, leaving the p–side of the junction with a net negative electrostatic charge. It is as if the n–side had a high electron pressure and the p–side low electron pressure. When the union is formed, the valve is opened so that this electron gas flows from the high to the low-pressure region.

That is, as the atoms lose charges and ionize, areas with non–mobile charges are produced. These fixed charges will oppose the continuation of other similar charges (charges of the same sign are repelled; charges of the different sign are attracted) (Fig. 8.4).
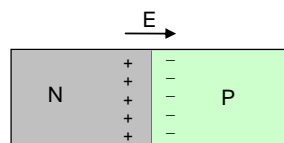

Fig. 8.4 p-n junction.

This process leads to a dynamic balance between the movements of electrons and holes and the creation of an electric dipole around the interface that produces an electric field in a direction perpendicular to the interface that moves the particles in the opposite direction. In milliseconds the process reaches equilibrium since the statistical force that pushes the electrons on the side to fill the gaps on the p-side is balanced by the force of the electric field created by the electrons and holes that have been moved from their original materials.

The electric field presents a barrier to keep crossing the majority carriers (electrons on the n-side and holes on the p-side). But the union does not impede the flow of minority carriers. If there are electrons on the p-side (and there will not be many because there are more holes there) and reach the junction, they will be accelerated through to the n-side. On the p-side next to the junction there will, therefore, be no electrons, (since they are immediately taken to the n-side) so electrons will come from a little farther in the area to cover their voids. This current is called diffusion current. In the same way, it happens with the holes, minority carriers on the n-side.

The above description very simplistically explains the operation of the pn junction, key for all solid-state electronics. We will see below that if on a device of this nature luminous radiation effects, the electric charges generated will follow the direction imposed by the electric field in such a way that they can be extracted by the metallic contacts of the crystal toward the outside; this electronic device is a solar cell.

8.2 Conversion of sunlight into electricity

Let us go back to the photoconductive effect: a photon collides with an atom (an atom of Si more likely since there are millions more of them, but also possibly of P or B) and releases an electron, leaving behind a hole. Suppose that this creation of an electron–hole pair takes place on the p-type material side. The electron and the gap wander around the crystalline structure with a speed determined by a parameter dependent on the material called Mobility.

The electron of the electron–hole pair has a relatively short time in which it is free because it is very likely to recombine with any of the numerous gaps in that material p. However, if the electron–hole pair is created close enough to the joint, there is a good chance that it will diffuse into the joint, and when it does, it will be accelerated through the electric field. If the gap reaches the union, it will be repelled.

The electron, once it has crossed the junction, will remain on the n-side since it rarely has the energy to jump back the barrier to the p-side. It has little danger of recombining with a hole because there are few holes on the n-side.

A similar situation occurs when the electron–hole pair is created by the light on the n-side. In this case, it is the gap that diffuses in the union being accelerated toward the p-side where there are very few electrons.

The only work done by light is the separation of electrons and holes in an atom.

The charge imbalance in an illuminated cell (electrons stacked on the n-side and holes on the p-side) creates a potential difference, and if the two sides are connected by an outer cable, a stream of electrons will flow from the n-side toward p (where there are fewer electrons) doing work in an external load.

If a solar cell that is connected to an external load is illuminated, there will be a potential difference across the load and a circulation of current that leaves the external circuit through the positive terminal and returns to the cell through the negative. In these operating conditions, the cell behaves like an energy generator and shows the maximum interest from our point of view. The phenomena that take place inside the device can be described in the following way.

Photons that strike the cell with energy equal to or greater than the width of the band-gap are absorbed in the semiconductor volume and generate electron–hole pairs that can act as current carriers.

The electric field, or the potential difference, produced by the pn junction is the cause of the separation of the carriers before they can recombine again and, therefore, the cause of the flow of the current by the external potential difference, thus supplying power to the load.

In summary, the current delivered to a load by an illuminated semiconductor diode is the net result of two internal components of current that are opposed:

(a) The photogenerated or photocurrent current I_L due to the generation of carriers that produces illumination.

(b) The diode current or dark current I_D due to the recombination of pins that produces the external voltage necessary to be able to deliver energy to the load, which is, in turn, a function of the voltage.

8.3 Basic structure of a solar cell

A semiconductor, without pn structure, although it is illuminated does not cause the circulation of electrical current. If we expose it to light, the only thing we would achieve is that the semiconductor would warm up and that, simply, the electron–hole pairs that generated the light would disappear, at most, at another point inside the semiconductor. The pn junction makes possible the circulation of the electric current thanks to the presence of an electric field.

Virtually all currently available solar cells are constituted by a pn junction as described above. In silicon cells, which are the most widely used in practice, the junction is achieved by diffusing a layer of phosphorus on a silicon wafer that is originally all contaminated with boron. The junction is very shallow, with typical values of width-diffused layer (region n) of 0.2–$0.5\,\mu$m. It is common to name this layer as an emitter.

It is necessary to fabricate a pn junction so that the crystal lattice of the semiconductor is not interrupted when passing from one region to another. The use of special technologies is therefore necessary, for example, the diffusion of dopants for silicon cells and the epitaxy techniques in the liquid phase and metalorganic compounds (MOCVD) for GaAs cells.

As indicated, the existence of the pn junction makes possible the existence of an electric field in the cell, with the direction of the n-side to the p-side that separates the eh pairs. This field directs the holes toward the contact on the p-side, which causes the extraction of an electron from the metal that constitutes the contact, and directs the electrons toward the n-side contact by injecting them into the metal.

The cell is a sheet of silicon (wafer), about 300 μm thick, with a pn junction very close to the surface—the largest number of generations occurs in the first microns so it is convenient that the electric field of the union pn is close to the surface to conduct loads efficiently toward metal contacts.

The other important concept in the structure of a solar cell is that which refers to the design of what we call the frontal metallization grid, the metallic contacts that must be made to extract the electrical current from the cell. It should not be forgotten that a metal is an absorbing material to light. The front face of the cell, which receives the solar radiation, has a metallic contact in the form of a grid that, while collecting the charges, must allow the photons to pass inside the crystal (Fig. 8.5).

Consequently, at least the contact that we call frontal, the one on the side of the cell that is directly exposed to the Sun, cannot completely cover the surface of the cell. The percentage of surface covering coating is called factor of shade. You can think then that it should be as small as possible but if it becomes too small, one of the parameters of

Fig. 8.5 Frontal metallization grid and busbars.

the solar cell whose influence we will study later, the series resistance, increases and that means a loss of efficiency of the cell. Thus, we must arrive at a compromise in the value of the coating factor in such a way that it is low enough to allow the passage of sunlight and high enough so that the series resistance of the cell is maintained in tolerable levels. The design of the grid has to reconcile these two objectives that are opposite: the coating factor, surface occupied by the metal with respect to the total area of the cell, is of the order of 4%. The compromise solution that is usually adopted is to use contacts in the form of a comb. In contrast, the electrical contact on the unlit face covers the entire area.

Usually, the illuminated face is covered with a layer of antireflective material to increase the percentage of solar energy absorbed. The usual coloration of the cells is dark blue matte to prevent the photons from being reflected on the surface. As the silicon wafers are quite specular and of a light metallic gray color, it is necessary to apply an anti-reflective layer or, also, perform a chemical attack on the surface that produces a layer composed of microscopic tetrahedrons.

With the application of any of these techniques, sometimes with both, it is possible to minimize losses due to reflection to negligible figures. Currently, other cell colorations are being developed to expand the catalog of products for building integration; although the conversion efficiency decreases.

The thickness of the cell is a compromise between two factors: minimizing transmission losses, associated with photons that do not find a link with which to interact, or what is the same to the transparency of the wafer; and minimizing recombinations, the longer the path that the charges have to travel until metallization, the greater the probability that they will recombine. It is important to note that the thickness of the wafers is of the same order of magnitude as that of the tools used to cut the crystalline silicon ingot in these. Practically 40% of the material is lost in the cut.

8.4 Characteristics of a solar cell

8.4.1 V-I curve

Fig. 8.6 shows in blue the locus of voltage and current values that can be present in a diode. In red, the values of a solar cell illuminated, the result of adding to the current of the diode an amount I_L, due to the illumination.

For the study of photovoltaic cells, it is usual to change the polarity references, considering I_L as a positive quantity (instead of negative as it appears in the figure). Taking the generation currents as positive, you can write:

$$I = I_L - I_D(V)$$

which is the characteristic equation of the solar cell, valid in all its operating ranges, included when the device acts as a power receiving diode because the recombination exceeds the generation.
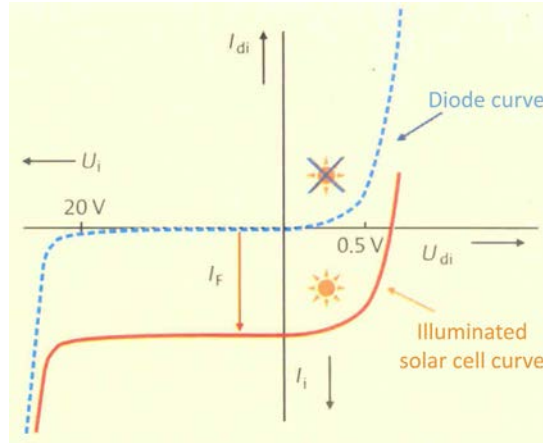
Fig. 8.6 VI curves of a diode and an illuminated photovoltaic cell.

The equivalent electrical scheme attending to the previous expression is shown in Fig. 8.7.

Mathematically, and considering for simplifying that the diode current can be expressed through the model of a single exponential, the characteristic equation of the device is.

$$I = I_L - I_D(V) = I_L - I_o \left[\exp \frac{eV}{mkT} - 1 \right]$$

where e is the charge of the electron, k is the Boltzmann constant and m is a dimensionless parameter (Fig. 8.8). (Sometimes mkT/e is denoted as Vt; with m=1, Vt (300 °K) $\cong$ 25 mV.)

This form of representation adopts the agreement of signs to consider positive the generation currents (which is the opposite to that usually used in electronic circuits that use diodes). With this agreement, the first quadrant of the I-V plane corresponds to the operation of the cell delivering current to a load under positive voltage; that is, it corresponds to the operation of the device as an energy generator. The larger the surface of the cell exposed to the sun, the greater the current generated for the same irradiance value (Fig. 8.9).
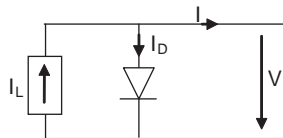

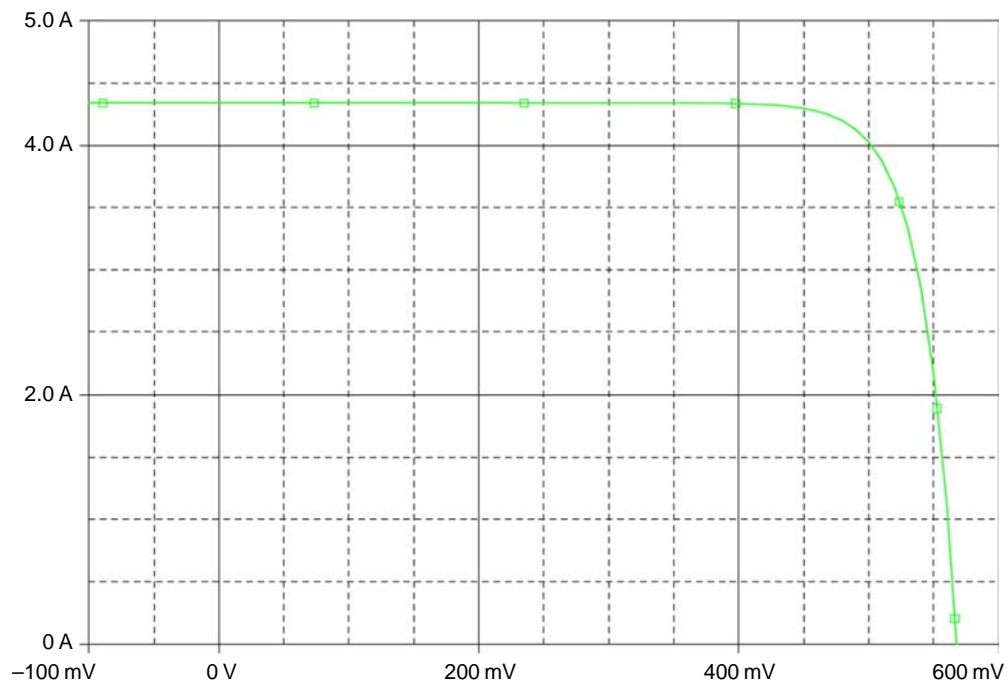**Fig. 8.7** Simplified equivalent electrical diagram of a solar cell.

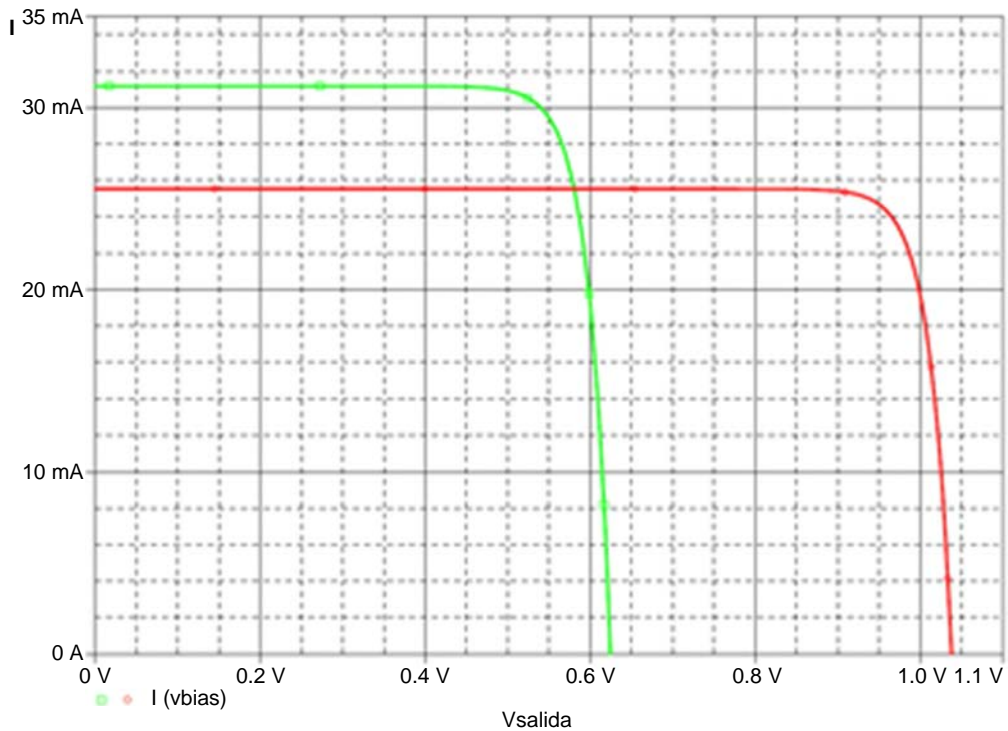**Fig. 8.8** V-I curve for a silicon photovoltaic cell subjected to a certain irradiance.

Fig. 8.9 VI curves for a given irradiance cells Silicon *(green)* [light gray in print version] and Gallium Arsenide *(red)* [dark gray in print version].
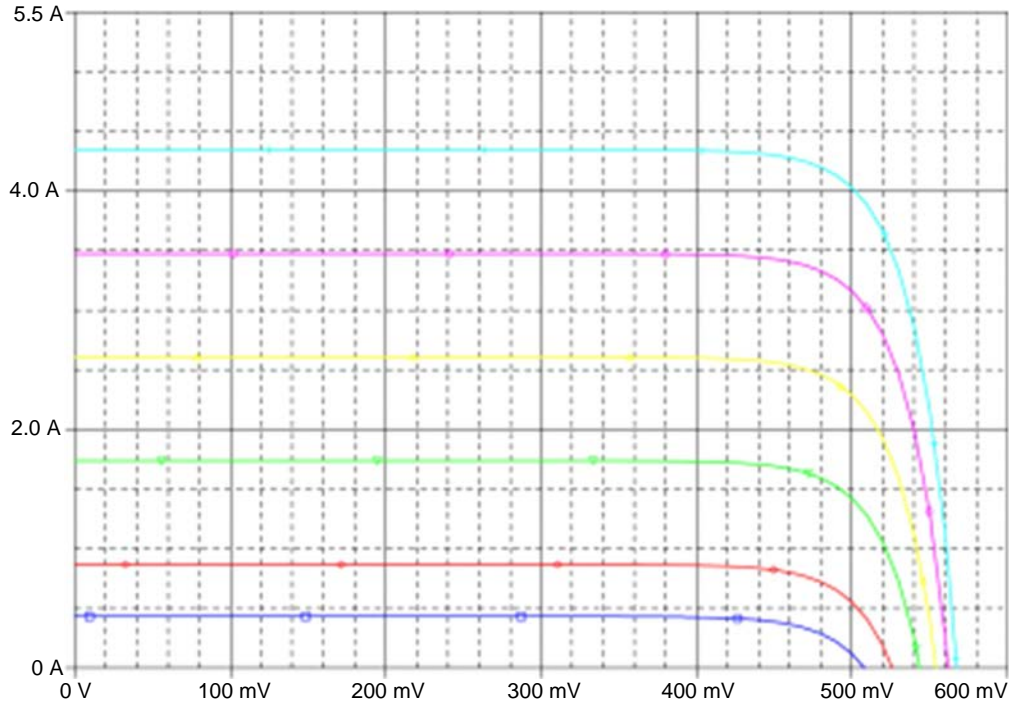
Fig. 8.10 Variation of VI curve with the irradiance value (G = 100, 200, 400, 600, 800, and 1000 W/m²).

Within a wide range of operation, the photocurrent of the practical solar cells is directly proportional to the intensity of the incident radiation. Fig. 8.10 shows the change in the VI curve by varying the illumination intensity. It is evident that with an increase in irradiance an increase in the obtainable power will be achieved.

Therefore, given a photovoltaic cell, there will be a VI curve for each irradiance value to which it is subjected.

8.4.2 Short-circuit current and open-circuit voltage

As can be seen in the previous figure, the greater value of the current in the generation region is obtained for short-circuit conditions, V=0. According to the previous equation, the short-circuit current Isc is given by.

$$Isc = I(V = 0) = IL$$

If the device is kept in open circuit ($I = 0$), it will autopolarize with a certain voltage, which is the highest it can withstand in the generation region. It is about the open-circuit voltage, sometimes denoted as V_{oc} and its value is such that the photocurrent

is completely compensated by the polarization current. This is, $I_L = I_D$ (Voc), in open–circuit conditions and, taking into account Eq. (1) that defines it, it results:

$$V_{oc} = m\frac{kT}{e} \ln\left(\frac{I_L}{I_o} + 1\right)$$

In addition, in order to have a model closer to reality than the ideal cell we have analyzed up to this point, we should include two elements that are the series resistance and the parallel resistance, which affect the efficiency of the cell.

The series resistance of the cell, R_s, is an internal resistance due to factors such as the resistance of the semiconductor with which the cell is manufactured. The current generated in the solar cells circulates toward the contacts through the resistant semiconductor material, circulating in the region of the base, which is not too doped in general and the emission region, which, although it is largely doped It is very close. In addition to what was previously considered, the resistance of the metallic contacts with the glass contributes to the typical losses of the series resistance, in addition to the resistance of the metallization mesh. If the coating tends to zero (the mesh lets in more light), the series resistance increases (tends to infinity). It is commonly assumed in practice that all these resistant losses can be represented by a resistance which is called the solar cell's series resistance, R_s.

The parallel resistance R_p appears due to imperfections in the quality of the pn junction, and is responsible for the existence of current leakage.

Taking into account these two resistances, the equivalent model of the cell remains as shown in Fig. 8.11.

And the mathematical expression that relates current and voltage is.

$$I = I_L - I_D(V) = I_L - I_o\left[\exp\frac{e(V + R_s I)}{mkT} - 1\right] - \frac{V - R_s I}{R_p}$$

In the following, the influence of the series and parallel resistance values in the VI curve for given irradiance and temperature conditions are shown exaggeratedly (Figs. 8.12 and 8.13).
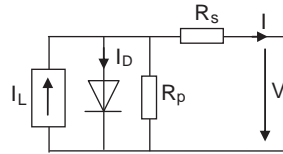

Fig. 8.11 Electrical diagram simplified to four equivalent elements of a photovoltaic solar cell.
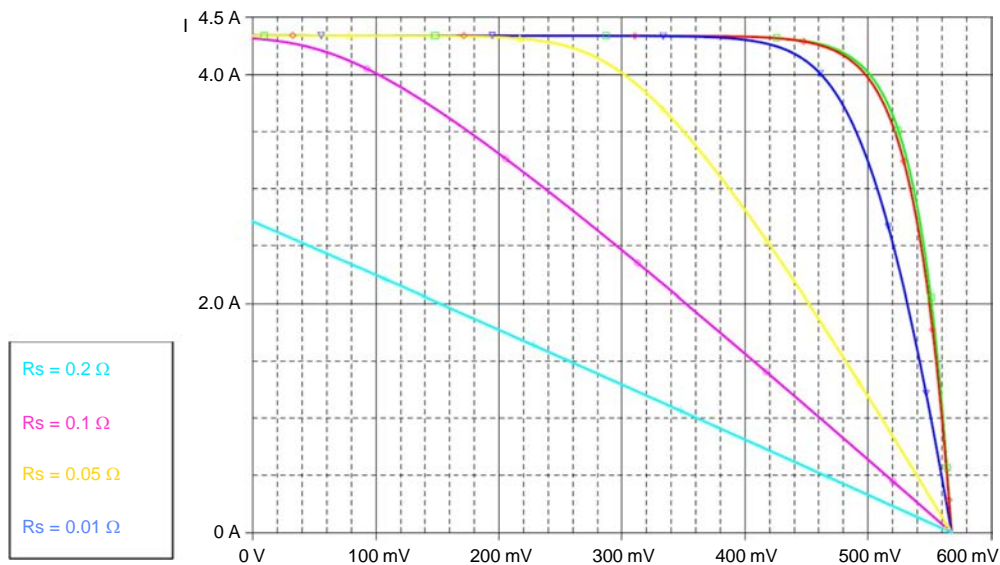
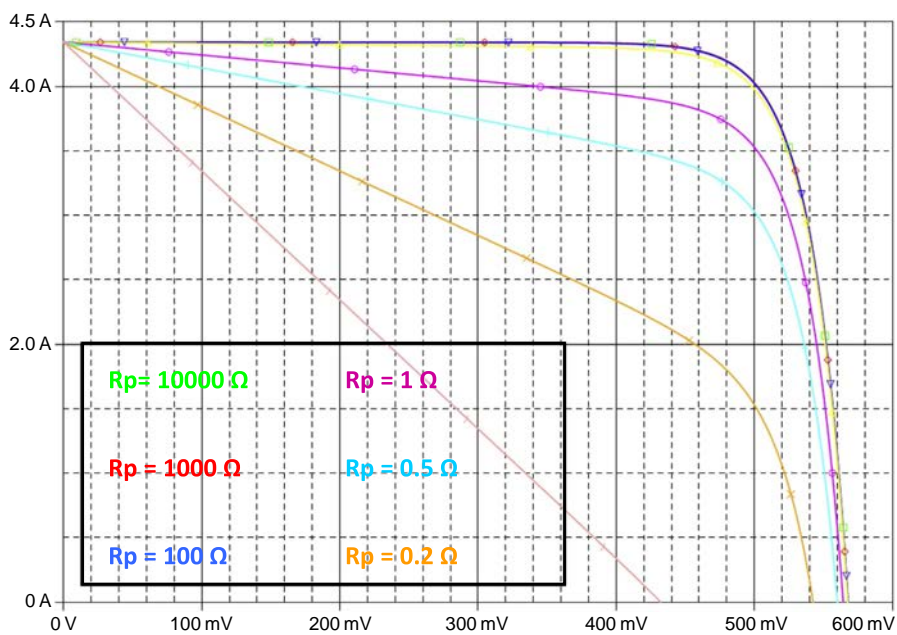**Fig. 8.12** Effect of the series resistance on curve VI.

Fig. 8.13 Effect of parallel resistance on curve VI.

8.4.3 Power curve. Maximum power point

As already indicated above, the region of the characteristic curve between I_{SC} and V_{OC} corresponds to the operation of the cell as a generator. For each point of curve VI (Fig. 8.14), there is a value of voltage and working current, that is, a power $P = VI$, which can be represented as shown in Fig. 2.18.

When the cell is short-circuited, the current value in this quadrant of the VI curve is the maximum, but the voltage is zero, so the power that is delivered is zero. In the same way, leaving the cell open-circuit (not connecting it to anything), the current is zero, so that, even if the voltage is high, the power delivered is zero.

If the energy is supplied to a load with nonzero resistance, the power delivered to the resistance is given by the product $P = IV$. There is an operating point (I_{mpp}, V_{mpp}) for which the power delivered is maximum: it is the point of maximum power. The values of I_{mpp} and V_{mpp} can be obtained from the maximum condition.

8.4.4 Fill factor

The product $I_{mpp} * V_{mpp}$ that gives the maximum power delivered to the load, is obviously smaller than the product of the largest current that can be extracted from the cell by the higher voltage, $I_{sc}*V_{oc}$. The parameter defined by the quotient $I_{mpp} * V_{mpp}/(I_{sc}*V_{oc})$
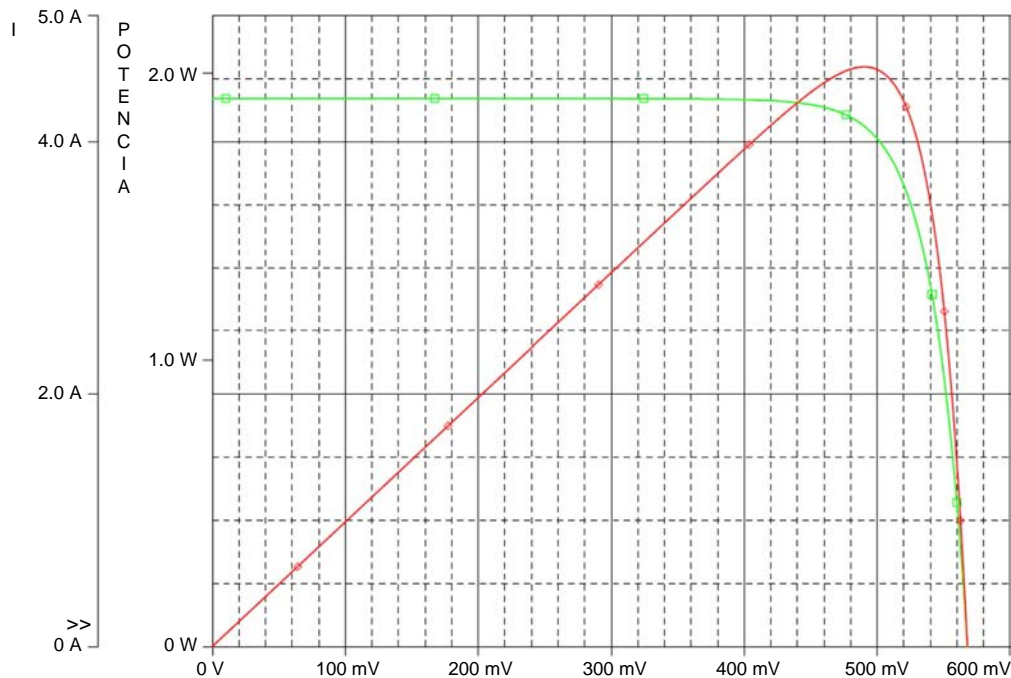

Fig. 8.14 Curve VI and power curve of a photovoltaic cell.

is always less than unity. This quotient, called fill factor, FF, is usually used as a quantification of the shape of the characteristic curve. The form factor is a parameter of great practical utility, which varies little from one device to another and takes values that are around 0.7 0.8 for many crystalline semiconductor cells (Si, GaAs, InP, etc.).

Using the definition of the form factor, the maximum power delivered by the cell can be written as.

$$P_{max} = FF*V_{oc}*I_{sc}$$

8.4.5 Cell conversion efficiency

The energy conversion efficiency of a solar cell is defined as the quotient between the maximum electrical power that can be delivered to the load and the power of the incident G radiation over the device.

$$\eta = P_{max}/G$$

Naturally, this efficiency and the maximum power are obtained only if the load resistance is adequate, given by V_{pmp}/I_{pmp}.

For example, when we say that a commercial cell has an efficiency of 15%, it means that if we had a cell surface of 1 m^2, for every 100 W/m^2 of incident radiation, only 15 W would be delivered to the rest of the circuit.

And what would be the maximum efficiency that can be expected? It depends on the material of the cell. In the case of Silicon, exposed to solar radiation (without concentrating it), 22% of the energy of the AM 1.5 spectrum does not have enough energy to create the pair eh; another 32% is lost because the photons have more energy than 1.11 eV. Therefore, only 49.6% of the energy (efficiency) could be converted. In addition, efficiency losses due to reflection, internal resistance, recombination processes, etc.

8.4.6 Influence of temperature

The short-circuit current increases slightly with temperature (almost not seen in the figure) but there is a strong decrease in the open–circuit voltage so the performance of a solar cell decreases with temperature.

The photocurrent I_L increases slightly with the temperature due, in part, to the increase in the diffusion lengths of the minorities and partly to the narrowing of the bandgap, which shifts the absorption threshold toward lower energy photons. The improvement of the photocurrent with temperature is more pronounced in GaAs cells than in Si cells, but in all cases, the variation is small and, in first approximation, I_L can be considered independent of temperature (Figs. 8.15 and 8.16).

Therefore, the operating temperature of the photovoltaic solar cells has a very significant effect on the electrical response of the module. Taking into account that, in
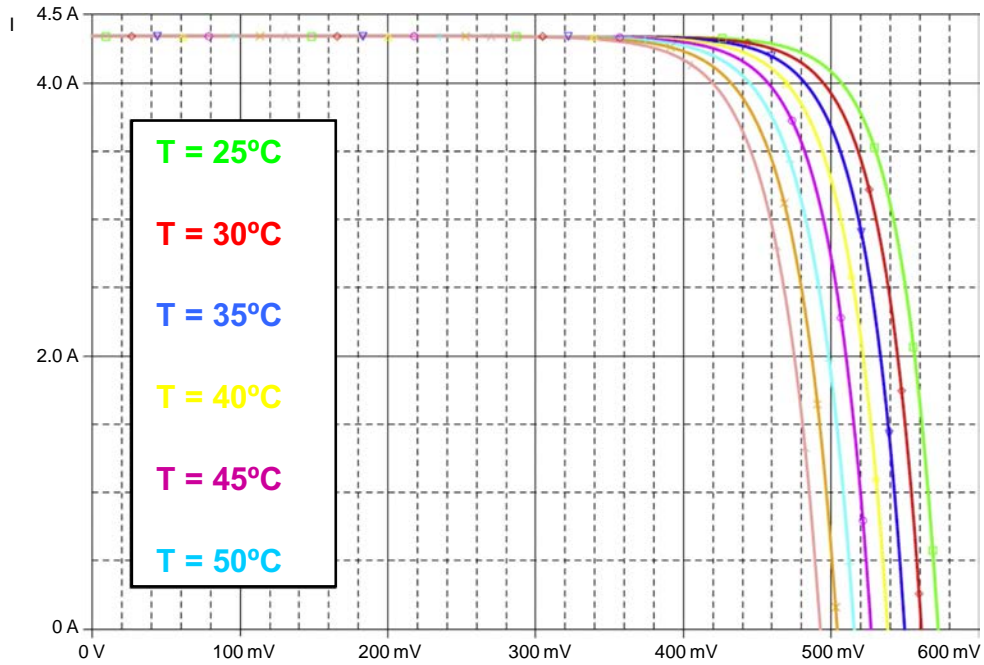
Fig. 8.15 Effect of temperature on curve VI of a photovoltaic cell subjected to a certain irradiance.
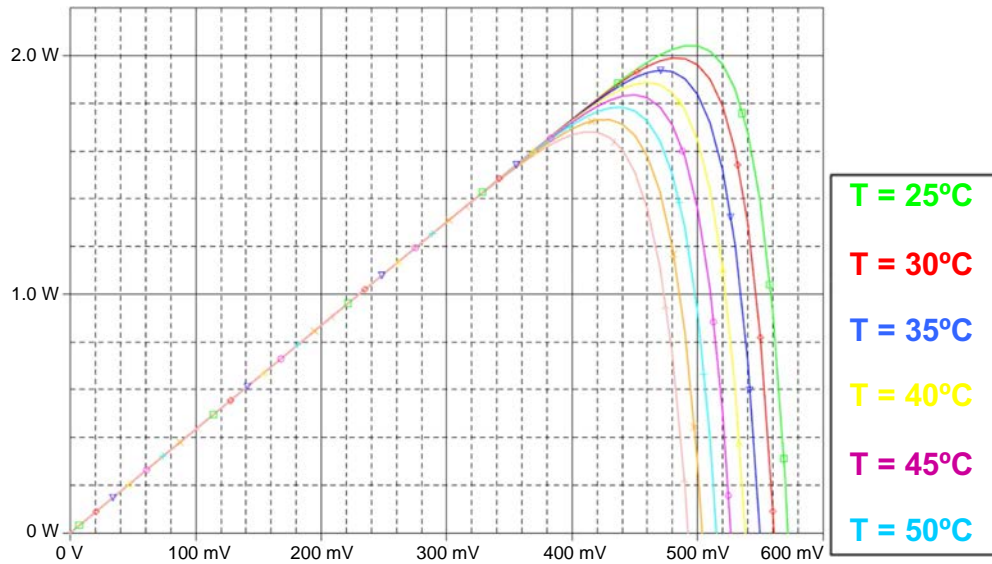

Fig. 8.16 Effect of temperature on the output power of a photovoltaic cell at a certain irradiance.

terrestrial applications, the solar cells can easily be heated up to 70°C and that in space applications the temperature can be higher, it forces us to incorporate an adequate modeling of the temperature coefficients of the main electrical parameters.

8.4.7 Influence of concentration

There is a strategy aimed at reducing the costs of producing photovoltaic energy in large quantities, which consists in causing light to fall on the cell after concentrating it by means of an optical device. This idea is represented schematically in the figure as well as some elementary concentrator systems.

In a first approach, in photovoltaic systems, a concentration system is based on an optics that collects energy on a surface and transmits it on the surface of the cell. The underlying idea in these systems is to change cell area by concentrator area supposedly much cheaper (Fig. 8.17).

As a consequence of the use of a concentrator system, the cell is subjected to an X-fold higher irradiance. The number X is usually designated as the number of suns and measures the level of concentration at which the cell works (sometimes denoted as C, concentration index).

As indicated, within a wide range of operation, the photocurrent of the practical solar cells is directly proportional to the intensity of the incident radiation. This proportionality allows the following approach: If the photocurrent at the illumination level defined as a unit (usually 1 Sun = 1000 W/m^2) is I_{L1}, the photocurrent at an illumination level X (concentration factor: X Suns) times superior is.

$$I_L = X\, I_{L1}$$

Fig. 8.17 Two images of concentration cells and Fresnel lenses for concentration.

It must be taken into account that, when working in concentration, the cell will operate at higher temperatures. The development of these systems requires paying special attention to the cooling systems of the cell.

8.4.8 Standard test conditions (STC)

We have seen that the electrical behavior of a photovoltaic cell, that is, its characteristic IV, changes according to the conditions of illumination and temperature. To allow comparison between cells, standard test conditions (STC) have been established, universally used and defined as follows:

Irradiance: $100\,mW/cm^2$ ($1000\,W/m^2$)

Spectral distribution: AM 1.5

Normal incidence

Cell temperature: 25°C

Regarding the spectral distribution, it must be considered that the rays of the sun, when crossing the atmosphere, undergo a modification, so that part of the radiation is reflected, and part is transmitted. The layers of air cause part of the radiation to be dispersed and another absorbed. In this way, not only less energy reaches the surface of the earth than it reaches the outside of the atmosphere but also changes its spectral distribution.

The trajectory length through the Earth's atmosphere traversed by the direct sunbeam, expressed as a multiple of the path traveled to a point at sea level with the sun directly above it is called Air Mass (AM, dimensionless).

$$\text{It is calculated as } AM = P/P_{or}\,(1/sen\o)$$

where P is the local air pressure (Pa), Po is $1013 \times 105\,Pa$ ($1013\,bar$) and ø is the solar elevation angle.

The spectrum changes with the AM. The AM 0 spectrum is that which is outside the atmosphere (a ray of sunlight does not pass through any mass of air in the atmosphere). AM is equal to 1 at sea level with a cloudless sky when the sun is directly above and the local air pressure is equal to P_o. It is generally accepted that the most realistic terrestrial spectrum for general use is provided by a sun height angle of 41.81 (which corresponds to AM = 1.5).

As can be seen, for STC it is considered that irradiance of $1\,kW/m^2$, with a spectral distribution of AM 1.5, is incident on the module. For AM 1.5 2% of the energy falls in the ultraviolet portion, 54% in the visible and 44% in the infrared.

8.5 Cell types

Within the photovoltaic solar energy, it is generally accepted as a method of classification of the different technologies that are used that of the materials that in the solar cell perform the conversion of solar energy/electric energy.

The most widespread technology is that of monocrystalline silicon, x-SI (or sc-Si, or m-Si), followed by that of polycrystalline silicon, p SI, amorphous silicon, a Si, high-performance cells, generally GaAs or related compounds InP, InAs, TeCd, CIS, etc. Finally, multi–junction cells and bifacial cells are presented.

8.5.1 Monocrystalline silicon solar cells

Monocrystalline silicon cells are the cells we usually refer to as silicon cells. As the name implies, the entire volume of the cell is a single crystal of silicon. It is the type of cells whose commercial use is more widespread nowadays (Fig. 8.18).

The manufacturing process of the wafer, all of it, a single crystal of silicon, which will constitute the cell, begins by extracting the silicon from the sand.

In this first extraction process, silicon still contains a large number of unwanted impurities and we usually refer to it as metallurgical grade silicon. The subsequent refining process first involves manufacturing $SiHCl_3$ (trichlorosilane) with it, which in a first phase will still contain a large number of unwanted elements. This is done because $SiHCl_3$ is a liquid compound, with liquids being easier to purify than solids. After this purification process, $SiHCl_3$ of high purity is obtained. Then it is necessary to "recover" the solid form of silicon. Mixing $SiHCl_3$ with H_2 and heating it gives polysilicon (solid) and HCl. This polysilicon, although it is more purified, still does not constitute a monocrystal. The final production of the monocrystal can be done by the process known as Czochralski. The final result is a circular bar of silicon (ingot, ingot), which can measure several meters and have a diameter of several inches. This bar, by means of a cutting process, is from which the wafers with which the monocrystalline silicon solar cells are manufactured are finally extracted. During the cutting processes of silicon a large amount of material is wasted (40%–50%).

8.5.2 Polycrystalline silicon solar cells

The use of polycrystalline silicon cells constitutes a strategy of cost reduction by reducing the cost of wafers. Polycrystalline silicon is no more than silicon consisting of crystalline
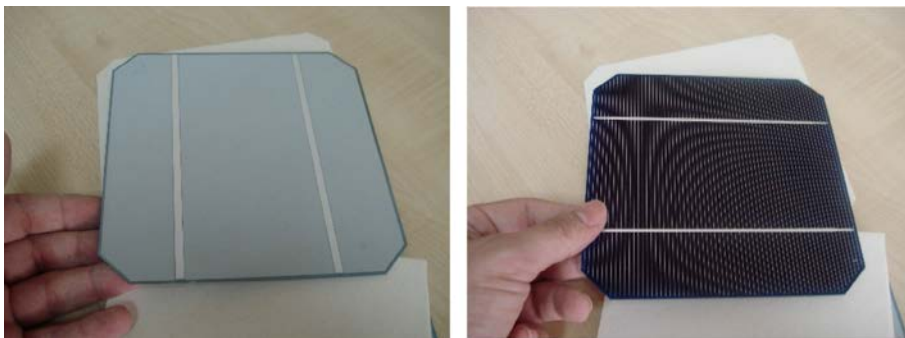
Fig. 8.18 Back and front of a monocrystalline silicon cell.

silicon grains. In principle on this material, you can use the same manufacturing techniques as those used for the manufacture of monocrystalline silicon cells although it is necessary to make the following observations.

The polycrystalline silicon grain boundary constitutes an additional source of recombination, so it is expected that the efficiency of these cells is lower than that of their monocrystalline counterparts. The loss is due to V_{occ} since it has been shown that with the polycrystalline silicon cells practically the same short-circuit current can be obtained as with the cells of monocrystalline material (Fig. 8.19).

The shorter diffusion lengths require some modifications in the design of the cells as shown Fig. 8.20 in which the existence of a double union increases the collection efficiency of these devices. The multicrystalline material causes some of the technological processes described above to have some additional difficulty, especially those that, like

Fig. 8.19 Polycrystalline silicon cell.

Fig. 8.20 Double union structure suitable for the manufacture of multicrystalline silicon cells.

texturing, depend on the crystalline orientation of the material. In the laboratory, efficiencies of 16.8% have been achieved with large–area cells. At the level of industrial production, the limit efficiencies of this type of cells are around 17%.

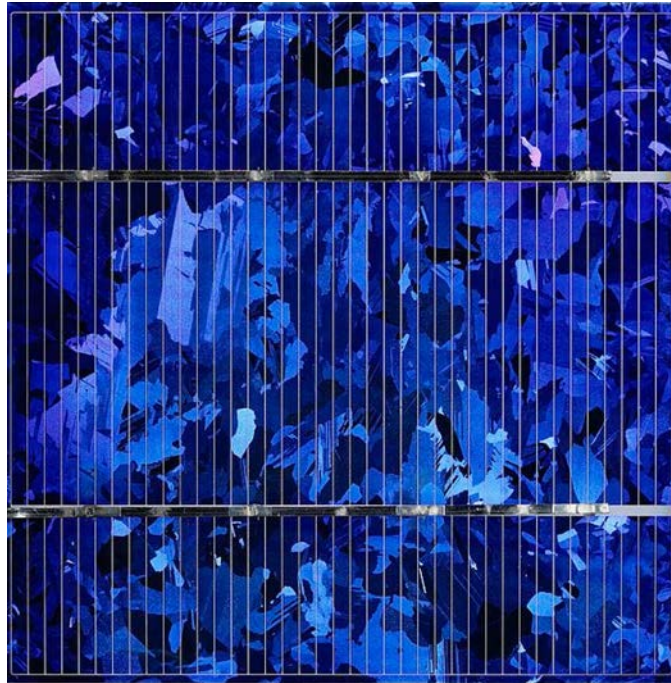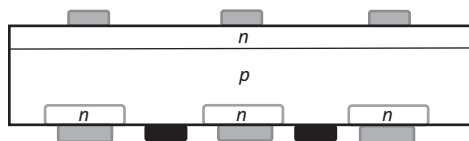### 8.5.3 Thin-film technologies

Polycrystalline thin–film solar cells are understood as those in which the thickness is between tenths and several microns, no >4 or 5, formed by multiple grains, microcrystals of the material, grouped in order to form the sheet. The development of polycrystalline thin–film materials and their application in photovoltaic devices is clearly aimed at reducing production costs, with the following objectives:

— Find semiconductor materials that can absorb sunlight in extremely thin layers of them, of the order of $1\,\mu m$ compared to the hundreds of microns required for crystalline silicon, so that the cost associated with the materials must be reduced.
— Can deposit these thin layers or thin sheets of material on cheap and affordable substrates such as plastic, glass, etc.
— Being able to deposit these thin sheets by simple methods and easy to adapt to industrial processes on a large scale. Thinner layers should lead to faster processes and lower capital costs.
— Being able to manufacture complete modules during the deposit process of the thin films and in this way reduce the production costs, and finally,
— Being able to convert sunlight into electricity in an efficient way keeping all these partial objectives together.

Several materials meet the industrial requirements of efficiency and cost in a competitive way. These materials are amorphous silicon (Si), thin-film polycrystalline silicon, CdTe, copper and indium selenide (CuInSe$_2$), and AsGa. All these materials can be deposited on affordable substrates, by a large number of methods potentially applicable on an industrial scale and ranging from vacuum techniques to simple chemical deposition methods.

During the last years, different materials have been studied for their application in this type of photovoltaic cells, CdSe, CuO, Cu2O, $Zn_3 P_2$, $Cd_{1-X} Hg_X$ Te, p Si, GaAs, CdTe, and CIS…, but only the last two have emerged with enough force to be considered as a possible alternative to monocrystalline silicon technology in terms of production cost, efficiency and stability. Efficiencies around 16% or 17% have been achieved in both technologies. Several processes and reaction paths have been identified as capable of producing high-quality sheets and therefore high-quality photovoltaic devices.

The thickness required of the absorbent sheet in a device depends on the absorption coefficient, α, of the material used. High values of the absorption coefficient mean that the light is absorbed by the material traveling a lower path the greater the value of the coefficient. That is, the greater the absorption coefficient, the lower the so-called effective absorption length and therefore the smaller the thickness of material required.

In materials with very high absorption coefficients, such as $CuInSe_2$, and CdTe, 90% of the incident photons are absorbed in $<1\,\mu m$. of thickness, while in the case of crystalline Si, with a lower absorption coefficient, dozens if not hundreds of microns are needed to reach its maximum photocurrent.

An important property required of the absorber of a solar cell is that the photogenerated carriers must have lifetimes, τ, that are long enough to allow these carriers to leave from the absorbing region.

In almost all these cases, the thin sheets are polycrystalline. The individual crystallites are generally of good quality but are interrupted by numerous grain boundaries. Grain boundaries are regions of disorder with high densities of structural defects and segregated impurities. They are also generally regions of high recombination. In addition, charge entrapment in the energy levels of grain boundaries can form potential barriers that hinder or impede transport of carriers.

In many cases the grain boundaries can come to dominate the operation of the polycrystalline solar cell, becoming the efficiency obtained strongly dependent on the grain size of the material involved (Fig. 8.21).

For other direct gap materials with a higher absorption coefficient, such as GaAs and $CuInSe_2$, or CIS, the grain sizes can be small (up to two orders of magnitude lower than Si) and still produce very high efficiencies, acceptable, comparable to that of the corresponding monocrystal.

8.5.4 Amorphous silicon cells

Amorphous silicon lacks the ordering of silicon atoms in the form of a crystalline lattice. Consequently, due to this characteristic, no semiconductor property would be expected from this material. However, we must mention that when in the context of solar cells we talk about amorphous silicon it must be understood that a certain amount of hydrogen has been incorporated into the material. It is then spoken of hydrogenated amorphous silicon and is designated by a Si:H. The solar cells that we usually see in calculators and watches are made of amorphous silicon (Fig. 8.22).

In amorphous silicon, one would expect a high density of defects that would prevent the material from exhibiting minimal transport and recombination properties to be feasible from the photovoltaic point of view. However, hydrogen tends to be incorporated into those silicon bonds that are free and which are mainly responsible for the poor transport and recombination properties of the material, reducing its influence, to the point that the material is feasible to manufacture cells with an efficiency around 10%.

Compared to crystalline material, amorphous silicon is much more absorbent (gap width 1.7 eV instead of 1.1 eV), only thicknesses less than micron being required to absorb most of the sunlight. The amorphous silicon cells are manufactured by depositing the silicon directly on a cheaper substrate (glass, plastic, etc.) being possible the deposition
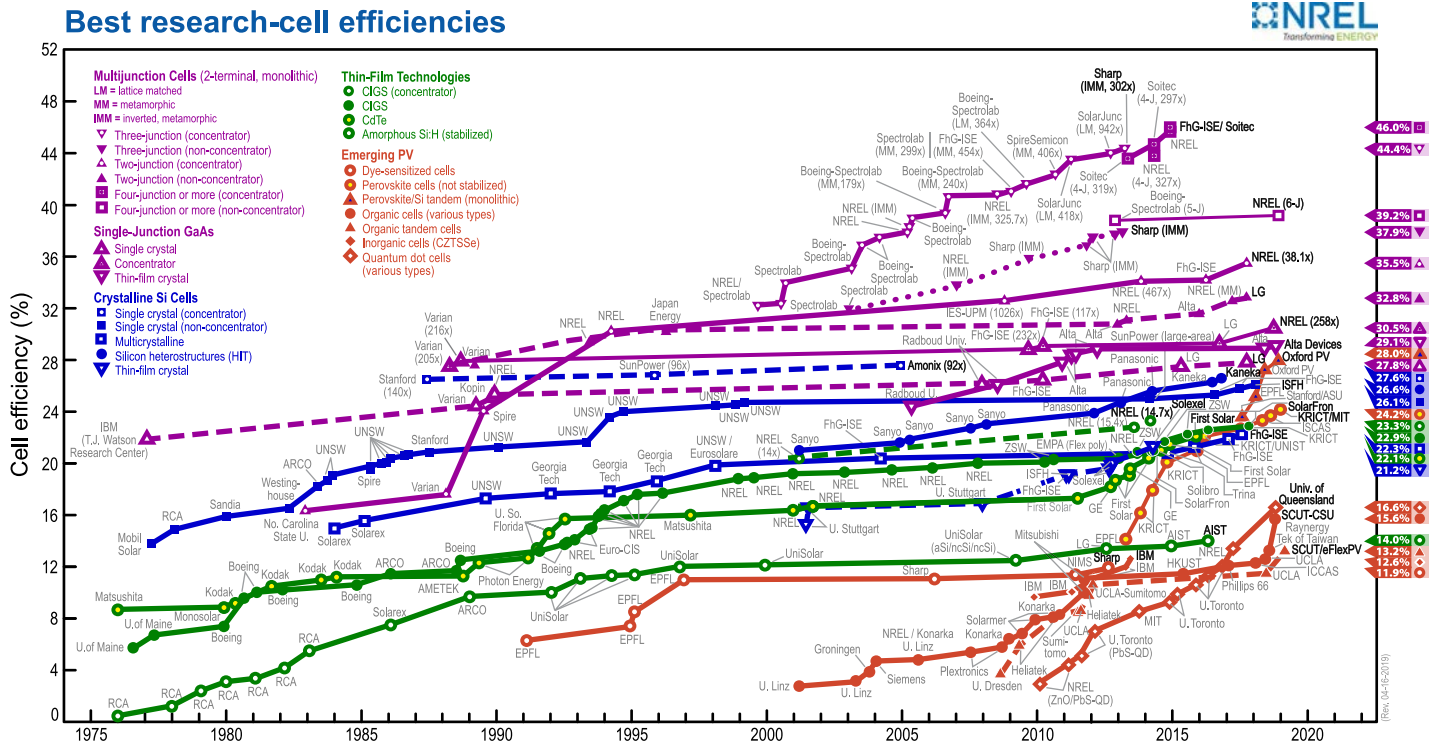
Fig. 8.21 Best research-cell efficiencies. *(Reprinted with permission by the National Renewable Energy Laboratory, https://www.nrel.gov/pv/cell-efficiency.html, Accessed April 24, 2019)*

Fig. 8.22 Amorphous silicon.

on large surfaces, of the order of square meters. In addition, its high energy consumption during the production cycle makes the energy return time < 1 year.

Another advantage of amorphous silicon is that, by alloying it with nitrogen or carbon, the value of its gap can be increased and, with germanium, it can be decreased, which makes the relatively simple manufacturing of tandem or multigap cells possible. It has been calculated that with this, an efficiency of 24% should be possible, combining the amorphous silicon with germanium alloys that would give an approximate gap of 1.45 eV and with C or N to obtain a gap of 2.0 eV in a structure of two terminals and three pn junctions.

8.5.5 Gallium arsenide and semiconductor III–V solar cells

The GaAs is a direct gap material which implies that it is a very absorbent material. A few microns of material are enough to absorb all the incident light. Consequently, the photovoltaically active layers in this cell are located on the upper part of the substrate on which they have been grown, which simply plays a mechanical supporting role.

Given its high cost, GaAs cells are investigated in the context of their use in concentration systems. From an industrial perspective, GaAs solar cells are frequently used in space applications because of their resistance to radiation.

In P cells are used in space applications, also because of their resistance to radiation. Their applications on land have been discarded due to the high cost of preparation of the glass, and the control of its properties. The measured efficiencies are around 21% for homounion, 20.5% for AM1.5, and 18% for surface homounions, which separates it from terrestrial applications.

8.5.6 Cadmium telluride solar cells

In principle, the main attraction of CdTe as a candidate for solar energy absorbing material is the value of its separation energy between the conduction and valence bands, energy of the "gap," which is 1.4 eV and is corresponds to the optimal theoretical value for the use of the solar spectrum, so the interest of the scientific community was great about it in such a way that in a few years its study went from the laboratory scale to preindustrial development (Fig. 8.23).

The first cell based on CdTe that achieved an efficiency >10% was developed by Kodak in 1982. Since then several groups have worked intensively on the development of these cells. The biggest manufacturer is currently Firs Solar, having achieved efficiencies higher than 15% (Fig. 8.24).

In recent years, the greatest achievements in the development of solar cells based on CdTe have been made by researchers from the University of South Florida (USF), which have achieved efficiencies of 15.8%, which means obtaining the first solar cells not based on monocrystals that exceed the 15% efficiency barrier, which is considered the limit for talking about high efficiency cells.

Fig. 8.23 Partial view of a 100-kW photovoltaic plant of TeCd located in Aragón (Spain).
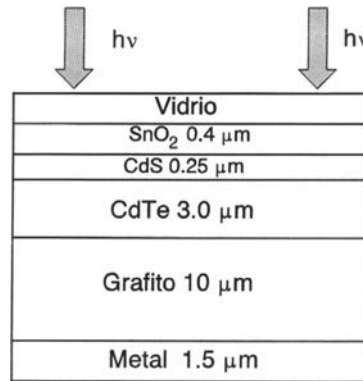
Fig. 8.24 Cross section of a cell of CdTe/CdS.

8.5.7 Copper and Indium selenide solar cells

Copper and Indium selenide (CulnSe$_2$ or CIS) was one of the first thin-film materials to achieve efficiencies >10%. The first monocrystalline cell of CulnSe$_2$ with 12% efficiency was built at Bell Laboratories in 1974.

The use of monocrystals is not useful for its practical application, so once the validity of the material was demonstrated, the development of thin-film CIS devices began.

The first cell prepared by thermal evaporation was developed by Grindle in 1980 and reached a yield of 5%. But the development that definitely launched the race to obtain high-efficiency CIS cells was carried out by Mickelsen and Chen at the Boeing Company. This device known as Boeing cell was prepared by evaporation and obtained an efficiency of 10%.

The characteristics of most CuInSe$_2$ devices, with efficiencies higher than 10%, are that they were manufactured with an arrangement where the CIS is deposited on glass or alumina coated with a metal layer of Mo, and having a composite window layer usually by cadmium sulfide, CdS, or zinc cadmium sulfide, $Cd_x Zn_{1-x} S$, in combination with a transparent conductive oxide. The majority of these cells having been prepared by thermal evaporation or by selenization of indium copper alloys or binary precursors, $ln_x Se_y$, $Cu_x Se$, etc.

The leading group currently in CIS technology is the company Siemens Solar Industries (SSI) which has developed a module of $0.4\,m^2$ area and an efficiency of 9.7%. This development represents the highest efficiency known for a module based on thin-film technology.

8.5.8 Multiunion cells

In cells based on a single gap, photons whose energy is less than the value of this gap cannot be absorbed and, therefore, are lost. Multi-junction cells are a strategy to take advantage of these photons (Fig. 8.25).

While single-gap cells have the potential to achieve efficiencies of 40.7% (assuming the Sun as a blackbody at 5759 K and maximum concentration) the two-gaps systems have a potential of 55.5% and those of three gaps, 63.4%. The process can be continued until an infinite number of gaps are considered, obtaining the limit of the photovoltaic conversion efficiency, 86% (Fig. 8.26).

There are two types of configurations for tandem or multigap systems:

— Stacked systems

In these systems, the cells are placed one behind the other in descending order of their gap. Photons that are not absorbed by the preceding cells can be absorbed in the following
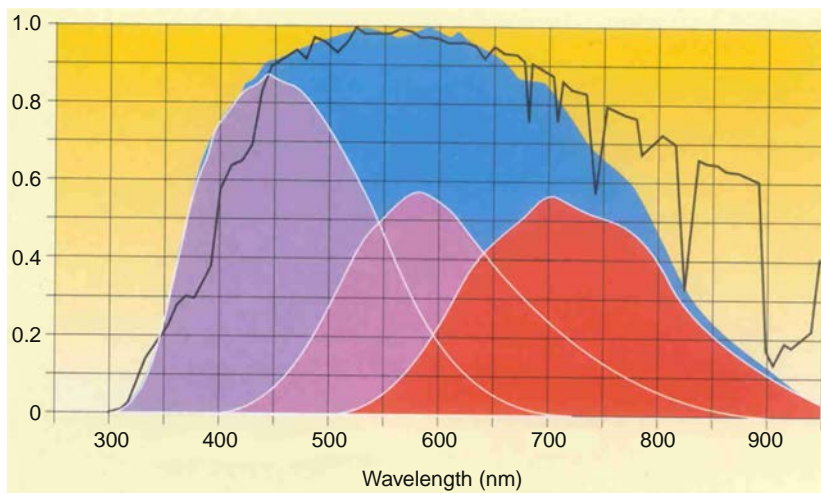

Fig. 8.25 Diagram of operation of multi-junction cells.
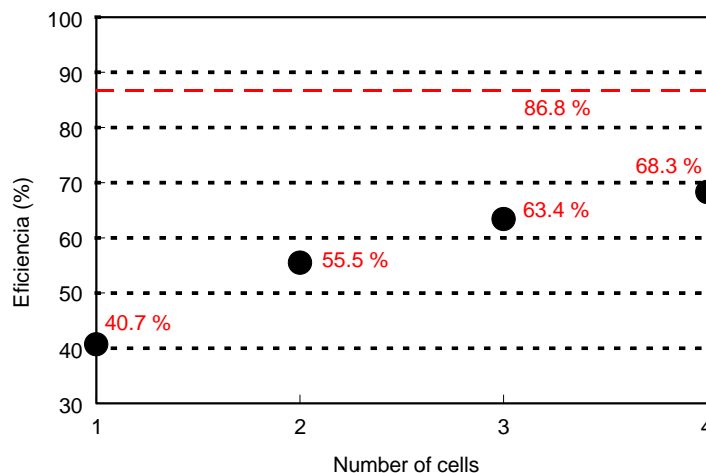
Fig. 8.26 Efficiency and number of cells in tandem configuration.

cells. Stacking is said to be monolithic when all cells are manufactured on the same wafer and mechanically, when the cells are manufactured separately and then attached, for example, using a special adhesive.

One of the biggest problems that appear associated with monolithic systems is how to make the electrical connection of the cells. To solve this, one of the procedures consists of manufacturing a tunnel diode (a diode that is barely rectifying) between the two cells. However, this interconnection, despite everything, often introduces a series of resistance value that is excessive for the operation of the cell in concentration. Another strategy is the use of an interconnection.

With this procedure, the base of the upper cell is connected to the emitter of the lower cell by a controlled succession of chemical attacks and metallization processes. The major drawback of this method comes from the increase in the factor of shadow resulting from the existence of a second metal grid. With this technique, three-terminal devices can also be manufactured, although they are difficult to apply in practice immediately in current photovoltaic systems that are intended for two-terminal devices.

—   Spectral splitting systems

In a spectral splitting system, light from the Sun is separated into different spectral components and distributed to the cells by means of a series of filters (Fig. 8.27). One of the

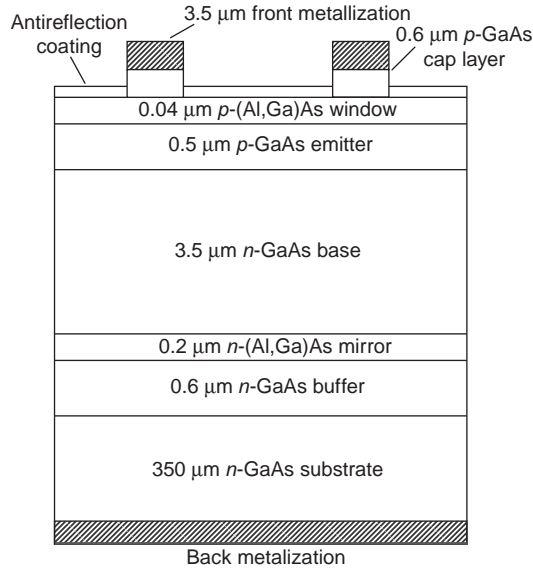**Fig. 8.27** Spectral splitting.

Fig. 8.28 Tandem cell structure of GaInP/GaAs.

advantages of these systems is that it is compatible with the use of already existing gap cells. For example, efficiencies of 29.4% were achieved at 170 soles through a system that jointly used GaAs and Si cells of conventional structure.

The results with GaInP / GaAs tandem cells gave results of 21.8% efficiency in the first work with a large–area cell ($1\,cm^2$). The champion in these devices has had efficiencies of 29.5% (AM1.5) and 30.2 (180 soles). Its structure is shown in Fig. 8.28.

8.5.9 Bifacial cells

They are cells with both sides enabled for the transformation of energy. They have great advantages in devices of static concentration although it has not been very accepted at the moment, due mainly to the complex development of the bifacial structure. Obviously, for this, they require the existence of a metallization grid on their back face. In principle, its first advantage over monofacial solar cells would reside in its ability to collect albedo radiation (solar radiation reflected in the ground) once installed in appropriate modules. Another of its potential advantages lies, however, in its use in flat concentrators like the one shown in Fig. 8.29. As shown in the figure, the flat concentrator directs the light rays that impinge on the part of its surface that is not covered by cell toward the back of it. In this way, it concentrates light, depending on its specific design, by a factor of 2–4.

8.5.10 Nanostructured TiO2 cells sensitized by dye and organic cells

Solar cells based on nanostructured materials, both organic and inorganic, represent a low–cost alternative with significant potential to overcome the performance of
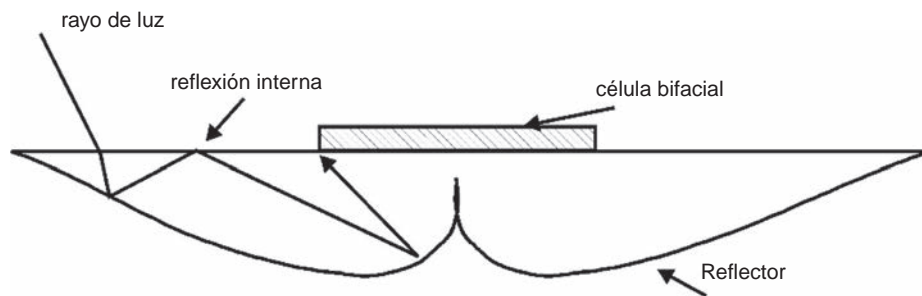
Fig. 8.29 Bifacial cell located in a flat concentrator.

conventional pn binding cells. These cells can be formed by combining nanostructured semiconductors, conjugated polymers, dye molecules, and redox electrolytes. This type of cells bases its interest on its production potential at a low cost both for the materials to be used and for the possible methods. The general idea is the creation of nanodominios within the structure of different materials that increase the contact area in the photoactive interfaces, promoting the generation of photocarriers and their collection.

The first significant breakthrough was published by Grätzel in 1991 with the use of mesoporous titanium dioxide nanoparticle (TiO_2) films. The scheme of the Gräztel cell calls is shown in the figure, the current efficiencies of these devices are around 11%.

The Graetzel solar cell is composed of nanoscopic crystals of titanium oxide (TiO_2) coated with an organic dye (the sensitizer). TiO_2 is a large gap semiconductor oxide (3.2 eV). Because of its wide bandgap, TiO_2 only absorbs the ultraviolet part of the solar emission and therefore very little conversion efficiency is achieved.

The TiO_2 is immersed in a liquid electrolyte containing a redox couple (I^-/I_3^-). The TiO_2 grains are in contact with each other and ensure the conduction of the electrons to the electrode.

Under illumination, the dye absorbs the incident photons and accumulates enough energy to be able to inject an electron into the TiO_2 conduction band that diffuses through the nanostructured matrix of titanium dioxide and is directed to the contact with the outer circuit, generating a photocurrent.

The dye is regenerated with dissolved species in the electrolyte that carry gaps to the counter-electrode. After the injection, the reduced form of the redox couple in solution, regenerates the oxidized dye, while the oxidized form of the redox couple is reduced to the counter-electrode, thus closing the regeneration process. The counter-electrode is covered with platinum to catalyze the electrolyte reduction.

The process is inspired by photosynthesis, a chemical process that allows plants to feed themselves by consuming light energy. The chlorophyll located on the surface of the leaves absorbs sunlight and distributes the electrons, whose energy is used in other parts of the plant.

In their current state, sensitized solar cells cannot compete in terms of efficiency or durability with other alternatives in the solar energy market. Doubts have been raised about the stability of the dye, whose degradation, even if it occurs very slowly, would render the ovarian cell useless in the medium or long term. Another drawback is the liquid phase, among other things because it is not easy to perfectly seal the organic solvent, with which the cell can be dried gradually and become unusable. For this reason, many of the current investigations are aimed at simplifying the production process and at the same time achieving better mechanical properties, for example, giving the cell flexibility. Another objective is to make a solid cell with sensitized nanostructured TiO_2 semiconductor and a solid medium that replaces the liquid as a void transporter. Solid–state cells have been made with CuI as a substitute for the electrolyte and in principle they are stable, but their efficiency is lower, in particular, because the formation of voids in the structure cannot be avoided.

Another approach to this concept is the devices based entirely on organic materials known as massive heterojunction where they are arranged in a disorderly manner at the macroscopic level but with photovoltaically efficient nanodominios.

8.6 The photovoltaic module

For practical use, the solar cells are electrically associated in different combinations that allow obtaining the current and voltage values necessary for a given application and are encapsulated between materials that protect them from the effects of the weather, isolating them electrically from the outside and, finally, it gives mechanical rigidity.

When two or more photovoltaic cells are connected in series, the assembly behaves with another equivalent VI curve. When in series, all the cells are crossed by the same intensity of the current, but the voltage in the terminals of the set is the sum of the existing tensions in each cell (Fig. 8.30).

On the other hand, when several cells are connected in parallel, they are all subjected to the same voltage, with the current at the output of the set equal to the sum of the currents generated by each of the cells (Fig. 8.31).

As can be seen, the short-circuit current and the open-circuit voltage of a module can be calculated from the simple expressions,

$$I_{sc\ module} = I_{sc\ cell} \times N_P$$

$$V_{oc\ module} = V_{oc}\ cell \times N_s$$

where N_s and N_p are the number of associated cells in series and parallel, respectively (Fig. 8.32).

In the connections of the same number of cells, whether in series or in parallel, the same maximum power value is available. What changes are the voltage and current values at which said maximum power is obtained. The connections are made through conductive tapes.
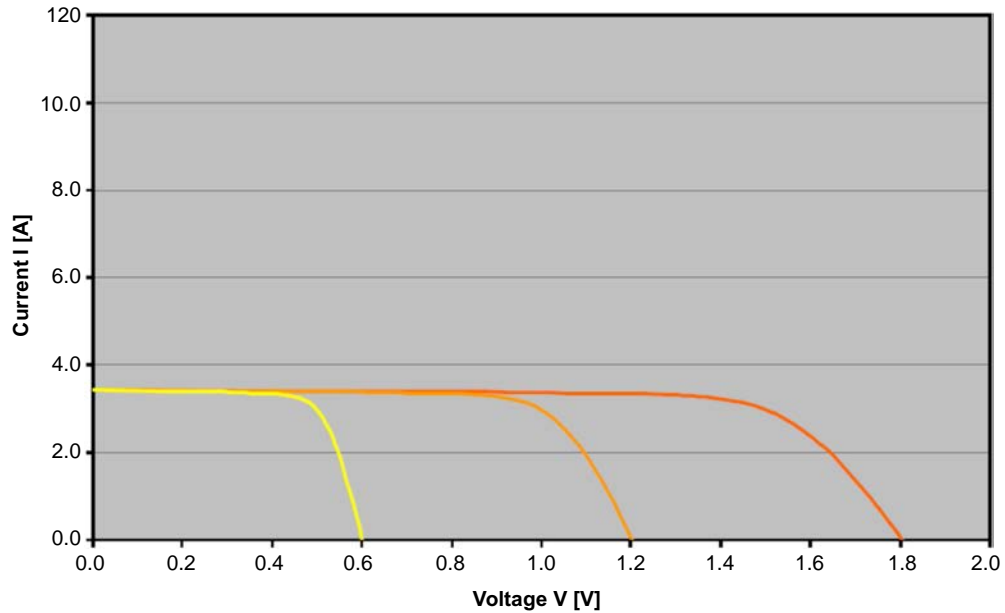
Fig. 8.30 Equivalent V-I curve for the connection of several equal cells in series (*yellow* [light gray in print version]: one cell; *orange* [light gray in print version]: two cells: *red* [dark gray in print version]: three cells).

Fig. 8.31 Equivalent V-I curve of several parallel cells connected in parallel (*yellow* [light gray in print version]: one cell; *orange* [light gray in print version]: two cells: *red* [dark gray in print version]: three cells).
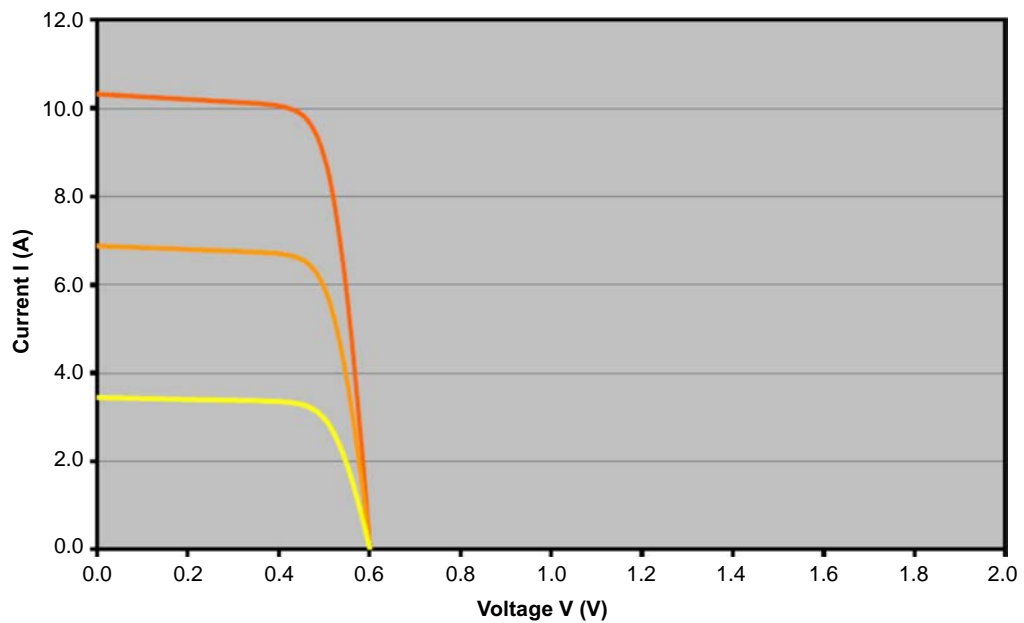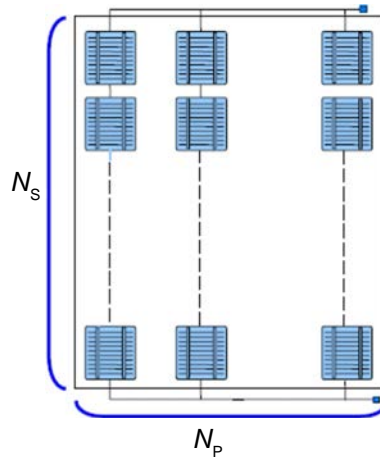
Fig. 8.32 Disposition of cells in series and in parallel in photovoltaic modules.

A photovoltaic module is the smallest, complete environmentally protected set of interconnected cells.

The lifetime of the modules, under normal operating conditions, must be >25 years and is determined by the duration of the encapsulation that must be impermeable to water and resist thermal fatigue and abrasion.

The details of the mechanical assembly of a panel vary with each manufacturer. Despite this, there are common points for all the realizations. To protect the cells, they are immersed in an encapsulating material (usually EVA and ethylene vinyl acetate), forming a "sandwich" type structure. After a rolling phase (curing), the cells are completely embedded in the encapsulant without possible contact with air or humidity and without air bubbles.

The front of the panel (area exposed to sunlight), has a tempered glass (impact resistant) that protects the cells from weather agents (rain, hail, snow, dust) and blows. The glass used has a low content of lead, so as not to reduce the transmittance of the light through it.

The back has a layer of dielectric protection material (usually Tedlar) or another sheet of glass (in glass–glass panels that are used in building applications).

In the modules without back glass, an aluminum frame usually serves to give mechanical rigidity to the assembly, facilitating, in turn, the assembly of the panel to the support. The outer frame is made of aluminum to prevent deterioration by oxidation. Several holes, located in different parts of its perimeter, make it unnecessary to use drilling machines, avoiding the risk of accidentally damaging the PV panel.

On the back of the panel are the electrical contacts, with one or two plastic junction boxes, with removable cover and side holes for the entrance and exit of the connection cables (Fig. 8.33).

Fig. 8.33 Example of connection box that is placed on the back of a photovoltaic module, with one of the connection cables.

There is also room to allow the installation of protection diodes whose utility we will analyze later. Both the cover and the side holes are designed to provide environmental protection and allow a better mechanical anchorage for the connection cables. Inside the box, there are two output terminals. The positive terminal has the symbol (+), or a red mark; the negative has the symbol (−), or a black mark.

8.7 Characteristics of a photovoltaic module

As indicated, a photovoltaic generator is constituted of many solar cells electrically associated with each other. Such cells are not, in general, identical, so the exact determination of the characteristic IV of the set, even in the case of knowing the characteristics of each individual cell, can become a very complex calculation problem. Fortunately, however, the resolution of most practical problems does not require such accuracy and the simple model that results from accepting the following assumptions as valid can be resorted to:

(a) The effects of parallel resistance are negligible.
(b) The generated current, I_L, and the short-circuit current, I_{cc}, are equal.
(c) exp. $(V + IR_s)/mkT) > 1$ in any working condition.
(d) All the cells of the same generator are identical and work equally illuminated and at the same temperature.

The voltage drops in the conductors that interconnect the cells are negligible.

The electrical behavior of a photovoltaic module, that is to say its characteristic VI, under certain lighting and temperature conditions, can be obtained from the characteristic information that, together with the module, the manufacturer must supply and that it is constituted by several parameters obtained in standard conditions of measurement (STC), already mentioned.

Under these conditions are measured, at least, the maximum power that can pass the module, $P_{MAX,}$ the short–circuit current, I_{sc}, and the open–circuit voltage, $V_{oc.}$

The characterization of the module is completed with the measurement of the nominal operating temperature of the cell (NOCT), defined as the temperature reached by the solar cells when the module is subjected to the following operating conditions:

Irradiance: $80\,mW/cm^2$ $(800\,W/m^2)$

Spectral distribution: AM 1.5

Normal incidence

Room temperature: 20°C

Wind speed: $1\,m/s$

There are other conditions, called standard operation conditions that correspond to $1000\,W/m^2$ of irradiance on the plane, the temperature of the device equal to the nominal operating temperature of the cell (NOCT) or module, and air mass $AM = 1.5$.

The parameters that can be found in the data sheets of different manufacturers are listed below.

8.7.1 Electrical parameters

− Maximum power point

The point of maximum power is the point where the product of voltage by current gives a maximum power under specified operating conditions. In particular, it is interesting to know the value of the voltage and the current at that point (at given conditions), Voltage at the point of maximum power (V_{mpp}), and Intensity at the point of maximum power (I_{mpp}). In particular, manufacturers usually provide these values under STC conditions.

− Short-circuit current (I_{sc})

It is the output current with the terminals short-circuited at a given temperature and irradiance.

In particular, under STC conditions it is called $I_{sc,STC}$

− Open-circuit voltage (V_{oc})

It is the voltage with zero current (the module is in open circuit, i.e., unloaded) at a given temperature and irradiance. Under STC conditions: $V_{oc\ STC}$

− Maximum nominal power (P_{max})

It is the maximum low power with STC. The unit used is the W_p (read: watt peak), although it is not a recommended unit. The correct terminology is "the peak power is 50 W" and not "the power is 50 W_p."

— Minimum power (P_{min})

It is the minimum voltage guaranteed by the manufacturer for a module (among the maximum power values), under STC conditions. Some manufacturers indicate the tolerance band between which the maximum power may be. Its measurement is given in W_p. This measure is given for STC. Since the actual working temperature of the cell is not that of this test, although this value is close to the real power value that the module gives us, it is still lower.

— Curve VI

As we know, the voltage-current characteristic shows us the output current of a photovoltaic generator as a function of the output voltage, at a certain temperature and irradiance, $I = f(V)$.

Some manufacturers indicate the standard VI curve only. Others indicate several among them the one of operation in conditions of measurement of the NOCT, much more realistic, although still over their real parameters of work.

It is missing a work curve under approximate real average conditions, that is, NOCT and average irradiation of the place to market the panel or a family of curves in different working conditions (NOCT and different irradiations), which would be close to the real possibilities of work and would allow to adjust more easily the real design of power of the installation.

Below is the result of a measurement (Fig. 8.34), made in the laboratories of the Department of Electrical Engineering of the University of Zaragoza, of the VI curve of a certain photovoltaic panel, and the VI curve extrapolated to STC.

Also usually appear values such as the fill factor, the ratio between the maximum output power of the device to the product of the open-circuit voltage and the short-circuit current. $FF = P_{max}/(V_{ca} I_{cc})$, and which is sometimes used to indicate quality, or series resistance is a characteristic of solar cells, independent of the particular conditions of operation.

Another parameter of relevance is the efficiency of conversion, relation (dimensionless, usually expressed as a percentage) between the electrical power generated by a device at its irradiance, measured under standard test conditions (STC).

8.7.2 Thermal parameters

— NOCT

It is defined as the average equilibrium temperature of the cell within a module under reference conditions of $800 \, W/m^2$ of irradiance, $20°$ of ambient temperature, wind speed of $1 \, m/s$, open circuit, mounted in open rack and with normal incidence, at noon.

Result of PVPM power measurement
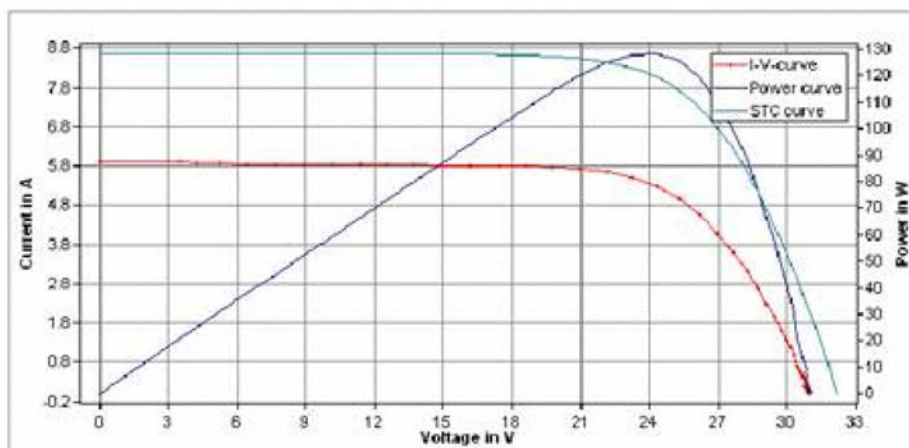
File: F:\General Electric\sexta.SUI

PVPM Serial No.: PVPM6020C00706

Sensor: SOZ-03 mono #2904

Date of measurement: 18.01.2007 13:12:45
Description: Panel FV General Electric
Número de serie A98A200610030034

Measurement results

Values at STC:	
Peak power P pk:	**196.3W**
I pmax0:	7.96A
U pmax0:	24.7V
I sc0:	8.67A
U oc0:	32.2V

Calculated values:	
Rs:	0.6 Ohm
Rp:	331.6 Ohm
FF:	0.70

Conditions during measurement:	
Cell temperature T mod:	37.1°C
Irradiance E eff:	680W/m2

Maximum values (actual):	
I sc:	5.90A
U oc:	31.0V

Values at MPP:	
P max:	128.8W
I pmax:	5.41A
U pmax:	23.8V

Fig. 8.34 Result of the measurement of a photovoltaic module by means of a device for measuring curves VI.

— Temperature coefficient for short–circuit current

The current-temperature coefficient is defined as the change of the short-circuit current of a device per unit of temperature change. Absolute or relative values can be used. Symbol α:

— Temperature coefficient for open–circuit voltage

It is a coefficient that indicates the variation of the open–circuit voltage of a device per unit of change in the temperature of the cell. Symbol β:

— Coefficient of variation of maximum power with temperature

Change of the maximum power of a cell per unit of temperature change. Symbol γ is sometimes referred to simply as a temperature coefficient (although it is more accurate to use its full name).

The following shows how the maximum power, the open–circuit voltage and the short–circuit current vary with the temperature. The graph is taken from a manufacturer's catalog (Fig. 8.35). The variation of curve VI versus irradiance and the corresponding power-voltage curve is shown in Fig. 8.36.

8.7.3 Other physical parameters

These are maximum parameters or ranges for which their initial conditions do not degrade.

— Permissible module temperature: Working temperature range (°C)
— Maximum relative humidity (%)
— Maximum voltage of the system: is the maximum voltage than the module can support given its insulation.
— Surface pressure (N / m^2)
— Maximum torque: torsion angle supported (°).
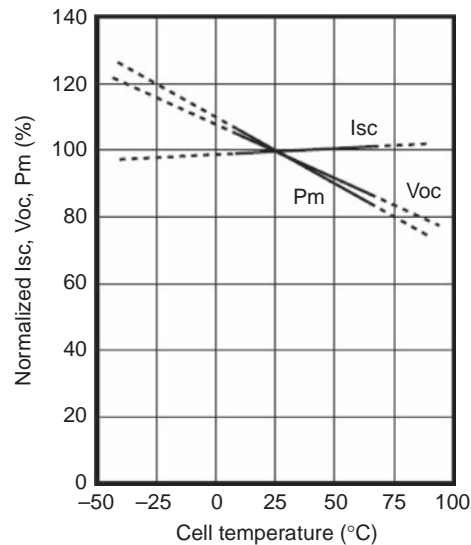— Hail: Grain size (mm) and impact speed (m/s) it can support.

Fig. 8.35 Normalized variation of the short-circuit current parameters, Icc, open-circuit voltage, Vca, and maximum power Pm for a specific module.
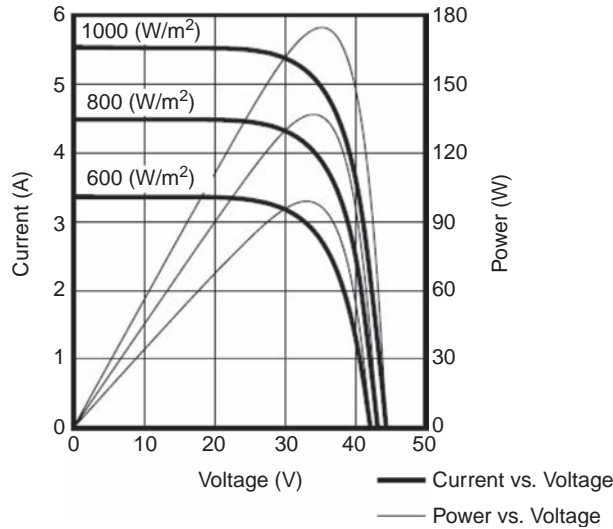
Fig. 8.36 Variation of curve VI vs irradiance. $T_c = 25°C$.

— Dimensions: Length (mm), Width (mm), Thickness (mm)
— Weight (kg)

Sometimes we also talk about the packaging factor, which is the relation between the total cell area and the module area (in %).

8.7.4 Behavior under any conditions of operation

It is common for manufacturers' catalogs to include other additional information such as, for example, the VI curve at various illuminations and temperatures, etc. However, under the established assumptions, knowledge of the four mentioned parameters is sufficient to calculate the curve VI of the module in any operating condition defined by an irradiance value, G, and an ambient temperature value, T_a.

To address this calculation, a good compromise between simplicity and accuracy is to accept as valid the following hypotheses:

— The short-circuit current of a solar cell depends exclusively on the irradiance and through a linear function. That is to say:

$$I_{sc}(G) = C_1 G$$

where C_1 is a constant of value:

$$C1 = \frac{Isc(100 \text{ mW/m}^2)}{100 \text{ mW/m}^2}$$

This hypothesis supposes to neglect the effects, on I_{sc}, of the temperature of the cell and of the spectral distribution of the radiation. Under real operating conditions, the error that this implies is $<0.5\%$.

— The open–circuit voltage of a module depends exclusively on the temperature of its solar cells, T_c, and in the range of actual operating conditions:

$$\beta = dV_{oc}/dT_c$$

This hypothesis supposes to disregard the effects on $_{Vca}$ of the illumination. However, the strong variation of I_o with temperature makes the error due to not considering the variation of I_{cc} is typically $<1\%$.

Analogously, there is a variation of power dP/dT_c

— The working temperature of the cells depends exclusively on the irradiance and the ambient temperature, according to the linear function.

$$T_c - T_a = C_2 G.$$

where C_2 is a constant of value:

$$C_2 = \frac{TONC \; (^\circ C) - 20}{80 \; mW/cm^2}$$

This hypothesis supposes to neglect the effects on T_c, of the speed of the wind, or what is the same, to think that the dissipation of the heat from the cells to the environment is dominated by the mechanisms of conduction through encapsulation, in front of those of convection on the surface of the latter. There is ample experimental evidence that this is true.

The NOCT value of the modules that make up the current market ranges between $42^\circ C$ and $47^\circ C$, so that the C_2 value does between $0.27^\circ C$ and $0.34^\circ C$ / (mW / cm^2). A reasonable approximation, when the value of NOCT is not known, is to assume $C_2 = 0.3^\circ C$ / (mW/cm^2) although the manufacturer usually provides the NOCT value.

Therefore, the nominal power value of a photovoltaic generator under conditions STC, P_n (and regardless of considering other type of losses that will be studied in Chapter 4), for each value of global irradiance incident on the surface of the photovoltaic module G, and ambient temperature, T_a, the generator will present a maximum power P_m (power of the maximum power point) that can be obtained from the application of the following expression:

$$P_m = P_n \frac{G}{G_{STC}} [1 - \gamma(T_c - 25)]$$

$$T_c = T_a + \frac{TONC - 20}{800} G$$

where T_c is the cell temperature, NOCT is the nominal operating temperature, γ is the coefficient of variation with the temperature of the maximum power and G_{STC} is the irradiance in STC, $1000\,W/m^2$.

Next, it is presented as variable to curve VI as a function of irradiance (maintaining the temperature of the cell at 25°C). The graph has been extracted from the manufacturer's catalog sheets.

The following graph in Fig. 8.37 shows how the VI curve changes (and the maximum power) as a function of temperature. The graph has been extracted from the manufacturer's catalog sheets.

8.8 Work point of a photovoltaic module

We will analyze the voltage and work current in the direct connection of a module or set of modules to a direct current load as shown in Fig. 8.38. For simplicity, the load that we are going to consider is a resistance R. The work point can be obtained mathematically, solving the system of equations composed of the equations of definition of the two existing elements in the electric circuit, that is, the expression $i = f(V)$ (characteristic VI) of the photovoltaic panel and the equation of definition of the load, $V = RI$ in the case of resistance. Graphically it is very intuitive to find the result, making the intersection of the characteristic I (V) of the module and the line of the current by the resistance as a function of the voltage between its terminals (straight line of slope R).

Fig. 8.39 shows the curve VI of a given module for given irradiance and temperature conditions and the line corresponding to a resistance (of $3\,\Omega$). The point of operation when connecting these two elements is the point where they intersect both curves ($I = 4.4685$ A and $V = 13.405$ V in the figure). This will be the common voltage for the load and the PV module for the defined temperature and irradiance.

The resistive load establishes the point of operation of the photovoltaic module, being in general, and as it happens in this case, a point different from the point of operation that provides the maximum power of the module or system for those conditions (point of maximum power).

Throughout the day, the conditions of irradiance and temperature will change, so that, even when the module or generation system is connected to the same load, the point of operation (intersection between the VI curve of the photovoltaic generation system and the resistance) is going to change. Fig. 8.40 shows how the voltage and working current will vary as the irradiance changes (the cell temperature has been kept constant), and therefore the amount of power delivered to the load and even the efficiency in the transfer of the power put that we move away or approach the point of maximum power to those conditions.
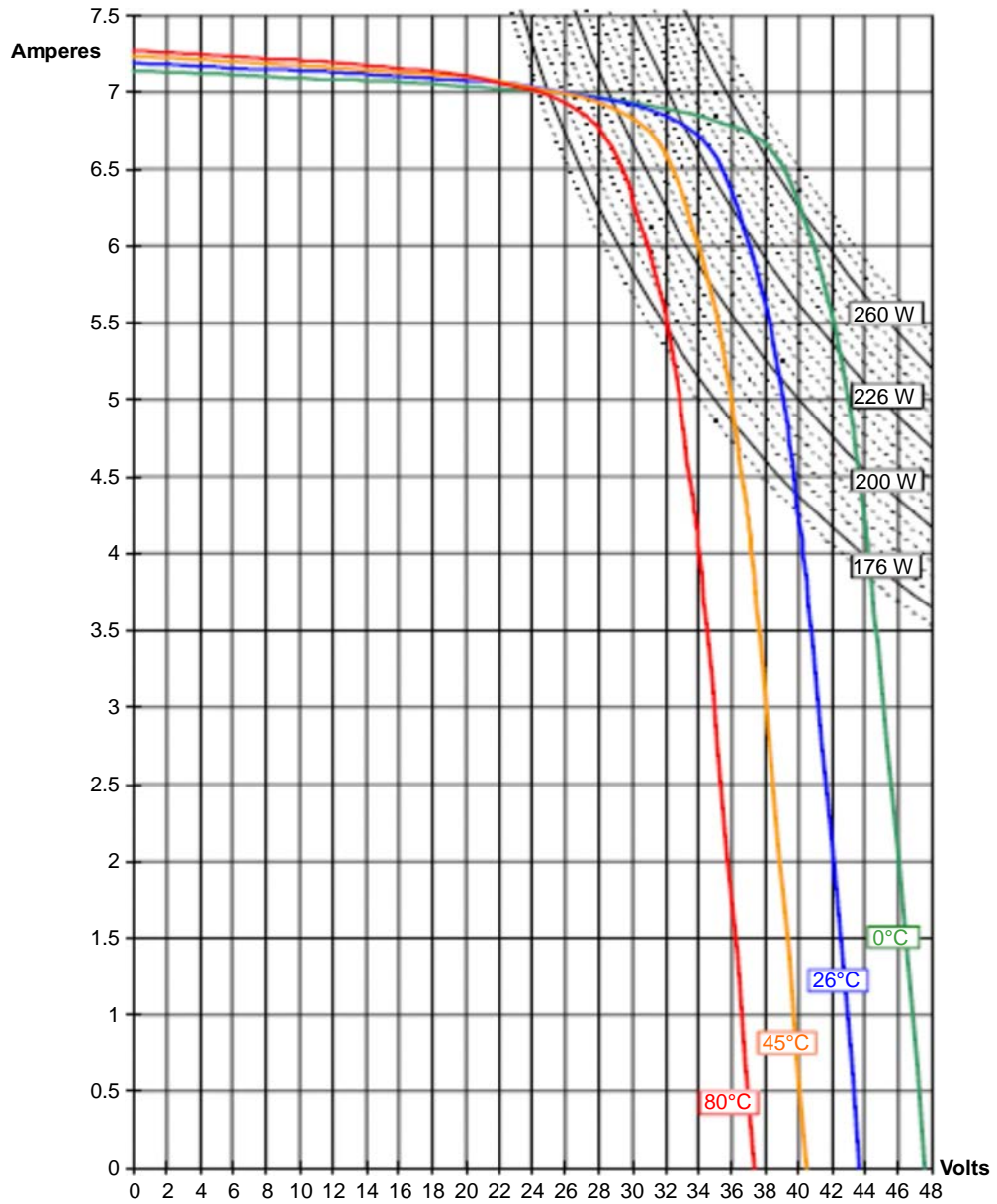
Fig. 8.37 Variation of the curve VI of a module with the temperature of the cell, irradiance $G = 1000 \, W/m^2$.
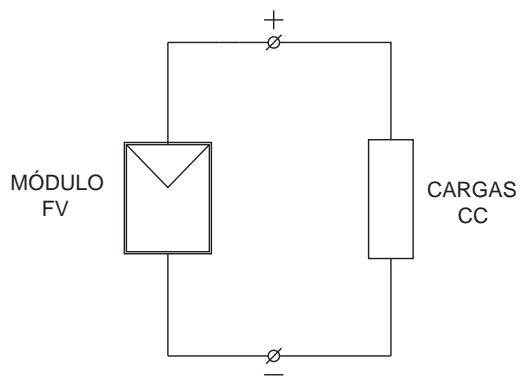
Fig. 8.38 Direct connection of a photovoltaic module to a direct current load.
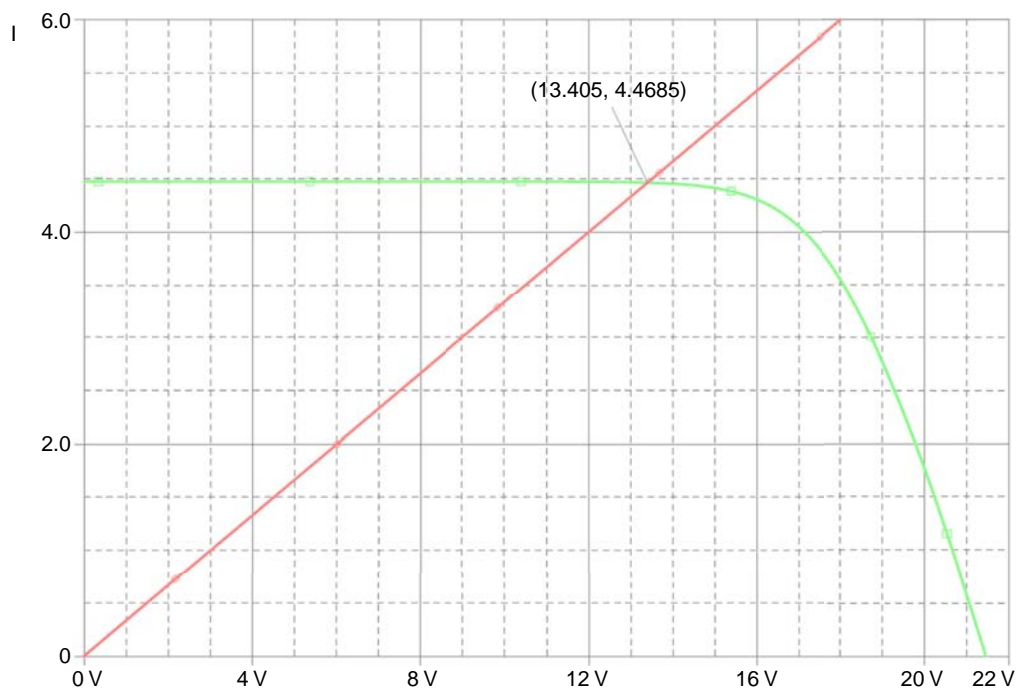

Fig. 8.39 Graphical method of determining the working point of a photovoltaic module (or group of modules) directly connected to a resistor.
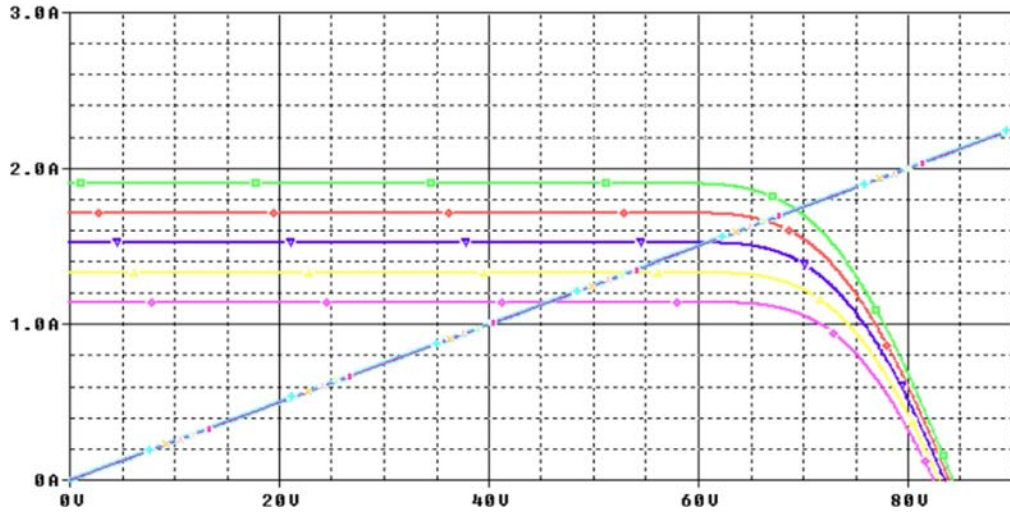
Fig. 8.40 Evolution of the point of work before variations in irradiance.

In the same way, if the load connected directly to the photovoltaic generation system changes, the work point will change, and with it, the working voltage, the intensity of the current, and the power (Fig. 8.41).

As a result, it can be concluded that in the general case of direct connection, it may not work at the maximum power point, and the power transfer of the photovoltaic generator to the load will not be optimized. To improve this situation, certain intermediate circuits are connected between these two components (tracking systems of the maximum power point).

Fig. 8.41 Evolution of the working point for various resistive loads.

8.9 PV applications

The applications of photovoltaic solar energy are varied, being able to separate into two large groups:
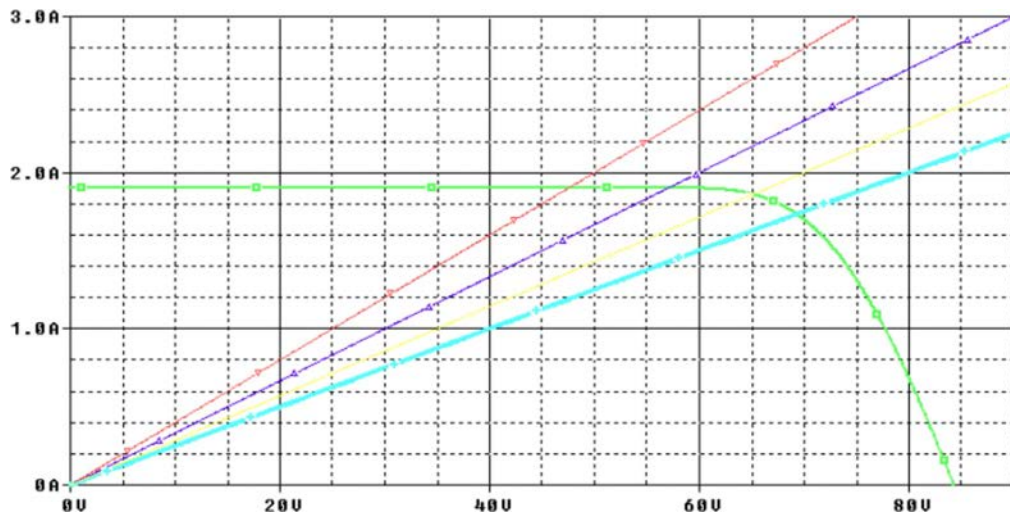- Isolated installations (autonomous systems)
- Installations connected to the network

Autonomous photovoltaic systems are those that try to cover a certain energy from solar energy by means of photovoltaic conversion, without being connected to the electricity grid. Photovoltaic solar energy has been used in a multitude of applications that can range from artificial satellites to pocket calculators. The main applications of photovoltaic solar energy in autonomous systems can be classified into:
- Electrification of homes and buildings
- Autonomous lighting
- Agricultural applications
- Pumping and water treatment
- Signaling and communications
- Other specific applications: hydrogen production, environmental applications, oxygenation of water, cathodic protection of pipelines, space applications or supply of electric vehicles, among many others, since the versatility of photovoltaic systems allows use in a growing number of applications.

Fig. 8.42 shows the different subsystems that may be present in an autonomous photovoltaic system. The complexity of the system, and even the different component subsystems of it is very dependent on the application and specific constraints of each installation.

Photovoltaic electrification installations are modular in most cases, with the possibility of making extensions or modifications in them after their execution. This possibility allows raising facilities that increase their size over time, satisfying the different needs that may arise, although it is true that in cases where this expansion is foreseeable, they should try to use equipment compatible with the successive planned extensions.

In addition to photovoltaic generation, in the so-called hybrid systems, combinations of wind and solar systems, solar–diesel, etc. can be obtained.
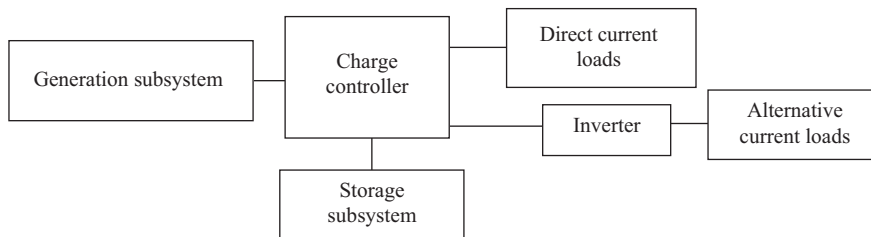

Fig. 8.42 General scheme of autonomous photovoltaic installations.

In addition, there will be protection systems for people, animals, and facilities (switches, fusing, grounding, etc.), monitoring and control systems (regulators, demand control systems, counters, sensors, and visualizers or recorders) data.

The availability of a generator or a small gasoline generator that operates on demand allows greater flexibility. Some reasons to start the group are the periodic recharging of the batteries for maintenance, equalization, or the mandatory recharging of the batteries due to excessive discharge, and of course the need of the user to have energy in the moments when there is no sufficient generation capacity and/or accumulation.

Photovoltaic systems connected to the power grid have been the subject of growing interest in recent years in all industrialized countries. At present only a very small percentage of electricity is used in isolated installations of electrical networks.

A photovoltaic grid connection system is a type of installation involving three elements: the photovoltaic modules, the inverter, and the power line. In this type of systems, the energy generated by the photovoltaic modules goes directly to a DC/AC inverter that converts the direct voltage into alternating current, injecting the energy produced in the electrical network.

Photovoltaic installations are low-voltage electrical installations (which can later be connected to high-voltage systems).

In the configuration of a grid connection photovoltaic system, several factors determine the selection and design of the system. The main elements that should be used in the first phase of the design of the network connection system are described below.

The characteristics of the location of the site (longitude, latitude, height, and climatology), the layout of the photovoltaic modules, (orientation and inclination of the modules in fixed systems, or the type of tracking), and the corresponding shadow analysis, determine the amount of energy that can be generated by the system and subsequently injected into the electricity grid. If it is an installation on the roof, the available surface, inclination, and orientation of the same are very important parameters for the design of the PV system.

The main parameters for a given installation are:
— The site
— The power of the panel field
— The power and characteristics of the inverter or inverters
— The voltage and current levels chosen
— Protections and wiring
— The characteristics of the electrical network

If you opt for fixed installation, without solar tracking, the optimum angle of inclination of the photovoltaic generator can be related to the latitude of a certain place by means of the following equation where both angles are expressed in degrees and φ is the latitude of the place:

$$\beta_{opt} = 3.7 + 0.69\varphi$$

As mentioned in the previous chapter, solar tracking systems can also be used in order to increase capitation.

The maximum voltage of the system is reached in the open-circuit situation of the field of photovoltaic modules. This voltage is important since it defines the value of the maximum voltage existing in the generator and that the inverter must support.

As it will be seen, the way of connecting the modules to each other (number of panels in series and number of branches in parallel) is determined by the conditions of voltage values and currents that we want to reach, by the characteristics of each module, since There are modules of different voltages, due to the influence of the shading elements, and by the type of inverter or inverters that are required. The configuration of the system and the connections must correspond to the power and technical characteristics of the inverter.

8.10 Estimation of the production of photovoltaic systems connected to the grid

8.10.1 Evaluation of the behavior of photovoltaic systems connected to the grid

Photovoltaic systems connected to the network may differ in design, size, technology, or geographic location, therefore they may have different production, solar resource, and losses. The use of parameters that allow a comparison between several photovoltaic systems is of great interest for the detection of problems in the operation, or to guide the investment when choosing between different technologies, etc.

In the standard "EN 61724, Monitoring of photovoltaic systems. Guidelines for measurement, data exchange, and analysis (April 2000)" three parameters are defined to evaluate the behavior of the system:

the final production rate of the system,
the reference production index,
the performance ratio.

These parameters can be used to validate production estimation models and facilitate the comparison of the operational behavior and reliability of photovoltaic systems of different size, location, technology, etc.

8.10.1.1 Final system production index (final system yield), Y_f

It is the net output of energy E (kWh, in alternate) divided by the power value of the panel of characteristics of the panel field (P_o). It represents the number of hours that the PV generator would need to be operating at the rated power to provide the same power. The units are in hours or in kWh / kWp (in the latter, the amounts used to obtain the parameter are recorded).

$$Y_f = E/P_o$$

It is a normalization of the energy produced with respect to the size of the catchment field and therefore it is convenient to compare the energy produced by systems of different sizes (and quantify design benefits, components, or locations). (But, not taking into account the variability in solar radiation is not useful to identify operational problems.)

It is worth mentioning, for example, that when checking the VI curve of modules, it is seen that the precision of the values of P_{or} vary with the manufacturer and even within a manufacturer with the product.

8.10.1.2 Reference production (or productivity) index (reference yield) Yr

It is the total irradiation on the plane of the generator H (kWh/m^2) divided by the reference irradiance, G.

It represents the number of hours of the reference irradiance, equivalent to the one on the generator. If G is $1\,kW/m^2$, Y_r is the number of hours of peak sun (or radiation in units of kWh/m^2).

$$Yr = H/G \,(hours)$$

And $_r$ defines the solar radiation resource in the system. It is a function of the location, the orientation of the catchment area and the monthly and even annual variation of the climatology.

8.10.1.3 Performance ratio

Also called the ratio of behavior, performance factor or overall performance of the system is the quotient between the final productivity or "Final Yield," and the reference productivity or "Reference Yield."

$$PR = Y_f/Y_r$$

It is a dimensionless parameter. When normalizing with respect to irradiance, it expresses the overall effect of the losses on the output. These losses can be due to inefficiencies of the inverter, wiring, uncoupling of modules and other losses in dc/ac conversion, module temperature, incomplete use of the irradiation due to the reflection of the front surface of the module itself, dirt, snow, shading, system unavailability, and component failure. The selection of the components and the engineering of design and installation have a not insignificant effect on the energy production of the photovoltaic systems connected to the electrical network. Therefore, the PR comes to be a measure of how well dimensioned and maintained the installation is, and how much production approaches ideality.

The PR does not represent the amount of energy produced, because a system with low PR in a location of high solar resource could produce more energy than another with high PR value but in a less favorable location.
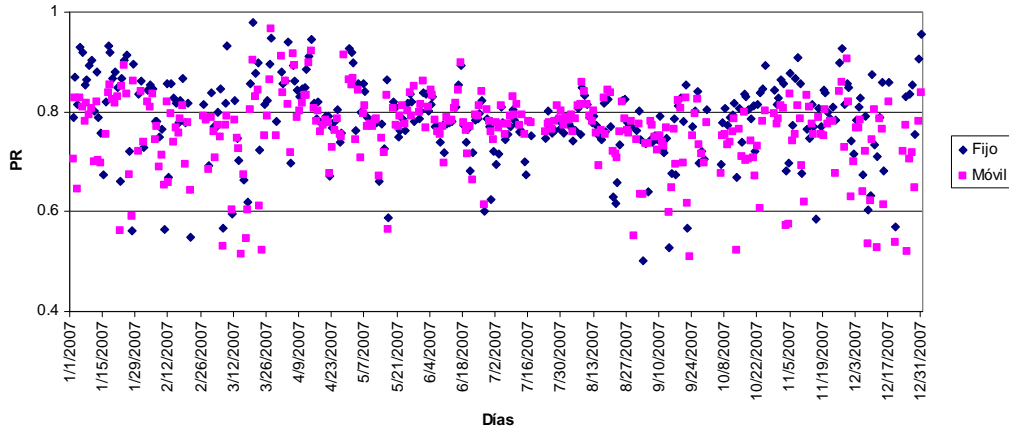
Fig. 8.43 Evolution of the PR values of a facility over a year.

It can be evaluated in monthly or annual periods. Due to the module temperature losses, PR values are higher in winter than in summer. If the fouling of the modules is also seasonal, it will also be reflected. The usual values of PR are usually between 0.6 and 0.8 (Fig. 8.43).

If it is calculated for shorter time intervals (weekly or daily) it can be useful to identify component failures, for example, diode failures, shading, fouling, snow, weld failures in connection boxes, fuse, or switch triggering, problems in the control of the tracking of the maximum power point, of the solar tracking systems, etc. Logically it is detected that there is a problem, not the cause. Problems such as fouling or degradation of the modules are only seen when looking at behavior with respect to other similar months or other years, etc.

If PR values decrease annually, it may indicate a permanent degradation of behavior. For example, you can show the degradation of the modules. For this, the data obtained when the system was not available (did not operate) must be eliminated. (If instead of modifying the module over time you would like to see the total behavior of the system, these data would not be excluded.)

The PR can be decomposed (and calculated) as the product of energy loss factors existing in the installation.

One could distinguish here between avoidable causes (such as the selection of the inverter, the dimensioning of the wiring, the control of the installed photovoltaic power, shading, etc.) and unavoidable causes (losses due to temperature, shading, etc.).

8.10.2 Losses existing energy in a photovoltaic installation

The energy produced by a PV installation is directly proportional to the incident radiation in the plane of the PV generator, but there are more factors that affect production.

It could be thought that a system with a PV generator of nominal power 1 kWp installed in a certain location and with such orientation and inclination that it receives an annual irradiation of 1800 kWh/m^2 would produce 1800 kWh, but experience shows that the energy injected into the network is noticeably lower. This is due to the fact that there are various energy losses and inefficiencies (optical, thermal, and electrical) present to a greater or lesser degree in any photovoltaic installation, which are presented below.

8.10.2.1 Losses due to noncompliance with the nominal power

A parameter of great importance in the description of a photovoltaic module is its nominal power. Due to the industrial manufacturing process, the photovoltaic modules of a certain manufacturer and model are not all identical, but their power values referred to the standard measurement conditions, STC, show a certain dispersion. In general, manufacturers guarantee that the power of a module is within a band that oscillates between $\pm 3\%$, $\pm 5\%$, or $\pm 10\%$ of the value of the nominal power, due to manufacturing tolerance. Unfortunately, in some occasions, it usually happens that the power of each of the PV modules is located in the lower values of that band of powers guaranteed by the manufacturer. Therefore, the production will be lower than what would be obtained if the panels performed with a real power equal to the nominal power. This decrease in production with respect to the ideal case is usually considered as a loss with respect to the ideal conditions, called loss due to noncompliance with the nominal power.

Currently sold so-called guaranteed power modules (with a slightly higher cost) in which the tolerance is, for example, $-0/+2.5\%$. That is, at least the power of any panel will be declared as a nominal power; the deviations of the real power from the nominal power value are always upwards. It is a good practice that should be increasingly demanded, in order to be able to make estimates of production (and therefore of economic viability) more adjusted.

On the other hand, the modules suffer a degradation over time that causes the power to be progressively reduced. In the case of crystalline silicon, this degradation is usually of the order of 0.7% per year.

8.10.2.2 Losses due to dust and dirt

They have their origin in the reduction of the power of a PV generator by the deposition of dust and dirt on the surface of the PV modules. It should be noted that two aspects, on the one hand, the presence of uniform dirt leads to a decrease in the current and voltage delivered by the PV generator and on the other hand the presence of localized dirt (as may be the case of bird droppings) This leads to an increase in mismatch losses and losses due to the formation of hot spots.

The losses due to dust and dirt depend on the place of installation and the frequency of rainfall can be estimated by visual inspection or by specific measures.

Dust losses on a given day can be 0%, the day after a rainy day and reach 8% when the modules "look very dirty." These losses depend on the inclination of the modules, proximity to roads, etc. An important cause of losses occurs when the PV modules that have frames have solar cells very close to the frame located at the bottom of the module. Other times they are the support structures that protrude from the modules and act as dust seals. Typical annual values are <4% for surfaces with a high degree of dirt.

8.10.2.3 Angular and spectral losses

The nominal power of a PV module is usually referred to standard measurement conditions, STC, which, in addition to $1000 \, \mathrm{W/m^2}$ of irradiance and 25°C of cell temperature, imply a normal incidence and a standard AM1.5 spectrum. However, in the usual operation of a PV module, the incidence of radiation is not normal, nor is the spectrum standard throughout the operating time.

The fact that solar radiation hits the surface of a PV module with a different angle of 0° implies additional losses (greater losses at higher incident angles). Angular losses increase with the degree of dirt.

On the other hand, photovoltaic devices are spectrally selective. That is, the generated current is different for each wavelength of the solar spectrum of the incident radiation (spectral response). The variation of the solar spectrum at any time with respect to the normalized spectrum can affect the response of the FV cells, resulting in energy gains or losses. In the bibliography you can find more detailed models that provide these types of losses.

The losses by angular and spectral reflectance can be neglected at solar noon ($\pm 2 \, \mathrm{h}$) and also when solar radiation is measured with a calibrated cell of equivalent technology (CTE) to the PV module. The annual losses are greater in cells with antireflective layers than in textured cells. They are greater in winter than in summer. They are also larger in higher latitude locations. They can oscillate between 2% and 6% during a day.

8.10.2.4 Losses of mismatch or connection

They are energy losses caused by the connection of photovoltaic modules of slightly different powers to form a photovoltaic generator. This has its origin in that if we connect two modules in series with different currents, the lower current module will limit the current of the series. In a similar way, it happens for the voltage of the connection of modules in parallel. As a result, the power of a PV generator is lower (or in an ideal case, equal) to the sum of the powers of each of the PV modules that comprise it. The losses of mismatch can be reduced by an installation ordered in powers (or currents in the point of maximum power) of the PV modules, as well as the use of bypass diodes.

The energy losses of mismatch are usually in the range of 1%–4%, if the PV modules are presorted before their installation.

8.10.2.5 Losses by the operating temperature of the cell

When the nominal power value of a panel is given, it refers to the STC conditions, in which the temperature of the cell is 25°C. But the operating temperature of the PV modules depends on the environmental factors of irradiance, ambient temperature, cell type, and encapsulation, wind speed, and cooling (aeration) of the modules from the rear. The temperature losses depend on the temperature difference in the modules and the 25°C of the STC conditions, and the wind. If the modules are suitably aerated from behind, this difference is of the order of 30°C over the ambient temperature, for an irradiance of $1000\,W/m^2$. In the case of integration of buildings where the modules are not separated from the walls or roofs, this difference can be increased between 5°C and 15°C.

As we know, a photovoltaic module has a lower power, the higher its operating temperature. This implies that the same incident solar irradiation the same PV system will produce less energy in a warm place than in a cold climate, or on a roof less than on a structure that allows a better ventilation of the modules, which is a loss with respect to the computation that could be done considering that one works in STC conditions. Detecting excessive heating will indicate safe poor efficiency.

The variation of power vs temperature is a function of technology. In the case of crystalline silicon, it is usually of the order of 4% or 5% for each 10°C of variation of temperature. In the case of amorphous silicon, this percentage is between 2 and 3. Losses due to operating temperature are usually an important part of the total losses of the installation.

8.10.2.6 Losses due to shading over the catchment field

In many cases the presence of shadows at certain hours of the day on the PV generator is inevitable, leading to certain energy losses caused in the first place by the decrease in solar radiation collection and by the possible effects of mismatch that may result. Also, important shadows of some photovoltaic panels can be produced on others that are in a fixed structure or in a solar tracker located behind.

8.10.2.7 Electrical losses in the wiring

Both in the continuous part and in the alternating part of a photovoltaic installation there are energy losses caused by the so-called Joule effect that occurs whenever current flows through a conductor of a determined material and section and are proportional to the square of the intensity.

These losses are minimized by appropriately dimensioning the section of the conductors according to the current flowing through them, as this reduces the electrical resistance since the expression of the resistance in DC is.

$$R = \rho \frac{L}{S}$$

ρ being the resistivity of the conductor material, it should also be mentioned that said resistivity is, in turn, a function of the temperature of the conductor itself. The temperature of 20 °C is usually taken as a reference (resistivity values at this temperature usually appear in the tables).

In particular, in the case of copper (or aluminum), the variation of resistivity with temperature is practically linear, being able to write the following expression that expresses the value of the resistivity at a temperature T'

$$\rho_{T'} = \rho_{20} \left[1 + \alpha_{20} \left(T' - 20\right)\right]$$

Specifically for the c, the resistivity at 20°C is ρ 20$=0.01785\,\Omega\,mm^2\,m^{-1}$ and the coefficient of variation of resistivity with temperature (at that reference temperature of 20°) is $\alpha_{20} \approx 4 \times 10^{-3}\,°C^{-1}$ (more accurate, 0.00393), which means that an increase of 10°C causes the resistance to vary by 4%.

The falls in the wiring can be very important when they are long and operate at low voltage in direct current. As a percentage, wiring losses are usually lower in high power plants than in small power plants. The maximum admissible value for the continuous part is 1.5%.

8.10.2.8 Losses in the inverter
(a) Losses for the performance of the dc/ac conversion.
The photovoltaic inverter can be characterized by the performance curve depending on the operating power. It is important to select a high–performance inverter under nominal operating conditions and it is also important to select the inverter power appropriately as a function of the power of the PV generator (e.g., the use of an inverter of excessive power depending on the power of the PV generator will lead to the system operating a lot of the time in very low- performance values, with the consequent losses of generation).
(b) Losses for the performance of tracking of the maximum power point of the PV generator.
The grid–connected photovoltaic inverter operates directly connected to the PV generator and has an electronic device for tracking the maximum power point of the PV generator (this point of maximum power changes with irradiance and temperature) whose control algorithms can vary between different models and manufacturers. The inverter can be characterized by a performance curve to monitor the point of maximum power defined as the quotient between the energy that the inverter is able to extract from the PV generator and the energy that would be extracted in an ideal monitoring. An additional problem may arise when there are shadows on the PV generator. In this case, there may be steps in the IV curve and the inverter operating at a point that is not the maximum power point.

In photovoltaic systems connected to the medium–voltage electricity network, a transformer is usually available, which also adds certain losses.

In addition to the losses considered above, there may be other specific ones for each installation, such as the inverter shutdown times due to maintenance, failures or malfunctions, the effects of lowering the performance of the PV modules at low irradiances, etc. Normally the losses in switches, fuses, and diodes are very small and it is not necessary to consider them.

8.11 Costs

In the first stage of development, industrial PV production was dedicated to autonomous applications—both spatial and terrestrial—but nowadays grid-connected applications have gained wide acceptance, and today photovoltaic energy is economically competitive.

The Swanson's Law (experience curve) observes that the price of the solar panels falls to 18%–20%, when the world production of panels doubles its sales. For instance, in 1980 the cost of PV modules was around 20USD/Wp and nowadays is some 0.3USD/Wp. The price of photovoltaic systems was divided by three in the last 6 years in many markets and the modules were divided by five.

According to NREL, US Solar Photovoltaic System Cost Benchmark: Q1 2017, the costs benchmark in the first quarter of 2017 for PV installations was 2.80USD/Wp for residential systems (size 3–10 kW), 1.85 USD/Wp for commercial systems (10 kW–2 MW), and 1.03 USD/Wp for fixed-tilt utility-scale systems (sizes >2 MW).

Many countries in the world have reached the so-called grid parity, that is, PV systems generate power at a levelized cost of electricity (LCOE, an economic assessment of a technology's or project's cost which includes the full span of its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital, etc.) that is less than or equal to the price of purchasing power from the electricity grid. In many parts of the world, LCOE of large-scale photovoltaic solar has been reduced by 73% between 2010 and 2017 reaching 10 cents per kWh. Technology cost reductions have been driven by efficiency improvements in the conversion of sunlight into electricity, economies of scale (providing competitive equipment prices and amortizing fixed costs over larger output) and more efficient production processes and improvements in supply chain management.