ENERGY AND TELECOMMUNICATIONS

Lecture Notes

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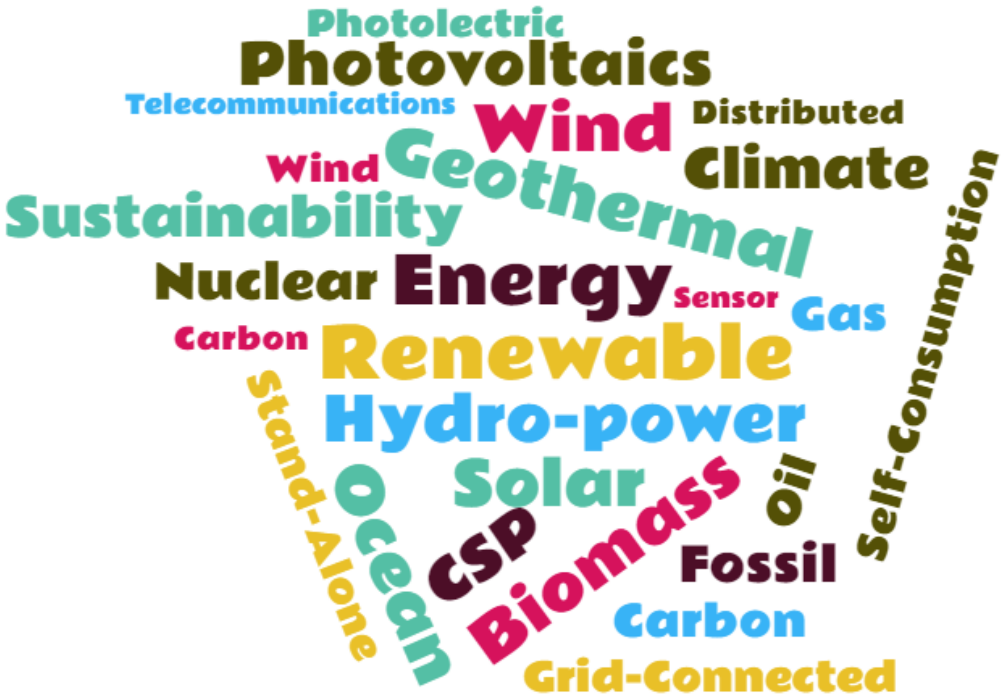
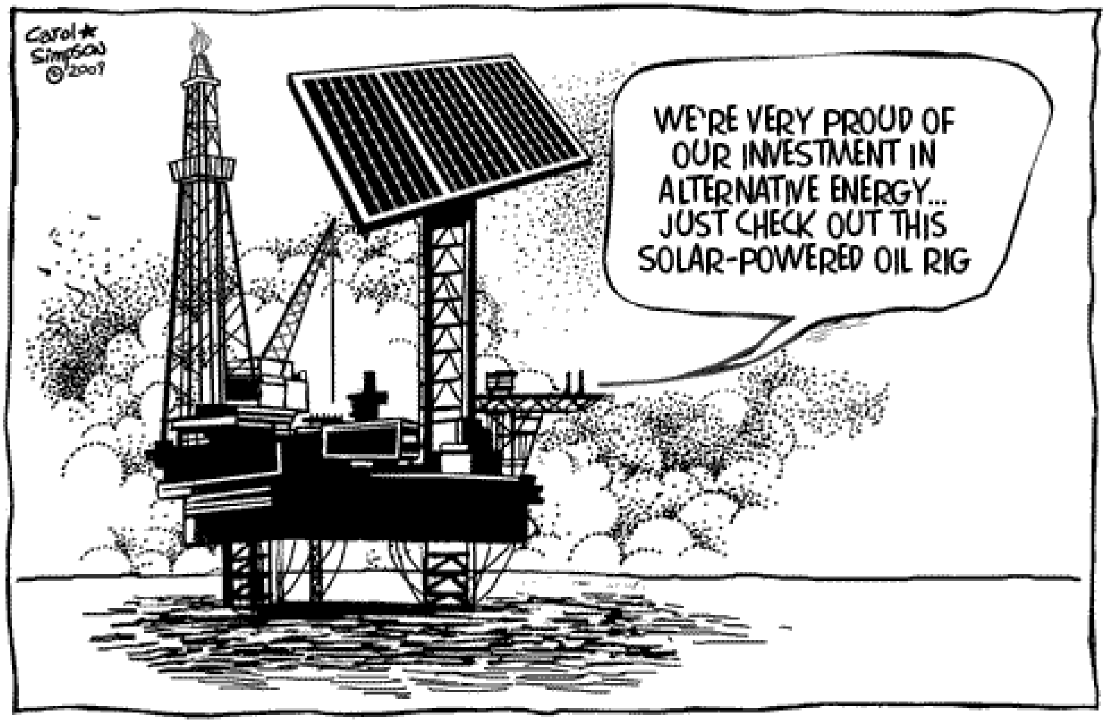


"We are star stuff harvesting sunlight."

Carl Sagan, American astronomer, cosmologist, astrophysicist, astrobiologist, author, science popularizer, and science communicator in astronomy and other natural sciences.



Energy and Telecommunications

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Energy and Telecommunications: Renewable Energies

Solar Energy

As we analyzed the basic concepts concerning renewable energies in the first chapter of the course the course, it is now time to focus on solar energy, more specifically on solar photovoltaics.

This chapter will begin with a **brief revision of solar thermal and CSP technologies**, followed by a **brief summary of the historical evolution of solar PV and the current situation of the sector**. A special focus will be given to the **situation of solar PV in Spain, which has suffered a radical change in 2019**.

Afterwards, we will study the **fundamentals of PV technology**, the **photoelectric effect** and the working principle of a **solar cell**. The **characterization of solar cells and modules and the design of stand-alone** (that might be of particular interest for telecommunication engineers) and **grid-connected installations** will complete these sections.

To summarize, the main goals of this chapter are:

To obtain a basic knowledge and an understanding of the current worldwide situation as regards solar energy

To become familiar with the fundamentals of solar photovoltaics

To be able to design solar PV installations

Energy and Telecommunications: Renewable Energies

Course Structure

This course has been divided into 4 chapters covering an introduction to renewable energies and related concepts, solar energy (including thermal and photovoltaics technologies) and wind energy. The final chapter will be focused on other REs, such as hydro-power, biomass, ocean energies, etc.

- ### Chapter 1: Introduction to REs

  The goal of this chapter is for students to become familiar with the basics of REs. This includes understanding the reasons why these technologies came about, with a special focus on climate change. It is also important to have a basic knowledge of the current situation in terms of renewable energies around the world and, obviously, in our country: Spain. Which country is leader in Photovoltaics or wind energy? How has the evolution of China been in the last decade? Which is the situation of Spain now and in the foreseeable future?

- ### Chapter 2: Solar Energy

  Solar Energy can be divided into thermal and photovoltaics. We will devote little time to the former, talking about solar thermal installations (and their design) but also about CSP (Concentrating Solar Power), where the energy of the sun is converted into heat and, afterwards, into electricity. Solar Photovoltaics (PV) will be the main topic of this course, given its relevance to telecom engineers. PV basics and practical issues will be dealt with, and some grid-connected and stand-alone installation examples will be analyzed.

- ### Chapter 3: Wind Energy

  Wind energy is a well-known technology, with several installations in Spain. Although under a different perspective, more related to communications and sensing, this technology is also associated with the telecom industry. Wind turbine theory basics, the structure of a modern wind turbine and current technological trends will be briefly explained.

- ### Chapter 4: Other Renewable Energies

  Hydro, biomass, geothermal and ocean energies will be dealt with in this final chapter. The relevance of hydro-power for electricity production will be discussed. In addition, the fundamentals of both biomass and geothermal energy will be also discussed. Finally, the different technologies associated with ocean energy will be briefly reviewed.

Acronyms

a-Si	Amorphous Silicon
BTS	Base Transceiver Station
CAES	Compressed Air Energy Storage
CEC-efficiency	California Energy Commission
CSP	Concentrating Solar Power
CVD	Chemical Vapor Deposition
E	Energy
E_g	Gap Energy
e-	Electron
EU	European Union
EVA	Ethylene Vinyl Acetate (PV Encapsulation Materials)
GH	Greenhouse
GHG	Green-house Gas
HZD	Habitable Zone Distance
IDAE	Instituto para la Diversificación y Ahorro de la Energía
IDAE	[The Institute for the Diversification and Saving of Energy]
I_{MP}	Maximum Power Current
IPCC	Intergovernmental Panel on Climate Change
I_{SC}	Short Circuit Current
IR	Infrared
LED	Light Emitting Diode
LCOE	Levelized Cost of Energy
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
P_{MAX}	Maximum Power (of a PV cell/module)
P-O	Perturbation and Observation algorithm (MPPT tracking in inverters)
PSH	Peak Sun Hours
PV	Photovoltaics
RE	Renewable Energy
REE	Red Eléctrica Española

Acronyms

SHM Structural Health Monitoring
SR_{AC} Sizing Ratio (Inverter Dimensioning)
STC Standard Test Conditions
SWH Solar Water Heating
TFC Total Final Consumption
TPES Total Primary Energy Supply
UV Ultraviolet
V_{MP} Maximum Power Voltage
V_{OC} Open Circuit Voltage

Symbols

A	Battery Autonomy
α	Orientation (of a PV Generator)
β	Tilt Angle (of a PV Generator)
β_{OPT}	Optimum Tilt Angle (of a PV Generator)
η	PV Efficiency of a solar cell/module/technology
η_{Inv}	Efficiency of an inverter
η_{Eu}	European Weighted Efficiency (Inverter)
G	Irradiance
κ	Conductivity
ϕ	Latitude
Q	Battery Capacity
S	Cable Section

Units

°C	Celsius (temperature)
J	Joule (energy)
K	Kelvin (temperature)
Mtoe	Million Tonnes of Oil Equivalent
ppm	Parts per million
ppb	Parts per billion
ppt	Parts per trillion
V	Volt (voltage)(electric potential)
Wh	Watt-hour (energy)
Wp	Watt-peak (power)(capacity)
W	Watt (power)(capacity)

Glossary

Blocking diodes These diodes are installed in series with the PV cells and their goal is to prevent the current generated from other panel array arranged in parallel (or from the batteries, if any) to be injected into other string.

By-pass diodes These devices offer an alternative path to the current in the occluded cell, thus preventing it from overheating and becoming damaged.

Charge Controller A charge controller is a key element in stand-alone PV systems. It is the "brain" of the system, as it controls the state of the batteries, using the energy produced in the PV modules to charge them or to directly power supply the associated loads.

Concentrating Solar Power High temperature solar thermal energy, also known as **Concentrating Solar Power (CSP)** is typically based in a **power-tower** scheme. A set of **heliostats** (mirrors) are oriented to focus the solar radiation onto a receptor situated in a tower, where a fluid is heated to be used to activate a turbine. The heliostats are normally controlled by computer to trac the sun and thus optimize production.

DC-DC Converter Device that allows a conversion of DC voltages. In a PV system a DC-DC converter allows isolating (making independent) the module output voltage from the load working voltage, which will be the one offered by the converter output.

Direct Gap Material In a direct-gap semiconductor, the electron transition (from the valence to the conduction band (photon absorption) or viceversa (photon emission)) fulfills momentum conservation, given that the momentums associated with the maximum energy of the valence band and the minimum energy of the conduction band are the same.

Grid Connected PV Installation PV system where the energy produced by the PV generator is injected into the power grid, thus acting as a conventional power plant.

Hot-spots The hot-spot problem may cause a PV module to malfunction or completely break, and it is originated by a complete or partial occlusion (shadowing) of one (or more) of the PV module cells. This occlusion can be caused by birds, leaves, etc. Hot-spots constitute a serious threat for PV installations.

Indirect Gap Material The situation is different in indirect gap semiconductors (e.g. Si) as there is a mismatch between these momentums. As photons do not have an associated momentum, the electron transition between bands in an indirect-gap material has to involve other particles, such as **phonons** (phonons are not real particles, but a perturbation on a set of atoms/molecules in solids or liquids). As other particles are involved, these transitions are less likely (in comparison to direct-gap materials).

Instantaneous self-consumption PV systems These are PV systems that can be understood as a subcategory within standalone installations, where batteries are not required, as the PV energy is instantly consumed as soon as it is produced. The energy produced when there is no consumption is lost.

Inverter an inverter allows conversion from DC to AC current,which can be of great use in PV installations.

Maximum Power Point MPP is the point (on the P-V curve of a solar PV cell/module) at which maximum power is produced.

Maximum Power Point Tracking Solutions implemented via algorithms in inverters to allow a PV system to operate on its MPP point.

Molten Salts Technology that allows energy storage (heat in this case) in CSP plants.

Nominal Operation Cell Temperature NOCT is defined as the cell temperature for the following conditions: solar irradiance of 800 W/m^2, solar spectrum AM1.5, air temperature of 20°C and wind speed of 1 m/s.

Nuclear Fusion can be understood as the process where several atomic nuclei join to give rise to a single heavier nucleus, releasing a huge amount of energy in the process.

Optimal Tilt Angle of a PV generator, is the angle that maximizes energy production over a given period (e.g. annual optimal tilt angle).

Photoelectric Effect is the working principle of PV technology. It explains why some materials (e.g. silicon) are able to produce an electric current when radiated by a specific kind of electromagnetic radiation.

PV Efficiency PV efficiency can be defined as the ratio of the produced electricity (in a solar PV cell/module) in terms of the energy derived from solar radiation.

Solar Irradiance incoming power of a given kind of electromagnetic radiation per square meter (or equivalent surface unit).

Solar PV Cell A solar PV cell is basically a PN junction with some special features, like a larger surface to enable a higher absorption of photons associated with solar radiation. This radiation is converted into current (electricity) by means of the so-called photoelectric effect.

Solarization A physical phenomenon that gives rise to a loss of transparency in some materials, for example polymers.

Stability referred to a PV cell/module/technology, is the ability of exhibiting a constant efficiency over time, given that some technologies show some degradation, for example due to UV solar radiation.

Stand-Alone PV Installation designed to power supply, independently from the power grid, installations, infrastructures or devices (e.g. homes, Base Transceiver Stations or network sensors).

Standard Test Conditions These conditions define the values of the key parameters to be considered for the electrical characterization of any PV cell/module (solar irradiation = 1000 W/m^2; cell temperature = 25°C and AM 1.5 solar spectrum).

String association of PV modules in series/parallel.

Texturization is based on writing a given pattern on the front side of the cell, for example with normal or inverted pyramids. Its goal is to maximize the likelihood of photons being absorbed by making those photons that are initially reflected have more than one interaction.

Watt Peak is the unit associated with the output electrical power (capacity) of a solar PV panel/module measured under certain specific conditions (STC: *Standard Test Conditions*).

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Chapter 2
Solar Energy

2.1. The Sun as an energy source: the fusion process in the stars

Given that this chapter will be devoted to solar energy, it might be useful to begin this section with a brief description of the process that allows stars to generate huge amounts of energy: the **nuclear fusion** process.

We all know that **the Sun is the main energy source of our planet**, thus being responsible for life on Earth. Whether directly (solar PV, solar thermal, CSP) or indirectly (wind power, hydopower, ocean energies, biomass, etc.), the sun is behind almost all the energy that we can harvest on Earth. Only a few exceptions, like geothermal energy, can be considered completely unrelated to the Sun (Figure 2.1).

> **Important! 1.1: Looking for life beyond our Solar System**
>
> Huge research efforts are currently being focused on finding **exoplanets**, i.e. planets outside our solar system that orbit other stars. Those planet should be within the so-called **HZD (Habitable Zone Distance)**, which depends on distance and luminosity of the associated star.

> **Question 1.1: The Sun and Fossil Fuels**
>
> In the previous chapter, we spent some time talking about fossil fuels but: do you know how they came about?
>
> Look for information and explain with your own words the relationship between the formation of fossil fuels and the Sun.

As can be derived from Figure 2.1, we are highly dependent on the sun, that contributes 5.4 million EJ (exa-jules = $10^1$8 jules) to the total energy available on Earth. Other mechanisms not directly related to the sun, like tides (where the Sun has some influence) or convection in volcanoes, show much lower figures.

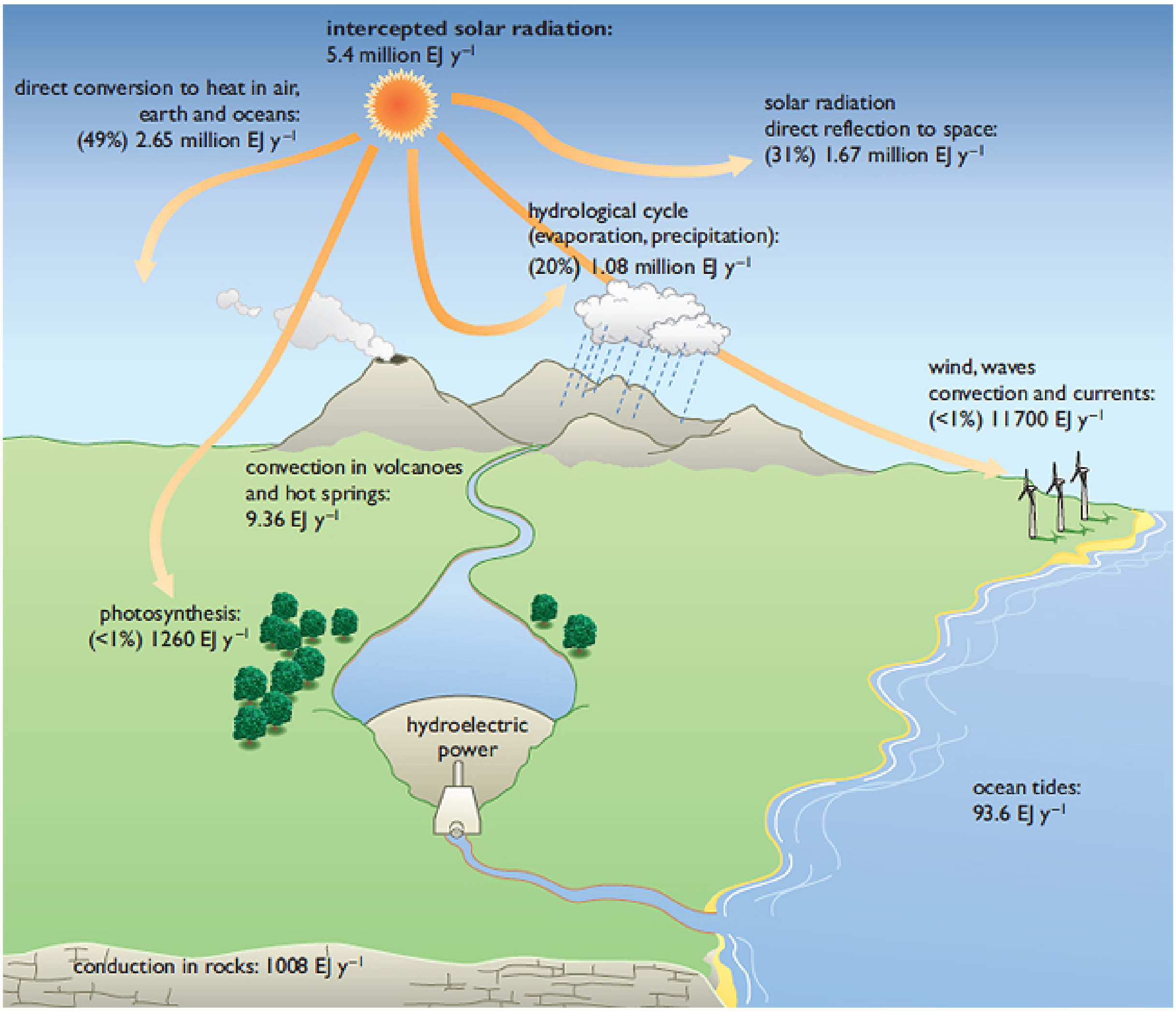


Figure 2.1. Schematic representation of the Sun's influence on different energy sources. Source: Open.edu `http://bit.ly/2BHKnFT`

2.1.1. Nuclear Fusion: Energy from the Stars

Without having to understand the underlying Physics, we realize that the Sun generates an incredible amount of energy that comes to as light radiation[1]. However, it is important to study the process that generates energy in the stars, given that it might provide an outstanding renewable energy source.

The Sun can be defined as a huge incandescent gas ball (a plasma), with a size approximately 1 million times larger than the Earth[2]. The sun is about 4600 million years old, more or less half its expected lifetime. It is formed by hydrogen (H, 73%) and hellium (He, 25%), with temperatures of around 5600°C at the surface and 15 million °C at its core.

How is energy generated in the Sun? Temperature and pressure are so high at the core, that H and He atoms are accelerated at very high speeds. When these particles collide, **nuclear reactions**

[1]Here, light has a broad sense, not limited only to the visible range, but also to other wavelengths such as ultaviolet (UV) or infrared (IR).
[2]The distance from the Sun surface to its core equals the distance from the Earth to the Moon (round trip)

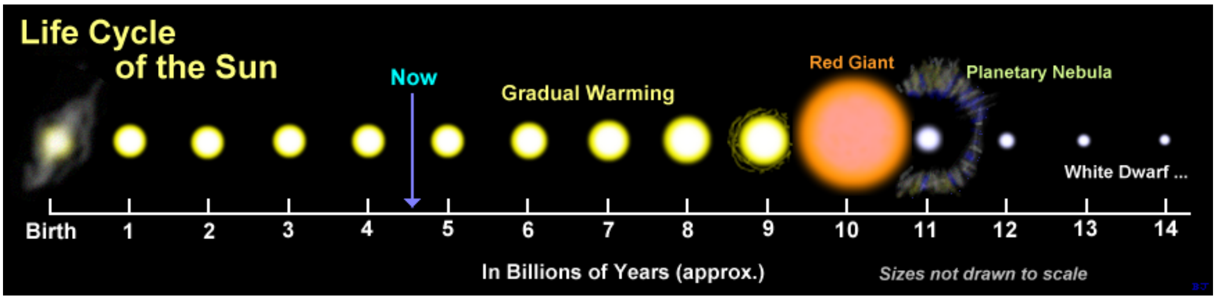


Figure 2.2. Life evolution of a star and current life of the Sun. Source: Wikimedia (CC-BY-SA 3.0) `http://bit.ly/2DiP2RQ`

take place.

Figure 2.3 shows an schematic representation of **nuclear fusion**. It can be understood as the process where several atomic nuclei[1] join to give rise to a single heavier nucleus, releasing a huge amount of energy in the process.

In the Sun, two H protons get so close that the strong nuclear interaction overcomes the mutual electrical repulsion. Deuterium (2H), which is formed in the process, will interact with another H proton, enabling the formation of 3He and releasing gamma radiation. The process ends with the formation of 4He.

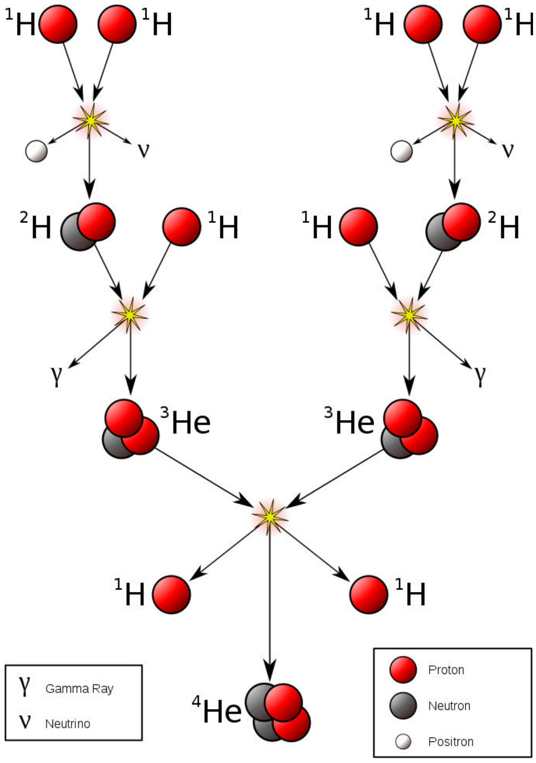


Figure 2.3. Schematic representation of nuclear fusion in the stars. Source: Borb (CC BY-SA 3.0) `http://bit.ly/2BKwdnC`

We are talking about gamma rays but, doesn't that sound ominous to you? **Gamma rays** are the most energetic radiation known in the universe however, although they are generated in the Sun,

[1] **Nuclei** is the plural of **nucleus**.

this radiation does not reach the Earth. We receive "light" in the UV, visible and IR ranges. This can be explained taking into account that the transit time of a photon. Thousands of years may go by from the moment a photon is created at the sun's core until it reaches the sun's surface and escapes (some models estimate this time in ≈ 170.000 years!). During its travel, the photon is continuously suffering interactions with other particles, for example scattering with free electrons. This way, photons lose energy until they are able to escape, thus having shifted their wavelength (and their energy) from gamma-ray to less energetic ranges.

Question 1.2: Gamma Rays

How do energy and wavelength of gamma rays compare to those of visible radiation?

In what events do gamma rays participate in the universe?

Are gamma rays used on the Earth? In which applications?

Answer these questions **in your own words**.

The next question is: how much energy is generated in the Sun? The famous **Einstein equation** can be used here:

$$E = mc^2 \tag{2.1}$$

In this expression, energy E and matter m are related by constant c (speed of light in vacuum). In the Sun 600 million tons of H are burnt per second to generate 596 million tons of He (via nuclear fusion) but: where are the remaining 4 million tons? They have been converted into energy during the process. Thus, using the previous equation, we obtain the following result:

100,000,000,000,000,000,000 KWh generated per second!

This estimation implies that the Sun is able to generate per second an amount of energy higher than the global energy consumption in a year. The problem is, of course, how to efficiently capture and use this energy.

Important! 1.2: Dyson Sphere

A Dyson Sphere is a hypothetical mega-structure, proposed by the physicist and mathematician Freeman Dyson, which will serve to optimize the energy harvesting of a given star. This structure will completely encompass the star and might supossedly serve to detect advanced extraterrestrial civilizations. In fact, last year this hypothesis appeared in the news after the detection of a star with weird behaviour.

More information: `http://bit.ly/2p6iNj1`.

2.1.2. Fusion reactors: replicating the stars in the Earth

The possibility of replicating the nuclear fusion that takes place in the stars on the Earth has been explored for many years. The idea is to develop reactors where the nuclear fusion process will be generated, thus obtaining an incredibly powerful renewable technology using hydrogen as fuel, quite a common element on the Earth. This is obviously a remarkably complex challenge, with different projects exploring its feasibility. One of the most well-known proposals is **ITER** (International Thermonuclear Experimental Reactor), whose facilities are located in Cadarache, France[1].

If this technology became feasible in the future, we would be facing a real energy (and probably social and political) revolution, having found a virtually unlimited energy source.

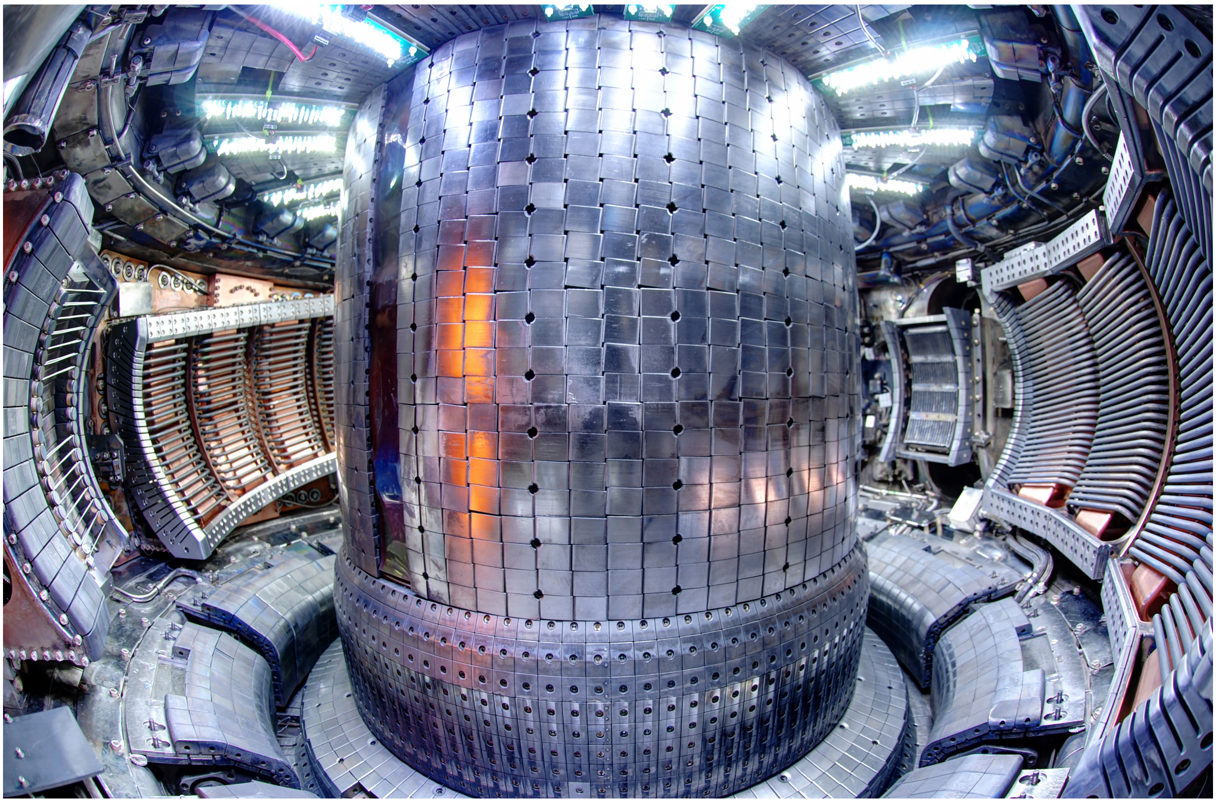


Figure 2.4. Image of a nuclear fusion reactor. Source: Wikimedia (CC BY-SA 3.0) `http://bit.ly/2hx6tls`

Question 1.3: Fusion reactor: projects

There are several different projects on fusion reactos around the world.

Look for information and explain, **in your own words**, one of these projects, including relevant information such as location, funding, current situation of the project, etc.

[1] For more information: `https://www.iter.org/`

2.2. Solar Thermal Energy

A possible solution for using the energy of the Sun is to directly employ it to generate heat (instead of converting it to electricity like in solar PV). This heat can then be used in different ways: to heat water or to generate electricity, for example.

In general, solar thermal energy can be classified by working temperature:

Low temperature for working temperatures lower than $90°C$

Medium temperature for working temperatures between 90 and $400°C$

High temperature for working temperatures higher than $400°C$

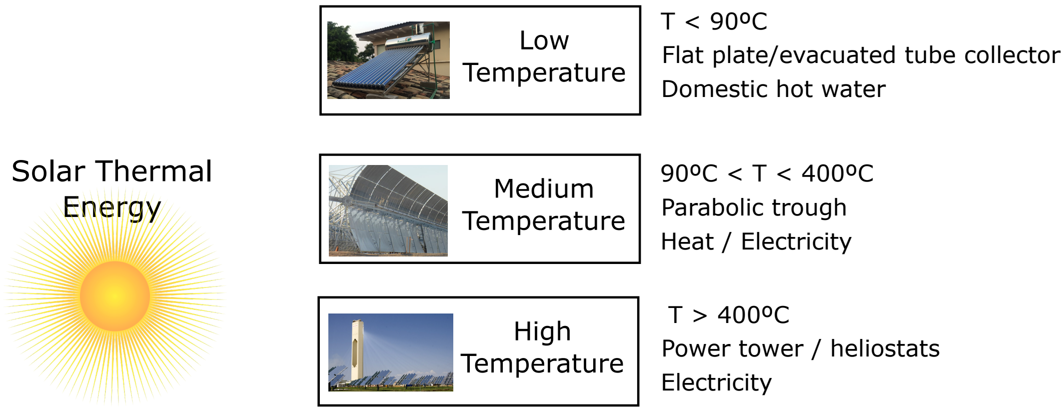


Figure 2.5. Solar thermal energy classified by working temperature. Source: Jesus Mirapeix.

This classification is necessary given its energy applications are different depending on the working temperature. Low temperature solar thermal is focused on domestic hot water for homes; while medium and high temperature applications are normally devoted to the generation of electricity.

2.2.1. Solar Thermal Energy: Low Temperature

Although we are probably more used to wind or solar PV energy, solar thermal energy, particularly low temperature installations (also known as *Solar Water Heating (SWH) Systems*), is widely employed in many countries. China is, for example, the world leader in installations, and it is very common in other countries like Greece, Turkey, Australia, Japan or Austria. Israel is another good example, with 85 % of its homes using these systems.

This is a mature and low-cost (and low-complexity) technology. The latter is especially true in locations with suitable weather conditions, where less sophisticated collectors will be chosen. Low-temperature solar thermal collectors can be divided into flat plate and evacuated tube types. The former work at temperatures up to $80-90°$ with a limited efficiency, being the typical choice for locations with abundant solar radiation.

Flat plate collectors are formed by a layer of absorber material (dark) covered by a protective glass. The absorber layer is in contact with tubes that carry a fluid (not necessarily water, most likely antifreeze solutions, thus avoiding problems at low temperatures) that will be heated and

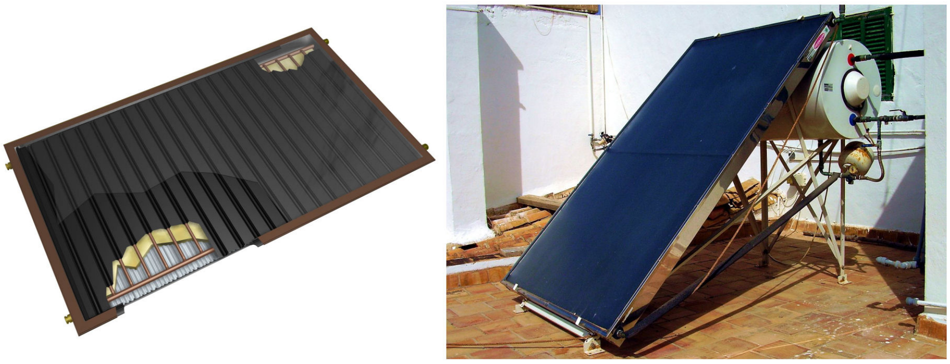


Figure 2.6. Flat plate collector (left). Illustration of a SWH system based on a flat plate collector (right). Source (left): `http://bit.ly/2zbKRRG`. Source (right): Chixoy (License CC-BY-SA 3.0).

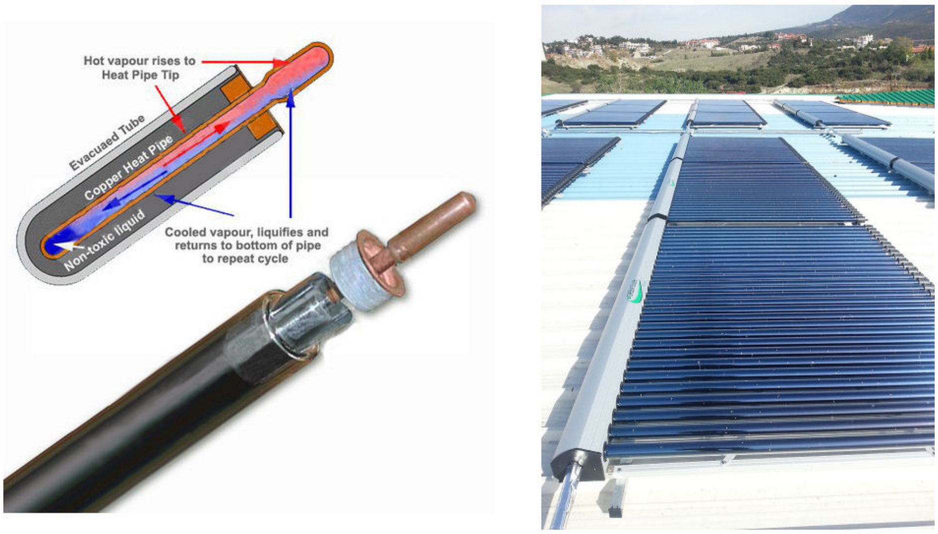


Figure 2.7. Working principle of evacuated tube collectors (left). Example of solar thermal system based on evacuated tube (right). Source (left): `http://bit.ly/2kUyt3x` (Public Domain). Source (right): Greensolarvacuum (License: CC-BY-SA 3.0) `http://bit.ly/2kWOGqv`.

transported out of the collector. These designs usually also consider isolating materials to reduce losses. These systems tend to be passive, with the water tank located above the collector. Support tanks providing hot water when needed can be also included. Active systems include a water pump and the water tank can be located elsewhere.

If a more efficient approach is required, **evacuated tube collectors** can be selected (Figure 2.7). In this case vacuum tubes are employed to reduce thermal losses and improve efficiency. **Direct flow** vacuum tubes have a working principle similar to flat plate collectors, whereas heat-pipe tubes involve the use of liquids that turn into gas when heated, moving up to the upper part of the tube and exchanging the heat with water. After this exchange, the gas is cooled and returns to its liquid phase, going down the tube and fulfilling the cycle. This way, the problem of tube overheating is avoided.

Question 2.1: Greenhouse effect

The greenhouse effect has been already discussed in this course. Both low-temperature collectors (flat plate and evacuated tube) are based on the greenhouse effect.

Look for information and explain, **in your own words**, the working principle of evacuated tubes.

Important! 2.1: Solar thermal: more applications

Solar thermal energy can be used for more applications, some of them of great interest in developing countries, like cookers (avoiding the use of biomass, where wood harvesting can be difficult), water purification or drying of agricultural products, thus avoiding the negative effect of insects and fungus.

2.2.2. Solar Thermal Energy: Medium Temperature

When working temperatures are above 100°C, solar thermal energy is normally used for the production of electricity. Medium temperature installations are typically formed by parabolic-trough mirrors designed to focused all the incoming radiation on a tube located above them (Figure 2.8). This tube is used to guide a fluid (HTF: Heat Thermal Fluid) (normally an oil, not water) that transports that heat that will eventually be used to generate electricity by means of a turbine.

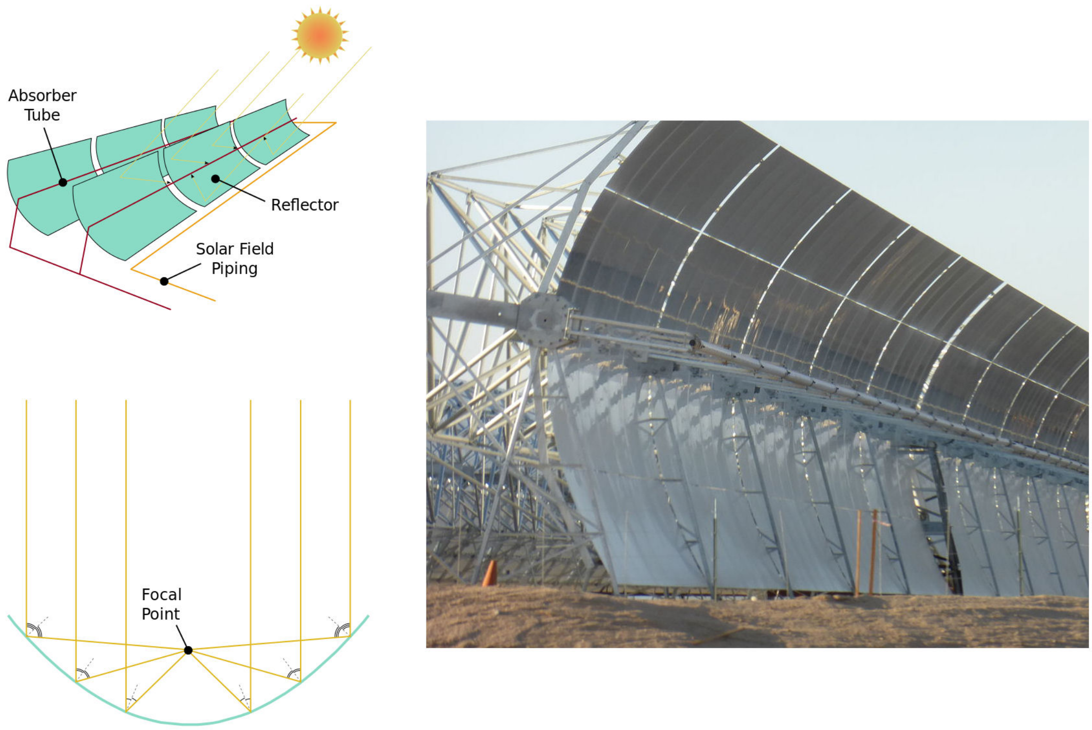


Figure 2.8. Working principle of a parabolic-trough (left). Parabolic-trough at the Harper Lake plant (California, USA) (right). Source (left): `http://bit.ly/2BxAAFE`, License: CC BY-SA 4.0. Source (right): `http://bit.ly/2Bx7Gpb` (License CC-BY-SA 3.0).

Why are oils chosen as HTF instead of water? Water has some disadvantages like:

It is aggressive, oxidant and leads to corrosion

It gives rise to a high vapour pressure

Its volume increases at solidification

Question 2.2: Are there parabolic-trough installations in Spain?

Look for information about this technology. Are there any installations in Spain?

2.2.3. Solar Thermal Energy: High Temperature / CSP

High temperature solar thermal energy, also known as **Concentrating Solar Power (CSP)** is typically based on the **power-tower** scheme depicted in Figure 2.9. A set of **heliostats** (mirrors) are oriented to focus the sun's radiation onto a receptor situated in a tower, where a fluid is heated to be used to activate a turbine. These heliostats are normally controlled by computer to track the sun and thus optimize production. As with parabolic-troughs, water is typically avoided as thermal fluid. As already explained in the previous chapter (section devoted to large-scale storage solutions), **molten salts** allow storing the generated heat, even enabling electricity production during the night.

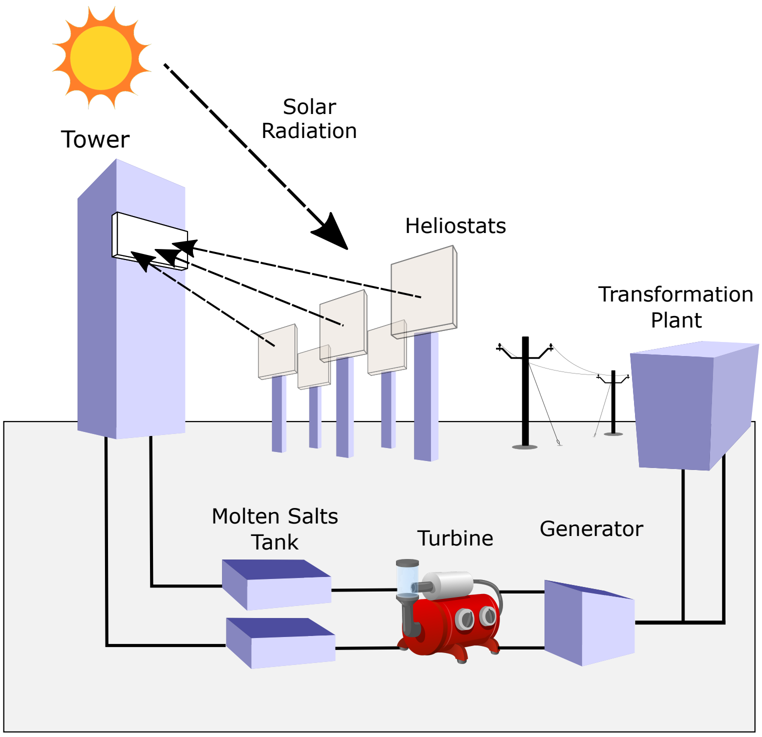


Figure 2.9. High-temperature solar thermal power / Concentrating solar power: power-tower scheme. Source: Jesus Mirapeix

A good example of a CSP plant is the Ivanpah Solar Electric Generating System, located in USA between Nevada and California, and with more than 300,000 installed heliostats (Figure 2.10).

Figure 2.10. Ivanpah Solar Electric Generating System, at Mojave desert (California). Source: Craig Butz/CC BY-SA 4.0. http://bit.ly/2CWqPNF.

This plant, that began operating in 2014, has 3 towers and a nominal capacity of 400 MW (enough power to supply around 140,000 homes).

It is worth noting that, although we are talking about a renewable energy, the fact that the plant covers a total area of $13km^2$ is considered by some groups as a negative impact, as they think that the plant might be affecting animals, for example. The cost of the plant was 2,200 million dollars, with a cost per MW of $5.5million\$/MW$. By comparison, a nuclear plant might cost around $8-10million\$/MW$ and wind power around ($1.5million\$/MW$). These figures should be only considered as an estimation.

Important! 2.2: Carbon Commentary

In this famous blog on renewable energies, this article was recently published about the Ivanpah plant:

Concentrating solar. 2014 - its first year - was a near disaster for the 400 MW solar tower and heliostats at Ivanpah in the California Mojave desert . This matters; Ivanpah is the biggest concentrating solar plant in the world. Power production was very much lower than expected and the maintenance requirements were heavy for this $2 billion project. Many worried that the developers had underestimated cloud cover and I heard rumors that contrails of aircraft flying into Los Angeles were helping reduce the yield. The second year was very much better and almost met business plan projections. The first year clouds may have been a result of the strengthening *El Niño* (which is now fading) and maintenance issues have been resolved by a series of what seem like simple technical fixes. The faith of investors and the power purchaser look better justified.

www.carboncommentary.com

Figure 2.11. Solar thermal furnace installation in Odeillo (France). Source: `http://bit.ly/2zewRXF`. License: CC-BY-SA 3.0.

Important! 2.3: Heliodyssee

Heliodyssee is a center open to the public located in the South of France, whose main attraction is the Solar furnace (world's largest) formed by a set of heliostats that focus solar radiation on a 40 cm^2 spot, with a concentration power equivalent to 10.000 suns. The history of this facility is interesting, as it supposedly started with the development of heliostats to be used as anti-aircraft weapons during the First World War (probably inspired by the Archimedes story that appears below). The furnace was built in 1962-68, having acted as a research center for solar thermal energy.

Important! 2.4: Archimedes and his Death Ray

Mirrors are known to have been used to cauterize wounds in the antiquity, but Archimedes might be regarded as one of the "fathers " of solar thermal energy ... at least if we agree with the legend. The historical accuracy of his defense of Siracuse is not clear, but he supposedly developed a set of mirrors able to focus the solar radiation onto the Roman warships that attacked his city, Siracuse. The system, if it really existed, seemed to not have been very successful, as the city was invaded and Archimedes killed by a Roman soldier.

Several teams have tried to replicate this experiment, from the TV show "Mythbusters"[a] to the MIT[b].

[a] `https://youtu.be/kAWBvZcBZOU`
[b] `http://bit.ly/1md1NdI`

Figure 2.12. Illustration representing the supposed defense of Siracuse by means of a set of mirrors designed by Archimedes. Source: `http://bit.ly/2zfyBzT`

Question 2.3: Archimedes and the Death Ray?

What is your opinion about this historical fact?

Look for information about the historical sources and the possible feasibility of the system. Do you think it was real?

2.2.4. CSP: Current Situation

As we already saw in the first chapter, Spain is the global leader in CSP installed capacity, with 2.3 GW in operation, followed by USA with 1.7 GW. These two countries account for around 75% of the global CSP capacity in operation in 2018 (last data available), but both countries have experienced a standoff since 2013 (Spain) and 2015 (USA), with a complete lack of new installations (see Figure 2.13). This situation seems to be changing in Spain, where the government has announced the target of adding 5 GW of CSP capacity by 2030. In this scenario, the new CSP capacity in recent years has been added only in emerging markets, mainly China and Morocco, followed by South Africa and Saudia Arabia.

It should be mentioned that the global CSP capacity sums up to 5.5 GW, while figures for other modern RE technologies, like wind (591) or solar PV (505) are much higher.

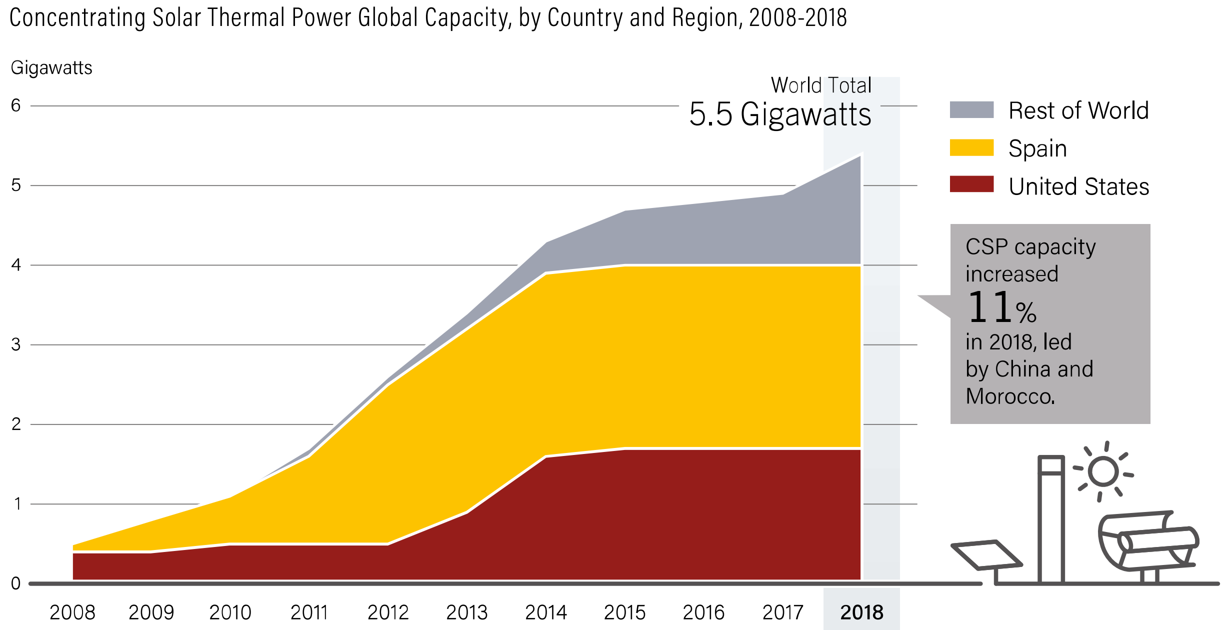


Figure 2.13. Evolution of global CSP capacity (2008-2018). Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

RENEWABLE ENERGY INDICATORS 2018

		2017	2018
INVESTMENT			
New investment (annual) in renewable power and fuels[1]	billion USD	326	**289**
POWER			
Renewable power capacity (including hydropower)	GW	2,197	**2,378**
Renewable power capacity (not including hydropower)	GW	1,081	**1,246**
Hydropower capacity[2]	GW	1,112	**1,132**
Wind power capacity	GW	540	**591**
Solar PV capacity[3]	GW	405	**505**
Bio-power capacity	GW	121	**130**
Geothermal power capacity	GW	12.8	**13.3**
Concentrating solar thermal power (CSP) capacity	GW	4.9	**5.5**
Ocean power capacity	GW	0.5	**0.5**
Bioelectricity generation (annual)	TWh	532	**581**

Figure 2.14. Global capacity associated with the main RE technolgies (2017-18). Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

2.3. Solar Photovoltaics: a brief history of its evolution

Solar Photovotaics (PV) allows a direct conversion of solar radiation into electricity, thus being completely different to solar thermal solutions. When can we date the beginning of solar PV? We should probably go back to the discovery and explanation of the **photoelectric effect**. In this regard, it is worth mentioning that **Albert Einstein**, regarded as the most important physicist of the 20th centurty, was awarded the Nobel Prize in Physics precisely for his **explanation of the photoelectric effect** (and not for his most well-known contribution, his Theory of Relativity.)

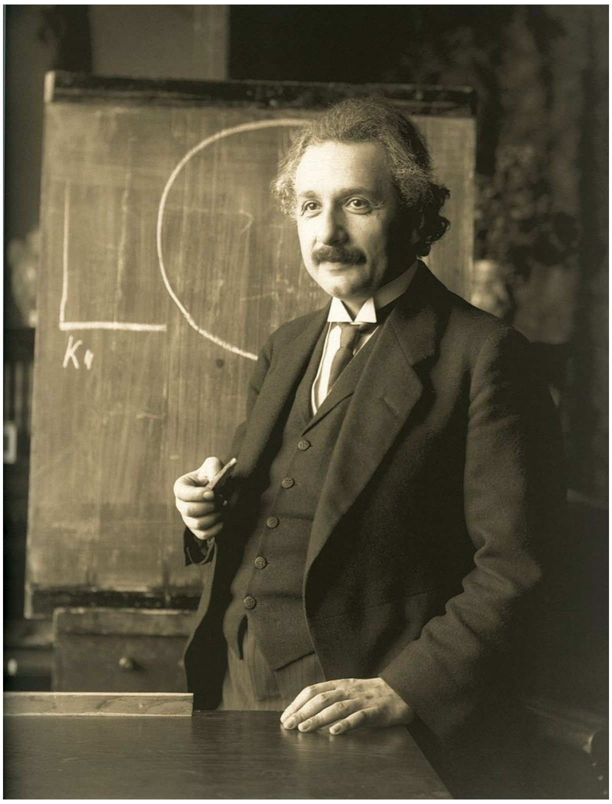


Figure 2.15. Einstein at a conference in Vienna (1921). Source: Wikimedia. License: Public Domain `http://bit.ly/2DvRGkG`

Einstein did not discover the photoelectric effect, as this phenomenon had been already observed by different scientists. A summary of the key events in **the first stage** of the evolution of photovoltaics is listed below:

1839 Edmun Becquerel discovered the photoelectric effect while he was working with metallic electrodes in a conductive solution, by noticing the appearance of an electric current with light radiation.

1873 Willoughby Smith discovered the photoelectric effect in solids (selenium).

1877 Adams y Day developed the first selenium PV cell.

1904 Albert Einstein published his first paper on the photoelectric effect, at almost the same time as another article on the Theory of Relativity.

1921 Einstein won the Nobel Prize in Physics for his explanation of the photoelectric effect.

1954 Researchers at the Bell Laboratories in Murray Hill, New Jersey (Chaplin, Fuller y Pearson) developed the first silicon PV cell, publishing the paper *"A New Silicon p-n junction Photocell for converting Solar Radiation into Electrical Power"*.

The second stage was based on a fast technological development driven by the aerospace sector:

1955 American companies focused on developing PV solutions for space applications. Hoffman Electronic (Illinois (USA)) produced PV cells of 3% efficiency at 1500 $/Wp[1].

1957 Hoffman Electronic obtained an 18% efficiency in its PV cells (in laboratory conditions).

1958 On March 17th, the first satellite powered by PV technology (Vanguard I) was launched. The satellite had 0.1W in an area of $100cm^2$ to power supply a backup transmitter of 5 MW that was fully operative for 8 years.

1959 Hoffman Electronic obtained a 10% efficiency in its PV commercial cells.

1962 The first telecommunication satellite, Telstar, was launched with a total PV capacity of 14 W.

1963 Sharp achieved a practical method for PV module fabrication. A PV system with 242 W was installed in a lighthouse in Japan.

1964 The Nimbus space ship was launched with 470 W of solar PV modules.

1966 The astronomical observatory with 1 kW peak power photovoltaic module field was tracked in the earthly orbit.

1977 The global PV module fabrication reached 500 kW.

Important! 3.1: Vanguard-I solar PV modules

Vanguard-I was the 4th satellite ever launched. **This was the very first time that PV technology was used for a real application**. 6 solar panels (0.5 W each), allowed the satellite to send data about the composition of the atmosphere back to Earth during 6 years.

Now that PV technology had evolved sufficiently, **the third stage** was focused on the development of huge PV installations devoted to electricity production:

1980 ARCO Solar (years later Siemens and Shell Solar) was the first company with a yearly production of 1 MW.

1983 Global production exceeded 20 MW.

1994 The first international conference on PV took place in Hawaii (not a bad place!).

1998 Second international conference in Vienna. 1000 MWp installed worldwide.

[1] Later in the course the relevance of this parameter (cost per watt-peak (Wp)) will be analyzed.

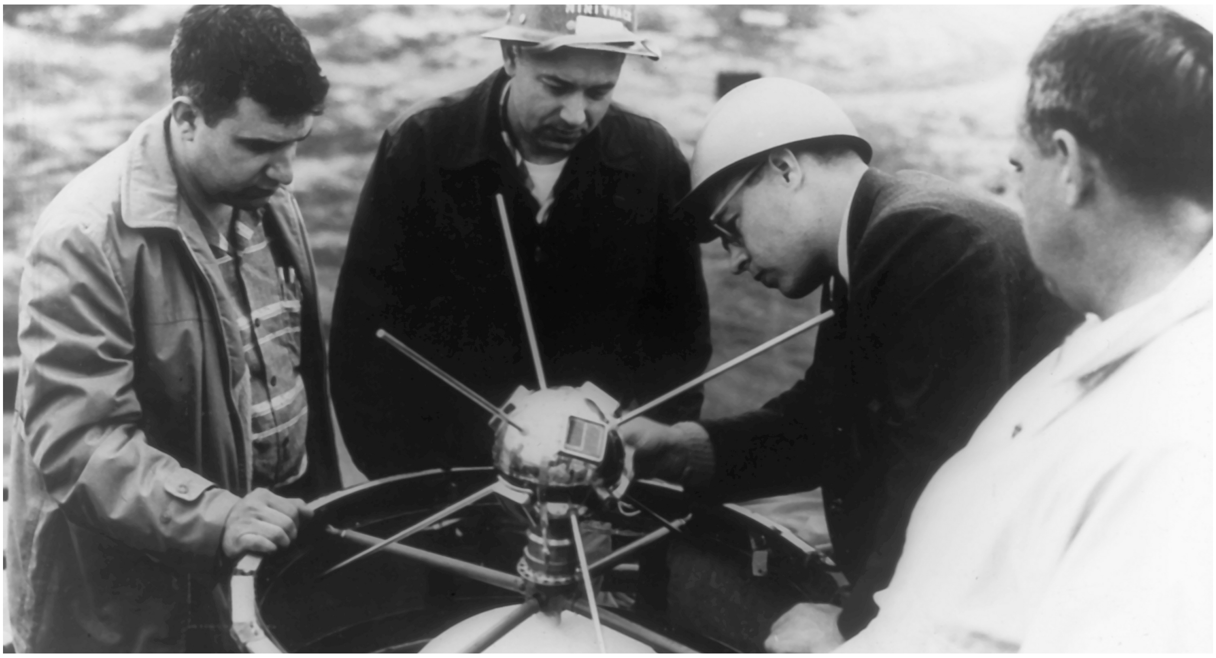


Figure 2.16. Vanguard-I scientists mounting the satellite in the rocket. Source: Wikimedia. License: Public Domain `http://bit.ly/2DJMvBn`

2002 More than 500 MWp produced that year.

2003 Third international conference in Japan. Society and developing countries actively back PV technology.

2010 More than 15 GWp fabricated.

Important! 3.2: Solar PV Evolution: Costs

This technological evolution has implied a parallel (and outstanding) evolution of the associated costs. The Vanguard-I modules cost many thousand dollars per watt. By the mid 1970s, this figure had dropped to 100 $, and nowadays this cost is significantly lower than 1$/W, and it is declining.

As a complement to the information we have just seen, **??** shows other milestones in the evolution of PV solar energy from 1941 to the present, such as when the 20% efficiency was first reached in silicon cells (1985) or the moment when 100 GW of global installed capacity threshold was surpassed (2012).

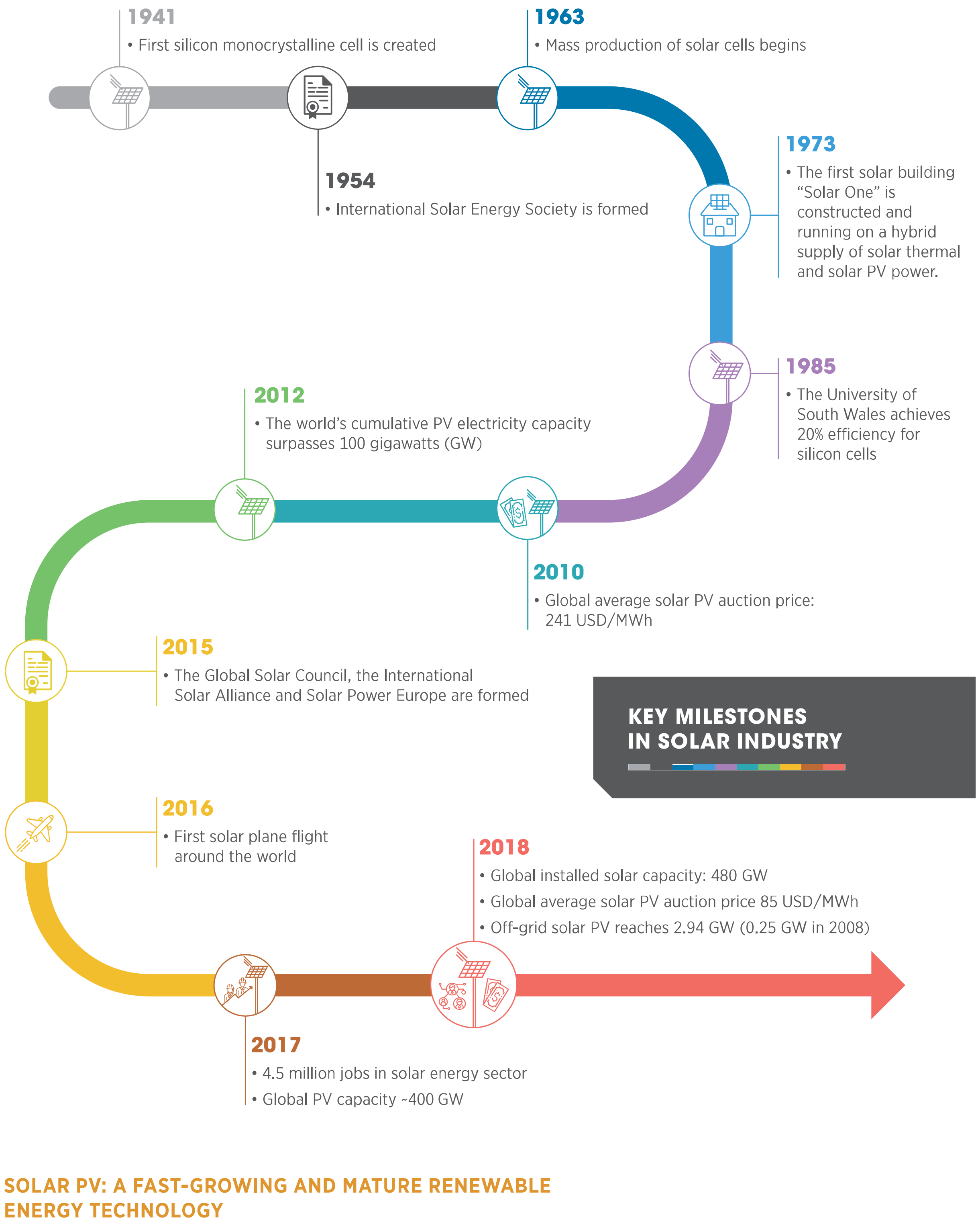


Figure 2.17. Evolution of solar PV (1941-2018). Source: Irena (Future-of-Solar-Photovoltaic). `http://bit.ly/3061Iao`

2.4. Solar PV: current situation

After this brief review of the historical evolution of PV technology, it is now time to review the current situation of this sector. Some key data were already presented in the previous chapter, with **China and the USA** dominating the global arena in gross capacity and **Germany, Italy, Belgium and Japan** in capacity *per capita*.

TOP FIVE COUNTRIES

Annual Investment / Net Capacity Additions / Production in 2018

	1	2	3	4	5
Solar PV capacity	**China**	India[2]/United States		Japan	Australia
Concentrating solar thermal power (CSP) capacity	**China/Morocco**		South Africa	Saudi Arabia	–
Wind power capacity	**China**	United States	Germany	India	Brazil
Solar water heating capacity	**China**	Turkey	India	Brazil	United States

Total Capacity or Generation as of End-2018

	1	2	3	4	5
POWER					
Solar PV capacity	**China**	United States	Japan	Germany	India
Solar PV capacity *per capita*	**Germany**	Australia	Japan	Belgium	Italy
Concentrating solar thermal power (CSP) capacity	**Spain**	United States	South Africa	Morocco	India
HEAT					
Solar water heating collector capacity[5]	**China**	United States	Turkey	Germany	Brazil
Solar water heating collector capacity *per capita*	**Barbados**	Austria	Cyprus	Israel	Greece
Geothermal heat output[6]	**China**	Turkey	Iceland	Japan	Hungary

Figure 2.18. Top 5 countries by capacity/generation as of end-2018. Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

The rate of growth of PV capacity in recent years is **absolutely remarkable**, showing the highest growth rate (among all RE technologies) in terms of electricity production. To illustrate this evolution, Figure 2.19 shows PV capacity in the period 2008-2018 by region. Within this remarkable rate of growth, the contributions of China, Japan and the USA in recent years clearly stand out.

It can also be very interesting to analyze the current situation in terms of the **shares (%) of these technologies with respect to electricity generation**. In this sense, **??** shows the top 10 countries in terms of such coverage considering both wind energy (in blue) and solar PV (in yellow). The analysis of this graph enables some interesting conclusions:

- The shares (%) of electricity generation is not directly related to the total installed capacity (of course). Different factors, such as the size of the country or the use of other energy technologies (derived from the use of fossil fuels, nuclear ...) have a decisive influence in this regard.

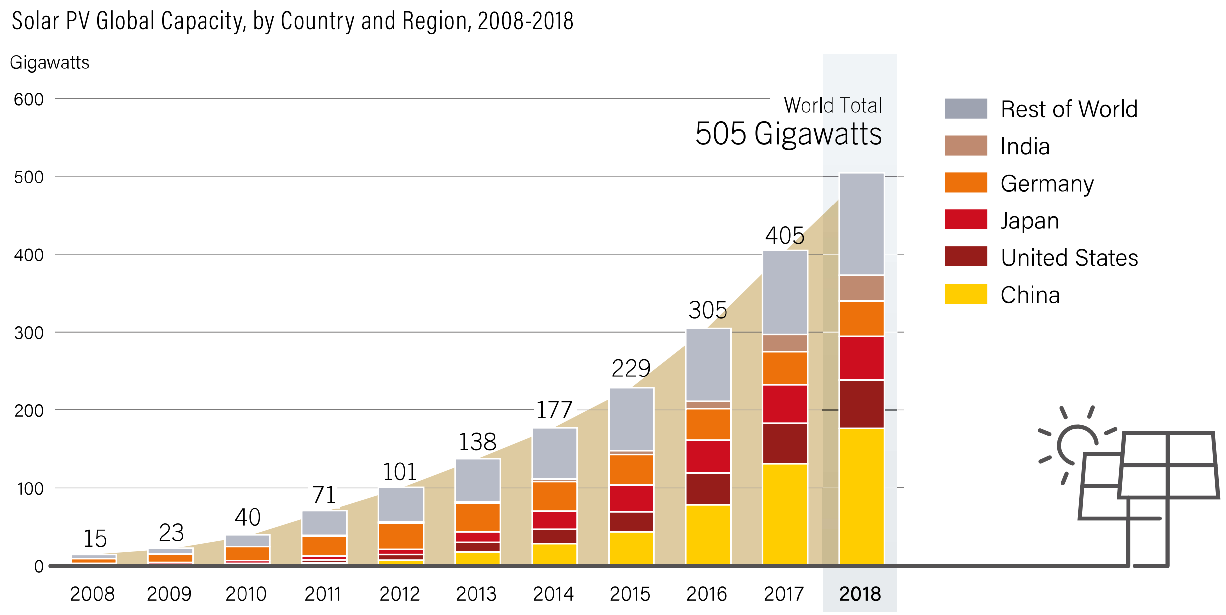


Figure 2.19. Evolution of PV global capacity by country and region (2008-2018). Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

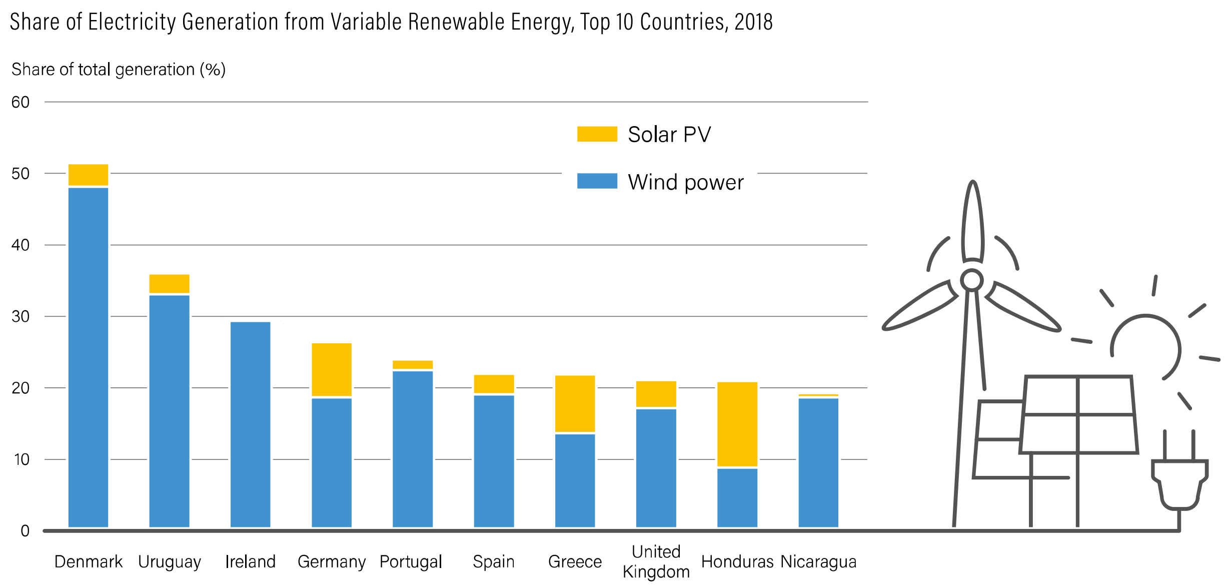


Figure 2.20. Top 10 countries in terms of shares (%) of these technologies with respect to electricity generation (2018). Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

- Despite showing the greatest growth today, PV solar power clearly contributes less on average than wind power, a technology that can probably be considered more mature in this regard.
- The contribution of solar PV to electricity generation is, even today, still modest, always standing (except in some small countries like Honduras) below 10%.

Important! 4.1: Solar PV growth

Figures can be very illustrative, but some data may help us to understand the real magnitude of this growth: **98 GW of solar PV capacity was added worldwide in 2017, increasing total capacity by nearly one-third**, for a cumulative total of approximately 402 GW.
In 2017 China has surpassed all expectations, adding more solar capacity (51.3 GW) than was added worldwide in 2015 (51 GW).

This is equivalent to the installation of nearly 40.000 solar PV panels every hour!

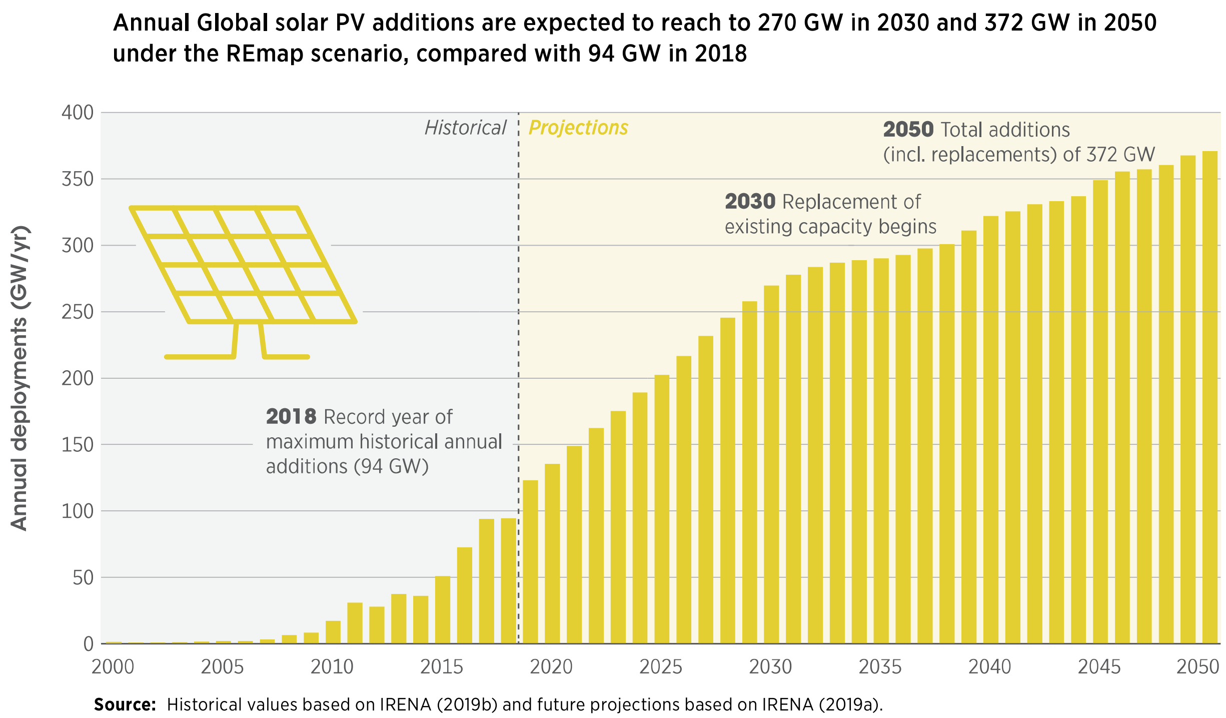


Figure 2.21. Evolution of solar PV capacity until 2018 (historical series) and up to 2050 (forecast). Source: Irena (Future-of-Solar-Photovoltaic). `http://bit.ly/3061Iao`

To better understand the relevance of solar PV, it is interesting to analyze the future perspectives that the main worldwide organizations have foreseen. In this sense, **??** shows, not only the evolution of facilities worldwide to date, but also **the increase in annual capacity up to 2050**. It could be seen how a very strong growth is expected until 2030, exceeding 250 installed GWp. At this moment it is expected that the panels of old installations will begin to be replaced, since the estimated lifetime of the panels ranges between approximately 25 and 30 years. **In 2050 it is expected to exceed 370 GWp**.

Important! 4.2: Figure 2.21

It should be noted that **??** does not show the total installed capacity (global) for a given year, but the **PV capacity added** in that year.

To fully understand this context, it is also necessary to analyze the global capacity increase in solar PV by regions, since as we have seen, countries like **China** are making a much greater effort than the rest. Thus, in the **prediction of PV capacity installed by 2030 and 2050**, **Asia is again the clearly dominant region**, followed by North America and, thirdly, Europe. In Asia, the outlook indicates that **in 2030 the installed capacity will be almost 7 times higher than the current one, and in 2050 ... 17!**.

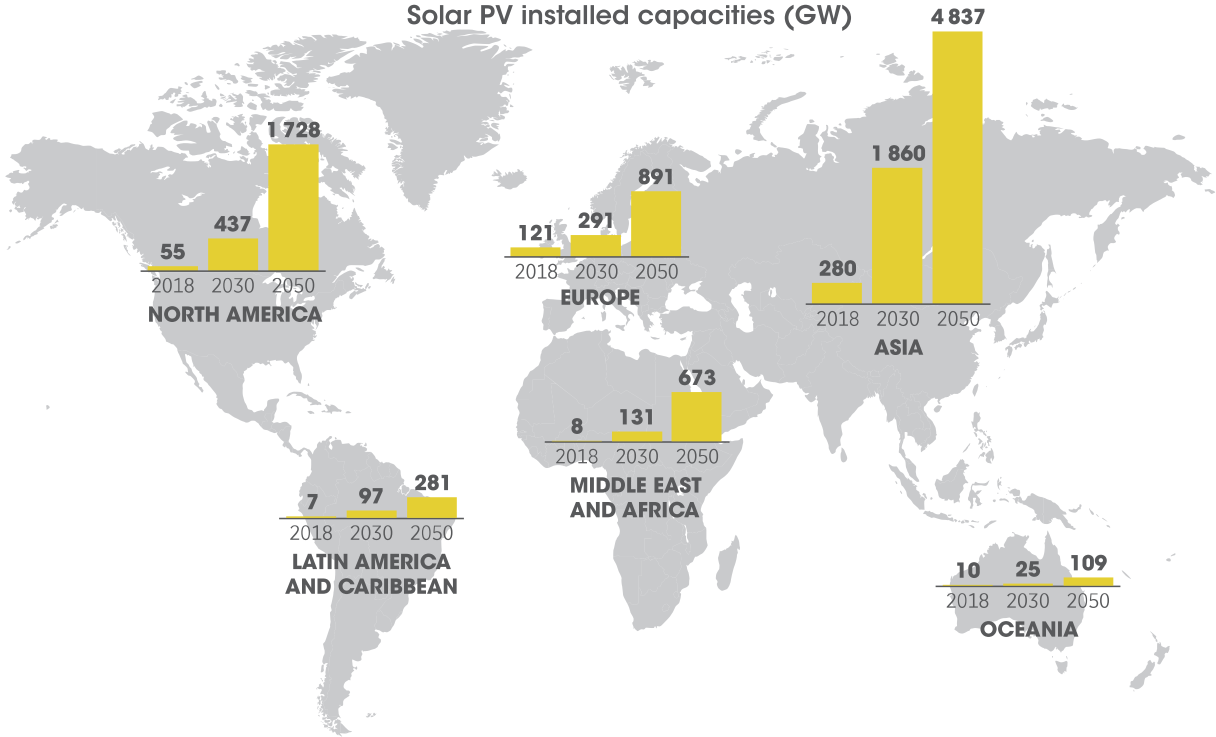


Figure 2.22. Evolution of solar PV capacity up to 2030 and 2050 (forecast) by region. Source: Irena (Future-of-Solar-Photovoltaic). `http://bit.ly/3061Iao`

There is also a clear **correlation between the evolution of installed PV power and the evolution of the cost associated with PV installations**[1]. As is generally the case with economies of scale, the increase in the scale of operation of a certain sector (in this case in the production of PV modules and the cost associated with PV installations in general) results in a reduction in unit cost. This fact can be observed in **??**, where there is a strong decreasing trend in the price of PV installations. It must be taken into account that the cost of an PV installation considers, not only the cost of the photovoltaic modules, but also the rest of the components (wiring, supports, inverters, etc.), as well as the cost of assembly and inspection and the so-called *soft-costs* (costs associated with design, request for permits, financing ...). As can be seen, not only has the trend been strongly decreasing in the last decade, but the predictions for 2030 and 2050 indicate that this trend will continue in the coming years.

[1] A typical indicator in this regard has been the cost of PV modules, although there are many more costs associated with a PV installation.

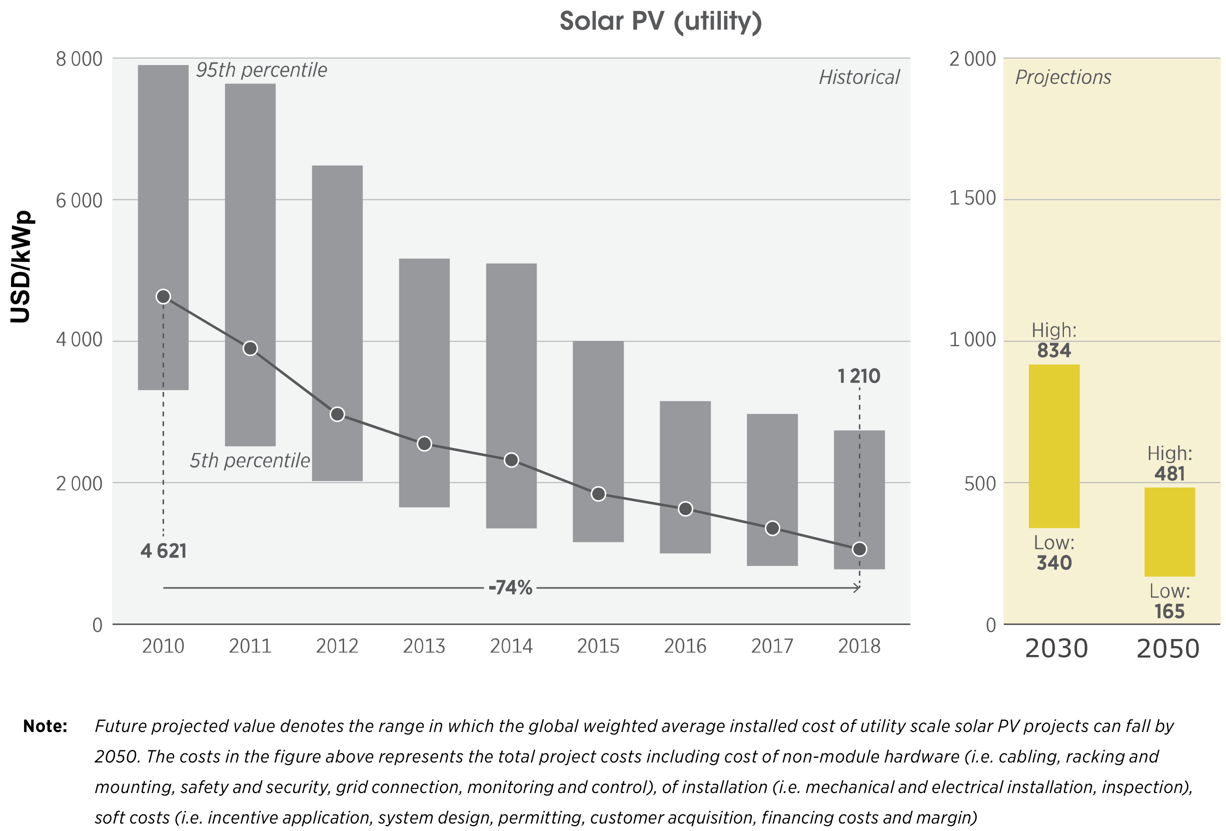


Figure 2.23. Evolution of costs involved in a solar PV installation (2010/18)/Forecast for 2030 and 2050. Source: Irena (Future-of-Solar-Photovoltaic). `http://bit.ly/3061Iao`

Important! 4.3: W_p: Watt-peak

This cost is usually expressed in $/Wp [a]. The concept of Wp (Watt-peak) will be explained in detail in future sections.

[a] W_p refers to **Watt-peak**, the unit associated to the power delivered by the panel for certain measurement conditions called EMC: Standard Measurement Conditions (in English: STC (textit Standard Test Conditions))

The **??** leads us to the concept of **LCOE** (***levelized cost of energy***, of great relevance in the context of REs. The **LCOE** is a parameter that allows a direct comparison between different technologies and measures the costs associated with a given generation plant (during its entire estimated life period: manufacturing, maintenance, operation, etc. costs).) divided by total energy production. Their units are $\$/Wh$.

The analysis of the **LCOEs** associated with solar technologies allows a better understanding of the current situation. **??** and **??** show the CSP, photovoltaic, hydraulic and wind (*onshore* and *offshore*) LCOEs, respectively. Logically, CSP shows a higher cost compared to solar PV, due to its lower maturity and implantation. Solar PV still shows LCOEs higher than wind and hydro, although we already know that the tendency to lower prices in photovoltaics is very significant. In this sense, it is necessary to take into account the value as a reference of hydro power, being a mature technology with several decades of implementation, as well as the strong growth that the solar PV is experiencing, which, as

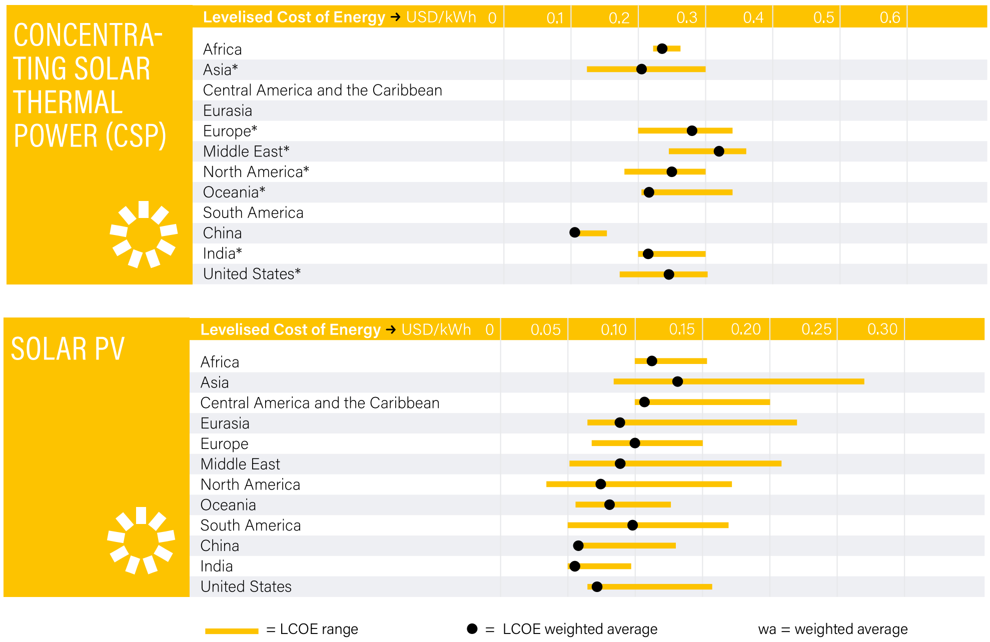


Figure 2.24. LCOE for CSP and solar PV (2018). Source: Renewables 2019 Global Status Report (REN21). `http://bit.ly/2rTdoy3`

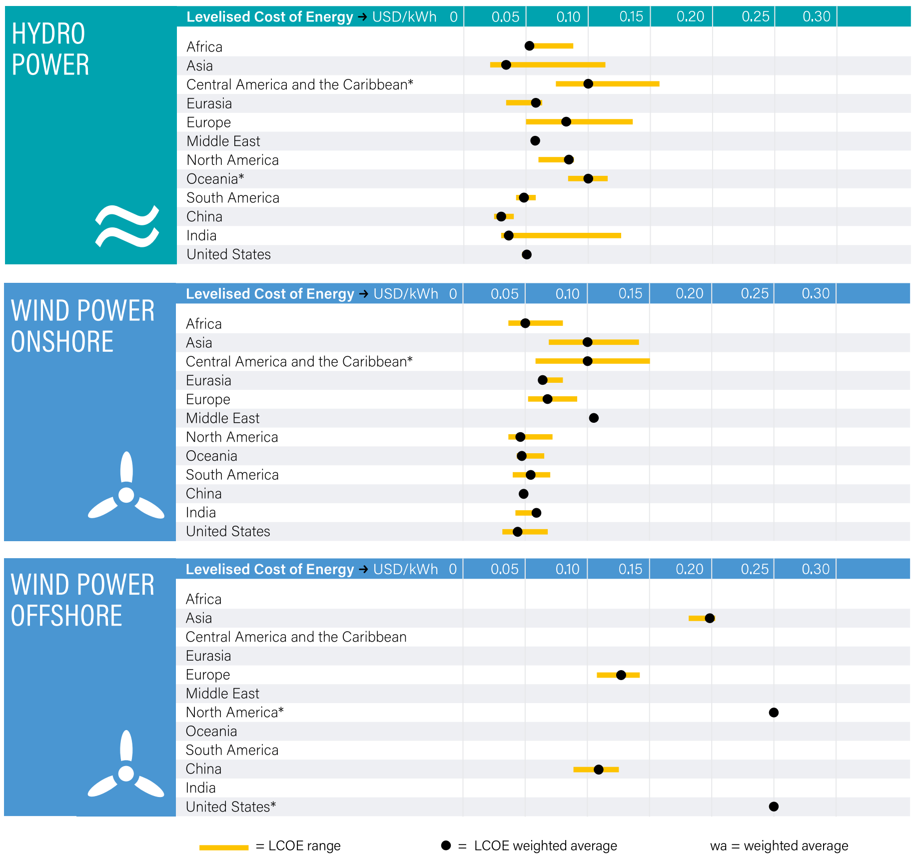


Figure 2.25. LCOE for hydro and wind power (2018). Source: Renewables 2019 Global Status Report (REN21). `http://bit.ly/2rTdoy3`

we know, has a direct influence on the associated prices.

There is an interesting concept related to this: **the PV learning curve**. With learning curves, the experience gained with a certain technology is expressed as learning rate, i.e. the percentage at which the unit cost decreases with every doubling of cumulative production[1]. This is related to the famous **Moore's law** for the number of transistors in integrated circuits, and in this case it is referred to as Swanson's law[2]. It states that **the price of solar photovoltaic modules tends to drop 20 percent for every doubling of cumulative shipped volume**. Figure 2.26 illustrates this idea, where the evolution of PV costs (module price) from the seventies to 2015. Current estimations show a decrease of PV module costs (**learning rate**) around **24%** for each doubling in the cumulative production.

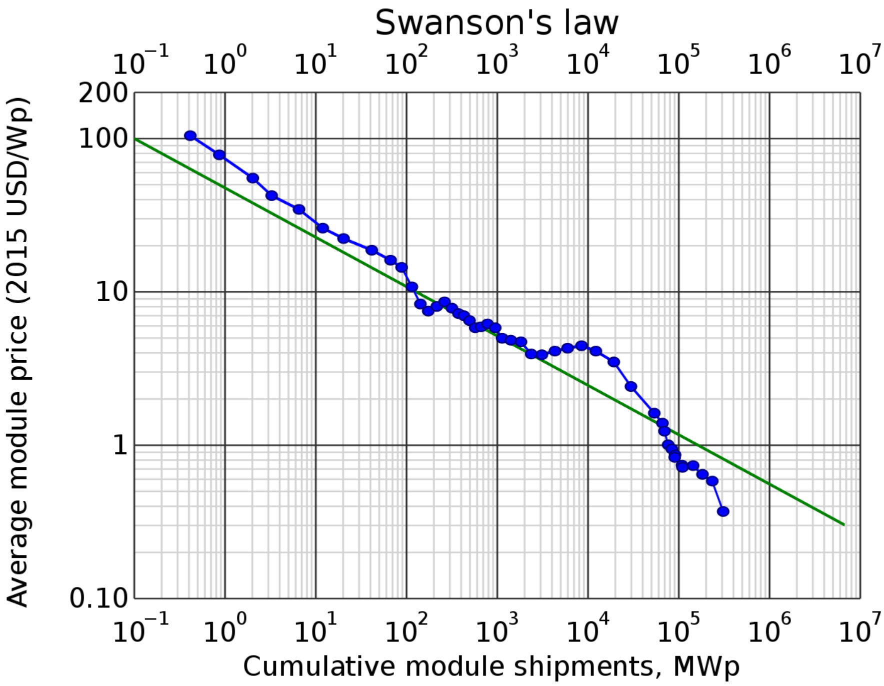


Figure 2.26. Swanson's law: evolution of the average PV module price. Source: Delphi234. License: CC0 http://bit.ly/2V4Vykr

Finally, it is worth highlighting the importance that REs and, in particular solar PV, are exhibiting in the creation of employment. As shown in the table of Figure 2.27, it is precisely the **solar PV sector** the one that most **jobs** occupied in 2018, with a total above **3.5 million**. Although the figure is very important, it is also necessary to indicate that approximately 60% of all these jobs were located in China, with only 96,000 in the European Union.

According to the growth forecasts for the coming decades, the number of jobs associated with the PV sector is expected to **multiply by a factor of approximately 3 and 5 for the years 2030 and 2050**, respectively.

[1] *"Prospects for PV: a learning curve analysis"*, Bob van der Zwaan and Ari Rab (Solar Energy).

[2] Named after Richard Swanson, founder of SunPower Corporation.

Estimated Direct and Indirect Jobs in Renewable Energy, by Country/Region and Technology, 2017-2018

	World	China	Brazil	United States	India	European Union[l]
	Thousand jobs					
Solar PV	**3,605**[e]	2,194	15.6	225	115[k]	96
Liquid biofuels	**2,063**	51	832[g]	311[h]	35	208
Hydropower[a]	**2,054**	308	203	66.5	347	74
Wind power	**1,160**	510	34	114	58	314
Solar thermal heating/cooling	**801**	670	41	12	20.7	24[m]
Solid biomass[b, c]	**787**	186		79[i]	58	387
Biogas	**334**	145		7	85	67
Geothermal energy[b,d]	**94**	2.5		35[j]		23
Concentrating solar thermal power (CSP)	**34**	11		5		5
Total	**10,983**[f]	**4,078**	**1,125**	**855**	**719**	**1,235**[n]

Figure 2.27. Jobs associated with REs (2017-18). Source: Renewables 2019 Global Status Report (REN21). `http://bit.ly/2rTdoy3`

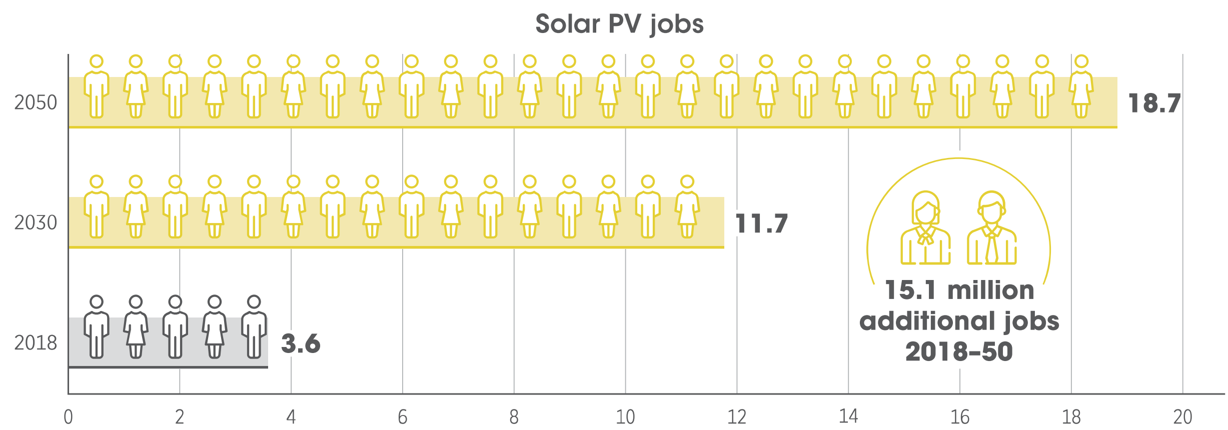


Figure 2.28. Jobs associated with solar PV: forecast for 2030/50. Source: Irena (Future-of-Solar-Photovoltaic). `http://bit.ly/3061Iao`

2.4.1. Solar PV: Current Situation in Spain

As already explained in the previous chapter (Section 1.10: RE policies), the current situation of the PV sector in Spain is somewhat different to the trends observed in the leading countries. Spain reached its top growth rate in 2008, backed by the subsidized policies (RD 661/2007 and RD 1578/2008) developed by the Spanish government (see Figure 2.29). However, the unstable situation generated, among other factors, by the financial crisis and the lack of stability in the regulation led to a review and cutback of these subsidies. This has caused an almost complete standstill of the PV sector in Spain, giving rise to a lack of additions to the PV capacity during many years.

With the situation described above, it is worth remembering the contribution of solar PV to power generation in Spain. As already shown in the previous chapter, the installed

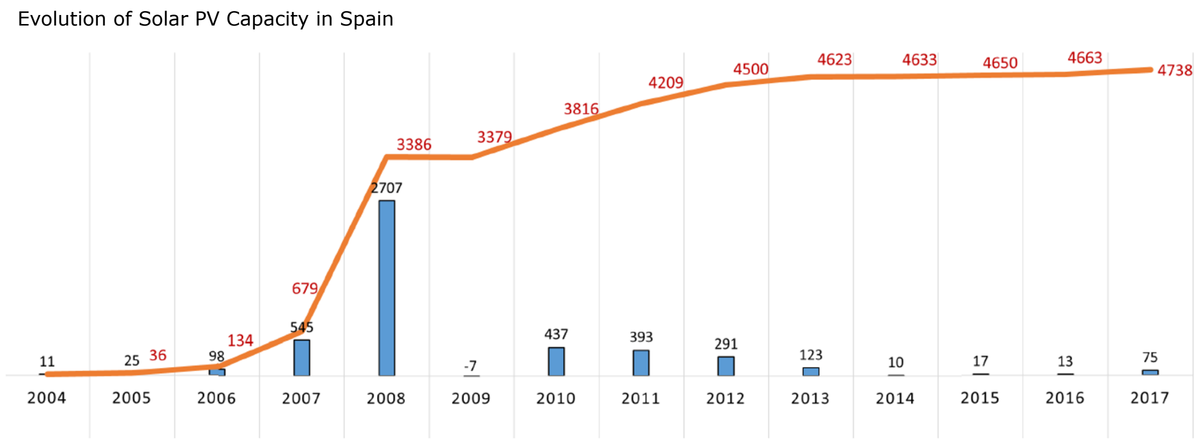


Figure 2.29. Evolution of solar PV capacity in Spain. Source: APPA. Licencia: Jesús Mirapeix.

PV power constitutes approximately **5 %** of the total Spanish generation system. This has resulted in relatively modest contributions in recent years, with a **3.5 %** of photovoltaic generation in 2019.

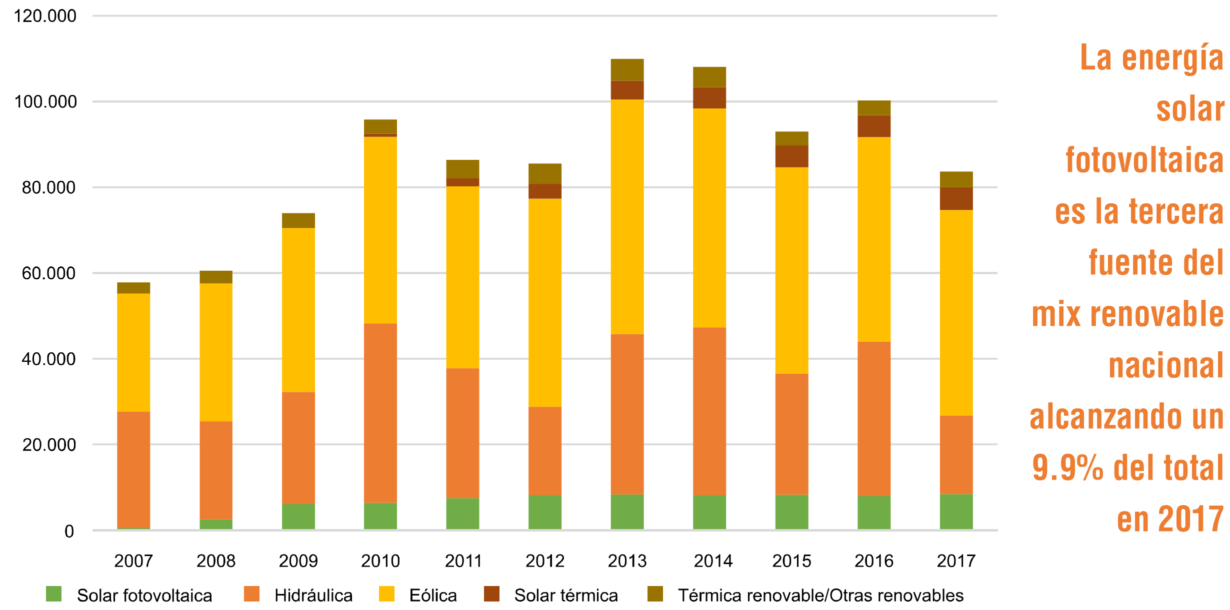


Figure 2.30. Evolution of electricity generation in Spain (2007-2017). Source: "El desarrollo actual de la energía solar fotovoltaica en España" (UNEF) `http://bit.ly/2QG0i05`

Within the renewable generation mix in Spain, solar PV is the third most important technology (around 10 % generation in recent years), clearly behind wind and hydro power. In **??** it can also be seen how solar thermal power (CSP) has gained relevance in recent years; in fact, Spain is the leading country by total installed capacity worldwide in this technology. One aspect to be highlighted regarding the data in this graph is the variability associated with wind and, above all, hydro power. The fluctuations of the latter have been very relevant in the Spanish generation mix in recent years, significantly influencing the associated CO2 emissions, for example. Within this scenario, it should be noted that PV solar generation is more stable in the long term (e.g. annually), which may present a certain advantage in the future when its contribution to the generation mix is more relevant.

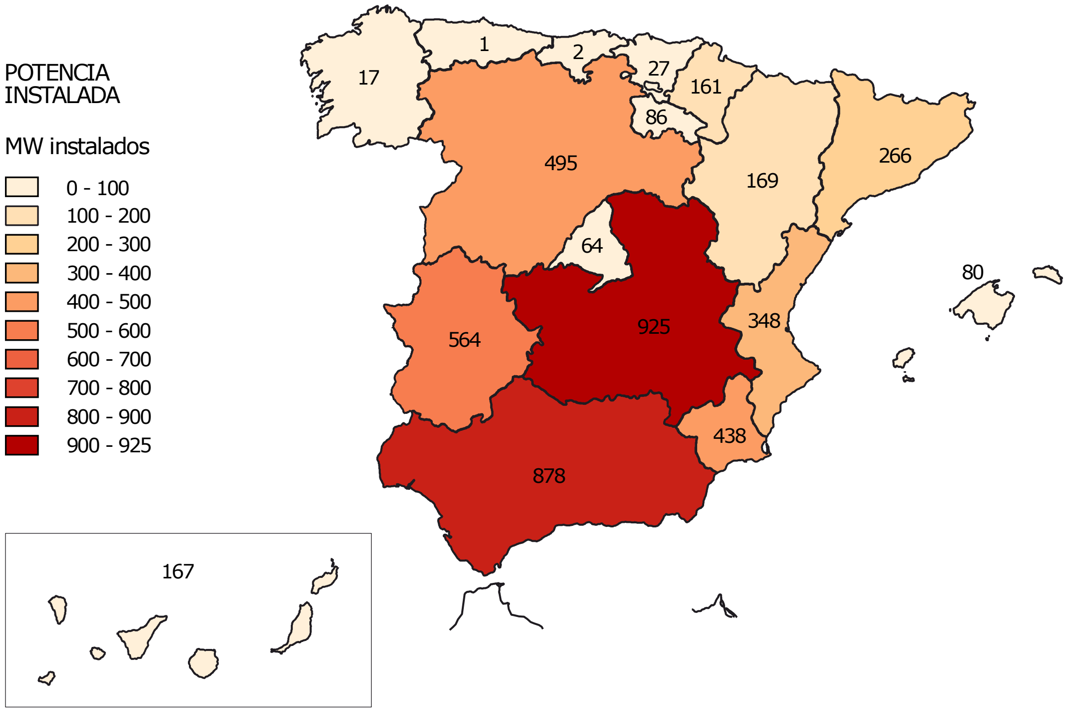


Figure 2.31. Solar PV capacity in Spain (MW, as of end 2017). Fuente: "El desarrollo actual de la energía solar fotovoltaica en España" (UNEF) `http://bit.ly/2QG0i05`

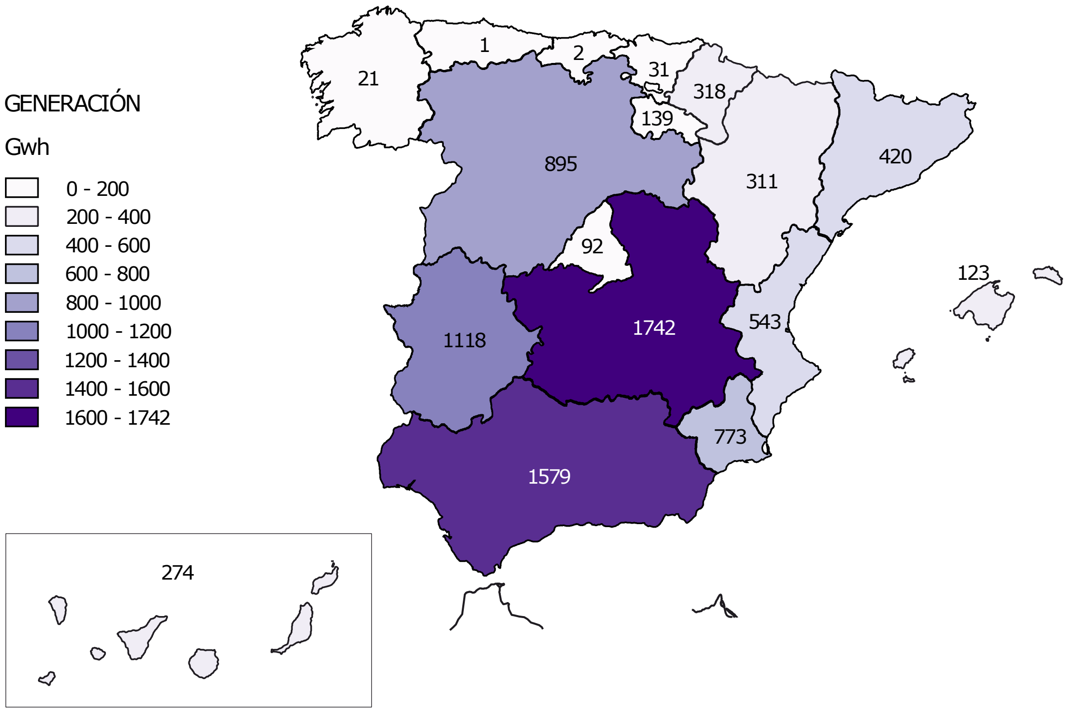


Figure 2.32. Solar PV electricity generation in Spain (GWh, as of end 2017). Fuente: "El desarrollo actual de la energía solar fotovoltaica en España" (UNEF) `http://bit.ly/2QG0i05`

It is also interesting to analyze the distribution of PV installations and their associated power in the different communities in Spain. The largest number of facilities is located in Castilla La Mancha, Andalucía, Extremadura, Castilla León and Murcia, adding approximately 70 % of the total Spanish PV capacity. As can be seen in **??**, the communities of northern Spain have very low figures, especially Galicia, Asturias, **Cantabria** and Basque Country. PV generation shows a strong correlation with the installed power (see **??**), although there is a certain correction factor associated with solar radiation [1], which as we know is greater the closer we get to the southern regions of Spain[2].

Spain: 2019 and beyond!

Despite the clear standstill of the solar PV sector in our country in recent years, **its near future seems very promising**. As we have seen, the Spanish PV capacity grew by approximately **4 GW between 2007 and 2012**, to show virtually zero growth rates in recent years: **48 MW between 2014 and 2017**. However, they have been awarded through auctions **3,9 GW**, which is undoubtedly an important boost for the sector, involving an investment of some **3,500 million euros**. The fact that these awards have been made primarily to Spanish companies will also imply a certain reactivation of the associated labor market [3].

RED ELÉCTRICA DE ESPAÑA

Potencia instalada nacional (MW)

	2016	2017	2018	2019 (*)
Hidráulica convencional y mixta	17.033	17.030	17.049	17.087
Bombeo puro	3.329	3.329	3.329	3.329
Nuclear	7.573	7.117	7.117	7.117
Carbón	10.004	10.004	10.030	9.683
Fuel + Gas	2.490	2.490	2.490	2.447
Ciclo combinado	26.670	26.670	26.284	26.284
Hidroeólica	11	11	11	11
Resto hidráulica (1)	-	-	-	-
Eólica	23.050	23.131	23.589	25.223
Solar fotovoltaica	4.686	4.688	4.714	7.824
Solar térmica	2.304	2.304	2.304	2.304
Térmica renovable/Otras renovables (2)	870	872	879	981
Térmica no renovable/Cogeneración y resto/Cogeneración (3)	5.966	5.802	5.729	5.688
Residuos no renovables(4)	496	496	490	490
Residuos renovables(4)	160	160	160	160
Total	**104.643**	**104.105**	**104.176**	**108.630**

Figure 2.33. Added capacity in Spain as of end 2019. Source: REE `http://bit.ly/37ZRclk`

Data provided by REE for the first 3 quarters of 2019 clearly endorse this change: **as of September 2019, PV capacity had increased in Spain in 1,541 MW**, a spectacular in-

[1] The parameter used to measure solar radiation is **irradiance**, which measures the power associated with solar radiation per unit area (W/m^2).

[2] An irradiation map of Spain can be found in the following section

[3] Source:" The current development of photovoltaic solar energy in Spain " (UNEF) `http://bit.ly/2QG0i05`

crease that totally changes the trend presented in **??**. And the trend is even more evident if we analyze the latest data published by REE: as of **November 2019 the installed PV power amounted to 7,824 MW** compared to 6,255 MW in September. Thus, in the absence of December's data, **in 2019 they had been installed in Spain ! More than 3GW of solar PV power!**

These data are even more eloquent if we attend to the projects that have already requested the corresponding REE permits, in particular the access and connection permissions to the transport or distribution power grid. At **November 30, 2019** there are requests **with the access permission granted totaling 75.7 GW**, with an additional 28.2 GW with access management in progress and 55.2 GW with the request denied at the moment. **These data speak for themselves and reflect a very important change in the sector**.

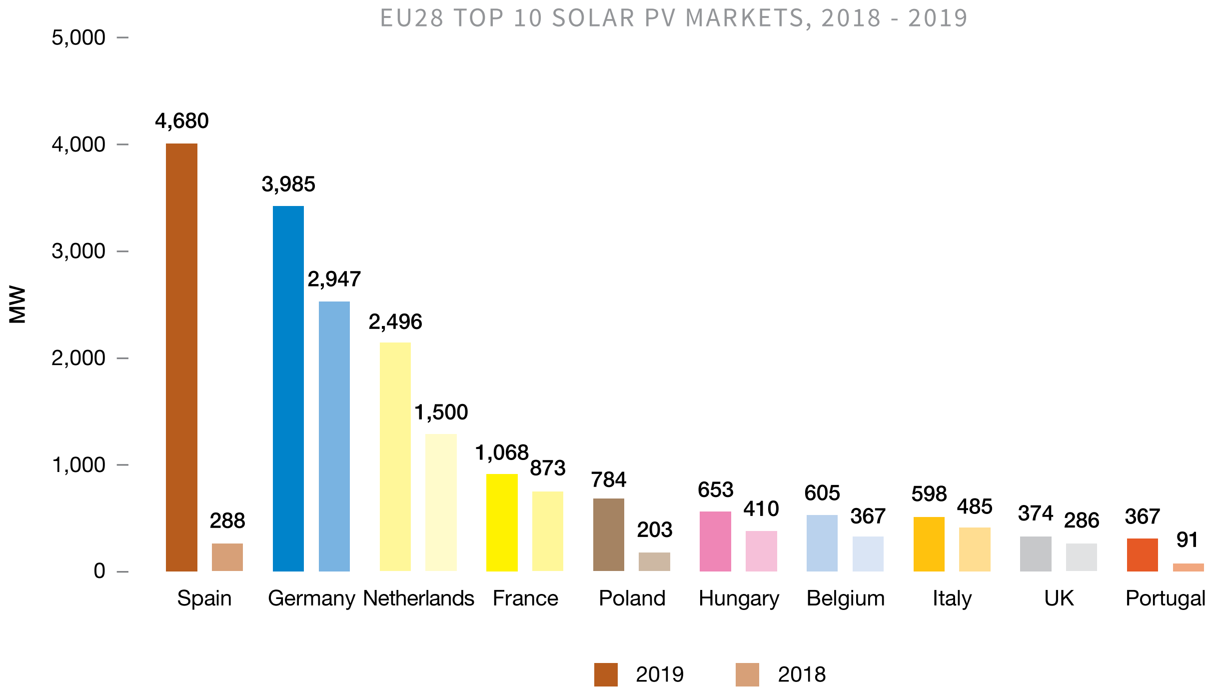


Figure 2.34. Top EU countries in terms of PV added capacity in 2018/19. Source: EU Market Ourlook for Solar Power 2019-2013 (Solar Power Europe). Link: `http://bit.ly/308c0cq`

The above data refer to installations connected to the grid, that is, large installations designed to inject all the electrical energy generated to the power grid for consumption by others, in the style of large conventional plants. As we will see, there are other types of PV installations (**self-consumption**) designed to consume locally (in a house, business, factory ...) the generated energy. In this area PV capacity has also increased, with some **300 to 400 MW new for self-consumption in 2019** according to UNEF forecasts.

The **explanation of this new situation in Spain** can be found in the following causes:

Power awarded in auctions as we have already commented, with for example 4,000 MW awarded in the July 2017 auction.

Increased activity of companies for the implementation of projects, not only associated with auctions, but also with facilities without additional market remuneration, which gives a clear idea of the current competitiveness of this technology (as previously commented regarding the LCOE).

Approval of Royal Decree-Law 15/2018 (RDL 15/2018) , (October 5)[1], *urgent measures for energy transition and protection of consumers* with a positive effect that is already being noticed and that has included the regulations for the definitive establishment of self-consumption in our country.

Indeed, to date there were a series of regulatory barriers that hindered the development of electricity consumption in Spain. Thus, RDL 15/2018 includes[2]:

1. administrative simplification of the bureaucratic and technical procedures required, as well as the registration in a register for installations up to 100 kilowatts.
2. the right to self-consumption shared by one or more consumers is recognized.
3. recognizes the right to self-consume electricity without tolls or charges, repealing the so-called "Impuesto al Sol" or self-consumption charges for the energy generated and consumed in your own facility.
4. RDL 15/2018 also includes provisions that have to do with tax regulations, whereby the measure is temporarily adopted to suspend the 7 % tax on the electricity generation, approved in 2012, for six months.

Question 4.1: Auctions

We have talked about auctions related to these new PV installations.

Look for information on how these auctions work in Spain, including how they are awarded and what possible advantages the winning companies have over facilities that decide to connect to the grid in a "normal" regime.

Question 4.2: PV plants in Spain

What is the largest PV plant in Spain in terms of capacity (nominal power)?

Are there any large-scale power plants close to Cantabria?

[1] Subsequently also approved Royal Decree 244/2019.

[2] Source: Study of the Macroeconomic Impact of Renewable Energies in Spain 2018 (APPA). Link: url http://bit.ly/2NfUGrO

2.4.2. PV Resource: Solar Radiation

Within the framework of renewable energies and, in particular in this case, of solar PV, it is important to take into account the availability of the **solar resource** (solar radiation or solar irradiance) at the chosen location. **Solar irradiance**, that can be defined as the incoming power of a given kind of electromagnetic radiation per square meter (or equivalent surface unit), will not be the same in Andalucia and Cantabria, for example. This is clearly shown in the map in Figure 2.35, where the annual average solar irradiance has been represented with a color map. As expected, irradiance in Spain is much higher than in Germany, for example. This factor should not be overlooked, as the same installation (e.g. a 10 MWp solar PV plant) will not produce the same amount of energy in Seville as it will in Berlin.

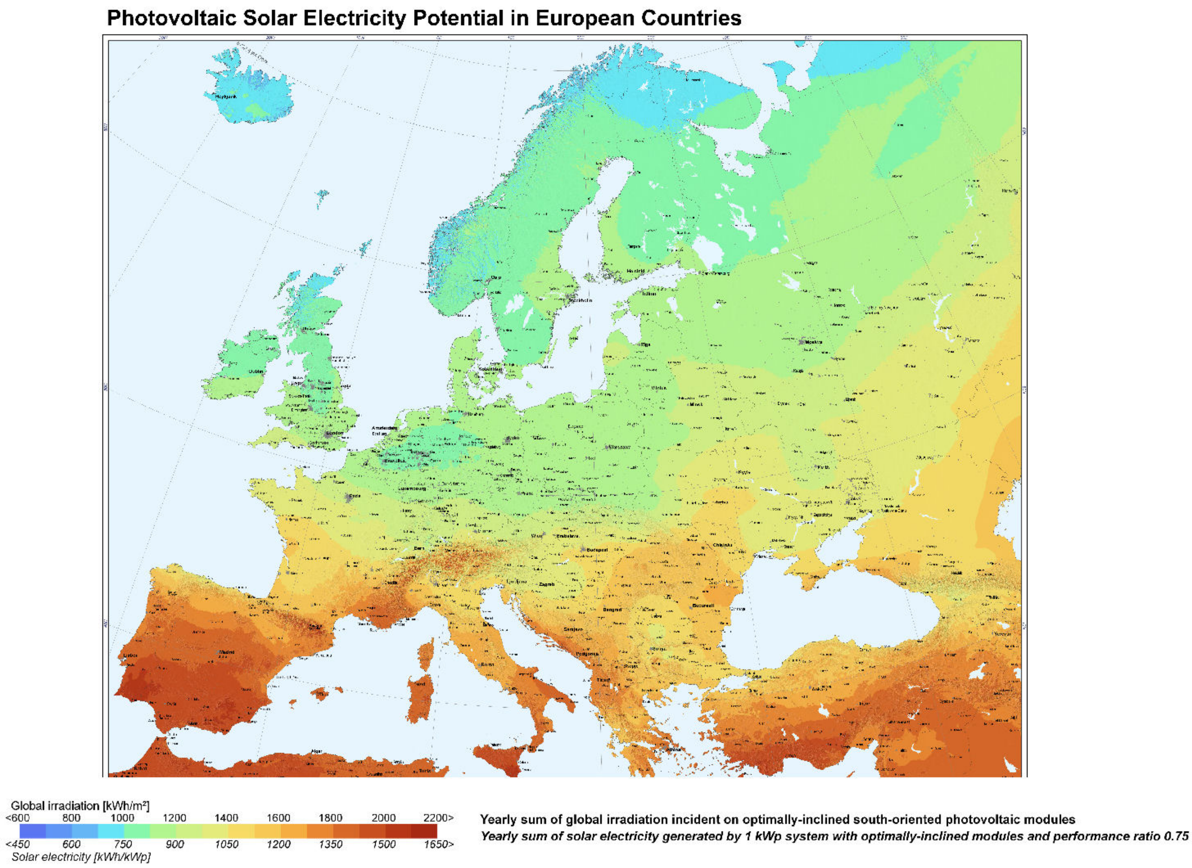


Figure 2.35. Solar resource (irradiance) in Europe. Source: PVGIS `http://bit.ly/2CaGXLZ`

Question 4.3: PV Estimation with PVGIS

PVGIS is an online tool developed by the Joint Research Centre of the European Commission, which enables retrieving geographical data of solar resource for solar installations, as well as studying their performance.

Using PVGIS (PV Estimation), estimate the production of a 10 MWp solar PV plant in Seville and in Berlin.

For Spain, in the detail map of Figure 2.36 we can see that the irradiance, as we know, is very different in the North or South of Spain. In fact, up to **5 zones are defined based on the average annual irradiance** received.

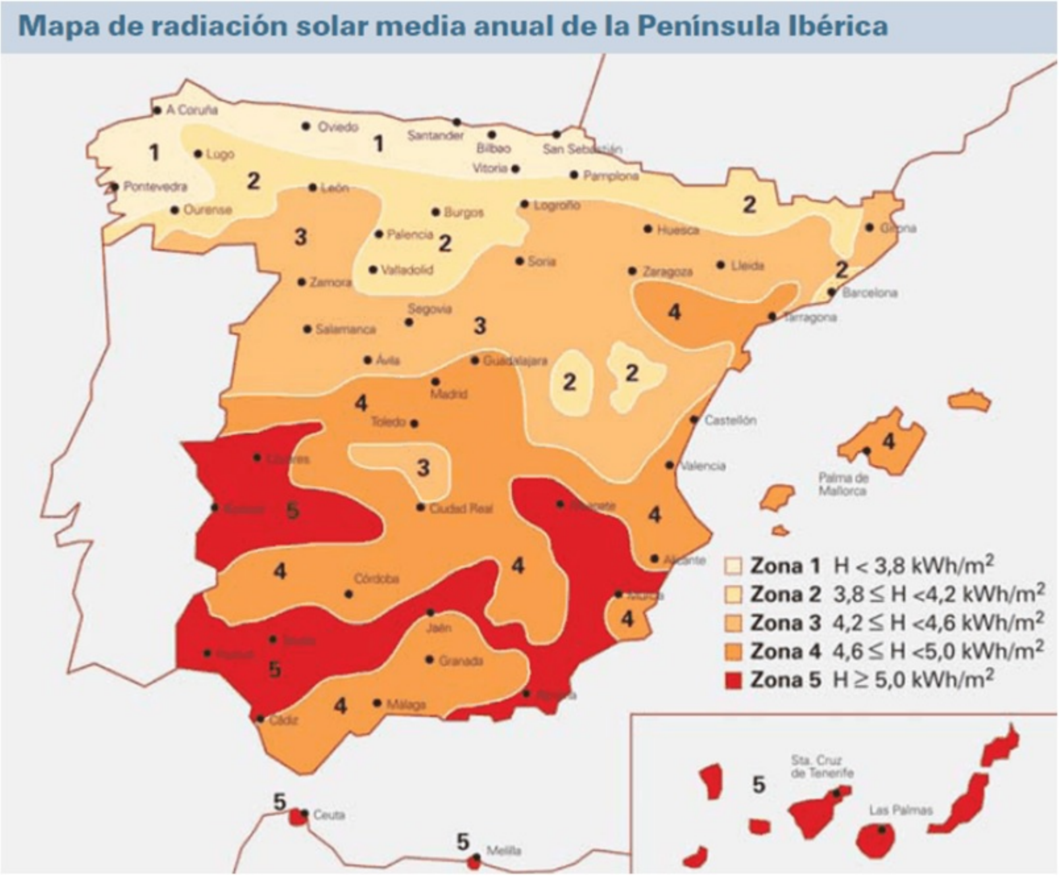


Figure 2.36. Solar radiation in Spain. Source: PVGIS `https://bit.ly/2CaGXLZ`

2.5. Solar PV Fundamentals: Photoelectric Effect and Solar PV Cell

Following this introduction on the solar PV framework, it is now time to describe the fundamentals that explain the working principle of a solar PV cell.

As already mentioned, a solar PV cell is based on the so-called photoelectric effect, discovered by Albert Einstein in 1904[1]

The **photoelectric effect**, represented in Figure 2.37, basically explains why some materials (e.g. silicon) are able to produce an electric current when radiated by a specific electromagnetic radiation. The features of this radiation are a key issue to understand the operation and **efficiency** (actual sticking point of PV technology) of a solar cell.

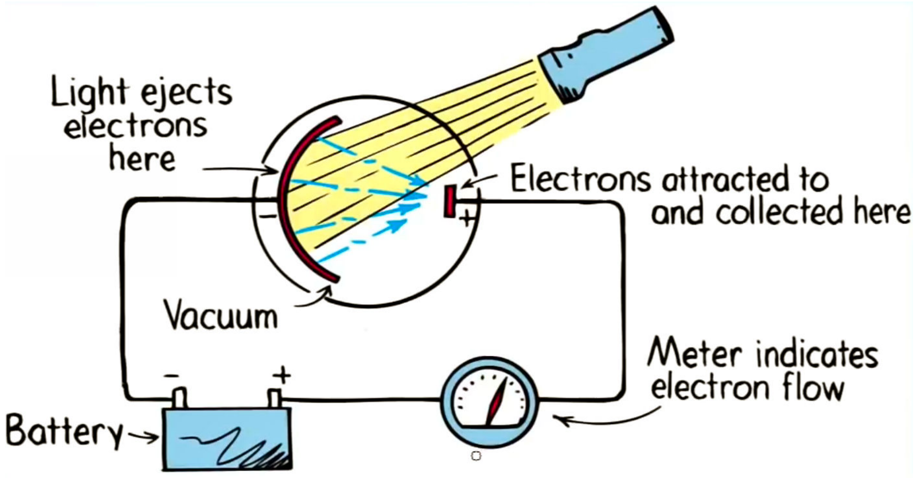


Figure 2.37. Schematic representation of the photoelectric effect. Source: Hewitt-Drew-it! PHYSICS 122. Photoelectric Effect (License: Youtube Standard) `http://bit.ly/2BGhEQV`

2.5.1. Solar PV Cell

A solar PV cell can be simply defined as a **PN junction** with a surface large enough to collect as many photons as possible[2].

We know that PN junctions are typically made of **Silicon (Si)**, but: why is Si the material of choice for building PV cells[3]? **Is Si the best material for this application?** The answer is clear: **NO!**

On the one hand, **Si is an indirect-gap material** (Figure 2.38), which means that a transition from the valence to the conduction band will be more complicated than in a direct-gap material (less likely, as represented in Figure 2.39, where the absorption coefficient of Si has been compared to other direct-gap materials, like Ge.). This has a direct influence on the thickness that solar cells need to achieve a given efficiency. To capture the same number of photons, direct-gap materials will only need a few microns of material thickness, while Si will a need much higher thickness, therefore more material,

[1] If you have just nodded your head ... please go back to the first sections of this chapter ;)

[2] This is a structure well-known by telecom engineers that is also used to build LEDs (Light Emitting Diode).

[3] At least up until now,: new materials are being researched in an attempt to produce higher efficiency solar PV cells.

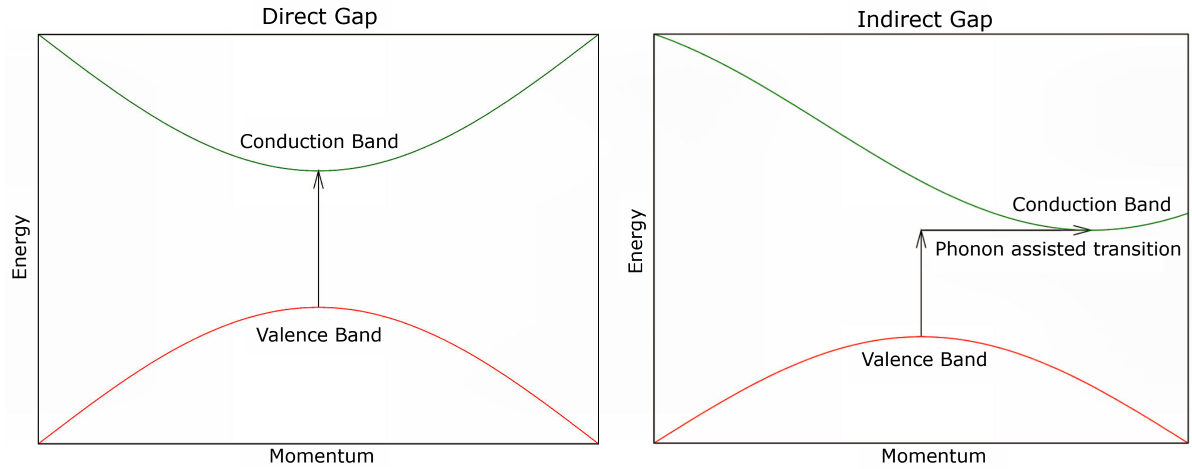


Figure 2.38. Elements with direct and indirect gaps. Source: `https://www.youtube.com/watch?v=7wF8Jm5Zhvk` (License: Public Domain)

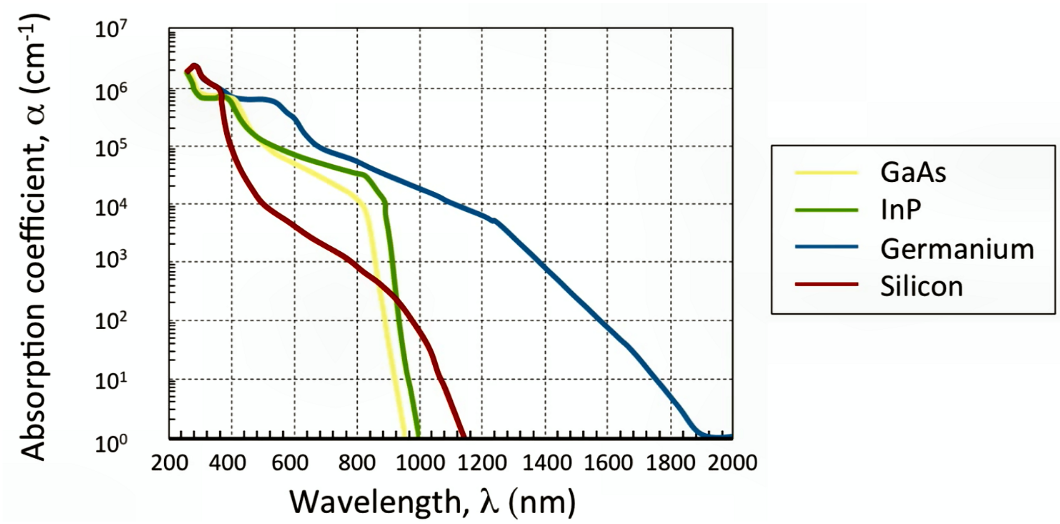


Figure 2.39. Absorption coefficients vs. wavelength for typical solar PV materials. Source: Curso EdX Solar Energy: 4.1. Properties of Crystalline Silicon. License: Creative Commons Attribution.

consequently involving a higher cost and weight[1].

Let's analyze this process of **photon absorption/emission** in more detail:

Interactions among particles (electrons, holes, photons, phonons ...) must observe the laws of energy and momentum conservation. The law of energy conservation implies that when an electron "falls" from the conduction band to the valence band, the energy lost in the process will be the same as the energy of the emitted photon (spontaneous emission of light). The law of momentum conservation implies that, if there is a difference in the momentums of the particles involved, this difference will have to be compensated for.

[1]Weight is a key factor in solar PV installations.

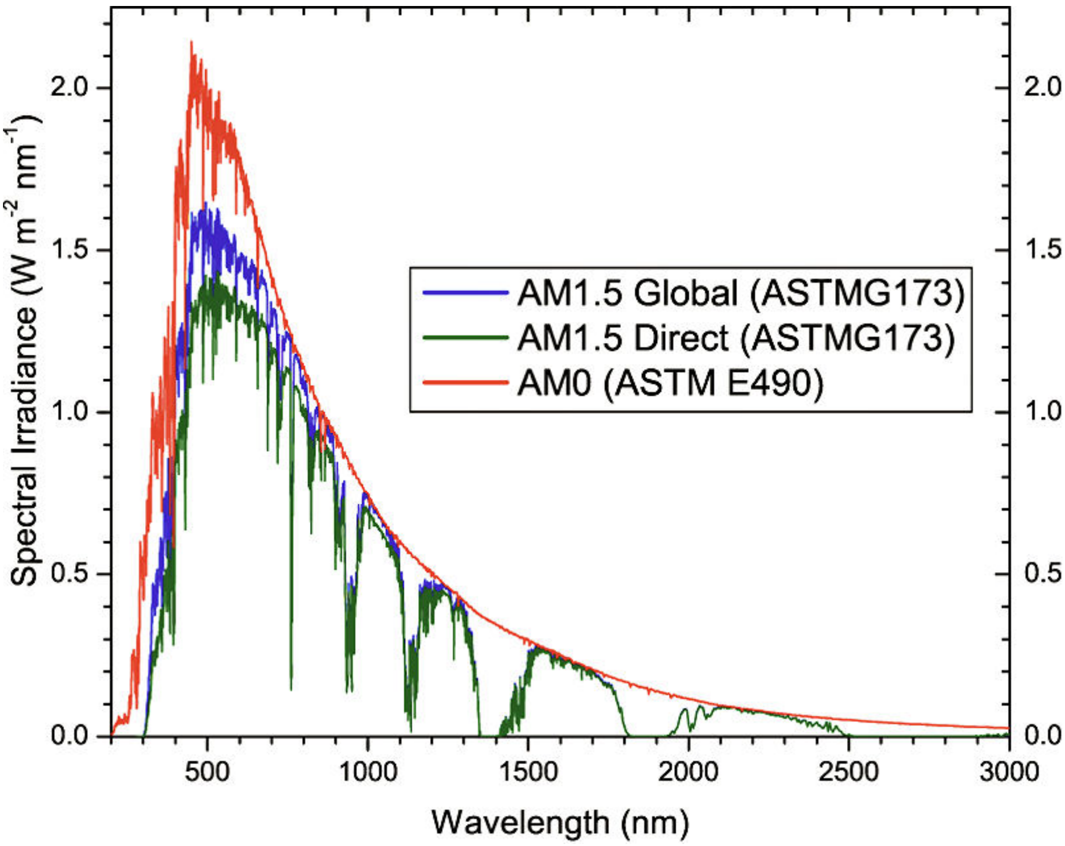


Figure 2.40. Spectral response of the Sun: AM0 standard (out of the atmosphere: e.g. for solar PV satellite applications) and AM1.5 Direct and Global standards (for thermal collectors and solar PV modules, respectively). Source: PVeducation `http://bit.ly/2EcG32u`

Direct Gap In a direct-gap semiconductor, the electron transition (from the valence to the conduction band (photon absorption) or viceversa (photon emission)) fulfills momentum conservation, given that the momentums associated with the maximum energy of the valence band and the minimum energy of the conduction band are the same.

Indirect Gap The situation is different in indirect gap semiconductors (e.g. Si) as there is a mismatch between these momentums. As photons do not have an associated momentum, the electron transition between bands in an indirect-gap material has to involve other particles, such as **phonons**[1]. As other particles are involved, these transitions are less likely (in comparison to direct-gap materials).

Apart from being an indirect-gap material[2], **Si** shows a **spectral response** that is **not optimal** in terms of the use/absorption of the solar radiation. The Si spectral response **only** goes up to **1.1 μm**, while the **solar spectrum** shows contributions at **higher wavelengths that can not be converted into electricity by a conventional Si solar PV cell**.

[1] Phonons are not real particles, but a perturbation on a set of atoms/molecules in solids or liquids.

[2] In fact, crystalline Si also exhibits a direct-gap transition with a gap energy E_{GAP} of 3.4 eV, thus associated with UV radiation.

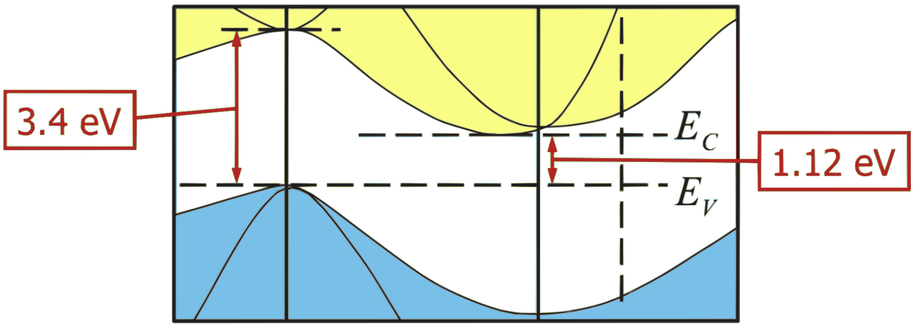


Figure 2.41. Crystalline-Si band diagram. Source: Course EdX Solar Energy: 4.1. Properties of Crystalline Silicon. License: Creative Commons Attribution.

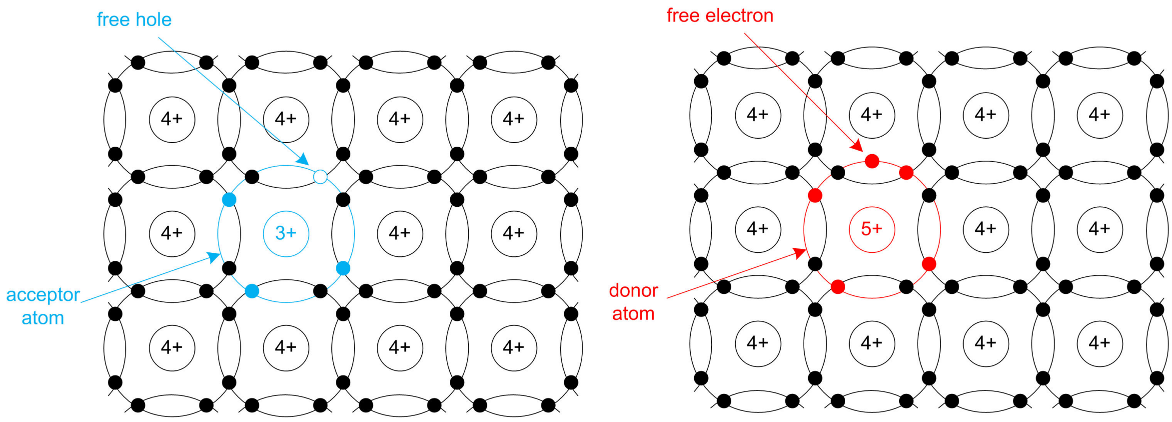


Figure 2.42. Crystal lattice formed by Si atoms: examples of p-type (left) and n-type (roght) semiconductors. Source: 2017 Electronic Circuits. `http://bit.ly/2EqZ1m5`

2.5.2. PN Junction

A solar PV cell is basically a PN junction with some special features. A PN junction is based on a semiconductor material, i.e. on a material able to carry an electrical current, but whose conductivity will depend on an external parameter like temperature.

It is worth noting that an atom is considered stable when its last orbit is complete, or it has at least 8 electrons (e-) there. Intrinsic semiconductors have 4 e- in their valence orbit: if many atoms come together (e.g. Si atoms) a crystal lattice is formed by means of the so-called **covalent bonds**.

A PN junction is obviously formed by the union of two (p-type and n-type) semiconductors (Figure 2.42). The p-type is formed with Si doped with an element with 3 e- (e.g. Boron B) in the valence layer, thus leaving a incomplete bond (the famous **hole**!). The n-type can be similarly generated, using in this case an element with 5 e- in the valence layer, like Phosphorus (P).

When the p and n semiconductors are put together (Figure 2.43), holes and e- will tend to diffuse to their opposite regions. When a hole and an e- meet in the process, they recombine and "disappear". This way, the n-type region loses e- (becoming more positive) and the p-type region loses holes (becoming more negative), thus generating a space charge region (or depletion layer). This space charge region (its electric field)

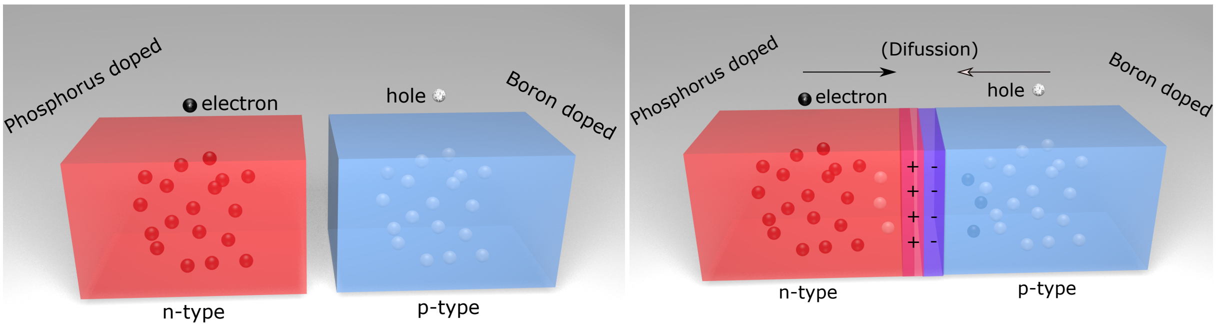


Figure 2.43. PN junction created with Si as base material dopped with p-type and n-type elements. Source: Jesus Mirapeix.

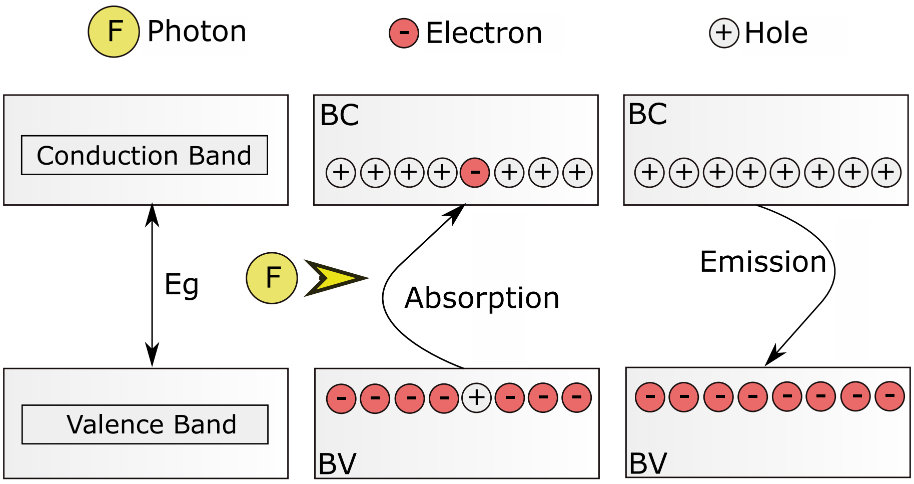


Figure 2.44. Absorption and emission processes in a semiconductor. Source: Jesus Mirapeix

opposes the diffusion process for both holes and e- (the positive potential of the n-type region opposes the holes coming from the p-side, and viceversa). Finally, the space charge region will prevent the diffusion process from going on, thus leaving equal concentrations on both sides. The potential of the space charge region in Si is of 0.5 V.

How is a photon absorbed in a semiconductor (Figure 2.44)? When a photon is absorbed by an atom, the energy associated with the photon is employed in lifting an e- from the valence to the conduction band. Obviously, the energy of the photon must exceed the energy gap of the material E_g, where the energy of the photon can be expressed as:

$$E = h\nu \Longrightarrow E = \frac{hc}{\lambda} \tag{2.2}$$

In this equation h is the Planck constant, ν the frequency of the photon and λ its wavelength (c is the speed of light in empty space (vacuum)).

How does the photoelectric effect take place in a solar PV cell? (Figure 2.45) If a photon with a suitable energy reaches the depletion layer of the cell (to facilitate this a thin n-type region is needed) and is absorbed by an atom, this will give rise to an **e-/hole pair**. The electric field enables the transition of the e- to the n region (hole to p

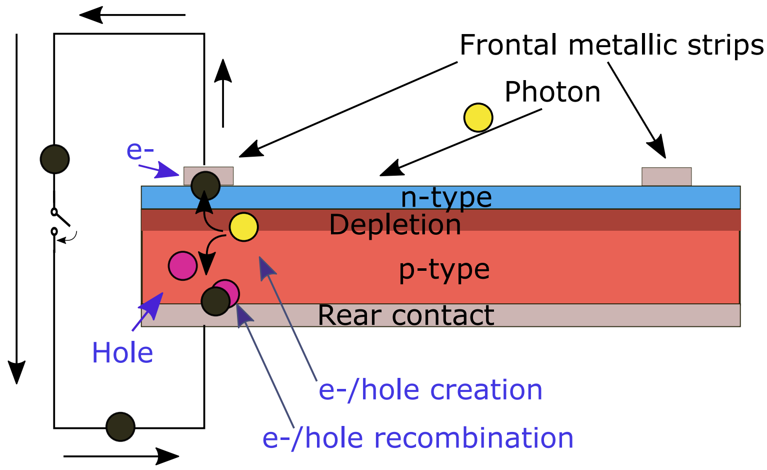


Figure 2.45. Schematic representation of PV cell operation. Source: Jesus Mirapeix

region). If there are metallic conducting strips attached to the cell, the e- will circulate, being attracted by the p region and enabling an e-/hole recombination, coming back to the original state of the system.

Now we know the basics of solar PV cells. Even if it seems obvious, it is worth noting that the photoelectric effect has **dynamic** behaviour, i.e. it is able to generate electricity under certain given circumstances, but it will not enable the storage of energy. To do that, a battery will be needed.

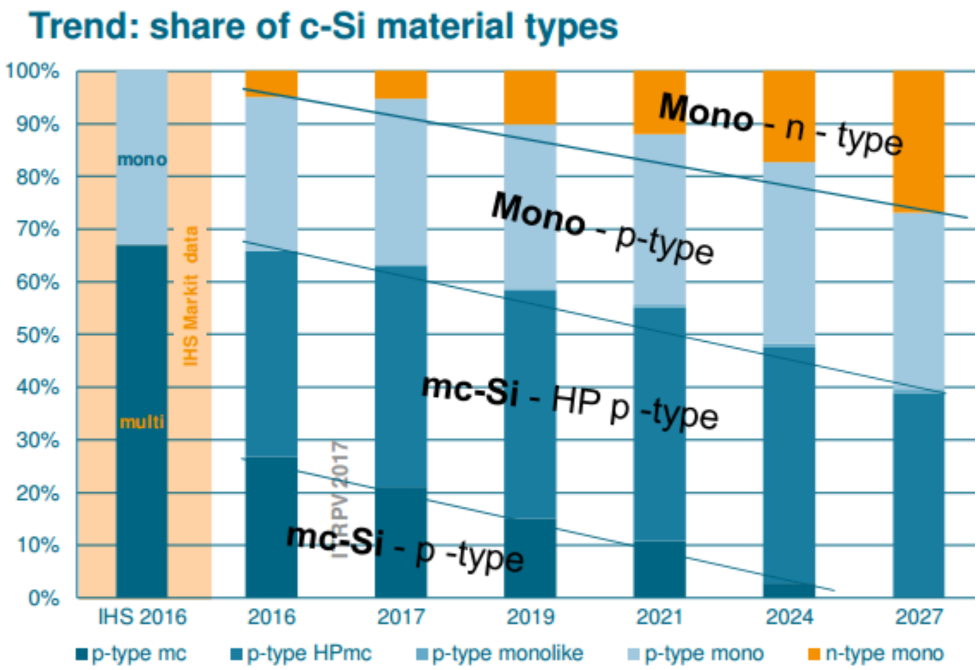


Figure 2.46. Forecast of the evolution of PV solar cells by crystalline Si material types. Source: aleo-solar.com `http://bit.ly/2Gx2YK1`

Important! 5.1: p and n-type solar cells

Even if the very first solar cell was **n-type**, **p-type**, as the one shown in Figure 2.45 cells have clearly dominated the PV scenario for decades. **p-type solar cells are built on a positively charged silicon base**, being the wafer doped with boron. n-type solar cells are built the other way around, i.e. with a n-type doped side acting as the basis of the solar cell.

p-type cells took the lead of the market due to their better resistance to radiations for space applications, which dominated the PV scene in the early days. After that, economies of scale set the evolution of these technologies.

However, it seems that **n-type cells (mainly mono) are starting to be relevant due to its improved efficiency and immunity to the light-induced degradation effect** (see Figure 2.46). This is mainly due to the absence of boron, which recombinates with oxygen damaging efficiency and performance.

2.5.3. How do photons interact will a solar PV cell?

Not all the photons coming to the Earth's surface as part of solar radiation can be used[1] to produce electricity in a solar cell. We have seen the Sun's spectrum in Figure 2.40, but it is also important to also know the **Si spectral response** (Figure 2.47). As can be observed, the Si spectrum comes up to around **1100 nm**, with an associated gap energy of E_{GAP} = **1.12eV**.

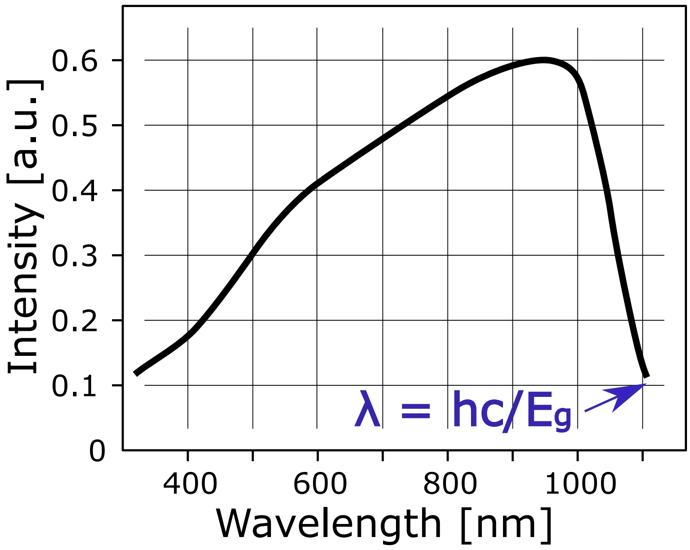


Figure 2.47. Si spectral response. Source: `http://bit.ly/2lyIsvM`. License: CC-BY-SA 3.0

Equation 2.2 (above) indicates that this wavelength is related to the gap energy so, what will happen if:

[1] At least by current conventional PV technology.

$E_{FOTON} < E_{GAP}$ If the energy of the incoming photon is lower than the gap energy, no interaction will take place and the photon will go through the solar cell.

$E_{FOTON} = E_{GAP}$ This is the ideal situation: the photon is absorbed and it will free an e- that will contribute to the total electric current.

$E_{FOTON} > E_{GAP}$ The photon will be absorbed, but the excess energy will be released as heat. This is an undesirable effect that can compromise the cell performance.

2.5.4. Solar PV Cell: Efficiency

The efficiency of a solar PV cell is a key concept for any PV technology: How is this parameter defined? This is very simple, PV efficiency can be defined as the **ratio of the electricity produced in terms of the energy derived from the solar radiation**.

$$Efficiency(\eta) = \frac{Power(electrical)(W)}{Irradiance(\frac{W}{m^2}) \cdot Surface(m^2)} \tag{2.3}$$

It is then necessary to measure the electrical power generated by the PV cell/module (watts), as well as the solar irradiance[1] (watts/m^2), considering the surface of the cell/module (m^2).

Current PV commercial technologies exhibit efficiencies of around **14 to 18 % (crystalline-Si)**, although other experimental technologies have achieved much higher efficiencies (60 %), but with costly procedures that prevent their mass production.

The next question that comes to our minds is: why is this PV efficiency so low?

Let's see the different factors that limit it:

0.5 % Series resistance

3 % Reflection and shadow provoked by the metallic strips

8.5 % Recombination losses

20 % Potential barrier

23 % Low-energy photons (IR photons)

32 % High-energy photons (UV photons)

Improving these figures with conventional crystalline-Si technology has proved to be a very complex task. On the one hand, losses due to the series resistance and the metallic strips are interrelated. If the strips surface is diminished, more photons will reach the n-type region, but the series resistance will increase. On the other hand, the Si spectral response limit the amount of photons that can be converted intro electricity. Finally, recombination and potential barrier losses are intrinsic to the PN junction and, consequently, very difficult to overcome.

[1] Solar irradiance can be measured with a pinarometer: https://es.wikipedia.org/wiki/Piran%C3%B3metro

Solar PV Cell: Structure

The “main core” of a solar cell, the so-called PV laminate, is the PN junction. However, there are more elements that form a commercial PV cell (Figure 2.48).

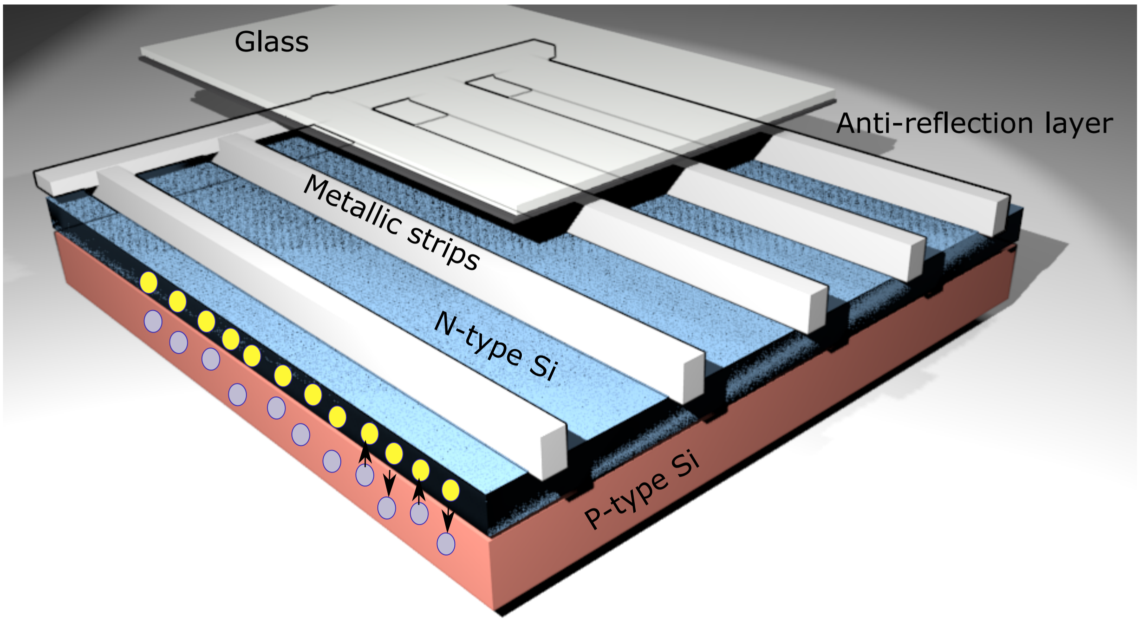


Figure 2.48. Schematic representation of the structure of a solar cell. Source: Jesus Mirapeix.

Glass layer The glass layer is used to protect the PV laminate (the PV cells). Special attention must be paid to the optical properties of the glass, given that its transparency is fundamental for achieving a maximum efficiency. There are some types of glass and polymers whose optical properties can become degraded over time. Solarization, for example, is a physical phenomenon that gives rise to this loss of transparency.

Anti-reflection layer Anti-Reflection Coatings (ARC) are typically used to avoid the reflection of photons in the PV cell.

Metallic strips They are necessary for conducting the electricity from the PV cells/panels to the devices/grid where it will be used.

Question 5.1: Solarization

You will find a very good example of solarization in the “Edificio I+D Teleco” building of the University of Cantabria. On the 2nd floor, where the offices of the Photonics Engineering Group are located, there is a corridor with several posters of scientific contributions made by the group. Look at these posters and see if you can find anything related to **solarization**.
Look for a physical explanation of this process and explain it **in your own words** using the pictures of the above-mentioned posters as an example.

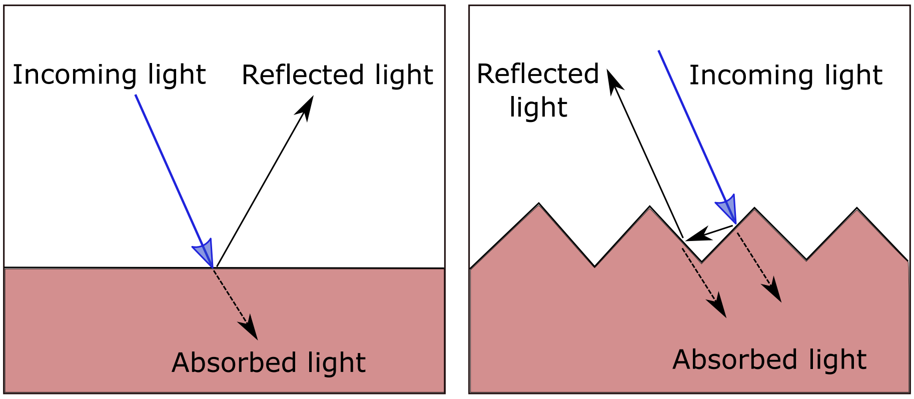


Figure 2.49. Texturized front layer of a solar PV cell. Source: Jesus Mirapeix.

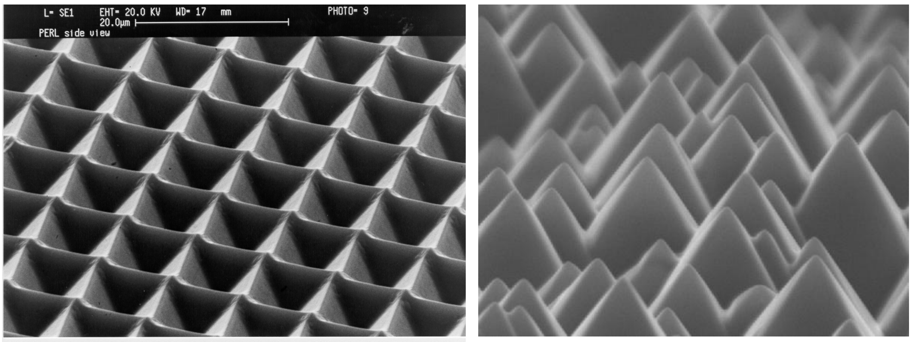


Figure 2.50. Examples of texturized solar PV cells: inverted pyramid (left) and pyramid (right). Source: `http://bit.ly/2F61VvW`. Images by The School of Photovoltaic & Renewable Energy Engineering, University of New South Wales.

Texturization is another key concept in PV technology (Figure 2.49). It is based on giving a certain texture to the front side of the cell, for example with normal or inverted pyramids (Figure 2.50). Its goal is to maximize the likelihood of photons being absorbed by forcing more than 1 interaction on those photons that are initially reflected. At this point it is worth pointing out that, when particle interactions are under analysis, Quantum Physics/Mechanics comes into play, where different events such as photon absorption, e- transitions and so on will be modeled as probabilities.

2.5.5. PV Technologies

There are different **PV technologie**s classified in terms of the materials used to build the PV cell. First of all, they all divided into cells based on **semiconductor wafers and thin film cells**.

The former constitutes the so-called **1st generation** of PV cells, clearly dominated by **crystalline-Si technology** (mono and poly-crystalline), with share of approximately 90 % of the global market.

Thin film technologies are used in **2nd to 3rd generations**. The former is based on conventional technologies, with amorphous silicon, CdTe, CIGS (Copper Indium Galium Diselenide) and CZTS (Copper Zinc Tin Sulfide) cells.

3rd generation solar cells are emerging thin-film technologies such as dye-sensitized, Perovskite[1], organic or quantum dot cells.

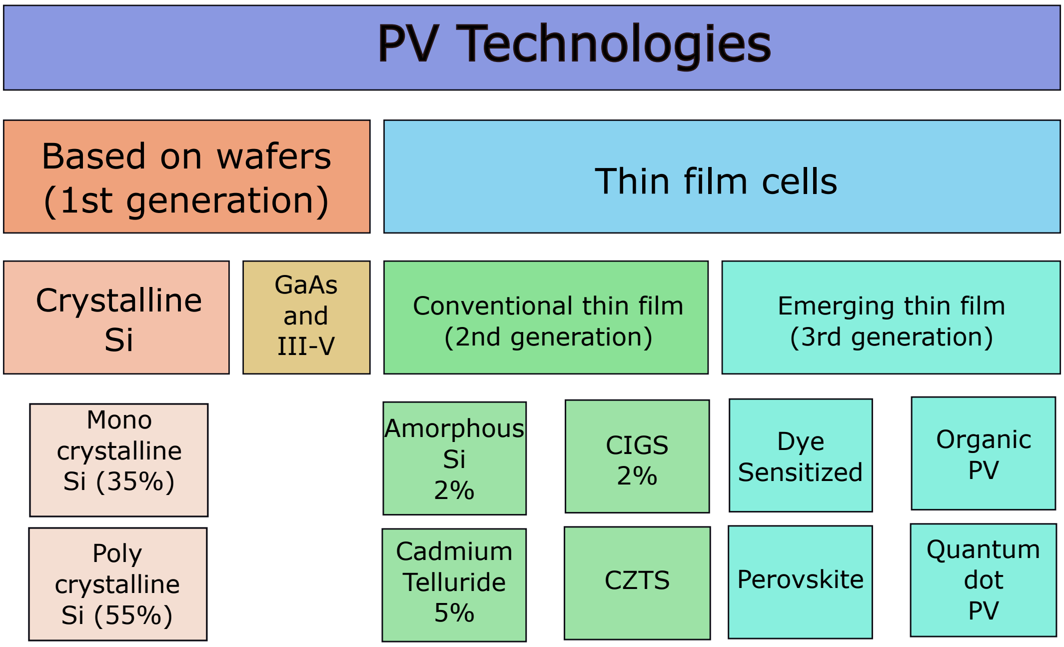


Figure 2.51. PV technology classification (% indicates market share). Source: Jesus Mirapeix.

A PV technology can be evaluated attending to different factors, such as:

Efficiency This key parameter has already been defined. Of course, new technologies attempt to obtain higher efficiencies for commercial purposes.

Stability Some technologies exhibit degradation over time, for example due to exposure to UV solar radiation.

Manufacturing cost This is a key factor when it comes to technologies suitable for mass production. Some technologies have got really high efficiencies (up to 60 %), but if their cost is too high, they are not suitable for commercialization.

Sustainability Some materials used for PV technologies may impose a environmental risk. In this regard, technologies without these disadvantages, like organic cells, are more likely to be successful.

As can be observed, the market is 90 % dominated by crystalline-Si. It is also worth noting that, although poly-crystalline Si has increased its market share in recent years due to an improvement in its efficiency and a reduction in its manufacturing costs, **current forecasts predict an increase in the market shares of mono-crystalline modules**.

2.5.6. PV Technologies: crystalline Si

Mono-crystalline Si has a slightly higher quality than poly-crystalline Si. In terms of the associated efficiency the former can deliver up to ≈ 18 % (for commercial cells/modules),

[1] More info on Perovskite solar cells on this article: `http://bit.ly/2ngUtYr`

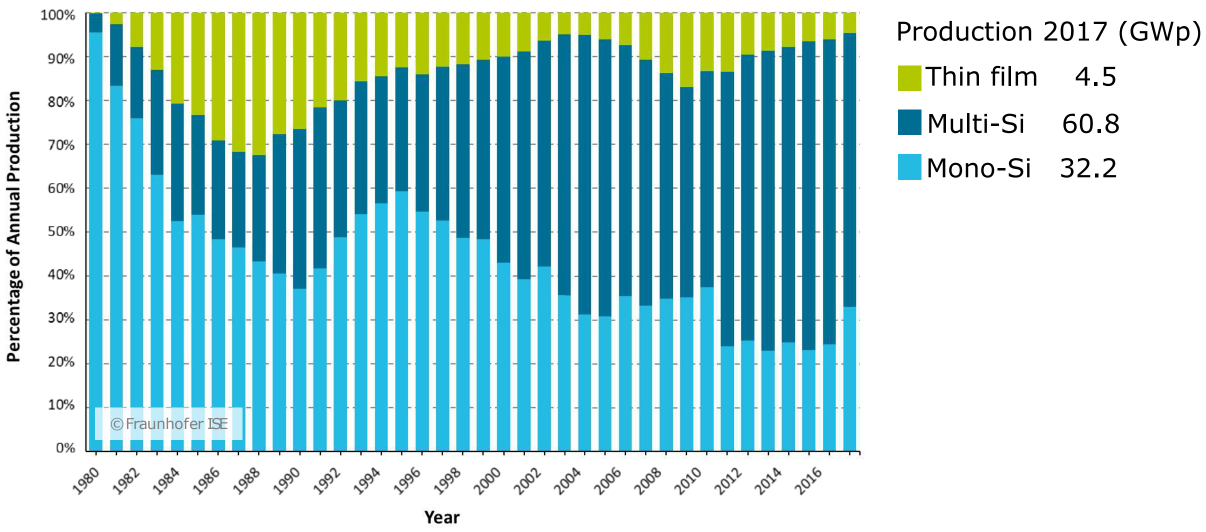


Figure 2.52. Production of PV modules according to technology up to the year 2017 (Source: Fraunhofer Institute for Solar Energy (Photovoltaics Report). Original image modified.).

while poly-crystalline may offer a maximum of 14 %.

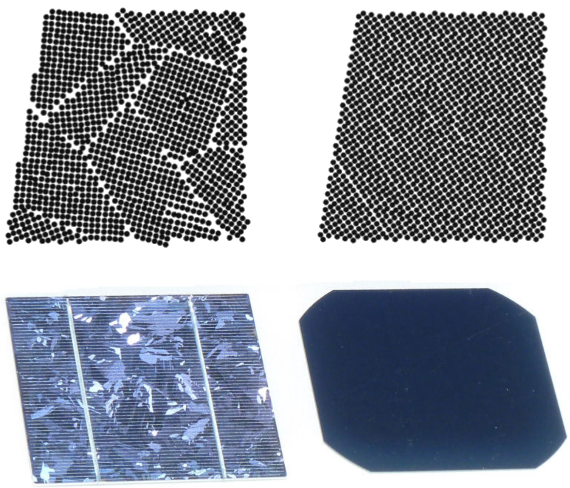


Figure 2.53. Comparison of a poly-crystalline (left) and a mono-crystalline (right) PV cell. Source (bottom image): `https://bit.ly/2JGaTT1`. License: original image by Klaus Mueller (CC BY-SA 3.0). Source (top image): Course EdX Solar Energy: 4.1. Properties of Crystalline Silicon. Licencia Atribución de Creative Commons (re-use allowed)

The simplest way of telling what kind of crystalline panel are we looking at is by means of a visual inspection (Figure 2.53). Mono-crystalline cells show a uniform black color, whereas poly-crystalline cells exhibit a non-uniform blueish color, where the formation of different "crystals" can be appreciated. These differences arise from the different manufacturing processes, where mono-crystalline Si comes from a higher quality material.

How are crystalline-Si cells manufactured? Although due to the limitations of the course the manufacturing processes of the different PV technologies will not be studied, we will briefly analyze the fabrication of crystalline-Si cells due to their relevance in the market.

The silicon needed for the PV cells has to go through several processes in order to reach the required quality standards. The first level is known as **metallurgical-Si**[1]. Only a 1 % is used to obtain **solar-grade Si** (also known as electronic-Si) and it is derived from quartz (SiO_2) by heating it up to 900°C. The resulting Si exhibits a purity of around 98 or 99 %.

Poly-silicon ingots (**with a purity of 99.9999 %**) can be obtained from this metallurgical-Si. The required processes imply the use of gases such as HCl at high temperatures to purify the Si, for example via Chemical Vapor Deposition (CVD)[2].

The mono-crystalline ingots can be obtained by means of the Czochralski or the floating-zone methods. In both cases, the Si is melted to obtain an ingot with a crystal oriented in one direction. To generate a poly-crystalline ingot several crystals are melted, giving rise to a standard ingot of 70x70x25cm.

Once the ingots have been created, it is time to produce the **wafers**. **Very precise cutting processes** are required, as the average thickness of a crystalline-Si wafer is around 150 to 200 μm, and for each manufactured wafer around 100 μm of material has to be discarded. After the cutting, other processes such as smoothing, texturizing, etc. take place.

2.5.7. PV Technologies: Thin film (2nd generation)

Figure 2.54. Thin film PV installation. Source: Fieldsken Ken Fields (CC BY-SA 3.0). http://bit.ly/21A2plW.

Thin film cells have a much lower thickness than crystalline-Si cells, around 5μm. This implies low weight and even flexibility in some cases, although their efficiency is

[1] About 70 % of metallurgical-Si is employed in the automotive sector

[2] It is important to note that this processes that imply high temperatures are associated with a high cost in terms of the energy required. More info on the CVD process: http://bit.ly/2ckESiE.

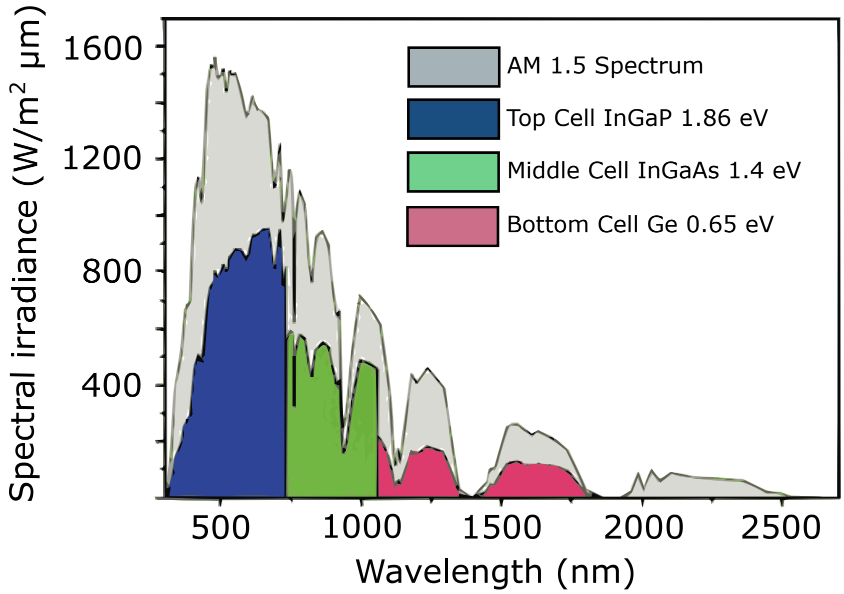


Figure 2.55. Spectral response of a multi-junction thin film PV cell.Source: (CC BY-SA 3.0). `http://bit.ly/21wSyy9`

also lower than the provided by crystalline-Si (an average of 6-8 %). There are several categories for thin film cells, depending on the chosen material: amorphous silicon (a-Si), cadmium telluride (CdTe) or copper indium gallium selenide (CIS or CIGS). Some of these materials are not environmentally friendly, which is a clear disadvantage.

One main advantage of thin film technology lies in the possibility of designing cells with more than one semiconductor material, the so-called **multi-junction solar cells**. This way, PV efficiency can be improved if the spectral response is tailored to obtain a wider spectral range, thus increasing the number of photons that can be converted into electricity. This idea has been illustrated in Figure 2.55, where InGaP, InGaAs and Ge PV laminates have been used.

2.5.8. PV Technologies: Thin film (amorphous-Si)

Within thin film technologies, a few lines will be devoted to amorphous-Si (a-Si). Although it has been used for years, its market share has decreased to 2 %.

The manufacturing process is completely different from the one used for crystalline-Si cells. Gas Si is deposited onto the chosen substrate, thus requiring much lower temperatures and involving a much simpler process. Obviously, the associated costs are significantly reduced.

The a-Si crystal lattice is not organized: it grows randomly. As a result, a-Si does not exhibit an indirect gap structure, but a direct gap, enabling an improved photon absorption. Figure 2.56 shows this effect, with an improved absorption of a-Si especially for the photons in the visible region.

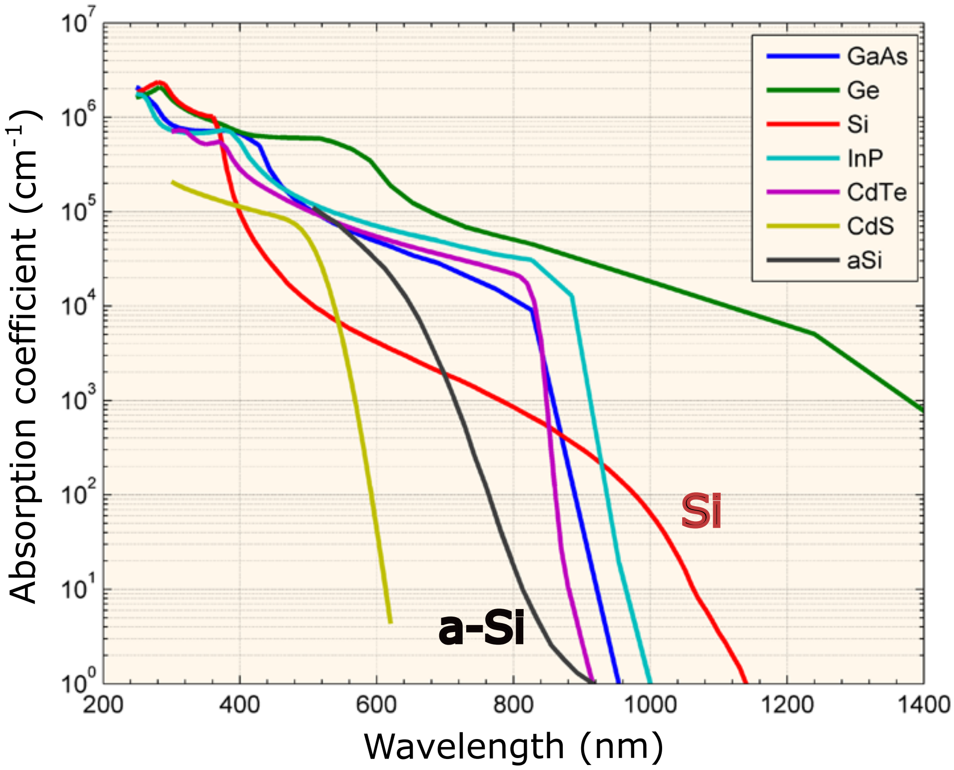


Figure 2.56. Absorption coefficient for different semiconductor materials. Source: `http://bit.ly/21xppTo`

Important! 5.2: Absorption Coefficient

The absorption coefficient determines how much the light will penetrate into a given material in terms of its wavelength. A material with a low absorption coefficient and a small thickness will imply a low probability of photon absorption.

Question 5.2: Absorption Coefficient

Figure 2.55 shows that there is a sharp drop in the absorption coefficient profiles for a given wavelength. On the other hand, the value of the coefficient is not constant for photon energies higher than E_{GAP}. Explain these phenomena **in your own words**.

The main features of a-Si cells will be revised in Table 2.1.

The **main disadvantages of a-Si** are its **lower efficiency** and its **shorter lifetime**. The latter is due to the degradation of the PV laminate with solar exposure, especially during the first few months of operation. All in all, this is a suitable technology, not only for its **lower price**, but also for locations where **shadows** can not be avoided or **diffuse**

Table 2.1. Advantages and disadvantages of a-Si technology

Advantages	Disadvantages
More simple manufacturing process	Lower efficiency (6-8 %)
Lower fabrication costs	Shorter lifetime (PV cell degradation)
Lighter PV cells	
Suitable for locations with diffuse radiation or shadows	
Better temperature response	

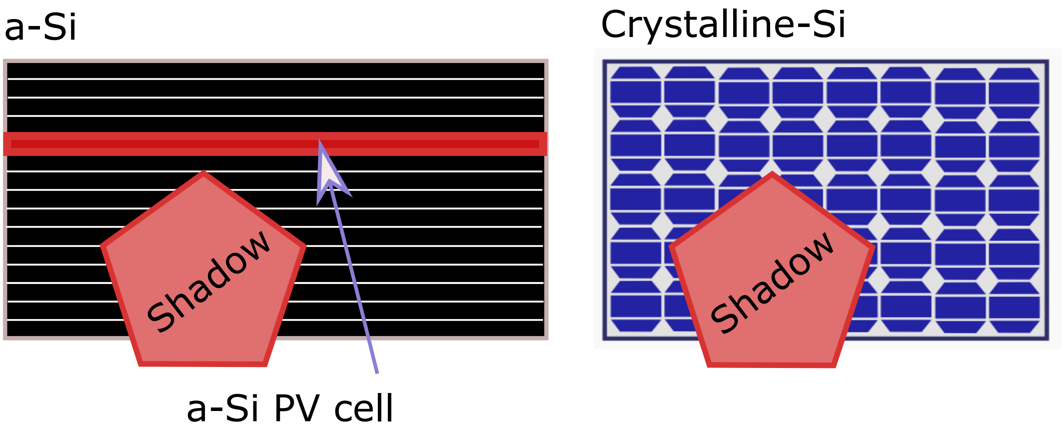


Figure 2.57. Shadowing with a-Si and crystalline-Si modules. Source: Jesus Mirapeix.

radiation[1] dominates.

Given the cell disposition in the a-Si modules, it is more difficult to completely shade a whole cell, which gives rise to an improved performance when shadows are projected on the panels[2]. This situation has been depicted in Figure 2.57, where it can be observed that it is easier for a shadow to completely cover a whole cell in a crystalline-Si module than in a a-Si panel[3].

2.5.9. PV Technologies: 3rd Generation (Organic Cells)

Within the **3rd Generation** "family", **organic cells** constitute a very interesting and promising technology. An organic solar cell, as shown in Figure 2.58, is formed by ***organic electronics*** that enable the generation of electricity by means of the photoelectric effect. Organic electronics is based on the employment of conducting organic polymer materials or small organic molecules. Organic refers to the carbon content of these materials, for example *henyl-C61-butyric acid methyl ester* ($PC_{61}BM$).

One of the main advantages of this technology is its viability for being mass-produced at very reduced costs, using for example printing technologies. Additionally, molecular engineering allows modifying certain characteristics such as the band-gap, which can be of great interest for improving the resulting cell efficiency. These materials are, in general, optimal in terms of light absorption.

[1]Diffuse radiation is provoked by clouds, while direct radiation refers to clear skies.

[2]Shadows should always be avoided in a PV installation, but there might be some situations (trees, power lines, chimneys) where this can not be prevented

[3]In an a-Si module like the one shown in the figure, a cell is a strip whose length is equal to the panel width.

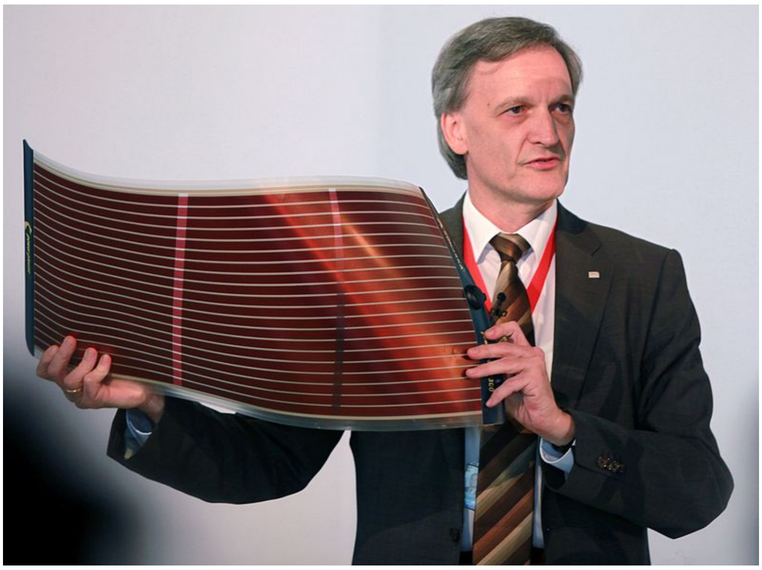


Figure 2.58. Organic solar PV cell. Source:`http://bit.ly/2ASKYX0`. License: CC BY-SA 3.0

As current disadvantages, low efficiency, low stability and reduced durability should be mentioned.

PV Technologies: Comparative

An overview of the main aspects related to PV technologies has been provided in the previous sections. In order to understand these main concepts, the following table summarizes them in terms of **efficiency**, **stability**, **production costs** and **sustainability**.

Table 2.2. PV Technologies: Comparative and Conclusions

Cell Type	Efficiency	Stability	Production Costs	Environmental Impact
Mono-crystalline Si	Very High	Excellent	Very High	Medium-Low
Poli-crystalline Si	Very High	Excellent	Medium	Medium-Low
Amorphous Si (mono-junction)	Low	Very Low	Low	Medium-Low
Amorphous Si (multi-junction)	Low	Low	Low	Medium-Low
III-V Materials	Very High	Excellent	Super-High	Potentially High
Thin film (other compounds)	Medium	Good	Low	Potentially High
Organic Cells	Low	Low	Potentially Low	Very Low

Environmental impact (sustainability) has been included in the Table 2.2, given that some technologies use compounds such as CdTe or InGaAs that may have an impact on the environment when being removed and recycled. These factors, not previously taken into account as PV technologies were just emerging, are now starting to be seriously considered within the PV sector.

Undoubtedly, the main goal of the PV industry is to improve cell efficiency at reasonable production costs. Research efforts are therefore being focused on overcoming the efficiency limit imposed by crystalline technologies. Figure 2.59 shows the highest efficiencies achieved with commercial cell/modules and Figure 2.60 presents efficiencies that have been measured in laboratories (non-commercial prototypes).

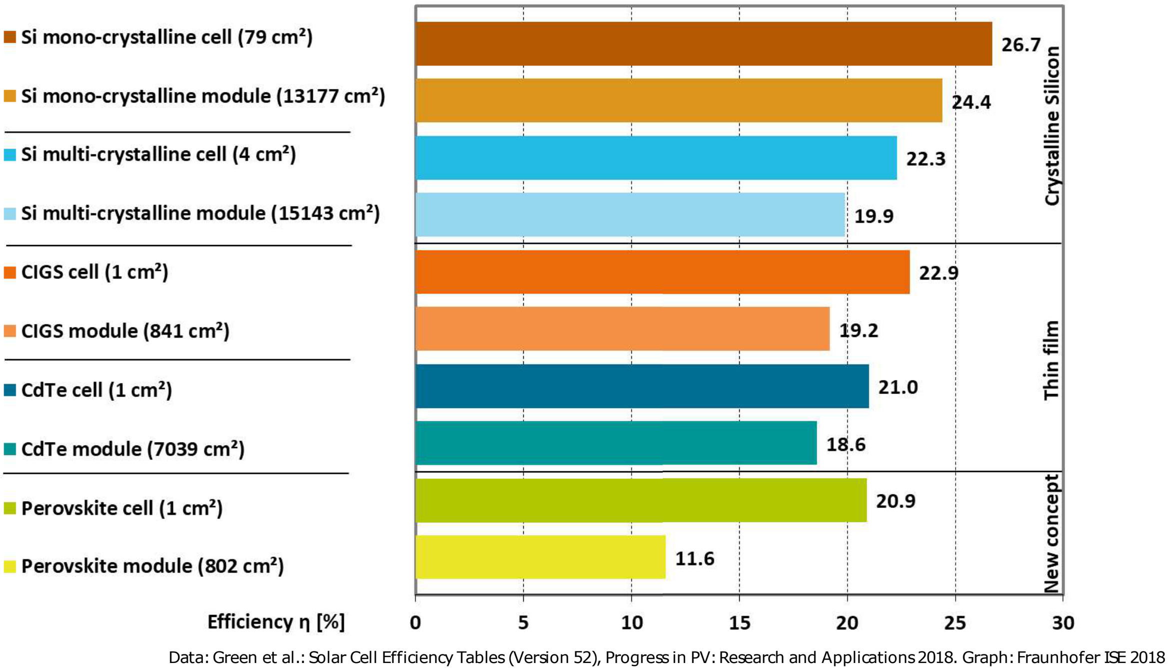


Figure 2.59. Efficiency associated with the main PV technologies. Source: Fraunhofer Institute for Solar Energy (Photovoltaics Report)/Data: Green et al.: Solar Cell Efficiency Tables (Version 52), Progress in PV: Research and Applications 2018.

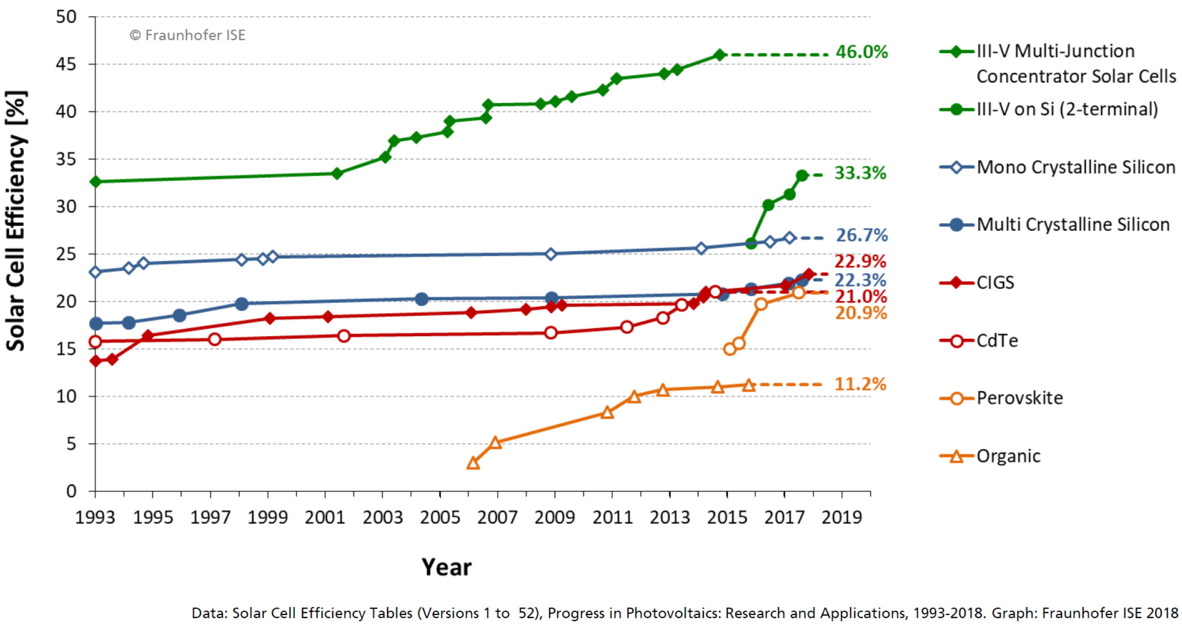


Figure 2.60. Efficiency evolution of PV technologies (laboratory prototypes). Source: Fraunhofer Institute for Solar Energy (Photovoltaics Report) / Data: Solar Cell Efficiency Tables (Versions 1-52), Progress in Photovoltaics: Research and Applications, 1993-2018. Graph: Simon Philipps, Fraunhofer ISE 2018.

2.6. Characterization of PV Cells and Modules

We have looked at the working principle of a solar PV cell in the previous sections. It is now time to see how a PV module/panel[1] is built and its main electrical features, temperature response and so on. This section describes the first stage for correctly designing a PV installation.

2.6.1. PV modules

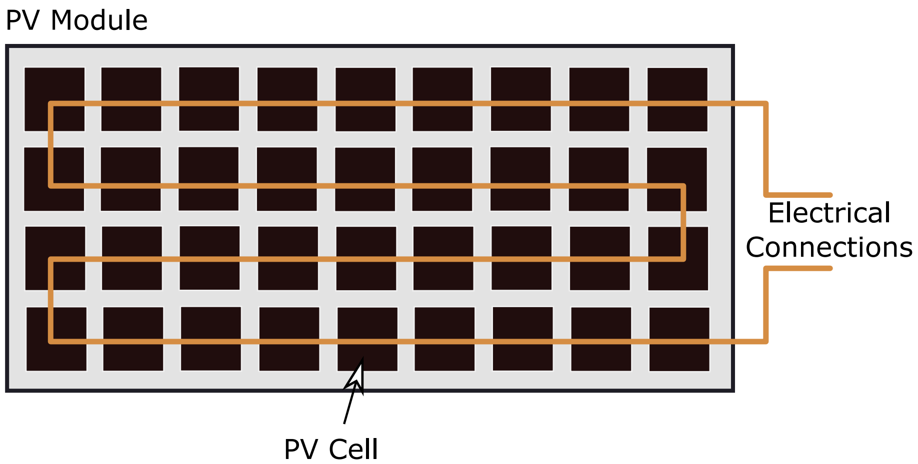


Figure 2.61. PV module with cells connected in series.

A solar PV module is usually formed by PV cells connected in series (see Figure 2.61). Although there are many possibilities, a standard crystalline-Si PV module could be the one shown in the figure, with 36 cells connected in series.

What will be the voltage at the electrical connectors of the panel? In this case $V_{PANEL} = 36 \cdot V_{CELL}$.

It is also common to find configurations with groups of cells (strings) arranged in parallel, e.g. 2 strings in parallel with 18 cells connected in series (each string). At this point, it might prove interesting to try to find out the current that will be delivered by the panel: Will the same current go through all the cells? Will there be deviations even if all the cells belong to the same model? We will answer these questions in the following sections.

2.6.2. PV Modules: Structure

Apart from the PV cells and their connections, a solar PV module is formed by the following elements:

Aluminium Frame It covers the module perimeter, providing mechanical protection. Its behaviour in terms of outdoor protection should be optimal[2]

[1] Module and Panel will be equally used during the following sections.
[2] The average estimated lifetime of a solar panel is about 20 to 25 years, depending on the manufacturer.

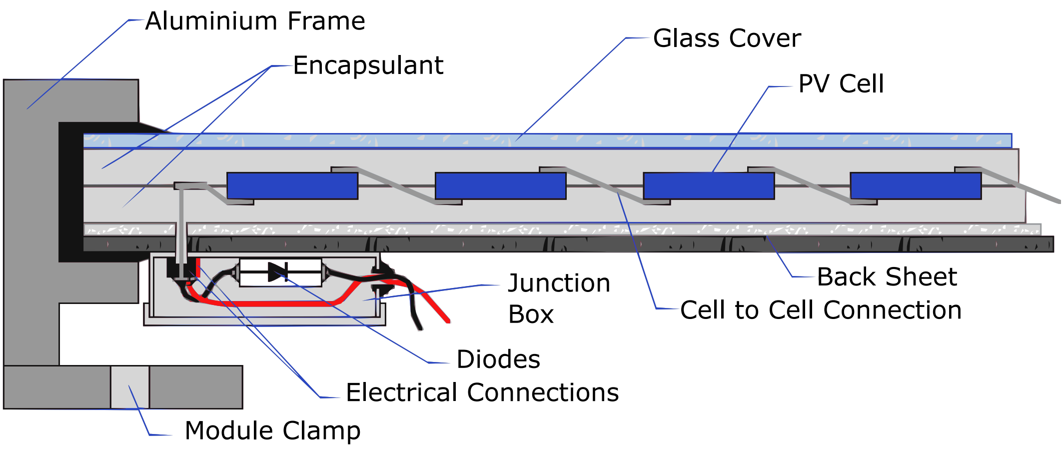


Figure 2.62. PV Module: Elements. (c) University of Jaén `http://bit.ly/2qCVnTb`.

Glass Cover It protects the PV laminate (the cells). Its optical characteristics (also in terms of aging) should be chosen so that the highest number of photons reach the cells.

Encapsulation Materials PV cells are not "free" within the panel. Encapsulation materials (resins) such as *ethylene vinyl acetate* (EVA) are used to provide additional protection against outdoor conditions (humidity, etc.).

Back Sheet It protects the back of the panel, where transparency is not required.

Junction Box It is normally located on the rear side of the panel. It should be hermetic (IP65) and it is formed by by-pass diodes, electrical connections, etc.

Module Clamp To facilitate the fastening of the module to its support (rails, solar tracking system, etc.).

Question 6.1: IP Code

Look for information about the IP Code (International Protection Marking), briefly explaining the code system and mentioning some examples related to REs or Telecommunications.

Different tests have to be carried out to verify the correct operation of the panel according to associated standards. UV-radiation, ice and water resistance (water fog) are some examples of these tests (Figure 2.63).

As occurs with any device, the manufacturing and installation of PV panels must follow different norms specified in international standards. There are many different norms, depending for example on the PV technology under analysis.

IEC 61215 Rev 2 (2005) Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval

IEC 61646 Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval

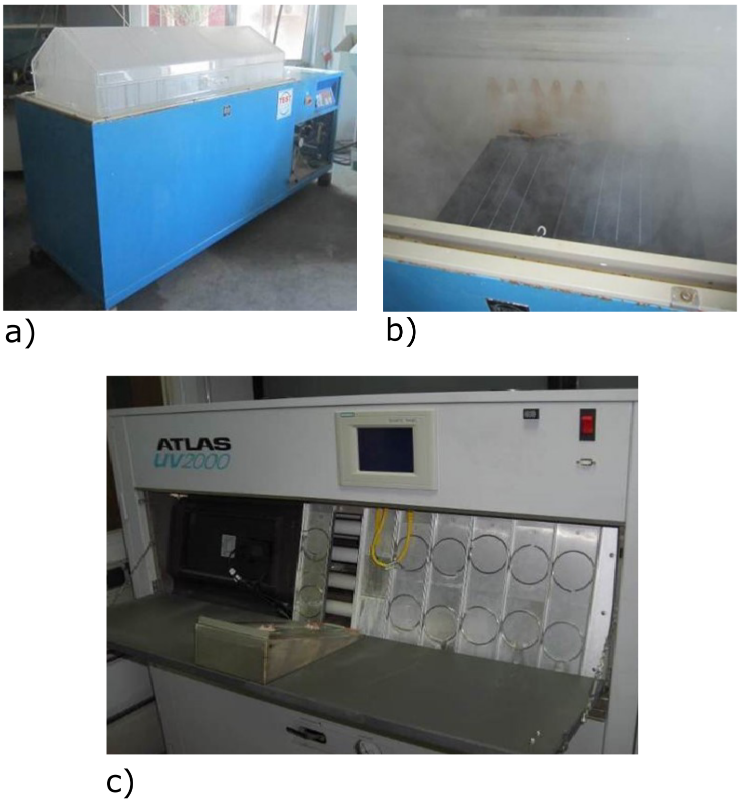


Figure 2.63. PV module tests: a) water fog; b) Detail of the PV module within the water fog tank; c) UV radiation aging test. Source: Jesus Mirapeix.

There are also standards concerning the different tests to be considered:

IEC 60904-1 Measurement of photovoltaic current-voltage characteristics (that will be specified by the manufacturer in the module *datasheet*)

IEC 60891 Irradiance and temperature corrections (the energy produced by the panel will depend on several factors, such as temperature or irradiance)

IEC 61345 UV radiation aging test (to verify that the glass, the encapsulation resins and the PV laminate are not degraded due to UV exposure)

IEC 61724 Mechanical tests (to verify that the mechanical resistance of the modules is good enough, for example to withstand hail)

Important! 6.1: PV Modules: Tests

There are more tests to be considered for PV modules: visual inspection, electrical characterization for different conditions (Standard Test Conditions (STC), Nominal Operation Cell Temperature (NOCT), electrical isolation, measurement of temperature parameters, hot-spot, thermal cycle...

2.6.3. Standard Test Conditions: STC

Imagine the following situation: You are an engineer working for a telecom company and your boss asks you to buy a 100 Wp PV module. We go outdoors to test the panel and it only delivers 40 W.

What is happening? Is the panel broken? Have you been cheated? Will you lose your job?

The first matter to consider is the conditions that were used to estimate the nominal power of the module:

Will the panel generate the same power on a sunny day as on a cloudy day? Will the panel produce the same power regardless of how it is mounted (e.g. if the panel is horizontally or vertically placed)?

The answer is pretty clear: NO!

The answer to this question is given by the definition of the **Standard Test Conditions (STC)**. These conditions define the values of the key parameters to be considered for the electrical characterization of any PV cell/module.

Irradiance As already commented, solar irradiance can be defined as the power (of a given type of electromagnetic radiation) per unit of surface. STCs define an irradiance of 1000 W/m^2[1].

Cell Temperature As will be analyzed in the following sections, temperature plays a key role in the performance of a PV module. This is why it is necessary to establish a temperature to estimate the power delivered by a panel. STCs indicate a temperature of $25°C$[2]

Sun Spectrum As studied in previous sections, the Sun's spectrum will greatly affect the module's performance, given that not all photons (associated with different wavelengths) can be converted into electrons. PV modules are characterized indoors (for practical reasons) with lamps, thus it is important to clearly define the spectrum of the light generated by these lamps (that should be similar to the Sun spectrum). This is defined by the AM1.5 spectrum, already shown in Figure 2.40.

2.6.4. Electrical characterization of PV cells/modules

The electrical parameters specified by the manufacturer in the **datasheet** are measured considering STCs. As an example, Figure 2.64 shows the characteristics of a commercial panel (Panasonic HIT N240/N235). These electrical parameters define the module's I-V (current-voltage) and P-V (power-voltage) curves, as represented in Figure 2.65.

[1] 1000 W/m^2 is the value that can be expected on a sunny day. A cloudy day may give rise to 100 W/m^2

[2] WATCH OUT! It is important not to mix up STC and NOTC temperatures!!!

■ **Specifications**

■ Electrical Performance under Standard Test Conditions (*STC)	
Maximum Power (Pmax)	87W (+10%/−5%)
Maximum Power Voltage (Vmpp)	17.4V
Maximum Power Current (Impp)	5.02A
Open Circuit Voltage (Voc)	21.7V
Short Circuit Current (Isc)	5.34A
Max System Voltage	600V
Temperature Coefficient of Voc	-8.21×10^{-2} V/℃
Temperature Coefficient of Isc	2.12×10^{-3} A/℃

*STC : Irradiance 1000W/m^2, AM1.5 spectrum, module temperture 25℃

■ Electrical Performance at 800W/m^2, NOCT, AM1.5	
Maximum Power (Pmax)	62W
Maximum Power Voltage (Vmpp)	15.3V
Maximum Power Current (Impp)	4.06A
Open Circuit Voltage (Voc)	19.7V
Short Circuit Current (Isc)	4.31A

NOCT (Nominal Operating Cell Temperature): 47 ℃

Figure 2.64. Example of module datasheet: electrical parameters for STC and NOCT conditions. Source: `http://bit.ly/2m7d73H`

It is now time to introduce the parameters that will the define the module electrical curves. **These parameters will be necessary to perform a correct design of a PV installation**.

Maximum Power P_{MAX} is the maximum electrical power that the module will deliver under STCs. This parameter is used as reference to name a specific model (e.g. HIT N240, where 240 denotes the module P_{MAX} `http://bit.ly/2D8bn28`). It is worth noting that this power will not be delivered by the module at all times, as it refers to the STC irradiance of $1000 W/m^2$ that will only be achieved at optimum weather and installation conditions. P_{MAX} is commonly expressed in **watt-peaks (Wp)**.

Maximum Power Voltage V_{MP} Voltage associated with the optimum working point of the panel, the one that delivers maximum power (MPP).

Maximum Power Current I_{MP} Current associated with the optimum working point of the panel, the one that delivers maximum power (MPP).

Open Circuit Voltage V_{OC} is the maximum voltage that the panel can deliver. It is therefore a good reference for carrying out the design and dimensioning (e.g. to estimate the voltage associated with a string of modules to verify if that voltage does not exceed the one specified for the inverter).

Short Circuit Current I_{SC} is the maximum current that the panel can deliver. It is therefore a good reference for carrying out the design and dimensioning.

These parameters can also be expressed in the datasheet for NOCT conditions. **NOCT (Nominal Operation Cell Temperature)** is defined as the cell temperature for the following conditions: solar irradiance of 800 W/m^2, solar spectrum AM1.5, air temperature

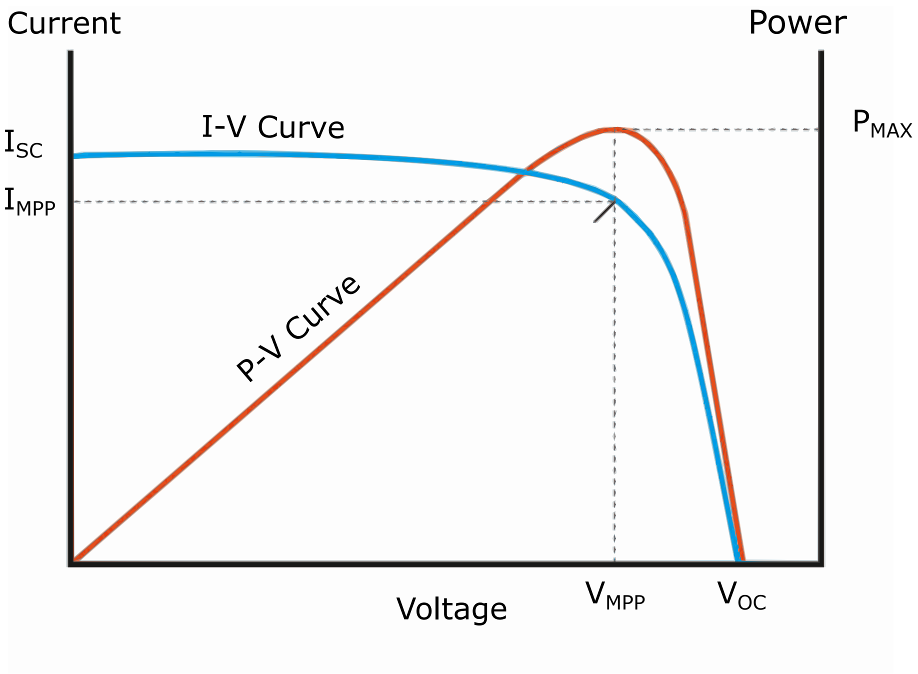


Figure 2.65. I-V and P-V curves of a solar PV cell. Source: `http://bit.ly/2wZ30du`

of 20°C and wind speed of 1 m/s. Obviously, the temperature of the cells will be very different from the air temperature[1] It is important to know the cell temperature as it will greatly affect the module performance. In Figure 2.64 the values of the main parameters estimated for the NOCT conditions have also been included. It is important to notice the difference between the STC and NOCT: see for example the value of the Maximum Power in both cases.

There is an expression for deducing cell temperature from the air temperature:

$$T_{cell} = T_{air} + G[\frac{(NOCT - 20)}{800}] \tag{2.4}$$

In this equation G refers to solar irradiance and $NOCT$ to the nominal cell temperature indicated by the module manufacturer.

[1] A good example to understand this might be the temperature of the pavement in summer.

Important! 6.2: STC and NOCT

Check again the STC and NOCT parameters indicated in Figure 2.64. The V_{OC} estimated for the STCs is 21.7 V, while for NOCT conditions is 19.7 V. Even if there seems to be a subtle difference, take into account that if many modules are connected in series (as is commonly the case in PV installations), this difference will be multiplied n times, where n is the number of panels in series.

CONCLUSION: an error in the selection of these parameters might lead to an incorrect PV dimensioning, where even some devices (e.g. inverters) might be jeopardized. The dimensioning of a PV system will **ALWAYS** refer to STCs.

2.6.5. PV Modules Connected in series/parallel

Imagine that we have a PV module like the one presented in Figure 2.64. What will happen if we connect **N modules in series**?

The answer is very simple: the association will have the same I_{SC}, as the same current will circulate for the cells. However, the output voltage of the association will be:

$$V_{OC} = N \cdot V_{OC} \tag{2.5}$$

This simple relationship is repeated if we want to consider N modules in parallel: in this case V_{OC} will remain constant and the current will be multplied by the number of panels in parallel:

$$I_{SC} = N \cdot I_{SC} \tag{2.6}$$

Important! 6.3: PV Series and Parallel Design

A typical recommendation in PV dimensioning is to always (if possible) go for **designs in series**. This is normally a better solution in terms of simplicity and costs, given that the **cable section** will be determined by the current.

This rule has its own exceptions, for example when the installation is affected by **shadowing**. We will discuss this case later on.

2.6.6. PV Module Response: Temperature and Irradiance

We have already seen the typical I-V and P-V curves of a PV module but, would you be able to explain **how that curve will vary with solar irradiance?**

We know that the curve is obtained for the STC irradiance (1000 W/m^2). Let's assume that the irradiance diminishes to 200 W/m^2 at steps of 200. We can intuitively suppose that the output power will decrease, but the behaviour of V and I will not be the same. This can be appreciated in Figure 2.66: variations in the irradiance give rise to a linear response of the module current, while the voltage remains unaffected.

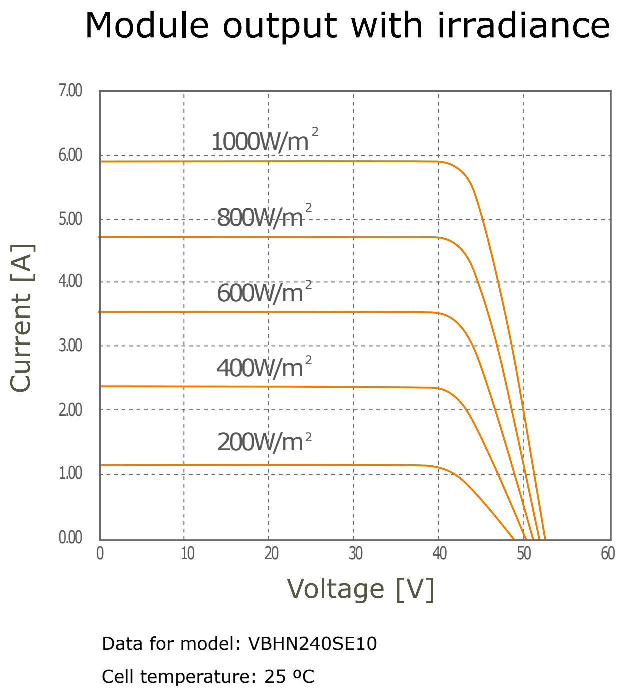


Figure 2.66. Variations of the module output with irradiance (model Panasonic HIT N240/N235).

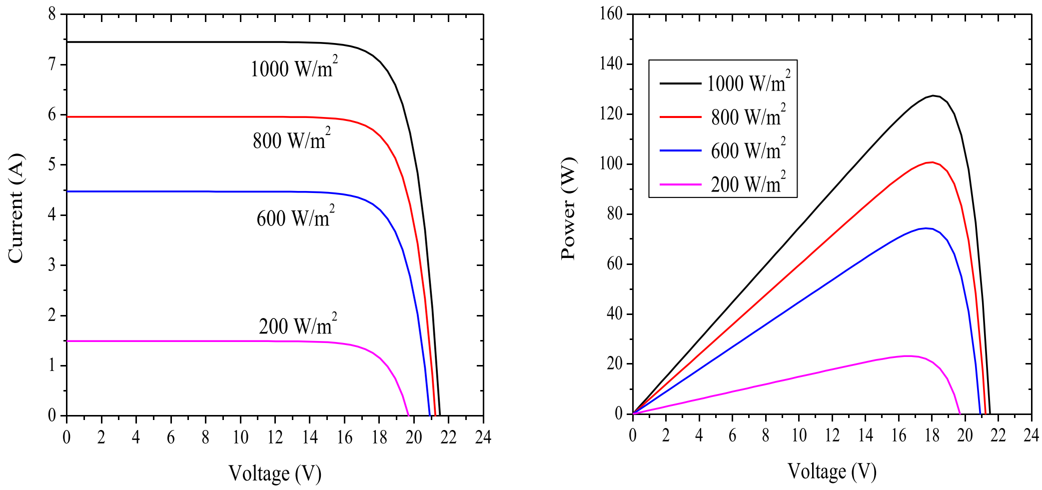
It can be easily derived from Figure 2.66 that higher irradiances will imply higher output powers. This has been represented in Figure 2.67, where the P-V curves have also been considered.

What will happen with these curves if temperature changes are now considered?

In this case the current will remain almost constant, but the voltage will vary depending on the chosen technology. In crystalline-Si modules these variations are large and should be taken into account in the system dimensioning. As Figure 2.68 shows, higher temperatures will cause lower output voltages (and viceversa).

This behaviour implies that in locations where low temperatures can occur, given that the output voltage of each panel will increase by X volts and, in an array in series with N panels, this increase will be $X{\cdot}N$ V[1].

[1] This can be especially dangerous for the inverters if only $V_{OC}(STC)$ has been considered for the estimations.



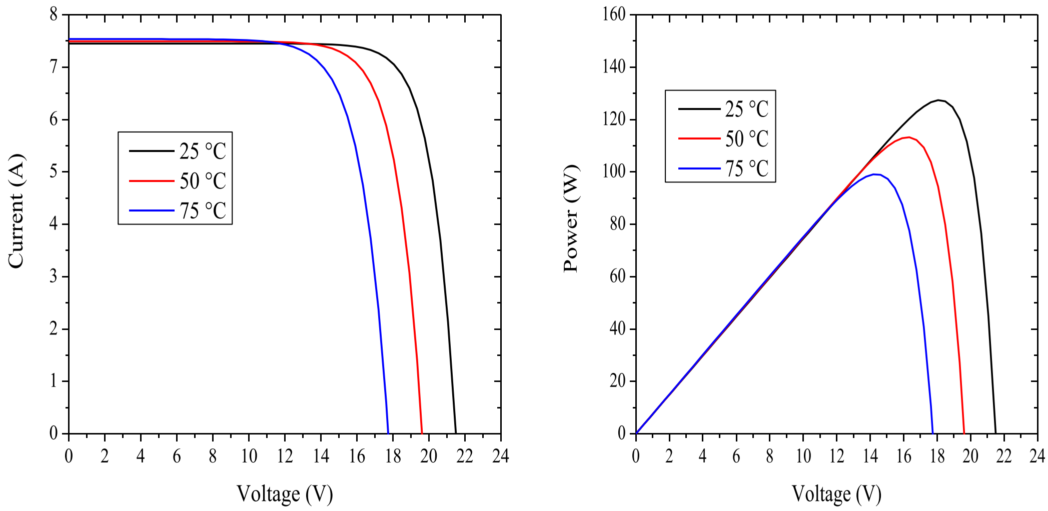
(a) I-V characteristics of the module at different insolation levels

(b) P-V characteristics of the module at different insolation levels

Figure 2.67. I-V and P-V curves in terms of solar irradiance: (Kyocera KC120–1 PV). Source: *A comparative study on converter topologies for maximum power point tracking application in photovoltaic generation (Bhattacharjee et al., 2014).*

Important! 6.4: Temperature Dependence in different PV Technologies

Not all the technologies exhibit the same temperature dependence. Crystalline-Si will exhibit much higher voltage variations (V_{OC} o V_{MPP}) than amorphous-Si, for example. This means that if a PV installation is being considered for a location with very low temperatures, this issue should probably be considered in the technology selection stage.



(c) I-V characteristics of the module at different temperature values

(d) P-V characteristics of the module at different temperature values

Figure 2.68. Temperature dependence of I-V and P-V curves of a commercial panel. Source: *A comparative study on converter topologies for maximum power point tracking application in photovoltaic generation (Bhattacharjee et al., 2014).*

Although the previous graphs are very illustrative, the dimensioning calculations will use the **temperature coefficients** provided in the datasheet. Checking Figure 2.64 again, we can see how V_{OC} is $-0.0821 V/°C$, which gives rise to a voltage deviation (in terms of its nominal value) of 8.21 V for a temperature excursion of 10 $°C$. The current coefficient is very low, which means that normally it will not be necessary to use it for the calculations.

Question 6.2: Temperature Response: Crystalline and Amorphous Si

Search the internet for two PV modules associated with crystalline-Si and amorphous-Si (or a similar thin-film technology). Compare the temperature coefficients and briefly explain the conclusions **in your own words**.

2.6.7. PV Modules: Hot-Spots

What are *hot-spots* in a PV Module? The hot-spot problem may cause the malfunctioning and complete breakdown of a PV module, and it is originated by a complete or partial occlusion (shadowing) of one (or more) of the PV module cells. This occlusion can be caused by birds, leaves, etc. Hot-spots constitute a serious threat for PV installations, so we will analyze this issue in detail.

Let's imagine an example: we have a standard panel with 36 cells in series. In normal operation conditions (direct radiation) these cells generate a current that is dissipated in the load R (a bulb or any other load connected to the module output).

What will happen if one of the cells is covered, for example by a tree leaf?

While the remaining 35 cells will generate current, cell C36 (Figure 2.69) will not contribute and will act as a load. The voltage generated by the other 35 cells will fall (inversely) on C36 (this will actually happen if the module is short-circuited, situation that may occur in stand-alone systems[1] with charge controllers). The current generated by the cells will also circulate through C36, becoming heat dissipated by the load. If the current is high, the power dissipated in C36 may also be too high and the cell will reach very high temperatures, leading to a **hot-spot**.

Question 6.3: By-pass Diodes

Look for information about **by-pass diodes in thin-film technologies**: is there also a restriction of 1 diode per 16 to 20 cells? How are these diodes implemented in the cells? Explain this briefly **in your own words**.

This situation may lead to in various problems, like damage of the PV laminate, of the encapsulation material or even breakage of the module's glass (Figure 2.70).

If hot-spots appear in a module, this usually implies its replacement. To avoid this situation, panels usually include so-called **by-pass diodes**. These devices offer an alternative path to the current in the occluded cell, thus preventing its heating and damage

[1] PV installations are often divided into **stand-alone** (the electricity generated is used locally, for example in a home or in a sensor network) and **grid-connected**.

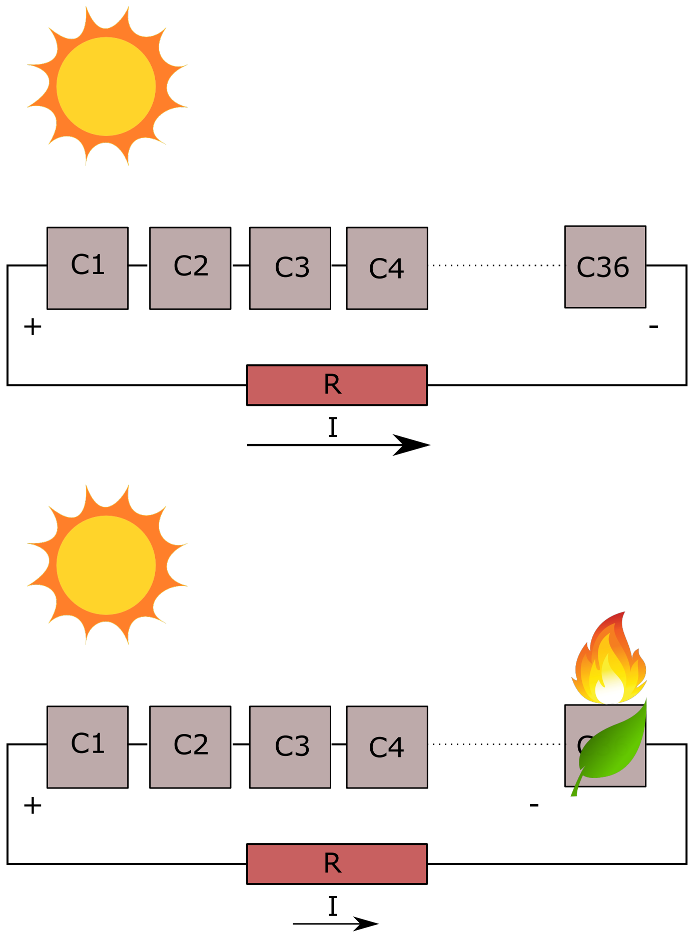


Figure 2.69. Example of the hot-spot problem: a PV module with 36 cells working in normal operating conditions (above); PV module with the last cell covered. Source: Jesus Mirapeix.

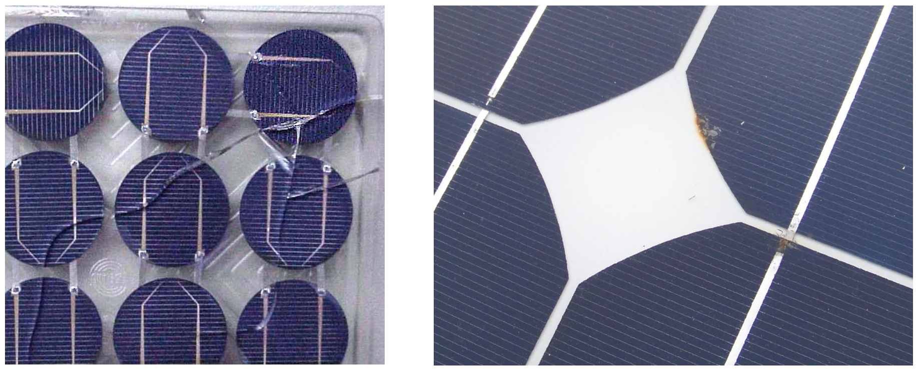


Figure 2.70. Examples of hot-spots effects: breakage of the module glass (left) and damage of the PV cell and metallic strip (right). Source: PVEducation `http://bit.ly/1M6tnpN` (left) / Europe-Solar `http://bit.ly/2qJI8jF` (right).

(see Figure 2.71). The ideal solution would be to include a by-pass diode per cell, but in commercial panels of crystalline-Si this is not possible, so 1 diode per 16/18/20 cells is included.

A partial/total shadowing of one or more cells will give rise to relevant losses in terms

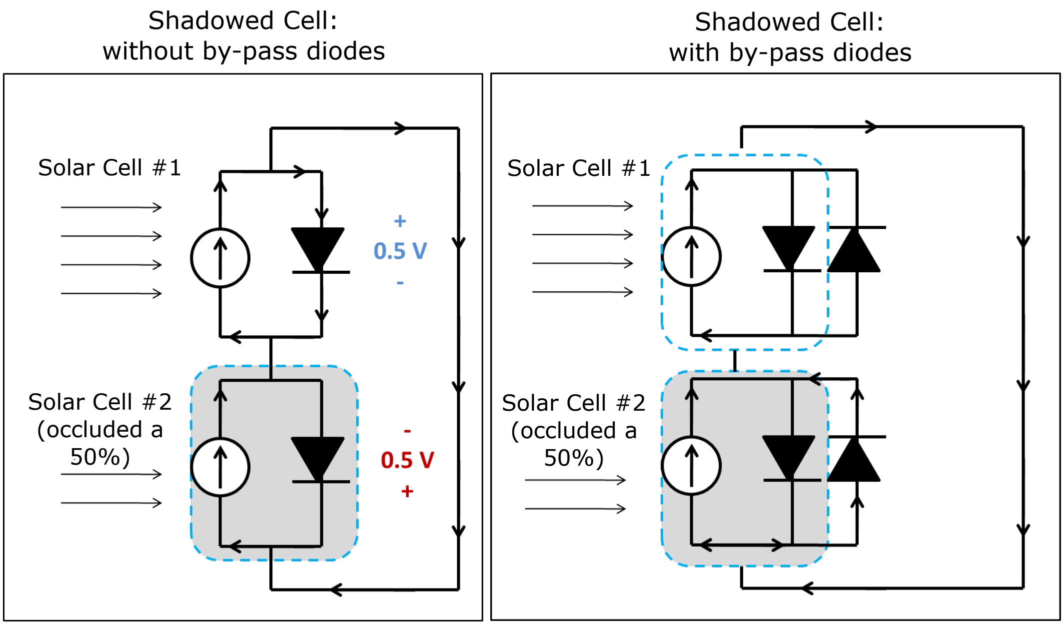


Figure 2.71. By-pass diodes to avoid hot-spot effects. Source: Jesus Mirapeix.

of the module output power. In fact, for a string of cells in series, the string current will be limited by the shadowed cell, thus decreasing the output power (Figure 2.72).

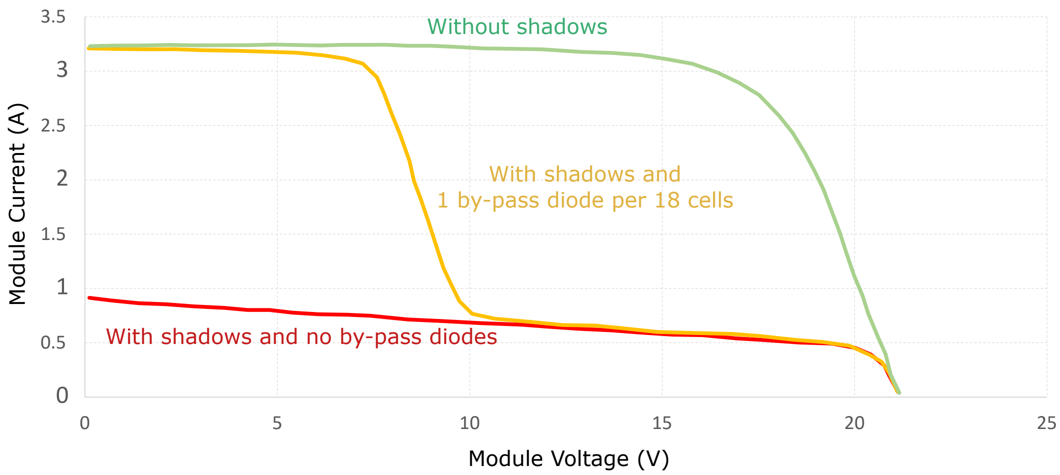


Figure 2.72. Shadowing losses in a PV module. Source: Jesus Mirapeix.

Finally, it is also worth noting that blocking diodes are also used in PV modules. These diodes are installed in series with the PV cells and their goal is to prevent the current generated by another panel array arranged in parallel (or from the batteries, if any) from being injected into another string. Let's see it this way: the current generated from the panels must always go from the modules to outside, because if the current goes into the panels, they might become deteriorated. Figure 2.73 shows an illustration of these blocking diodes.

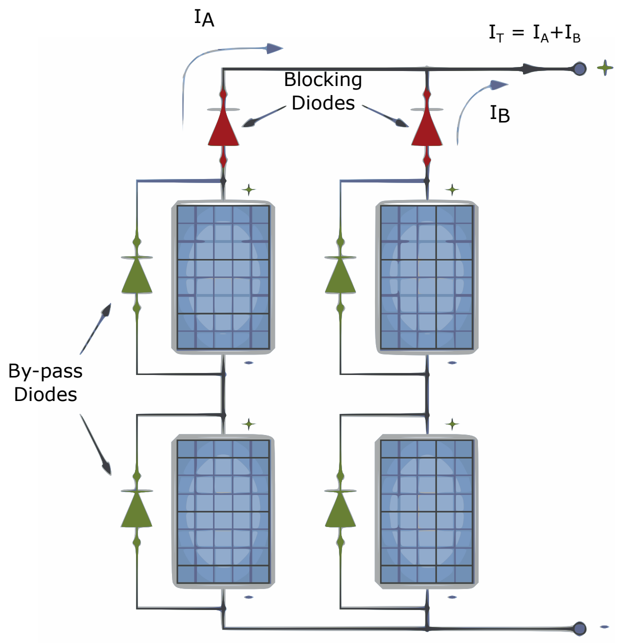


Figure 2.73. PV module with by-pass and blocking diodes. Source: Electronics-Tutorials `http://bit.ly/2d8LW2T`

2.7. PV Systems: Design and Dimensioning

The previous sections on solar photovoltaics really start to make sense when they are used to design a PV installation. Firstly, let's take a look at the different types of solar PV installations:

Stand-Alone Systems designed to power supply, independent of the power grid, installations, infrastructures or devices (e.g. homes, Base Transceiver Stations or network sensors). See Figure 2.74.

Grid-Connected Systems where the energy produced by the PV generator[1] is injected into the power grid, thus acting as a conventional power plant.

Both systems share many common features, but there are also remarkable differences from the point of view of the chosen devices, as well as of their use and legislation.

2.7.1. PV system: elements

We will start to analyze the elements that form a grid-connected system, which can be considered as the simplest scenario. As shown in Figure 2.75, a **grid-connected PV system** is formed by the **PV generator** (group of panels associated in series/parallel), **inverters**, the **distribution/protection subsystem** and a **power meter**.

On the other hand, a stand-alone system should also include a charge controller and usually also a storage subsystem, i.e. batteries. Let's briefly explain these elements:

[1] **PV generator** refers to all the PV modules installed in a given system.

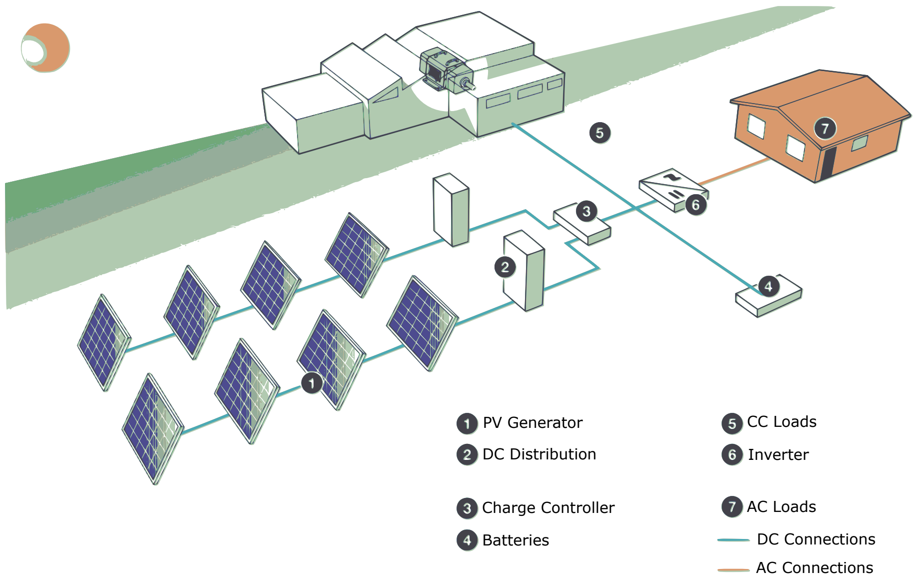


Figure 2.74. Schematic representation of a stand-alone PV system. Source: globalelectricity http://bit.ly/2ma1Jy.

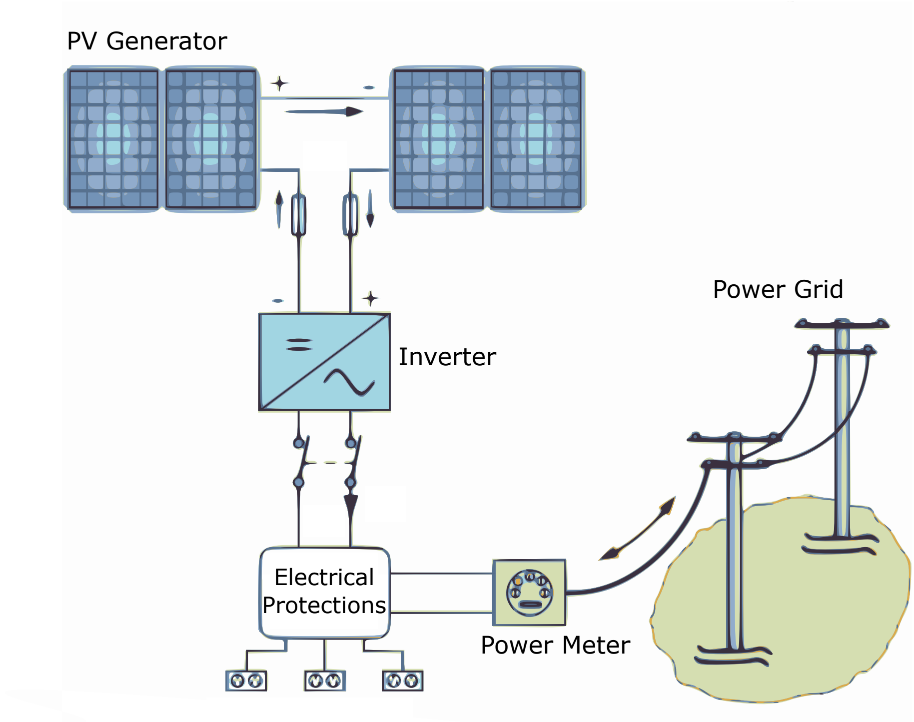


Figure 2.75. Schematic representation of a grid-connected PV system. Source: globalelectricity http://bit.ly/2ma1Jy.

PV Generator Group of panels that will convert the solar radiation into electricity.

Inverter PV modules produce DC electricity. In some situations AC current might be needed and inverters perform that **DC-AC conversion**.

Charge Controller In stand-alone systems, there are PV modules, loads (DC or AC) and batteries. Charge controllers manage the energy flux among these elements (e.g. from the modules to the loads and/or batteries if there is enough solar radiation; or from the batteries to the loads at night).

Batteries allow to store energy to be used when needed, for example at night or on cloudy days.

These are the main elements that form a PV system, but there are other important elements whose influence on the final cost may be relevant: cables, module supports, DC-DC converters, etc. The following sections will provide a detailed analysis of these elements.

2.7.2. DC-DC Converter

To clarify the use of this device it is important to remember the I-V curve of a PV cell/module. A PV installation can be associated with different kinds of loads: batteries, lights in a house or the power grid, for example. These loads will have their specific voltage and current requirements.

Imagine the case of a resistive load (Figure 2.76). For a solar irradiance of 1000 W/m^2 the inverter would work close to the optimum point MPP. However, if the irradiance were of 500 W/m^2, the PV module could only deliver part of the available power, as the working point would be far away from 1000 W/m^2.

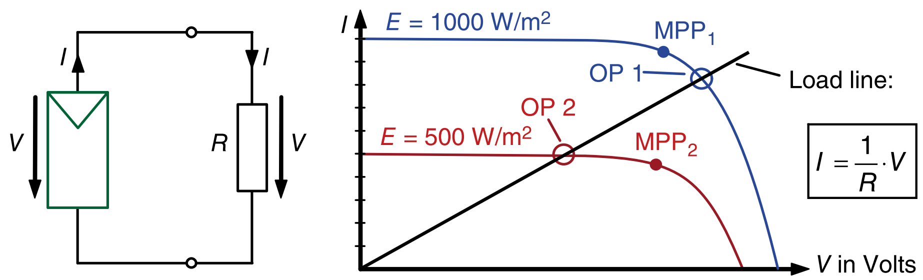


Figure 2.76. Example of PV module connected to a resistive load: solar irradiances of 500 and 1000 W/m^2. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens]

A DC-DC converter enables isolating (making independent) the module output voltage from the load working voltage, which will be the one offered by the converter output. Let's analyze this situation in Figure 2.77. It can be observed how now, working at a constant voltage, it is possible to be closer to MPP_1 and MPP_2 for different irradiances.

In addition, for PV systems with heavy consumptions and large distances between the elements (modules, batteries and so on), it might be interesting to convert the working voltage to a higher one (typically from 12 to 24 or 34 V, for example). This way, a reduction in the costs associated with the cables can be achieved.

The drawback of this solution is the converter efficiency, although it is normally above 95 %.

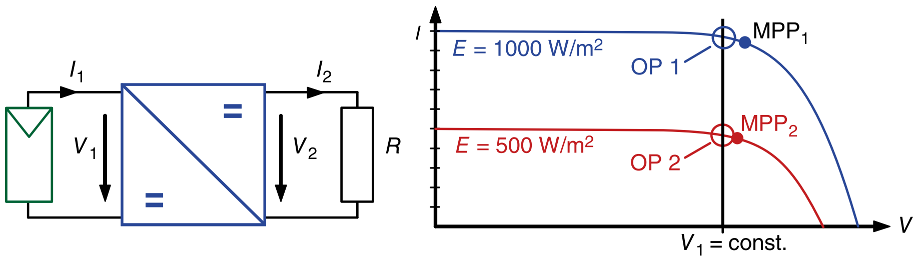


Figure 2.77. Example of PV module connected to a resistive load via DC-DC converter: solar irradiances of 500 and 1000 W/m^2. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens]

2.7.3. Inverter

As already mentioned, an inverter allows conversion from DC to AC current, which can be of great use in PV installations. Most PV systems include inverters, in both stand-alone and grid-connected systems. In the latter it will be always required and, in addition, high-quality inverters (those that produce high-quality sinusoidal signals) are necessary for obvious reasons in terms of the quality of the power grid service. Figure 2.78 shows two inverter models: for small-scale systems (left, for capacities up to around 2.5 kW) and for large-scale installations (solar farms) (right, PV plant in California of 35 MW).

Figure 2.78. Inverter models: (left) Model: SMA SUNNY BOY 1.5/2.5; (right) Model: Solaron 500KW

Inverters are key elements in a PV system. Consequently, the following sections will thoroughly explore these devices. Apart from mere DC-AC conversion, inverters are also used to:

- Achieve a high efficiency (> 95 %) for a wide range of output powers
- Perform a synchronous current injection (with the grid frequency)
- Carry out a MPP (Maximum Power Point) tracking
- Monitor the grid to prevent a possible situation of isolation from the grid
- Implement electrical protections
- Offer data management and visualization via app

Inverters can be classified in terms of their design (technology): without transformer, with transformer and high frequency inverters.

If high powers are in play, i.e. medium or large-scale PV systems are considered (over 5 KWp, for instance), a triphase inverter will normally be chosen, working with input voltages (from the PV generator) of 600 to 800 V.

The **efficiency of an inverter** is a key parameter that has remarkably improved in the last years, with values over 95 %. The efficiency of an inverter is defined as **the output AC power divided by the DC input power:**

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} \tag{2.7}$$

The manufacturer will include the efficiency curve, like the one depicted in Figure 2.79 on the inverter datasheet. As represented, efficiency depends on the power generated (also on the working voltage), with low values for low powers, reaching a maximum and then smoothly decreasing towards the highest powers.

What happens if the inverter is working for low powers? In this situation, the inverter self-consumption becomes relevant, implying a decrease of η[1]. An additional factor for efficiency loss is heat dissipation.

Figure 2.80 presents a comparative of the efficiency of different inverter technologies. Inverters without transformer exhibit the highest efficiencies, followed by high-frequency inverters.

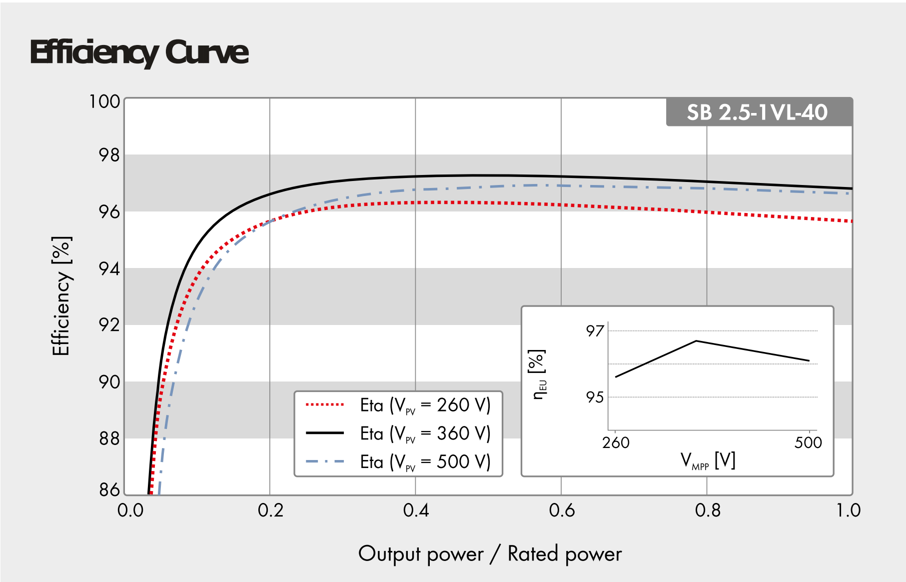


Figure 2.79. Efficiency curve for SMA Sunny Boy 1.5/2.5 inverter. Source: Sunny Boy 1.5/2.5 datasheet `http://bit.ly/2AICf5W`.

If we look at the datasheet of this model, we can see how the *efficiency* is calculated for two different parameters: **maximium efficiency** and **European weighted efficiency**. The former (in this case 97.2 %) indicates the efficiency for the optimum working point

[1] The inverter needs power supply to operate. This consumption must be considered in the dimensioning stage.

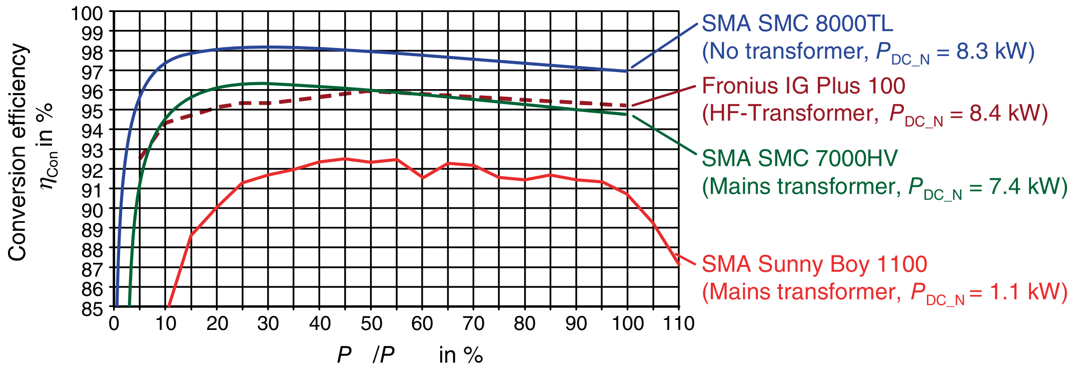


Figure 2.80. Efficiencies for different inverter technologies: (*no transformer*), hihg-frequency (*HF transformer*) and with low-frequency transformer (*Mains transformer*). Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

Technical Data	Sunny Boy 1.5	Sunny Boy 2.5
Input (DC)		
Max. DC power (at cos φ = 1)	1600 W	2650 W
Max. input voltage	600 V	600 V
MPP voltage range	160 V to 500 V	260 V to 500 V
Rated input voltage	360 V	360 V
Min. input voltage / initial input voltage	50 V / 80 V	50 V / 80 V
Max. input current	10 A	10 A
Max. input current per string	10 A	10 A
Number of independent MPP inputs / strings per MPP input	1 / 1	1 / 1
Output (AC)		
Rated power (at 230 V, 50 Hz)	1500 W	2500 W
Max. apparent AC power	1500 VA	2500 VA
Nominal AC voltage	220 V / 230 V / 240 V	220 V / 230 V / 240 V
Nominal AC voltage range	180 V to 280 V	180 V to 280 V
AC power frequency/range	50 Hz, 60 Hz / −5 Hz to +5 Hz	50 Hz, 60 Hz / −5 Hz to +5 Hz
Rated power frequency/rated grid voltage	50 Hz / 230 V	50 Hz / 230 V
Max. output current	7 A	11 A
Power factor at rated power	1	1
Adjustable displacement power factor	0.8 overexcited to 0.8 underexcited	
Feed-in phases/connection phases	1 / 1	1 / 1
Efficiency		
Max. efficiency / European weighted efficiency	97.2 % / 96.1 %	97.2 % / 96.7 %

Figure 2.81. Part of the SMA Sunny Boy 1.5/2.5 datasheet. Source: Sunny Boy 1.5/2.5 datasheet `http://bit.ly/2AICf5W`.

and the latter takes into consideration several weights considering the % of time that an inverter will operate in the different power ranges thorugh the day (depending on the location). This European efficiency η_{Eu} is defined as:

$$\eta_{Eu} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.10\eta_{30\%} + 0.48\eta_{50\%} + 0.20\eta_{100\%}, \qquad (2.8)$$

where $\eta_{5\%}$ is the inverter efficiency for an output power of 5% (in terms of the nominal value of the module power). η_{Eu} is therefore a much more interesting parameter to consider in system dimensioning. For any solar PV plant, it would be more interesting to know the average efficiency over the whole year than the efficiency for the optimum power.

To further clarify this issue, let's analyze Figure 2.82, where solar irradiance for Freiburg (Germany) is shown. The figure indicates the relative frequencies (of appearance) as well as the energy fraction (over the total annual solar energy) associated with each solar radiation. If we only look at the maximum efficiency, we will make a significant mistake in the final estimation of the system production. If a large-scale plant is under analysis, this error might imply a lot of money.

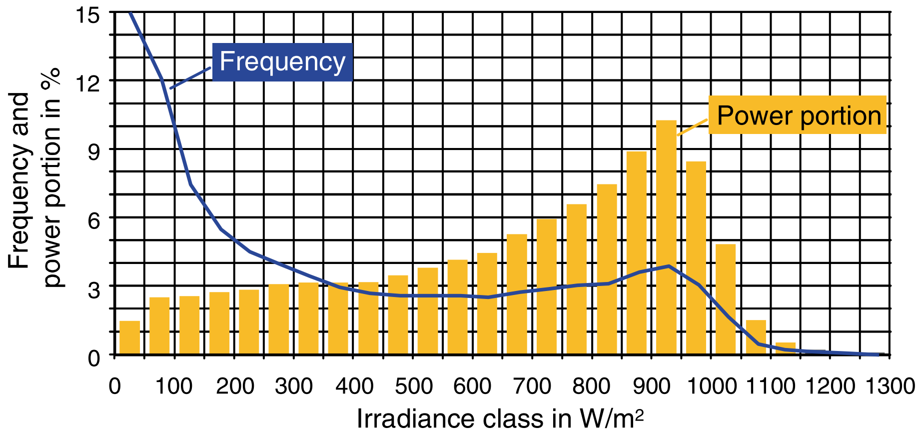


Figure 2.82. Relative frequencies and energy fraction associated with each radiation for Freiburg (Germany, 2000). Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

It is interesting to note that there is a third way of expressing the efficiency of an inverter: the California Energy Commission **CEC-efficiency**. Obviously, in this case the following equation takes into account the solar radiation at this location:

$$\eta_{CEC} = 0.04\eta_{10\%} + 0.05\eta_{20\%} + 0.12\eta_{30\%} + 0.21\eta_{50\%} + 0.53\eta_{75\%} + 0.05\eta_{100\%}, \quad (2.9)$$

2.7.4. Inverter: MPP Tracking

One of the key roles of an inverter is **MPPT**: *Maximum Power Point Tracking*. Following the points previously made for DC-DC converters, it is easy to understand that a PV generator (let's assume a single module, for example) will generate a given power in terms of the solar irradiance, the temperature and the load. The ideal situation would be to always work at the MPP point, but this will not be possible unless a control or tracking of this point be made.

Although there are different MPPT algorithms, one of the most commonly used ones is P&O (*Perturbation & Observation*). The working principle has been illustrated in Figure 2.83 and it is very simple: the voltage of the PV generator is modified and the associated power is evaluated to determine the MPP.

Question 7.1: Other MPPT Algorithms

There are many other MPPT algorithms. Search the internet and briefly explain, **in your own words**, another solution.

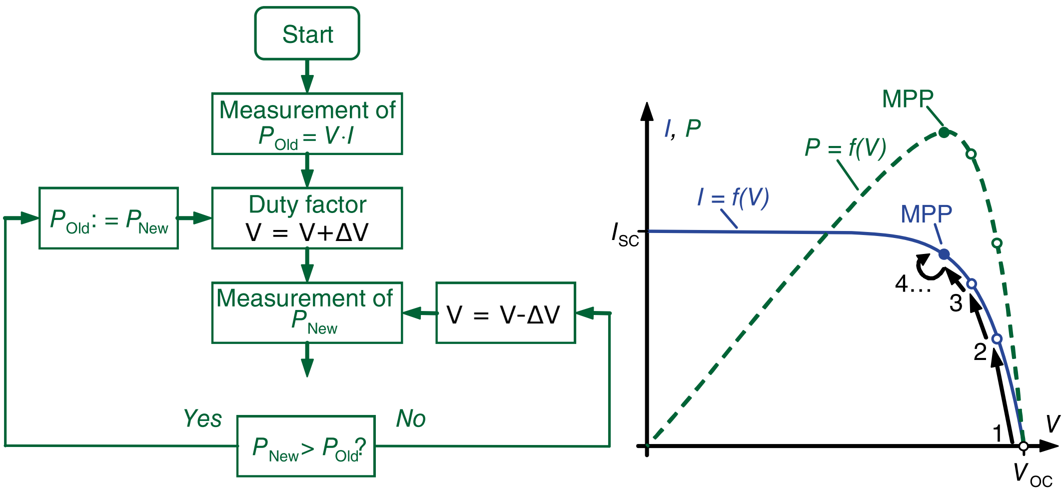


Figure 2.83. Flow chart and representation of the working principle of the P-O MPPT algorithm. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

2.7.5. Inverter: Configurations

When a PV system is being designed and dimensioned, it is necessary to determine the number of inverters to be used and how they would be deployed (their configuration). Let's check the different configurations that can be employed:

Central inverter Assuming a PV system with several PV modules distributed in more than 1 string, a central inverter is used to uniformly manage all the strings. The main advantage is that a single inverter is required (thus reducing the associated costs); while the main drawback lies in the possible losses derived from shadowing on one or more strings, for example, as the strings will be connected in parallel to the inverter. Basically, a central inverter is not able to manage the MPP of each string, but each string will be operating at a "mean" MPP estimated from all the strings. It should be mentioned that a central inverter will also mean more complicated DC cabling and, therefore, a higher cost.

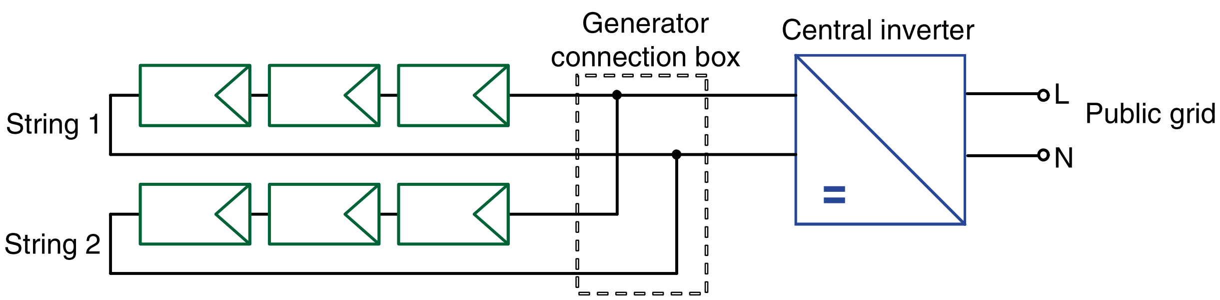


Figure 2.84. Schematic representation of a central inverter configuration. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

Important! 7.1: Central Inverter

All the strings associated with a central inverter should have the same characteristics. For example, it would not make any sense to choose a central inverter for strings with panels with different orientations or inclinations, as this would imply losses for the whole system. Notice that the inverter will try to find the MPP of the PV generator but, if the strings have different characteristics, it would be impossible to work at both MPPs. **Example:** it would be a bad design choice to use a central inverter for a PV system in a roof with two orientations (east/west) and panels in both sides of the roof.

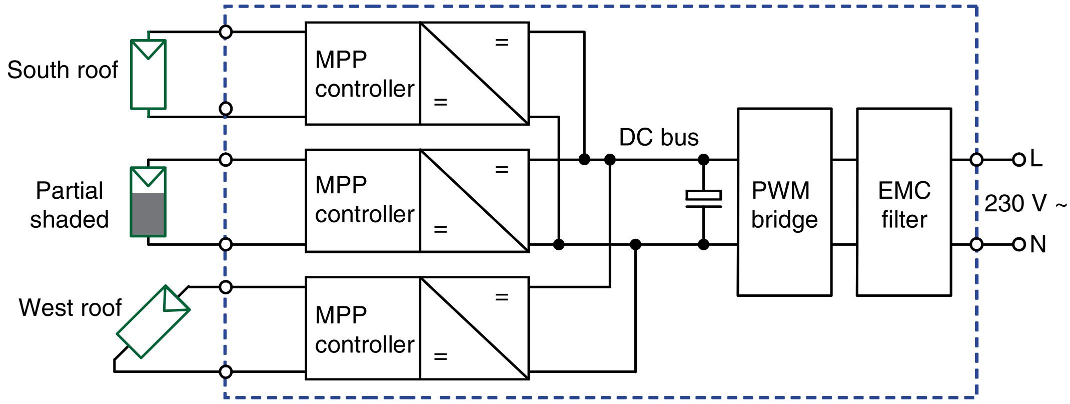


Figure 2.85. PV systems with strings with different characteristics (orientation, inclination, shadows ...). A central inverter should be avoided in this case and an inverter for each individual string (whith similar panels) should be considered. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

String inverter A string inverter is a more elegant solution. Even if it implies a higher number (and cost) of inverters, it also allows a more efficient management of the PV generator. Each string will be associated with 1 inverter and, therefore, efficient MPP tracking will be performed. The cabling is, in this case, simpler than for a central inverter. Connecting two strings in parallel to the same string inverter, may also be considered, but only if both strings share the same characteristics.

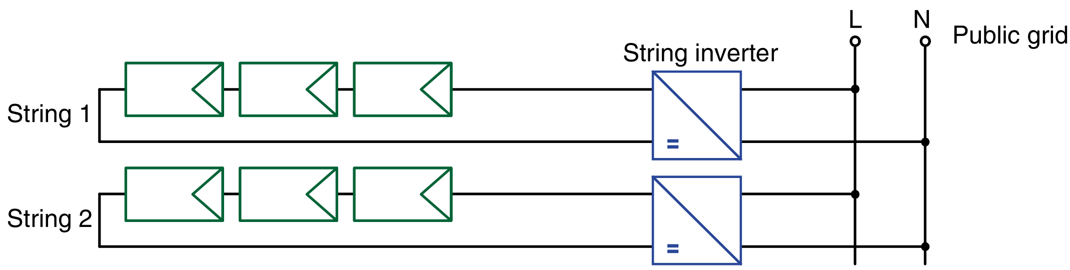


Figure 2.86. Schematic representation of a string inverter. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

Module inverter An inverter can be directly attached to a module, normally at the back of the panel. Although this concept implies that each individual module can work at its own MPP, it is often dismissed due to several drawbacks, except for certain specific or demo projects. One of these disadvantages is the location of the inverter, as it is highly recommended to deploy these devices indoors to extend their lifetime. It should also be mentioned that a failure in the module or the inverter will require the substitution of both elements.

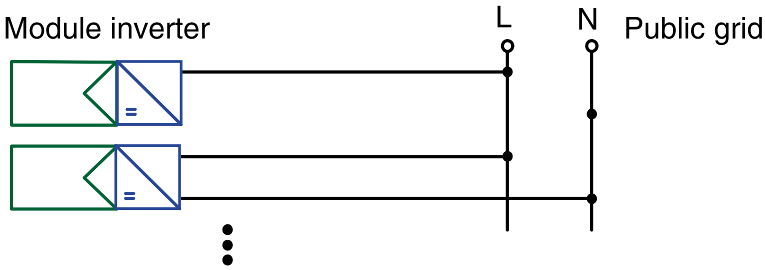


Figure 2.87. Schematic representation of a module inverter. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

Master-Slave Inverter This configuration is especially interesting for PV installations exceeding a given capacity threshold, for example above 30 KWp. Its working principle is simple: when production is low (early mornings, cloudy days, etc.) only the master inverter works. This way, a high load and efficiency are achieved. If the production of the system exceeds the thresholds of the master inverter, the slave-1 and, if needed, slave-2 will come into play.

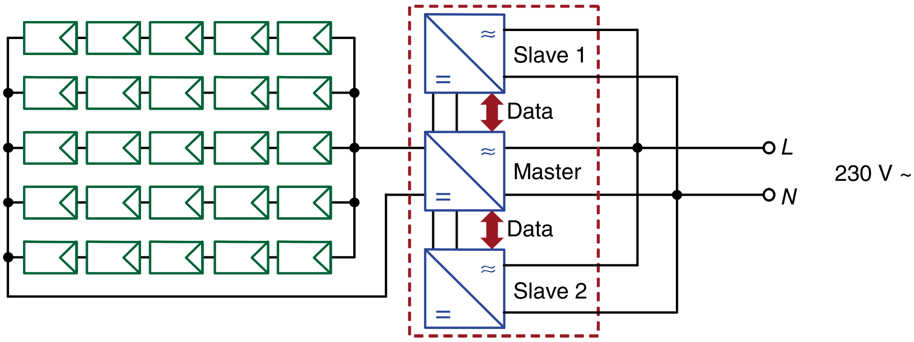


Figure 2.88. Master-slave inverter configuration. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

Inverter: Dimensioning

As will be explained in the final section on PV system dimensioning, there are 3 main aspects to be considered when choosing an inverter and to verify its suitable dimensioning within the whole system:

Inverter: Power Dimensioning The initial selection of an inverter for a PV string/generator is usually made based on its power. Traditionally, the following rule was recommended: the inverter power could be a 20 % less than its associated PV generator. This meant that for a 2 KWp generator, a 1.6 KW inverter could be used. This recommendation was based on the low efficiency (for low capacities) of old inverters, thus forcing them to work in medium/high capacity regions. The obvious drawback of this design is that in some situations (sunny days, low temperatures) part of the produced energy was lost, as it could not be managed by the inverter.

As current inverters exhibit an improved efficiency, a different rule is now recommended, the so-called sizing ratio (SR_{AC}):

$$SR_{AC} = \frac{P_{STC}}{P_{INV-AC}}, \tag{2.10}$$

where P_{STC} is the nominal capacity of the generator (of course, expressed for the STCs) and P_{INV-AC} is the nominal output power of the inverter (AC). Although there are different approximations, some studies recommend using a $SR_{AC} = 1.1$.

Question 7.2: Inverter: Power Dimensioning

Try to justify the use of the Sizing-Ratio parameter, i.e. why can we not assume that $P_{STC} = P_{INV-AC}$?

Inverter: Voltage Dimensioning Inverters have a maximum and minimum input voltage. This means that the voltage derived from the PV strings should always be within that range, also taking into account the effect of temperature on the module voltage.

Inverter: Current Dimensioning Inverters have a maximum input current I_{MAX} that should not be exceeded to avoid a possible damage. It must be verified that the PV string current does not exceed this I_{MAX}.

2.7.6. Power Meter

Grid-connected PV systems must include a power meter enabling the monitoring of the energy produced and injected into the grid. Let's see two examples to clarify this point:

In the first case, illustrated in Figure 2.89, a power meter is specifically used to measure the energy produced, while a second device is employed to estimate the energy consumed in the PV installation[1].

The second example, which has been represented in Figure 2.90, shows the use of a bi-directional power meter (the "solar energy meter" might be avoided).

The first situation was typical some years ago in those countries where RE subsidies (feed-in tariffs) were so high that they prevented the design of self-consumption (even partially) systems. However, in most of these countries (e.g. Germany) these subsidies have decreased, in some cases being even lower than the end-user cost of electricity (kWh). Logically, this situation makes self-consumption more suitable.

[1] Several different situations can be produced here, for example a roof-top PV installation in a home, where part of the energy might be used for self-consumption.

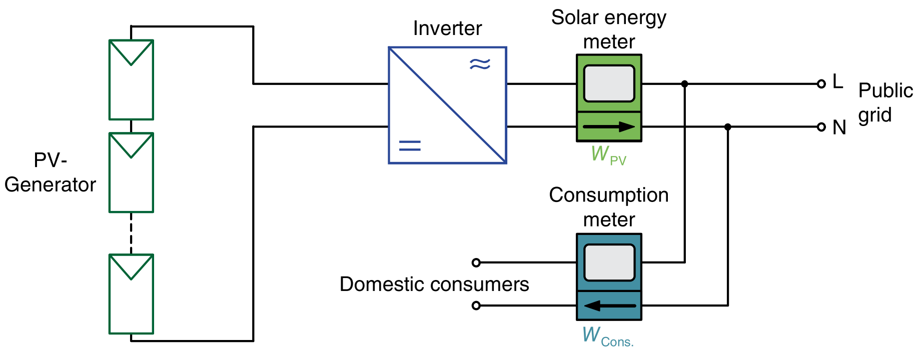


Figure 2.89. Example of PV system with uni-directional power meter. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

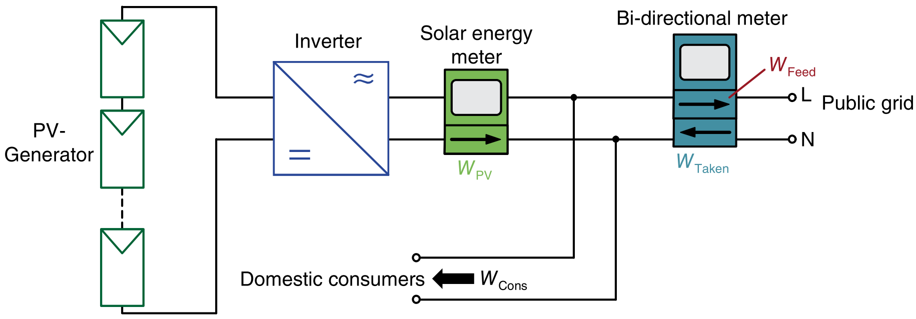


Figure 2.90. Example of PV system with bi-directional power meter. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

2.7.7. Charge Controller

A charge controller is a **key element in stand-alone PV systems**. It is the **"brain"** of the system, as it controls the state of the batteries, using the energy produced in the PV modules to charge them or to directly power supply the associated loads. Apart from this energy flow control within the system, a charge controller may also implement the following functions:

- avoid battery overcharges
- avoid battery over-discharges
- provide information on the battery charge state
- enable self-protection
- MPP tracking (optional)
- manual/automatic voltage selection: 12 / 24 / 48 V (optional)
- manual/automatic battery technology selection (electrolyte/gel)
- provide user with information

In Figure 2.91 the charge controller is connected only to DC loads, but there is no limitation in this regard. In fact, it is very common to find AC loads in a stand-alone system. In this case, it would be necessary to include an inverter associated with the

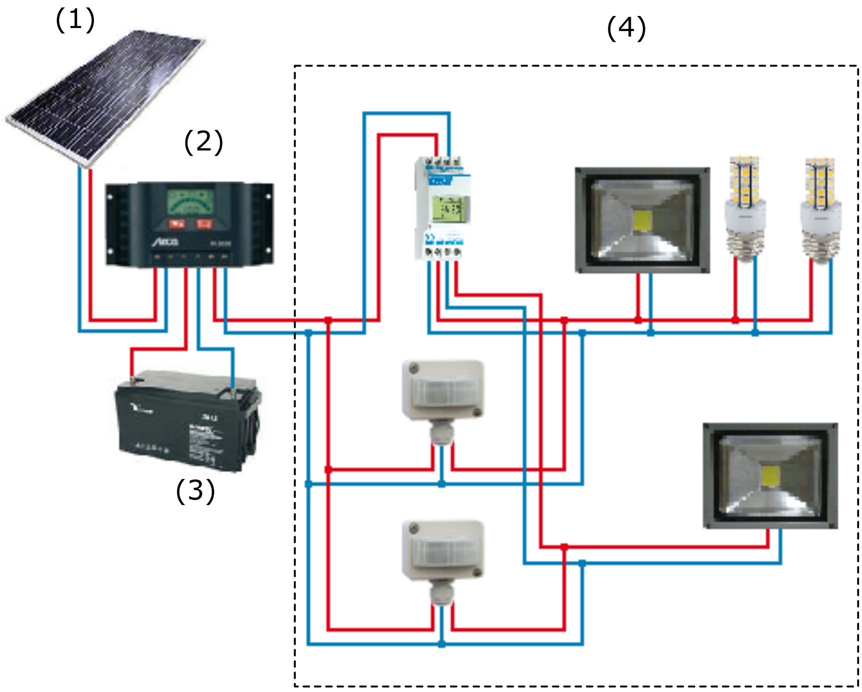


Figure 2.91. Example of a stand-alone PV system: (1) PV generator; (2) Charge controller; (3) Batteries; (4) Loads. Source: Jesus Mirapeix.

corresponding output of the charge controller or with the batteries, as will be commented later on.

It is worth noting that charge controllers implement three connections for: (1) PV generator, (2) batteries and (3) loads.

Figure 2.92. Example of charge controller: Steca PR 3030 LG.

The dimensioning of a charge controller within a PV system must take into account the chosen voltage (e.g. 12, 24 or 48 V) and the maximum input and output currents.

Important! 7.2: Charge Controllers: PWM and MPPT

An important decision to make in this regard is the charge controller technology:

PWM Charge Controllers are simple devices that basically act as a switch between the PV generator and the batteries. Pros: low cost, complexity and weight. Cons: low efficiency in comparison to MPPTs, as in PWMs the PV generator working voltage is limited by the battery voltage.

MPPT Charge Controllers are more sophisticated (and costly) and allow isolating the working voltages of the PV generator and the battery. This way, the PV generator can operate at its MPP, thus producing maximum energy. These controllers are especially suitable for large-scale PV systems or when irradiance or temperature conditions are far from optimal.

2.7.8. Batteries

Batteries are a key element in many stand-alone systems. In the so-called **instantaneous self-consumption systems** (that can be understood as a subcategory within stand-alone installations) batteries are not required, as the PV energy is instantly consumed the very moment that it is produced. The energy produced when there is no consumption is lost.

Why should we opt for a system where part of the energy is wasted? There is no single answer to this question: on the one hand, this will depend on the consumptions involved (for example, the design of a system for an office, a restaurant or a home will note be the same). On the other hand, batteries might imply a significant additional cost within a stand-alone system, especially if their average lifetime is considered (less than 10 years, well under the lifetime of other components, such as PV modules).

There are different technologies allowing energy storage in batteries: lead batteries, NI-MH, Lithium-ion, Lithium polymer, etc. Only lead batteries are used in PV systems, mainly due to their cost, cheaper than the other technologies. Figure 2.93 shows the costs associated with the initial investment in a conventional stand-alone PV system and the costs associated with maintenance of the installation after 20 years of operation. The contribution of the batteries to the overall cost is remarkable.

Providing a detailed description of the working principle of lead-acid batteries is beyond the scope of this course. However it is worth mentioning that these batteries are formed by an electrolyte (dissolved sulfuric acid: H_2SO_4) with a negative electrode (made of lead) and a positive one made of lead oxide (PbO_2).

Question 7.3: Lead Batteries

Search the internet for information about the working principle of lead batteries and make a brief summary of it **in your own words**.

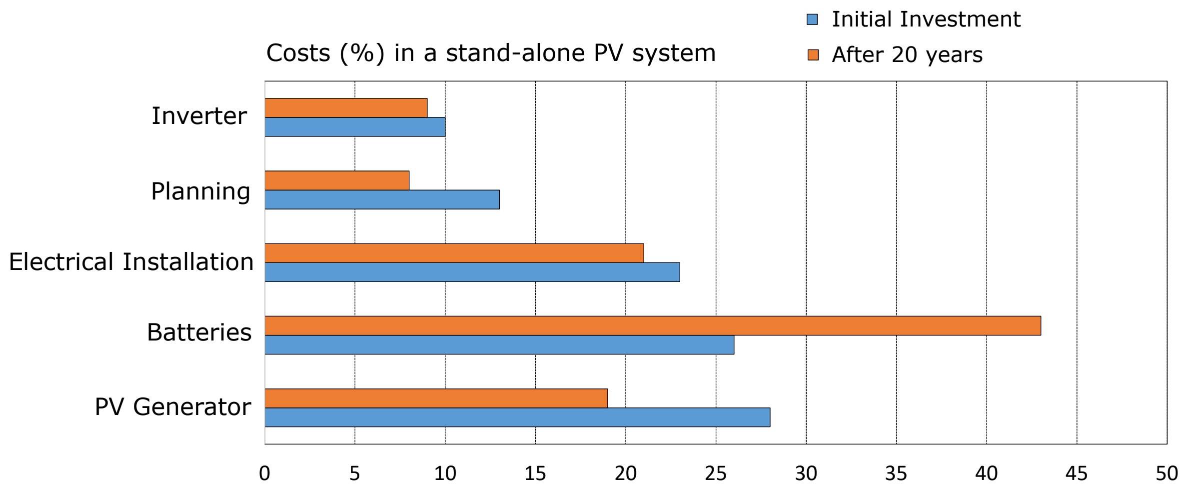


Figure 2.93. Costs associated with a stand-alone PV system: initial investment and after 20 years of operation. Source: Jesus Mirapeix.

Charge/discharge cycles give rise to a reduction in battery capacity[1], due to sulfation affecting the electrodes. Moreover, the capacity is further jeopardized for deep discharges, making it necessary to control them (via the charge controller) to avoid a shortening of their lifetime[2].

This degradation of battery capacity with charge/discharge cycles can be clearly appreciated in Figure 2.94. 4 different battery technologies have been studied, where different strategies like electrode design allow to achieve different lifetimes, although they might require specific control solutions.

Question 7.4: Car Battery ... also for PV systems?

Can a car battery be used in a stand-alone PV system? Explain this **in your own words**.

Although it will be presented in a dimensioning exercise in the following section, it is important to note that a key parameter in this regard is battery **autonomy**. It is expressed in days and can be defined as the time that the PV system can be operative under poor radiation conditions (cloudy days, etc.).

Low values of this parameter **(2-3 days)** will imply a cheaper, but less reliable solution; if **9 to 10 days** are considered, the situation will be the complete opposite. To make a good decision in terms of the battery autonomy it will be important to take into account the weather conditions where the system is located.

[1] The capacity of a battery is defined as the maximum energy that can be stored in the battery; energy that can be taken from the battery as electricity (Diccionario de Ingeniería Eléctrica/Universidad de Salamanca).

[2] The lifetime of a battery is defined as the time when battery capacity is under 80% of its nominal capacity.

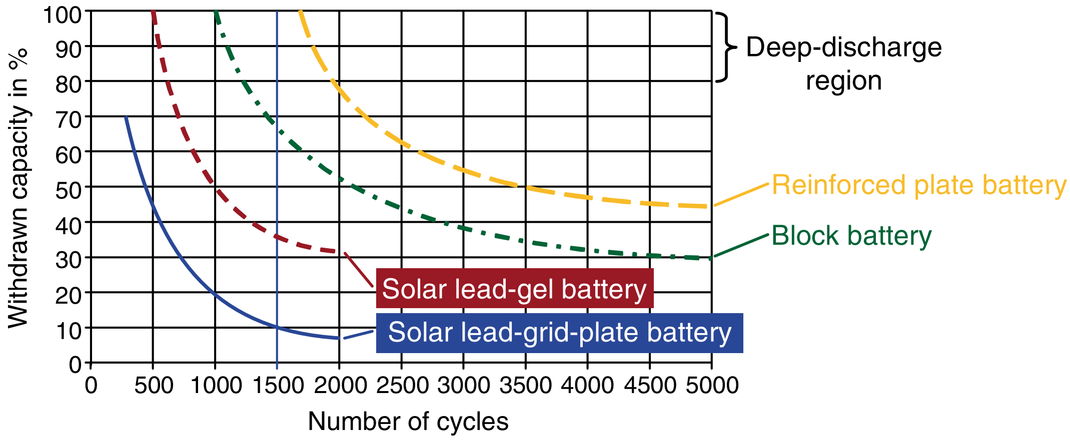


Figure 2.94. Capacity degradation of different battery technologies in terms of charge/discharge cycles. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

2.7.9. System cabling

Although the focus is normally on module selection, inverters, etc.; it is also necessary to pay attention to the correct dimensioning of cabling, as this may give rise, not only to technical problems, but also to an increase in the associated costs.

We already know that DC-DC converters can be included to increase the working voltage and allow a reduction in the associated current and, consequently, in cable diameter.

Although there are different alternatives, a possible solution to the **DC cabling dimensioning** lies in the use of the following expression:

$$S = \frac{2 \cdot L \cdot I}{\kappa \cdot \%}, \tag{2.11}$$

where S is the cable section (mm), L is the cable length, I the current, κ the conductivity (the conductivity of copper is $K_{CU} = 56$) and % the allowable voltage drop over the system voltage (normally 1, 2 or 3 %)[1].

[1] This % is calculated as the % (e.g. 2 %) over the working voltage: for 12V % it would be 0.24V.

2.8. PV Systems: Dimensioning

Having introduced the main concepts of PV technologies and systems, it is now time to analyze some examples of the dimensioning of PV systems. However, prior of all, two parameters must be mentioned that may have a huge impact on the system's performance: the **inclination and orientation** of the PV generator.

2.8.1. Tilt and Orientation of a PV Generator

Have you ever thought about why PV modules are always inclined? **Think about it and try to find a possible answer before continuing to read.**

A valid answer might be related to the module **self-cleaning**[1], which will occur with rain only if the panels are inclined (a horizontal panel would not be effectively cleaned).

However, the real correct answer refers to the optimum reception of solar radiation. What is the sun's path like during the year? We know that it is not constant: the Sun appears higher in the sky in summer and much lower in winter. This has a direct impact on a PV system, as a vertical panel, for example, would receive more light in winter than in summer.

The key is to set a tilt angle enabling a solar radiation with an incidence as orthogonal as possible on the panel surface, thus maximizing the captured radiation and, therefore, the energy produced. Figure 2.95 shows an example of panel tilt in terms of the Sun's path, while Figure 2.96 presents both tilt β and orientation α angles.

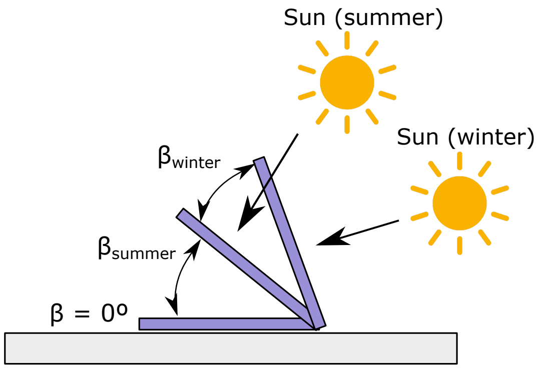


Figure 2.95. Tilt angle of a PV generator in terms of the sun's path (always looking for an orthogonal incidence). Source: Jesus Mirapeix

What is the **optimal orientation** for a module located in Spain? The answer is simple: South! This is the orientation that maximizes the capture of solar radiation. A panel oriented towards the North would not produce almost any energy. Orientation α is defined as the angular deviation with respect to the South ($\alpha = 0$ means South orientation.)

[1] A suitable maintenance of the panels in terms of cleaning their surface is a key factor for the system's production: if the panel surface is uniformly dirty, less light will reach the PV cells and, consequently, less energy will be produced. If there are spots of dirt, then a hot-spot problem may arise.

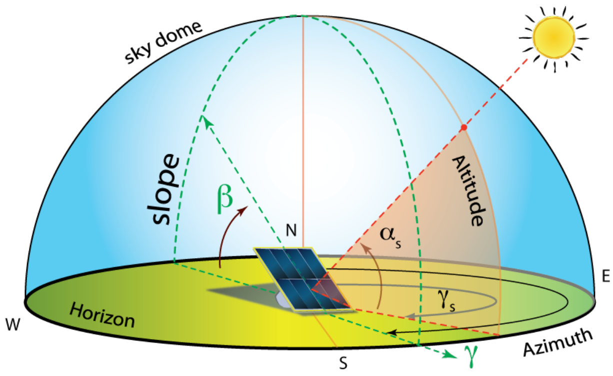


Figure 2.96. Tilt β and orientation α of a PV generator. Source: E-Education `http://bit.ly/2q0hw0h`

Important! 8.1: Orientation and hemispheres

It is worth noting that the South orientation is optimal only for locations in the Northern Hemisphere. PV systems in the Southern Hemisphere should be oriented towards the North.

In Spain, if it is possible (for example for a ground-based PV system) PV modules will be oriented towards the South. Nevertheless, there will some cases, for example for roof-top systems, where there will be no possibility of changing the given orientation.

2.8.2. Optimal Tilt Angle of a PV System

How is the optimal tilt angle of a PV generator at a given location determined? The answer is simple: in terms of the **location latitude**.

Design Period	β_{opt}	$K = \frac{G_{dm}(\alpha=0, \beta_{opt})}{G_{dm}(0)}$
December	$\phi + 10$	1,7
July	$\phi - 20$	1
Annual	$\phi - 10$	1,15

Figure 2.97. Optimal tilt angle β_{OPT} in terms of latitude ϕ. Source: Pliego de Condiciones Técnicas para Instalaciones FV Aisladas del IDAE `http://bit.ly/2CZgHak`

The IDAE recommends (for Spanish PV systems) the procedure described in Figure 2.97. The annual optimal tilt angle (the one that maximizes energy production per year) is calculated by simply subtracting 10 ° from the location's latitude. It is also possible to calculate and use optimal angles for given periods, like summer and winter. In the second column of the table the parameter K appears. It refers to the ratio between the radiation associated with the optimal tilt angle and the radiation associated with a horizontal installation of the module ($\beta = 0°$). There is also an equation that can be used to estimate β_{OPT}:

$$\beta_{OPT} = 3.7 + 0.69\phi \tag{2.12}$$

The PV module support options can also determine the final performance of the system. There are different types of supports:

Fixed support It only allows a single tilt angle, which will normally be the annual β_{OPT}.

Fixed support with different positions There are fixed supports that allow 2 or 4 different positions. This way, the tilt angle can be modified according to the time of the year, choosing for example the β_{OPT} for summer and winter.

Solar Tracking Systems Solar tracking solutions are motorized platforms where the PV generators are mounted, that track the Sun's path during the day (and throughout the year). The use of solar tracking systems (with one or two motorized axes) may give rise to a production increase **up to 40 %**.

Question 8.1: Solar Tracking Systems

Look for information about the different kinds of solar tracking systems (1 axis (polar or azimutal) and 2 axes) and briefly explain their main features.

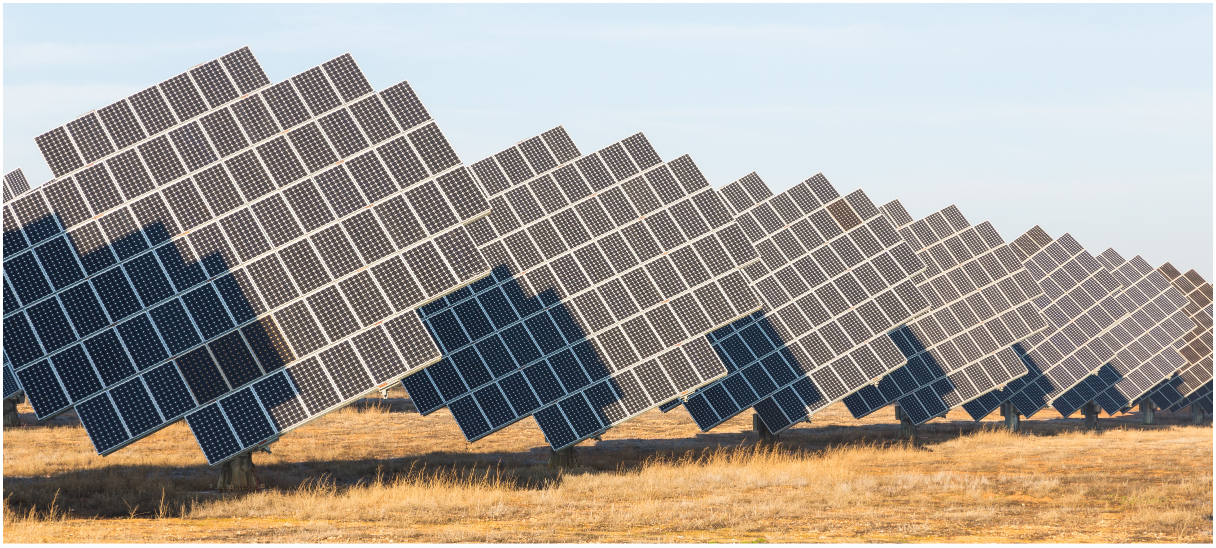


Figure 2.98. Solar tracking systems at a PV plant in Cariñena (Spain) (August 2015). Source: Diego Delso, delso.photo, Licencia CC-BY-SA. `http://bit.ly/2mhjWj1`

Question 8.2: Solar Tracking: Cariñena

Can you see any problems with the PV system design shown in Figure 2.98? Explain the problem and the possible effects it could have on the system: How would you solve it?

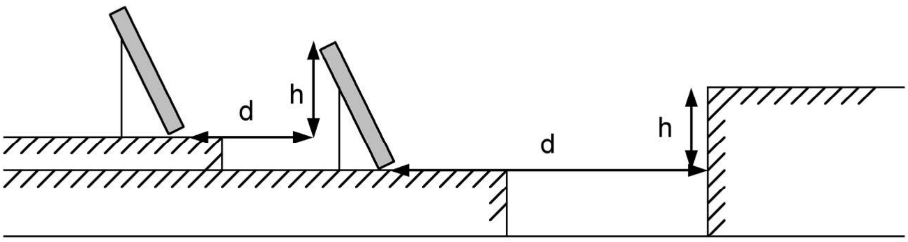
Some comments on the tilt angle of PV modules:

- If panels are tilted and there is more than one row of modules, they might cast shadows (one row on the other), situation that, obviously, should be avoided. Although the required calculations are simple, the IDAE suggests using the criterion given in Figure 2.99. A distance must be observed between consecutive rows to avoid shadowing (depending on the location latitude). Distance ***d*** can be estimated as:

$$d = \frac{h}{\tan(61^\circ - latitude)} \qquad (2.13)$$

And k, which appears in the table:

$$k = \frac{1}{\tan(61^\circ - latitude)} \qquad (2.14)$$



Latitude	29º	37º	39º	41º	43º	45º
k	1,600	2,246	2,475	2,747	3,078	3,487

Figure 2.99. IDAE procedure to avoid shadowing between modules in a PV installation. Source: Pliego de Condiciones Técnicas para Instalaciones FV Conectadas a Red del IDAEhttp://bit.ly/2D0Uvxx

- Generally speaking, roof-top PV systems (especially for homes) tend to use the roof's own inclination as tilt angle, thus avoiding the use of structures that might imply problems in terms of shadowing and, especially **wind resistance (drag force)**. The latter should be calculated and included in the associated project.

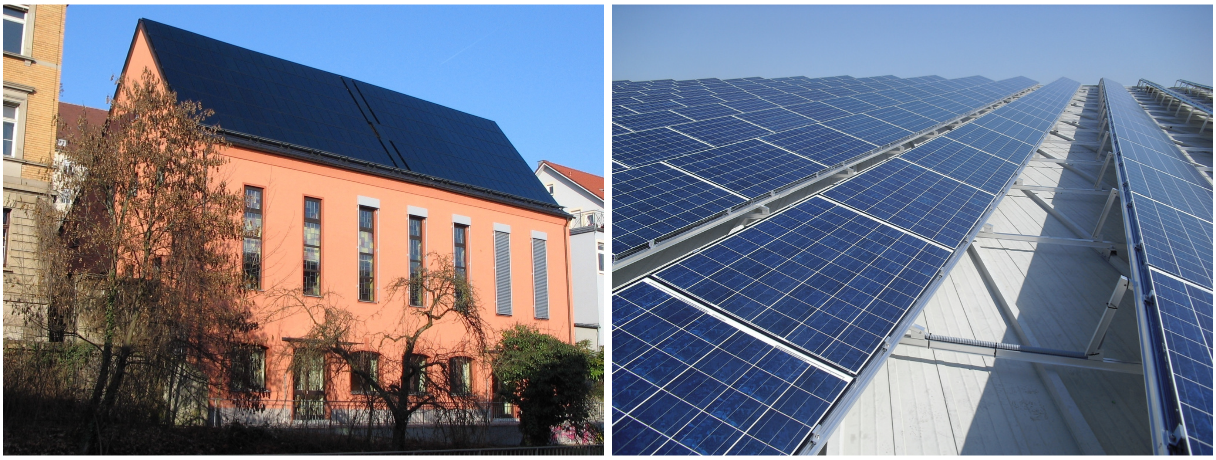


Figure 2.100. Examples of roof-top PV systems (left) using the inclination of the roof; (right) using a structure to establish a better tilt angle. Source: (left) Wikipedia http://bit.ly/2DgfpFH Free GNU License; (right) http://bit.ly/2CPua11 CC-BY-2.0

2.8.3. Shadowing

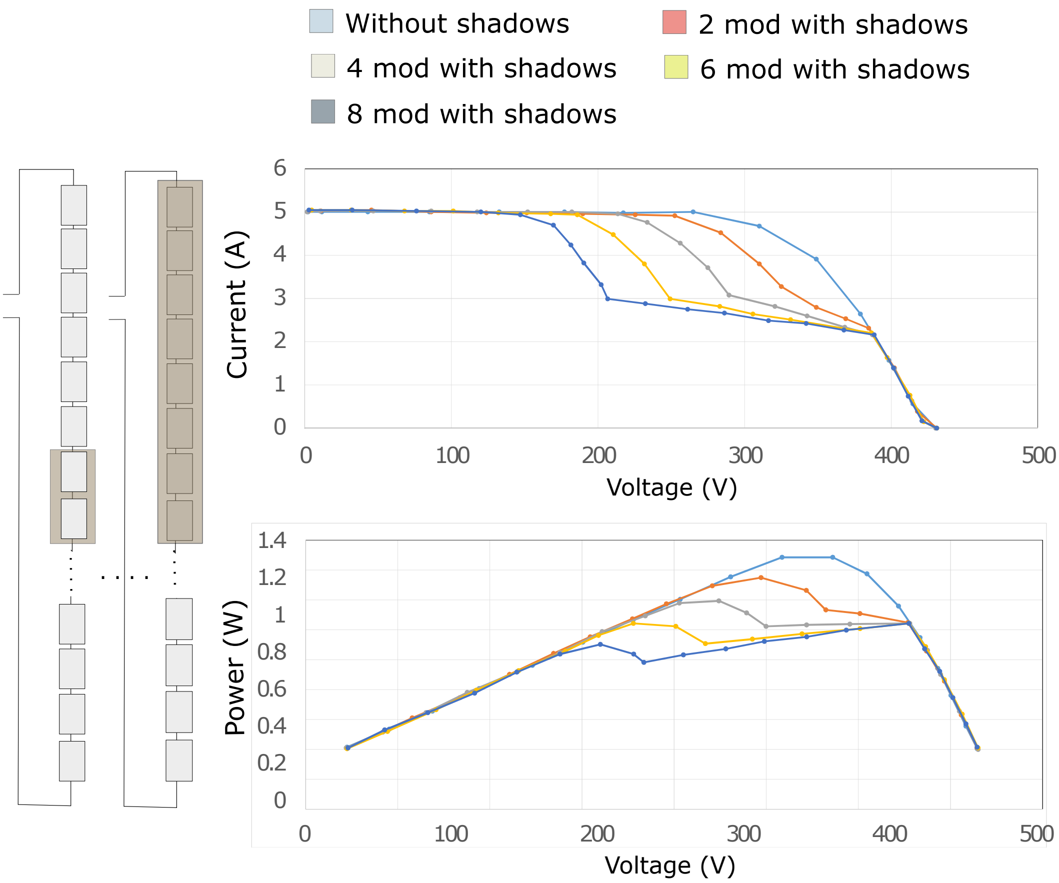


Figure 2.101. Shadowing losses in modules connected in series. Source: Jesus Mirapeix (Data: Planning and Installing Photovoltaic Systems (2nd edition)).

It is important to understand the effect of shadows in a PV system. Figure 2.101 represents the losses associated with a string formed by modules arranged in series. In this

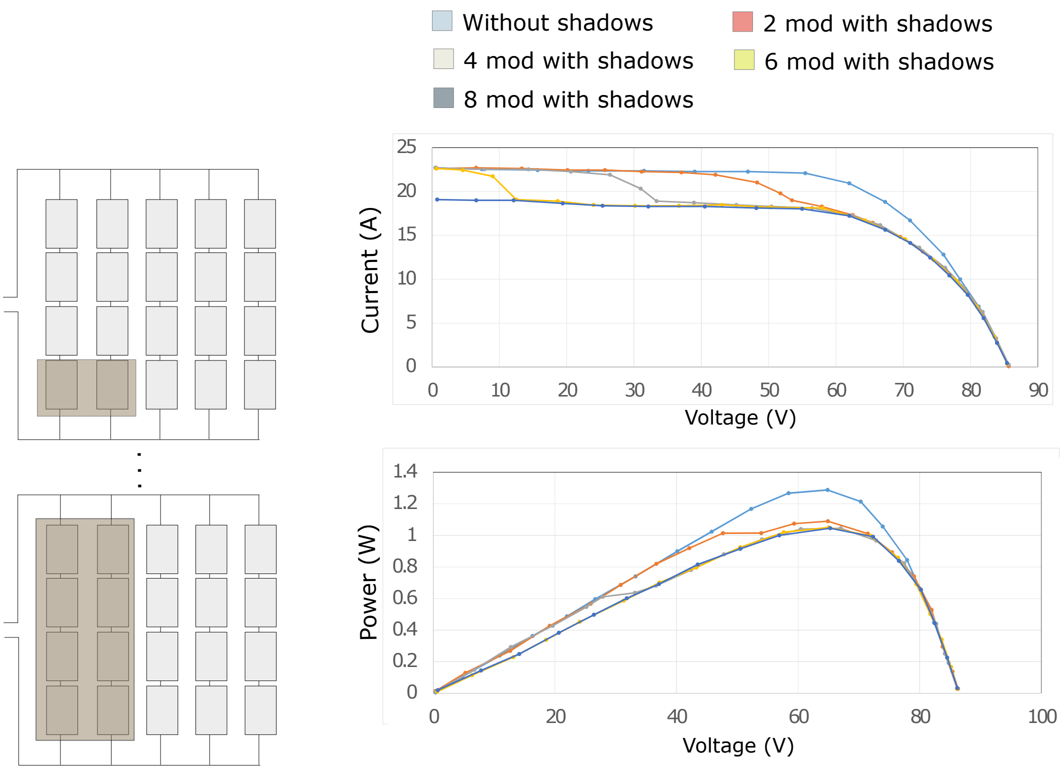


Figure 2.102. Shadowing losses in strings connected in parallel (I). Source: Jesus Mirapeix (Data: Planning and Installing Photovoltaic Systems (2nd edition)).

case, the losses are quite significant. However, if panels are mounted in strings connected in parallel, losses will vary according to the location of strings with respect to the shadows. If shadows affect more than 1 string (Figure 2.103), losses are significantly higher than if shadows affect several panels of the same string (Figure 2.102).

Important! 8.2: Shadowing: Design Recommendations

To conclude, it seems obvious that if shadows can not be prevented in the PV system, it would be highly recommended to follow a design with strings in parallel, where the least ammount of strings possible are affected by shadows. On the contrary, if there are no shadowing issues, the general recommendation is to favor a series design, thus giving rise a lower complexity design (and lower currents), among other factors.

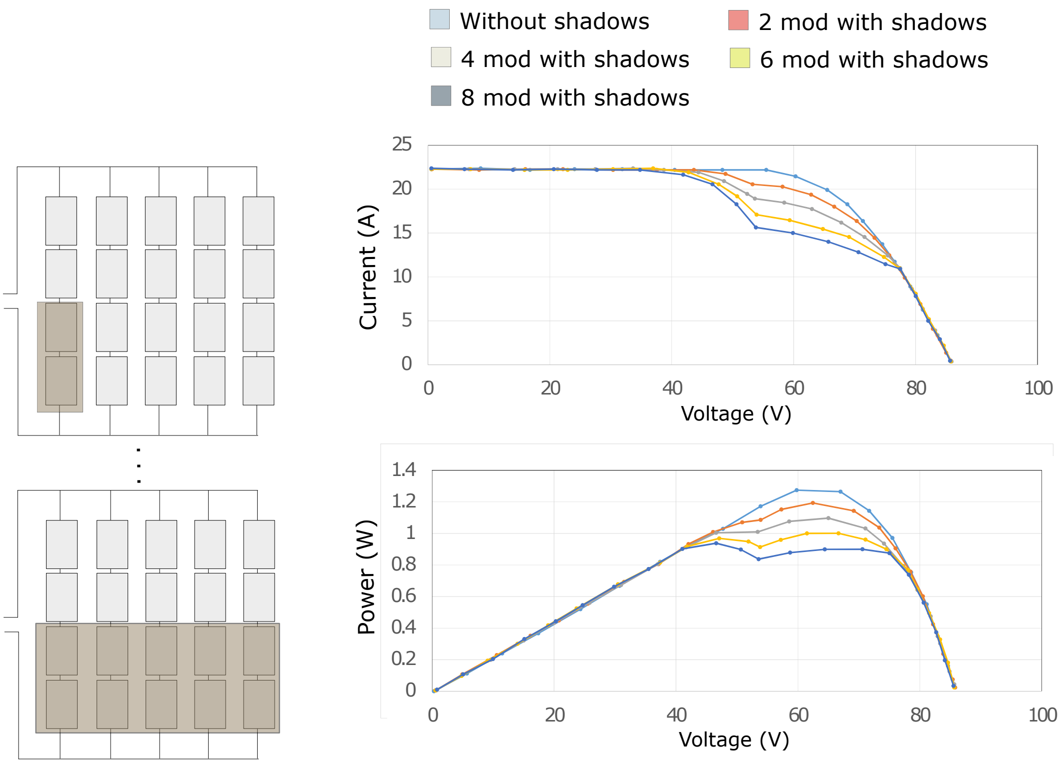


Figure 2.103. Shadowing losses in strings connected in parallel (II). Source: Jesus Mirapeix (Data: Planning and Installing Photovoltaic Systems (2nd edition)).

2.8.4. Exercise 1: Grid-Connected PV System

The data associated with this grid-connected system is listed below:

- Single family home
- Maximum investment of 35000 euros
- Roof surface = 51 m^2 (8.5 x 6.0 m)
- Southern orientation and roof tilt = 45°
- Roof completely free of shadows
- Estimated cost of installed KWp = 5500 euros
- The customer would like to produce as much energy as possible
- Temperature range: (-10°C, 40°C)
- Longitude and latitude: Spain

Initial Approach

Although this step is not necessarily required, it might be interesting to start with an initial estimation of the power/capacity of the final system. This can be performed in different ways, for example if the PV technology surface/power ratio is known[1].

[1] Normally, crystalline-Si will be always used, unless specific conditions require other solutions.

If we assume the use of mono-crystalline Si, the surface/power ratio might be $9m^2/kWp$. Thus:

$$\frac{51m^2}{9m^2/kWp} = 5.67kWp^1 \tag{2.15}$$

Selection of the PV Module

Having decided to use monocrystalline-Si, it is now time to choose a specific model. This decision will be influenced by our knowledge and experience with different manufacturers, etc. In this case let's assume that model SP 165-M 24V has been selected. The main parameters of this module are:

- Peak power: 165 Wp
- Length = 1.61 m; Width = 0.81 m
- V_{MPP} (STC) = 35.35 V
- I_{MPP} (STC) = 4.67 A
- V_{OC} (STC) = 43.24 V
- I_{SC} (STC) = 5.10 A
- Temperature Coefficient of V_{OC} : TK (V_{OC}) = -168.636 mV/K
- Temperature Coefficient of I_{SC}: TK (I_{SC}) = 2.0 mA/K
- Temperature Coefficient of P_{NOM}: TK (P_{NOM}) = -0.420 %/K

Estimation of the Number of Modules to be used

In this exercise, as we are dealing with a roof-top system, the number of modules will be dictated by the available roof surface[2]. As the roof and panel dimensions are known, the process is simple:

Panels installed horizontally

$$num\_panels\_length = \frac{Roof-Length = 8.5m}{Module-Length = 1.61m} = 5.27 \tag{2.16}$$

$$num\_panels\_width = \frac{Roof-Width = 6.0m}{Module-Width = 0.81m} = 7.41 \tag{2.17}$$

[1]**IMPORTANT!**: This information is merely an estimation and it does NOT imply any constraint for the following calculations.

[2]Please note that a "South" orientation has been assumed. Single-family homes normally have gable roofs (with two sloped sides). Of course, modules WILL NOT be installed on the North side of the roof, as the system will be installed in Spain (Northern Hemisphere).

Maximum number of panels: 5 x 7 = 35 modules (horizontally installed)

Panels installed vertically

$$num\_paneles\_length = \frac{Roof - Length = 8.5m}{Module - Width = 0.81m} = 10.49 \tag{2.18}$$

$$num\_panels\_width = \frac{Roof - Width = 6.0m}{Module - Length = 1.61m} = 3.73 \tag{2.19}$$

Maximum number of panels: 10 x 3 = 30 modules (vertically installed)

In this case, the optimum configuration is the horizontal one, as it allows placing 35 PV modules on the roof.

Important! 8.3: Module separation

If this does not appear in the manufacturer datasheet, it is advisable to consider a separation distance between adjacent modules to enable module refrigeration (espacially important for roof-top systems). This refrigeration will prevent overheating that, as already explained in the course, could greatly jeopardize module performance.

2.8.5. Module Voltage Range

Temperature will affect the performance of the modules, especially their output voltage. It is therefore necessary to calculate the output voltage variations using the corresponding temperature coefficients.

Important! 8.4: Temperature Range

For Spain, it is recommended to consider a temperature range between -10 **y** $70°C$ (i.e. with variations of -35 and $+45°C$ in terms of the STC cell temperature). Unless temperatures out of that range are specified, this is the temperature range to be used in calculations.

The resulting voltage range for V_{OC} y V_{MPP} will be:

$$V_{OC}(-10°C) = 43.24V + (-35°C) \cdot (-168.636mV/K) = 49.14V \tag{2.20}$$

$$V_{OC}(70°C) = 43.24V + (45°C) \cdot (-168.636mV/K) = 35.65V \tag{2.21}$$

$$V_{MPP}(-10°C) = 35.35V + (-35°C) \cdot (-168.636mV/K) = 41.25V \quad (2.22)$$

$$V_{MPP}(70°C) = 35.35V + (45°C) \cdot (-168.636mV/K) = 27.76V \quad (2.23)$$

Important! 8.5: Voltage Range

With these calculations we can verify the theory: a monocrystalline-Si standard module will exhibit a large output voltage variation for low and high temperatures. In these cases, these variations (in terms of both nominal voltages) are 6 and 8 V. For connections in series, this value will be multiplied by the number of modules in series in each string.

Important! 8.6: Temperature Coefficients

It is **VERY IMPORTANT** to pay attention to how the temperature coefficients are expressed in the datasheet. They can be expressed in mV/K (as in this example) or in %/K. In this case the % has to be applied to the value of the associated nominal parameter, V_{OC} in the following example (to clarify this issue, the previous calculations are repeated, but this time considering temperature coefficients expressed in %).

Temperature coefficients might also be expressed as %/K[1] (the temperature coefficient of power is always expressed in %):

- Temperature Coefficient of V_{OC} : $T_K(V_{OC}) = -0.400\,\%/K$
- Temperature Coefficient of I_{SC}: $T_K(_{ISC}) = 0.0232\,\%/K$
- Temperature Coefficient of P_{NOM}: $T_K(P_{NOM}) = -0.420\,\%/K$

And doing the calculations again for V_{OC}:

$$V_{OC}(-10°C) = 43.24V + (-35°C) \cdot (-0.400\,\%/K(43.24V)) = \\ 43.24V + (-35°C) \cdot (-0.1730V/°C) = 49.29V \quad (2.24)$$

2.8.6. Selection of Inverter

Generally speaking, for PV systems of up to 5 or 6kWp and where there are no further restrictions in terms of, for example, shadowing , the selection of a **central inverter** design is recommended.

[1] It is the same to express the temperature coefficients in K or ∘C, as a variation of 1 K is equal to a variation of 1∘C

How is the inverter selected? Let's use Equation 2.10:

$$SR_{AC} = \frac{P_{STC}}{P_{INV-AC}} \tag{2.25}$$

It has been mentioned that a factor of $SR_{AC} = 1.1$ is commonly applied. So, considering 35 modules of 165 Wp, the capacity of the PV generator will be of $P_{GEN} = 5775Wp$, and the power of the inverter should be:

$$P_{INV-AC} = \frac{5775Wp}{1.1} = 5.25kW \tag{2.26}$$

Any given model satisfying this requirement could be used. Let's use for example the Sunny Boy models of SMA (link to download the datasheet: `http://bit.ly/2Fu0k3T`).

Attending to the parameter *Max. recommended PV power (@ module STC)*, the model Sunny-Boy 5000-US might be chosen. However, taking into consideration the Sizing Ratio criterion, we should opt for the 6000 model (see *AC nominal power*)

The key parameters (from the dataset) for this dimensioning stage are:

- Max. DC voltage = 600 V
- Min. DC voltage = 250 V
- Max. input current / per string = 25 A / 20 A
- Number of MPP trackers / fused strings per MPP tracker = 1 / 4
- MPP voltage range = 250 V – 480 V

2.8.7. Module/Inverter Configuration: Number of Strings

Using the module voltage range previously determined, the maximum N_{MAX} and minimum N_{MIN} number of modules connected in series per string can be established:

$$N_{MAX} = V_{INVMAXDC}/(V_{MPP}(-10°C)) = (600V)/(41.25V) = 14.46modules \tag{2.27}$$

$$N_{MAX} = V_{INVMINDC}/(V_{MPP}(+70°C)) = (250V)/(27.76V) = 9modules \tag{2.28}$$

Only the condition for V_{MPP} has been checked, but we know that the open circuit voltage will always be the maximum that a module can produce, so this will always be the limiting factor in terms of the maximum number of modules connected in series per string:

$$N_{MAX} = V_{INVMAXDC}/(V_{OC}(-10°C)) = (600V)/(49.14V) = 12.21 modules \quad (2.29)$$

With these calculations three strings could be connected to the inverter (the selected model allows up to 4 inout strings). Each string will have 9 to 12 panels connected in series.

With this information, and having determined that the roof allows the installation of 35 modules, the best configuration in terms of number of modules/capacity should be chosen. In this case, this configuration would be formed by **3 strings with 11 modules per string** (33 modules).

Important! 8.7: Central Inverter

As already explained in this chapter, the inverter will be able to efficiently manage the MPP of the whole PV generator if the modules of each string exhibit the same features (tilt, orientation) and, of course, if **each string has the same number of modules**.

It is now necessary to verify that, for the chosen configuration, the current limitations of the inverter are also satisfied:

The maximum module current (short-circuit) is I_{SC}(STC) = 5.10 A. As three parallel strings have been defined:

$$3 \cdot I_{SC} = 15.30A \leq 20A \quad (2.30)$$

The current limitation of the inverter is therefore satisfied.

Important! 8.8: Final Design

The final design of the PV system will consist of 33 panels arranged in 3 parallel strings with 11 panels in series for each string. The 3 strings will be controlled by a central inverter.

Question 8.3: Final Revision: Inverter

Check the inverter datasheet again and verify that, according to the exercise's information, the chosen model will not give rise to any problems according to the final design. Justify your answer.

Question 8.4: Variations of the exercise

To verify that you have correctly understood the procedure used for this grid-connected PV system dimensioning, repeat the process, this time considering the following modifications:

- Roof: assume the same surface, but in this case the orientations will be East and West (Each roof side has the same surface: $51m^2$)
- Modules: look for other models of mono or poly-crystalline-Si modules and repeat all the calculations. Try to find out the PV module price.
- Inverter: choose a different inverter model (from another manufacturer) and repeat the necessary calculations to verify that it could be used in this system. Try to find out the inverter price.

2.8.8. Exercise 2: stand-alone PV system for a home

In the previous exercise we carried out different calculations associated with a PV system. However, there are aspects that are specifically limited to stand-alone PV systems, like the analysis of the energy demand, battery dimensioning, etc.

Let's see the information provided for this exercise:

- Stand-alone PV System for a home isolated from the power grid
- It will be used continuously between March and October, and intermittently during the winter.
- The customer wants an AC installation (loads)
- Small, shadowed roof: the system will be installed on the ground, on an area adjacent to the home (30 m away).
- Global efficiency of the PV system: 60 %.

Table 2.3. Energy Demand Analysis

Loads	P (W)	Nº	$P_{TOTAL}(W)$	Hours	Wh
Fluorescent Lamps	11	3	33	3	99
Kitchen Lamps	20	1	20	1.5	30
Other Lamps	100	2	200	0.2	40
TV	60	1	60	1	60
Microwave	700	1	700	0.4	140
Mixer	400	1	400	0.1	40
Refrigerator	80	1	80	5	400
Total			**1493 W**		**809 Wh**

Energy Demand

In this kind of PV system, it is very important to perform a correct study of the energy demand. In this case, the consumptions described in Table 2.3 have been assumed.

Important! 8.9: Consumptions in homes with stand-alone PV systems

Although many different scenarios can be described, there are situations (homes that are not considered as usual places of residence) were the consumptions will be reduced as much as possible. If the system is designed for an usual place of residence, an instantaneous self-consumption scheme, or a system backed by batteries might be suitable alternatives. Additionally, diesel generators or even power-grid backup could be also considered.

Solar Radiation Data

The home is located in Santander (latitude 43.47°).

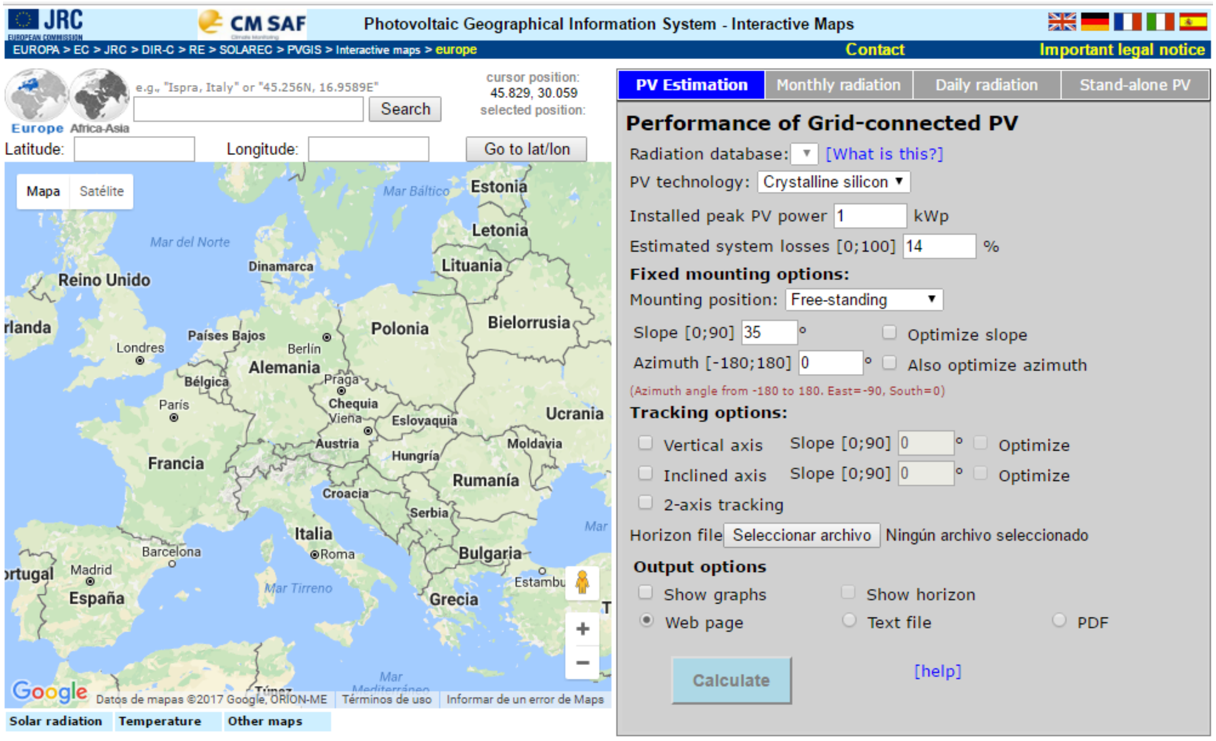


Figure 2.104. Screenshot of the online application PVGIS. Source: PVGIS (c) European Communities, 2001-2012. Reproduction is authorised, provided the source is acknowledged. `http://re.jrc.ec.europa.eu/pvgis/`

PVGIS will be chosen to retrieve these data: `http://bit.ly/2D3ZME1`

Fixed supports for the panels will be assumed and, consequently, the annual optimum tilt angle will be used. Following the IDAE criterion:

$$\beta_{OPT} = \alpha - 10 = 33.47°$$

PVGIS gives us the possibility of selecting the tilt angle for the irradiance data.

A common rule for these systems is to carry out the dimensioning for the worst case scenario, the "worst month" method.

It might be also interesting to work with irradiance data expressed in **peak sun hours** (PSH)[1]. In this case PSH = 2.29 hours.

Important! 8.10: Peak Solar Hours

PSH is an important concept. For a different location, use PVGIS to obtain the irrandiance data and try to estimate the equivalent PSH for a given day in August.

[1] PSHs are defined as the hours that, assuming a Sun with a constant irradiance of $1000W/m^2/$ (STC irradiance), give rise to an irradiance equivalent to the measured one.

Month	Hh	H(33)	TD
Jan	1410	2280	10.4
Feb	2180	3140	10.1
Mar	3610	4530	12.7
Apr	4380	4780	14.5
May	4960	4910	15.5
Jun	5400	5140	18.2
Jul	5430	5270	20.3
Aug	4770	5030	20.8
Sep	4100	4990	20.1
Oct	2730	3770	18.6
Nov	1550	2400	14.5
Dec	1310	2280	12.5
Year	3490	4050	15.7

Hh: Irradiation on horizontal plane (Wh/m2/day)

H(33): Irradiation on plane at angle: 33.47deg. (Wh/m2/day)

TD: Average daytime temperature (°C)

Figure 2.105. PVGIS data obtained for the chosen location. Source: PVGIS (c) European Communities, 2001-2012. Reproduction is authorized, provided the source is acknowledged. http://re.jrc.ec.europa.eu/pvgis/

PV Generator Dimensioning

The expression to be used in this case to estimate the capacity of the PV generator is:

$$P_{PV} = \frac{E}{G \cdot \eta_{SYS}} \tag{2.31}$$

Where E is the demanded energy, G the irrandiance (expressed in PSHs) and eta_{SYS} the global efficiency of the PV system. Consequently:

$$P_{PV} = \frac{809Wh}{2.28 \cdot 0.6} = 591.4Wp \tag{2.32}$$

The system's efficiency, 60% (0.6) in this case, should be specified in the exercise's information. It can be also calculated if the individual efficiencies of each system component are known:

$$\eta_{SYS} = \eta_{GEN} \cdot \eta_{CC} \cdot \eta_{C-GEN-CC} \cdot \eta_{BAT} \cdot \eta_{C-CC-BAT} \cdot \eta_{INV} \cdot \eta_{C-BAT-INV} \cdot \tag{2.33}$$

PV generator, charge controller, PV-generator/charge-controller cabling, battery, charge-controller cabling/battery cabling, inverter and battery/inverter cabling efficiencies are considered.

Battery sizing

The capacity of the batteries can be sized using the following expression:

$$Q = \frac{E \cdot A}{V \cdot T \cdot \eta_{INV} \cdot \eta_{CABLE}} \tag{2.34}$$

Where E is again the energy demand, A the battery autonomy, V the working voltage ($24V_{DC}$ in this case) and T the battery discharge depth (50 % will be assumed). Replacing these values in the previous expression:

$$Q = \frac{809Wh \cdot 5days}{24V \cdot 0.5 \cdot 0.9 \cdot 0.97} = 386Ah \tag{2.35}$$

Module Selection

As the PV capacity has been established in 591Wp and the working voltage is $24V_{DC}$, a possible solution would be to choose 4 modules of 150 Wp and 12 V to be deployed in 2 strings with 2 panels in series in each string.

A possible PV module model: Renogy 150 Watt 12 Volt Monocrystalline Solar Panel[1].

The module datasheet specifies a short-circuit current of $I_{SC} = 9.05A$. With the chosen design this will imply a total PV generator current of: $I_{SC} = 18.10A$.

Charge Controller Dimensioning

As indicated in the section on charge controllers, their sizing should take into account both input and output currents:

$$I_{INPUT} = 1.25 \cdot I_{SC-GENERATOR} = 1.25 \cdot 18.10A = 22.625A \tag{2.36}$$

$$I_{OUTPUT} = 1.25 \cdot (P_{DC} + (P_{AC}/\eta_{INV}))/V_{BAT} \tag{2.37}$$

Assuming AC loads:

[1] http://amzn.to/2qYV7OL

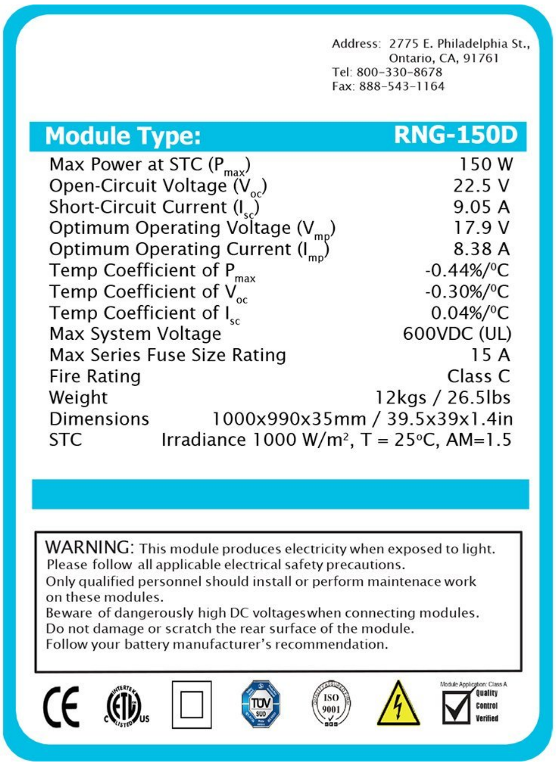


Figure 2.106. Data associated with the chosen PV module: Renogy 150 Watt 12 Volt Monocrystalline Solar Panel

$$I_{OUTPUT} = 1.25 \cdot (1493W/0.9)/24V = 86.4A \tag{2.38}$$

Now, an inverter must be selected with these data. A possible choice would be the Steca PR-3030 model, with a maximum input current of 30 A[1].

Question 8.5: Charge Controller Selection

Check the manufacturer datasheet and verify that the chosen model can be safely used in this system

Try to find possible alternative models and, if you can, their price.

System Design

Once the main calculations have been done, it is important to take a look at the resulting design. Figure 2.107 depicts two possible solutions.

While the scheme at the top proposes the connection of the inverter to the batteries, in the other solution it is directly attached to the output of the charge controller. Although the latter allows a less demanding use of the battery, the recommended design is,

[1] `http://bit.ly/2DmNDXZ`

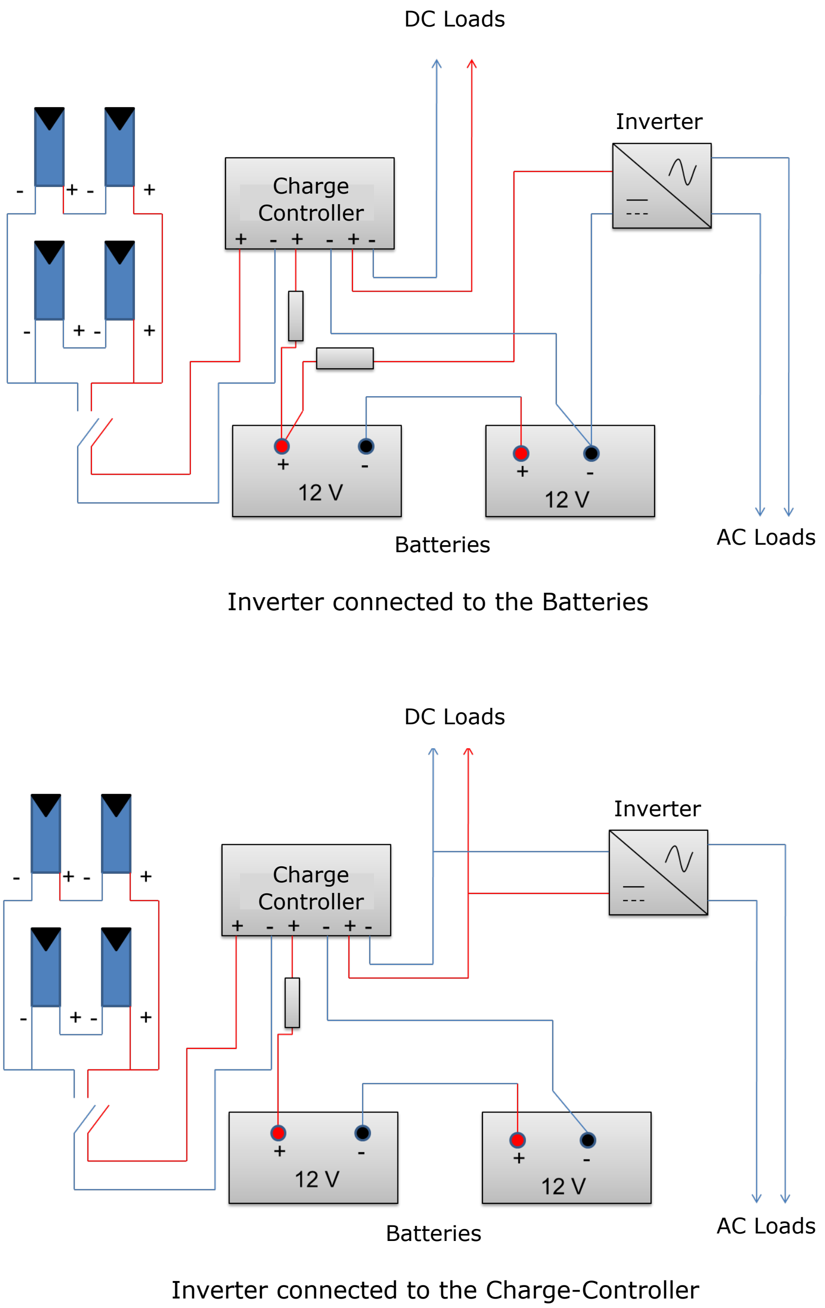


Figure 2.107. Possible solutions for a stand-alone PV system with AC loads. Source: Jesus Mirapeix.

generally speaking, the former.

The connection of the inverter to the battery is recommended because, depending on the chosen devices, the current demanded by the inverter (86A in this example) will clearly exceed the one offered by the charge controller. This way, it would be more expensive to buy a charge controller with these specifications than to connect the inverter to the battery.

Dimensioning in this exercise has now been finished. It only remains to determine the cable section (with Equation 2.39) and choose an inverter able to provide the required power.

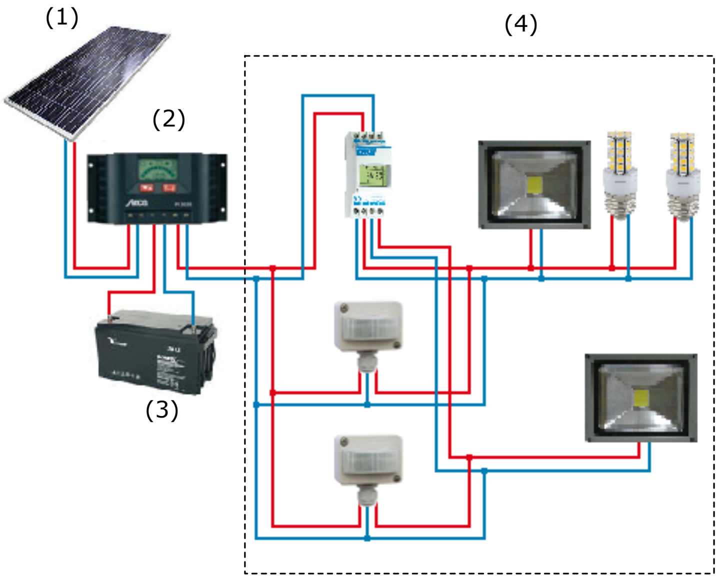


Figure 2.108. Stand-alone PV system: (1) PV generator; (2) Charge controller; (3) Batteries; (4) Loads. Source:Jesus Mirapeix.

2.8.9. Exercise: Stand-alone System for Home Outdoor Lighting

This is a very specific example, intended to serve as an exercise for analyzing the cable sizing of a PV system. This is in fact a real project, carried out following the TFG[1] by David Lavín in "*Instalación fotovoltaica aislada programable para alumbrado exterior con detector de presencia*"[2].

The goal of this project was to power supply a simple outdoor lighting system, which also included presence detectors, for a single-family home in Cantabria. Tthe system was intended, not only for lighting purposes, but also for anti-intruder purposes.

The system design was already presented in Figure 2.91. In this case, the PV system does not require an inverter, as all the consumptions will be performed in DC.

The chosen module is a 100 Wp model, with a 15 W charge controller and a 55 Ah battery. The project budget is also shown in Figure 2.110. It is worth noting that the cabling cost is significant (148 euros) in terms of the global budget (cabling is more expensive in this case than the PV generator, the charge controller and the battery).

Let's see how cabling sizing was carried out:

Charge-controller/Loads Cable To avoid installing the module on the home roof, it was finally installed on a concrete post (7 meters high), 29.5 m away from the charge controller protection box. Using Equation 2.39:

[1] TFG: Trabajo Fin de Grado [End-of-degree assignment].
[2] The project document is available at: `http://bit.ly/2DpnesS`

Figure 2.109. PV system images (from top to bottom and left to right): single-family home with the outdoor lighting system; detail of the installed PV module; 20W LED and PIR detector; charge controller and battery. Source: *Instalación fotovoltaica aislada programable para alumbrado exterior con detector de presencia (David Lavín)* . License: CC-BY-SA 3.0.

Ítem	Descripción	Cantidad	Precio	Precio Total
1	Módulo FV Policristalino 100Wp	1	69,10€	69,10€
2	Regulador de 15A	1	88,90€	88,90€
3	Batería AMG de 55Ah	1	99,90€	99,90€
4	Interruptor astronómico	1	132,69€	132,69€
5	Proyector LED (20W)	2	40,95€	81,90€
6	Lámpara LED (7W)	2	3,69€	7,38€
7	Detector de Presencia	2	6,65€	13,30€
8	Cuadro eléctrico	1	70,00€	70,00€
9	Cable 25mm	59m	2,13€	125,67€
10	Cable 2,5mm	51m	0,44€	22,44€
11	Material vario	-	67,18€	67,18€
*No se tienen en cuenta los gastos de instalación				Total: 778,46€

Figure 2.110. PV system budget. Source: *Instalación fotovoltaica aislada programable para alumbrado exterior con detector de presencia (David Lavín)* . License: CC-BY-SA 3.0.

$$S = \frac{2 \cdot 29.5 \cdot 4.58A^1}{56 \cdot \%} = 20.10mm^2 \tag{2.39}$$

A cable section of $25mm^2$ will be chosen.

PV Generator/Charge Controller Cable The cable length in this case will be of 5.5 m and the maximum current of 5.56 A. Repeating the previous process a cable section of $4.55mm^2$ was obtained, so a $6mm^2$ will be selected.

Important! 8.11: DC-DC Converter and Cabling in a PV System

This example has been included to point out the importance of performing a correct cable sizing. This will not only affect the proper operation of the system, but also the final system budget.

The designer must decide if including a DC-DC converter should be considered to increase the working voltage and, therefore, allow a reduction in the associated cost.

2.8.10. Exercise: PV System based in "The Martian"

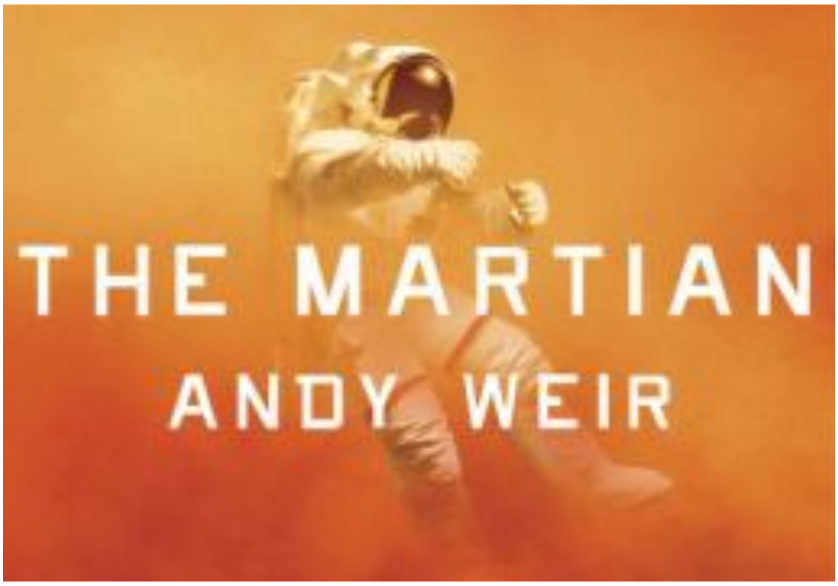


Figure 2.111. Cover of Andy Weir's novel "The Martian". Source: Wikimedia. License: Creative Commons Attribution 3.0 Unported. http://bit.ly/2mwwHaA

Andy Weir's novel "The Martian", which has also been adapted for the screen by Ridley Scott and features Matt Damon in the leading role, tells the story of an astronaut abandoned in Mars.

Our hero has to use all his resources to survive and, among his many adventures, he is forced to design a PV system (there were PV modules in the station up there) to power supply a Rover vehicle.

The novel and film are, by the way, very interesting. The first is particularly a tech and science "geeks", as the novel tries to be realistic at all times.

Inspired by this novel, the following exercise is proposed:

You are an astronaut abandoned in Mars, as your team has mistakenly assumed that you were killed in an accident caused by a martian storm and they are on their way back home (to Earth). Unfortunately, you can not communicate with the NASA, so your only chance of survival is to travel the 3500 km that separate you from the Mars Pathfinder location. It has some equipment that could allow you to communicate with the NASA and increase your chances of being rescued.

To travel that distance you have:

- *2 Mars Rover vehicles, each one with a 9000 Wh battery.*
- *The autonomy of each rover is estimated to be 35 km, assuming a fully charged battery and the consumption of the vehicle heating system for a standard mission (5 hours).*
- *The maximum speed of the Rover is 25 km/h.*
- *50 PV modules (Efficiency 10.2%) with a module surface of 2 m^2*

The average temperature on Mars is -60°C. This is why the Rovers include a heating system (power = 200 W). Suppose that a day on Mars lasts 24h30min, and that there are 13 hours of daylight (to simplify calculations, you can use a constant irradiance over 12 hours, for example).

1. Calculate how many panels are necessary to achieve your goal, and the time that it will take (round trip)
2. Repeat the previous section, assuming that you now have a RTG (Radioisotope Thermoelectric Generator) powered by Plutonium-238 that generates 1500 W as heat or 1000 W of electricity. You can assume that the RPG produces enough heat as to survive within the Rover or use the additional 1000 W of electricity to power supply the system.

Question 8.6: The Martian: Solution

Try to find a possible solution to this exercise. The solution will be published on the Moodle website of the course.

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