Sustainable and Green Technologies
Solar Energy

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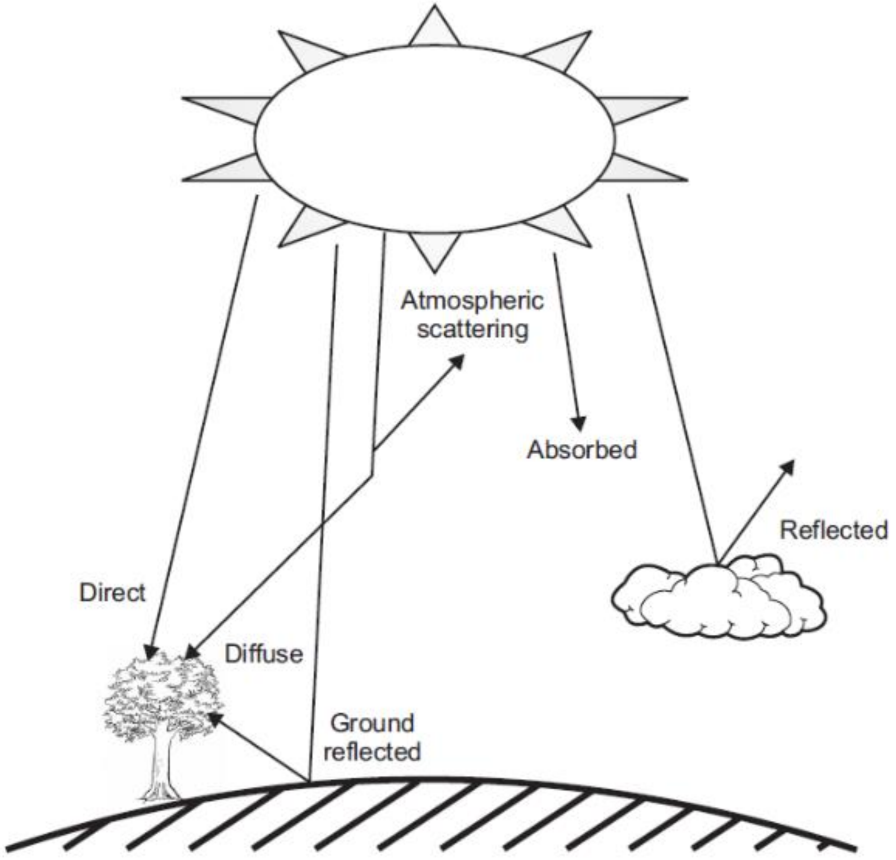
Today’s Outline

- Sun is the main energy source of our planet
- How is energy generated in the Sun?
- Solar Thermal Energy
- Solar Photovoltaics (PV)
- PV Technologies

Sun is the main energy source of our planet

- The Sun is a gaseous body composed mostly of hydrogen.
- Gravity causes intense pressure and heat at the core initiating nuclear fusing reactions.
- This means that atoms of lighter elements are combined into atoms of heavier elements, which release enormous quantities of energy.
- **Solar radiation often called the solar resource**, is a general term for the **electromagnetic radiation emitted by the Sun.**
- Solar radiation can be captured and turned into useful forms of energy, such as heat and electricity, using a variety of technologies.
- However, the technical feasibility and economical operation of these technologies at a specific location depending on the available solar resource.
- Every location on Earth receives sunlight at least part of the year.
- **What is Solar Energy?** https://www.youtube.com/watch?v=inPtRWtvDaM&t=19s

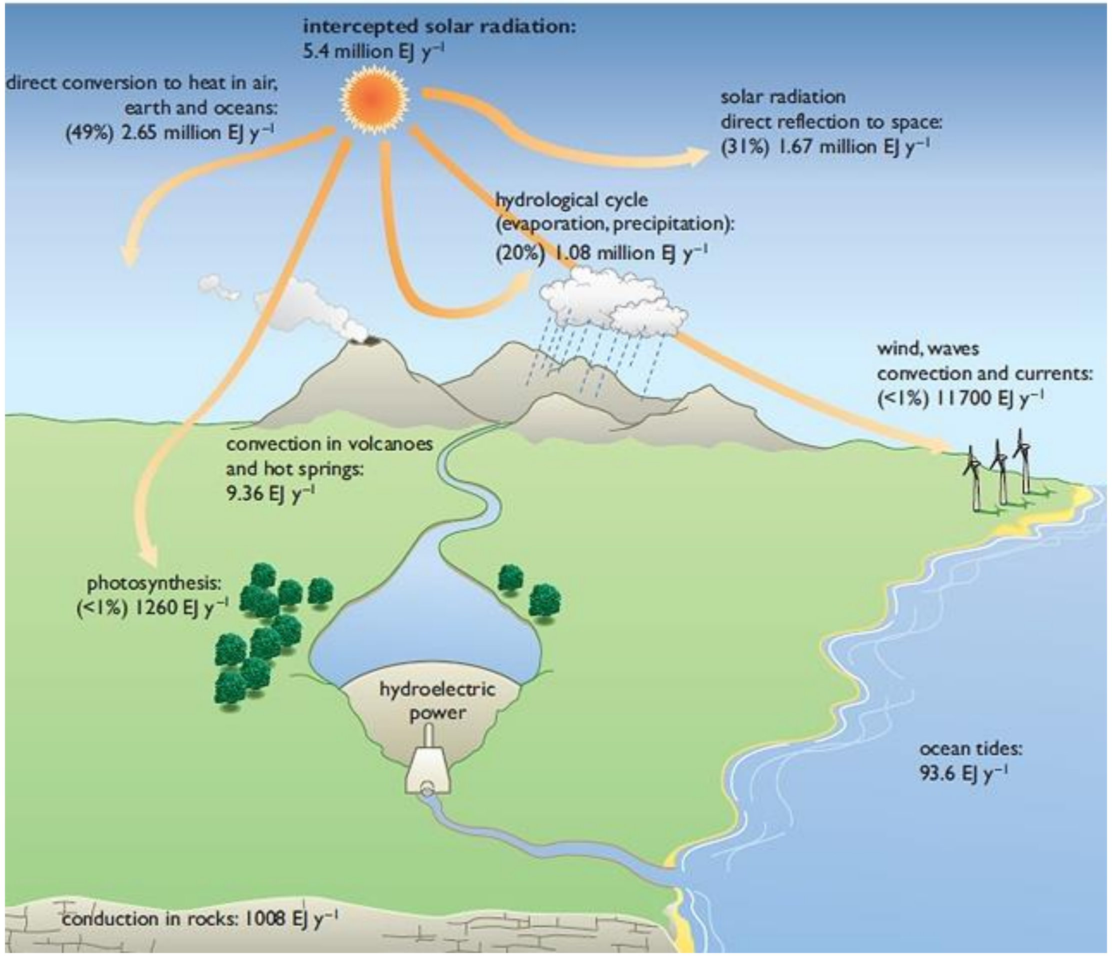
Sun is the main energy source of our planet



Atmospheric effects of solar radiation

- 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, hydo-power, 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.

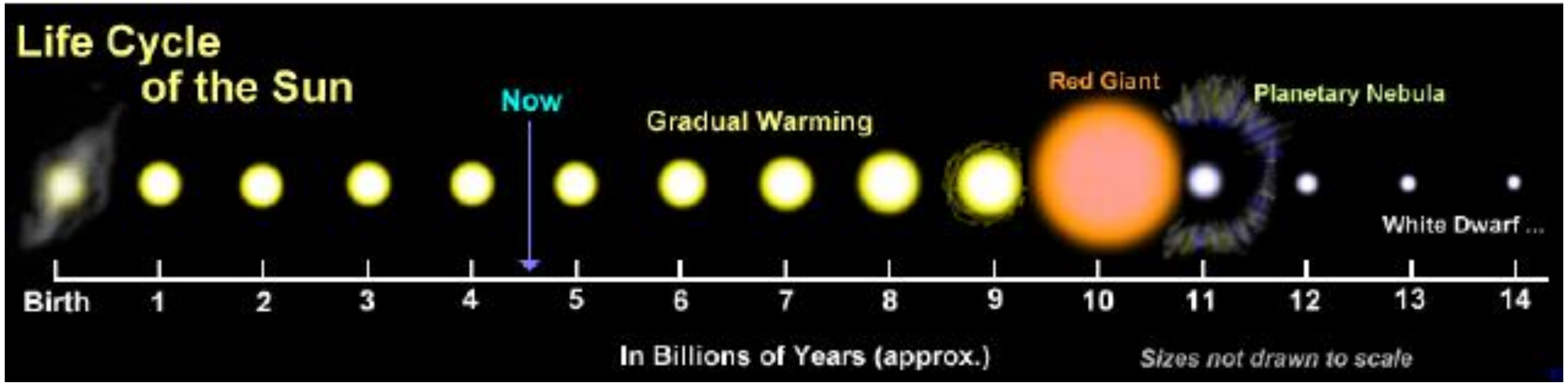
Sun is the main energy source of our planet



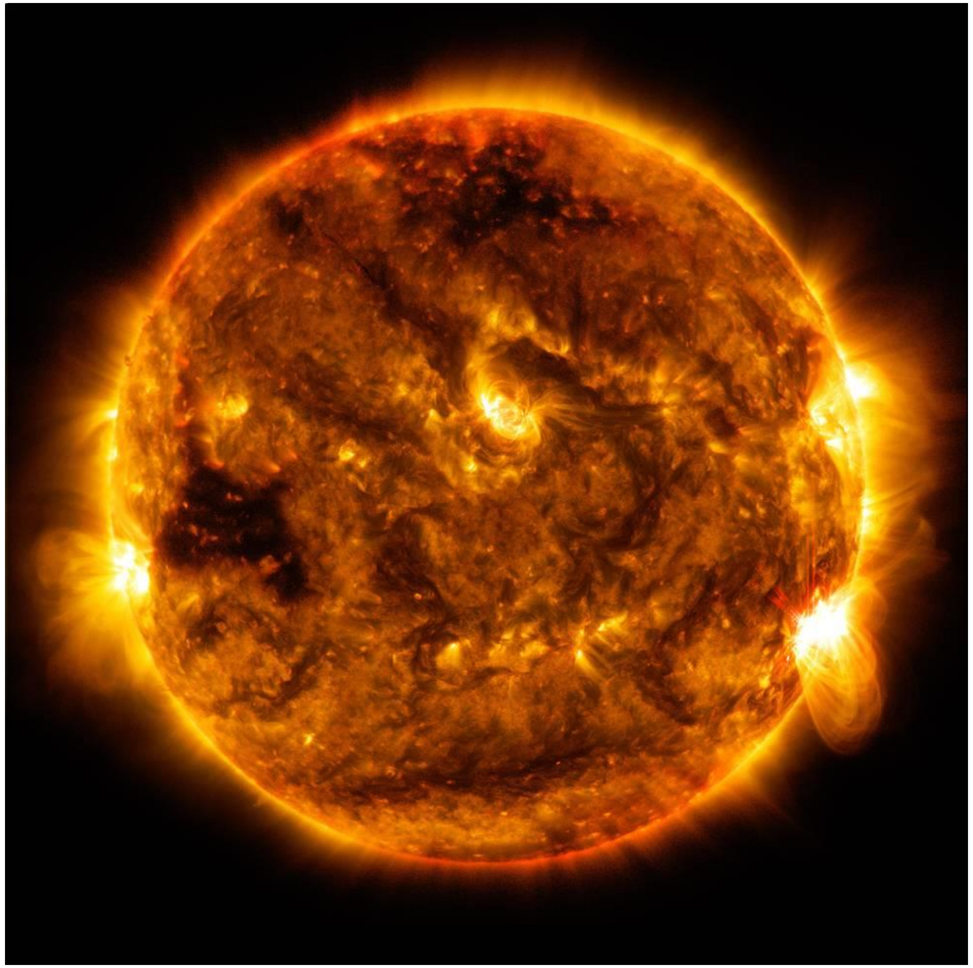
Schematic representation of the Sun's influence on different energy sources
Source: Open.edu http://bit.ly/2BHKnFT

- We are highly dependent on the sun, that contributes 5.4 million EJ (exa-jules = 1018 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.

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



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



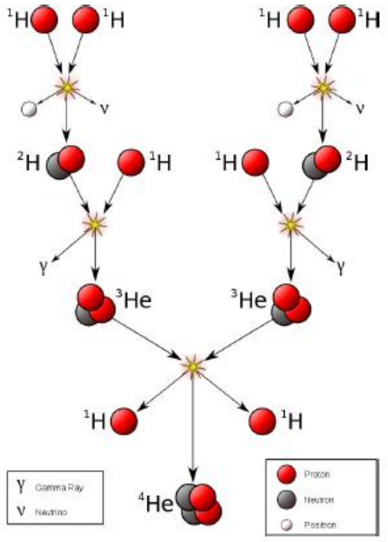
- The sun emitted a mid-level solar flare, peaking at 8:13 p.m. EDT on Oct. 1, 2015.
- NASA’s Solar Dynamics Observatory, which watches the sun constantly, captured an image of the event.
- Solar flares are powerful bursts of radiation.
- Harmful radiation from a flare cannot pass through Earth's atmosphere to physically affect humans on the ground, however -- when intense enough -- they can disturb the atmosphere in the layer where GPS and communications signals travel.

A mid level Solar Flare

Source: NASA/SDO**; Published:** April 4, 2018
https://solarsystem.nasa.gov/resources/768/nasas-sdo-sees-sun-emit-mid-level-flare-oct-1/?category=solar-system_sun

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** take place.
- In the Sun, two H protons get so close that the strong nuclear interaction overcomes the mutual electrical repulsion.



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

- **Gamma rays** are the most energetic radiation known in the universe however, although they are generated in the Sun, this radiation does not reach the Earth.
- We receive “light” in the UV, visible and IR ranges.

- How much energy is generated in the Sun? The famous **Einstein equation** can be used here:

$$E = mc^2$$

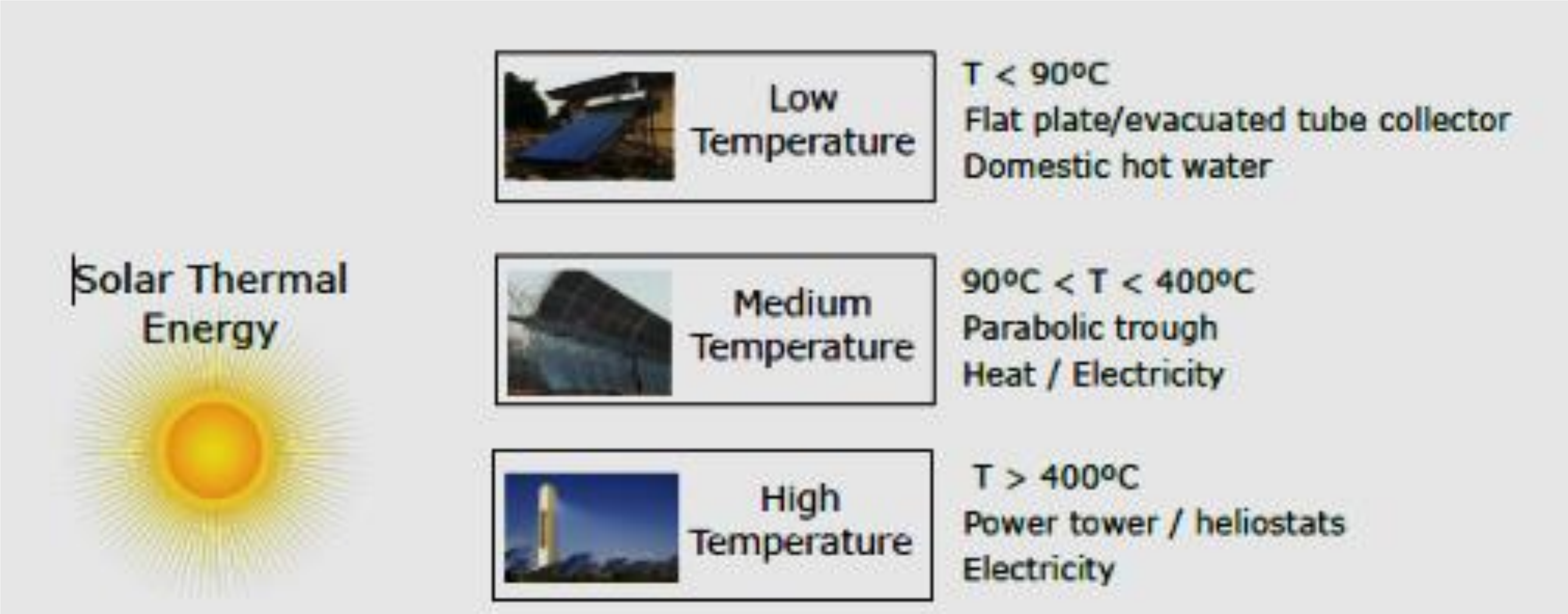
- In this expression, energy *E* and matter *m* are related by constant *c* (speed of light in vacuum).
- In the Sun 600 million tons of H are burnt per second to generate 596 million tons of He (via nuclear fusion) but: where are the remaining 4 million tons?
- They have been converted into energy during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

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 ^{o}C
  - **Medium temperature** for working temperatures between 90 and 400 ^{o}C
  - **High temperature** for working temperatures higher than 400 ^{o}C
- 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.



Solar thermal energy is classified by working temperature (Source: Jesus Mirapeix)

Solar Thermal Energy: Low Temperature

- Low-temperature installations (also known as *Solar Water Heating (SWH) Systems*), are 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.

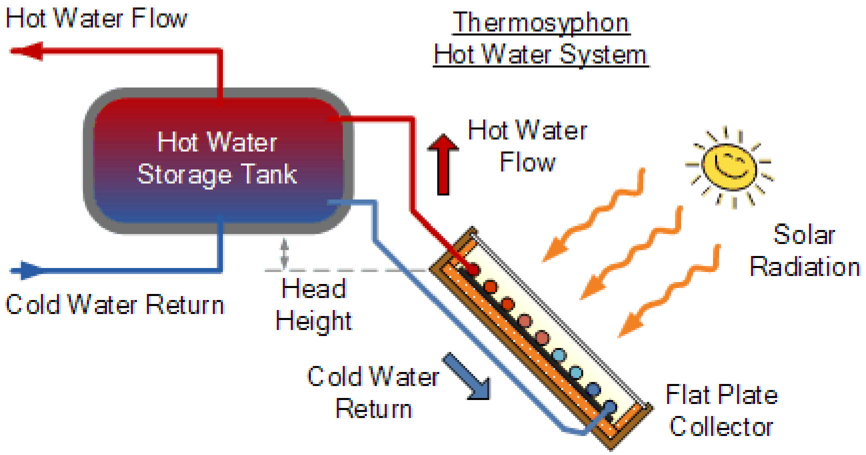
  - **Solar thermal energy | Simply explained | Photovoltaics vs Solar thermal systems**

  https://www.youtube.com/watch?v=JsAdmpq8zTU

6 Types of Solar Thermal Collectors
https://www.youtube.com/watch?v=rg1x4jJmSl4

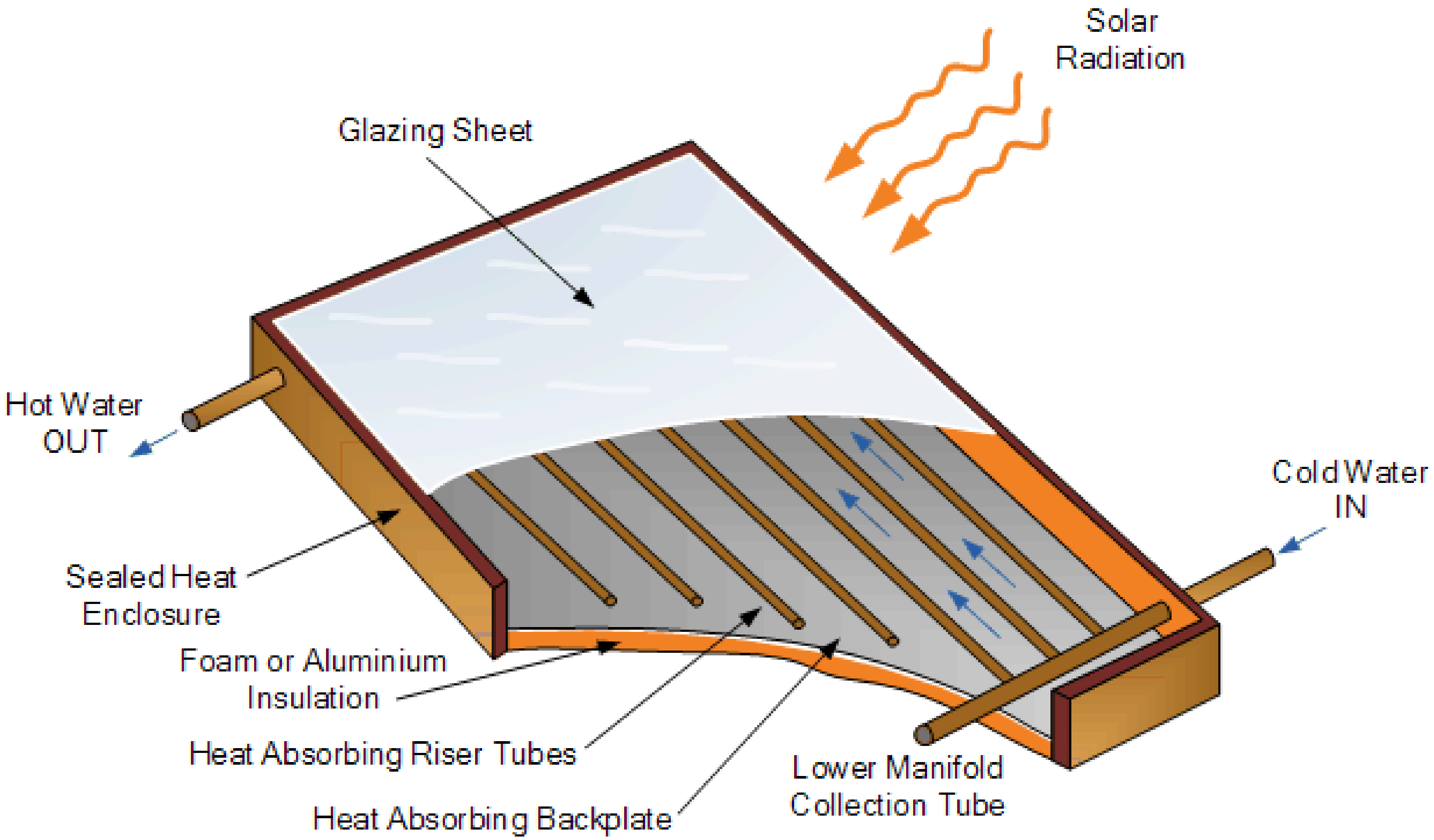
- This is a mature and low-cost (and low-complexity) technology.
- Low-temperature solar thermal collectors can be divided into flat plate and evacuated tube types.

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).



Thermosyphon hot water system

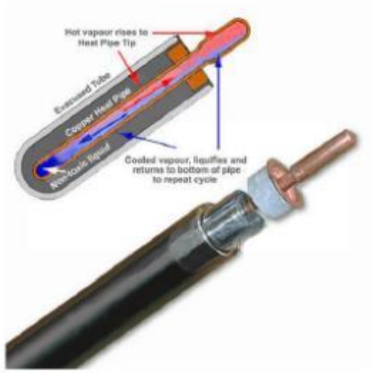
- **Flat plate collectors** are formed by a layer of absorber material (dark) covered by a protective glass.
- The absorber layer is in contact with tubes that carry a fluid (not necessarily water, most likely antifreeze solutions, thus avoiding problems at low temperatures) that will be heated and transported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



Typical flat plate collector (https://www.alternative-energy-tutorials.com/solar-hot-water/flat-plate-collector.html)

Evacuated tube collectors

- If a more efficient approach is required, **evacuated tube collectors** can be selected.
- In this case vacuum tubes are employed to reduce thermal losses and improve efficiency.



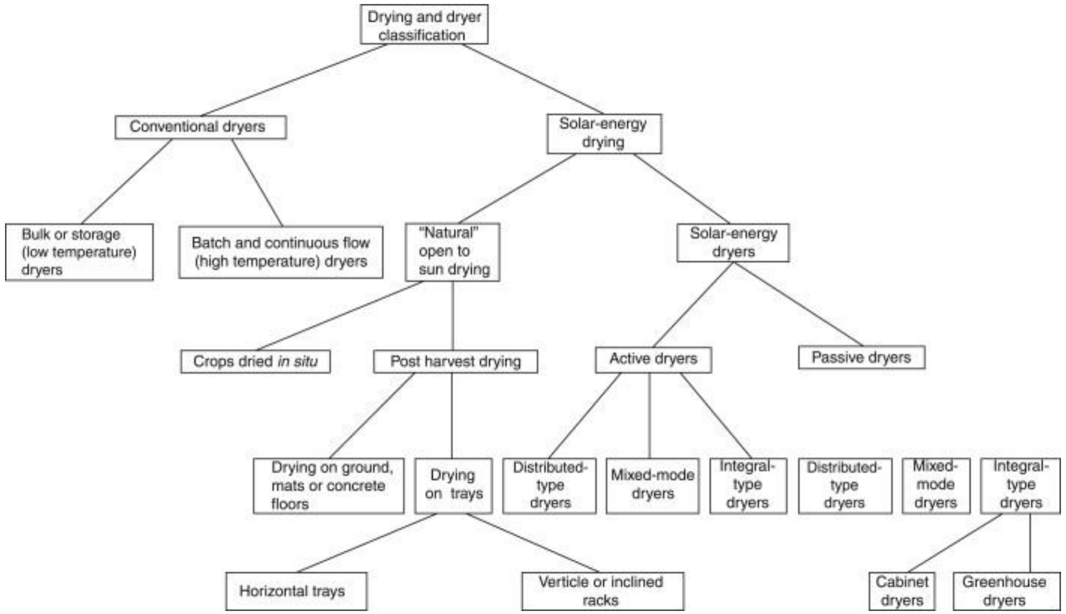
Working principle of evacuated tube collectors (left)

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/2kW0Gqv.

How the Evacuated Tube Solar Water Heater Collector Works https://www.youtube.com/watch?v=BGsmlIoiJN8

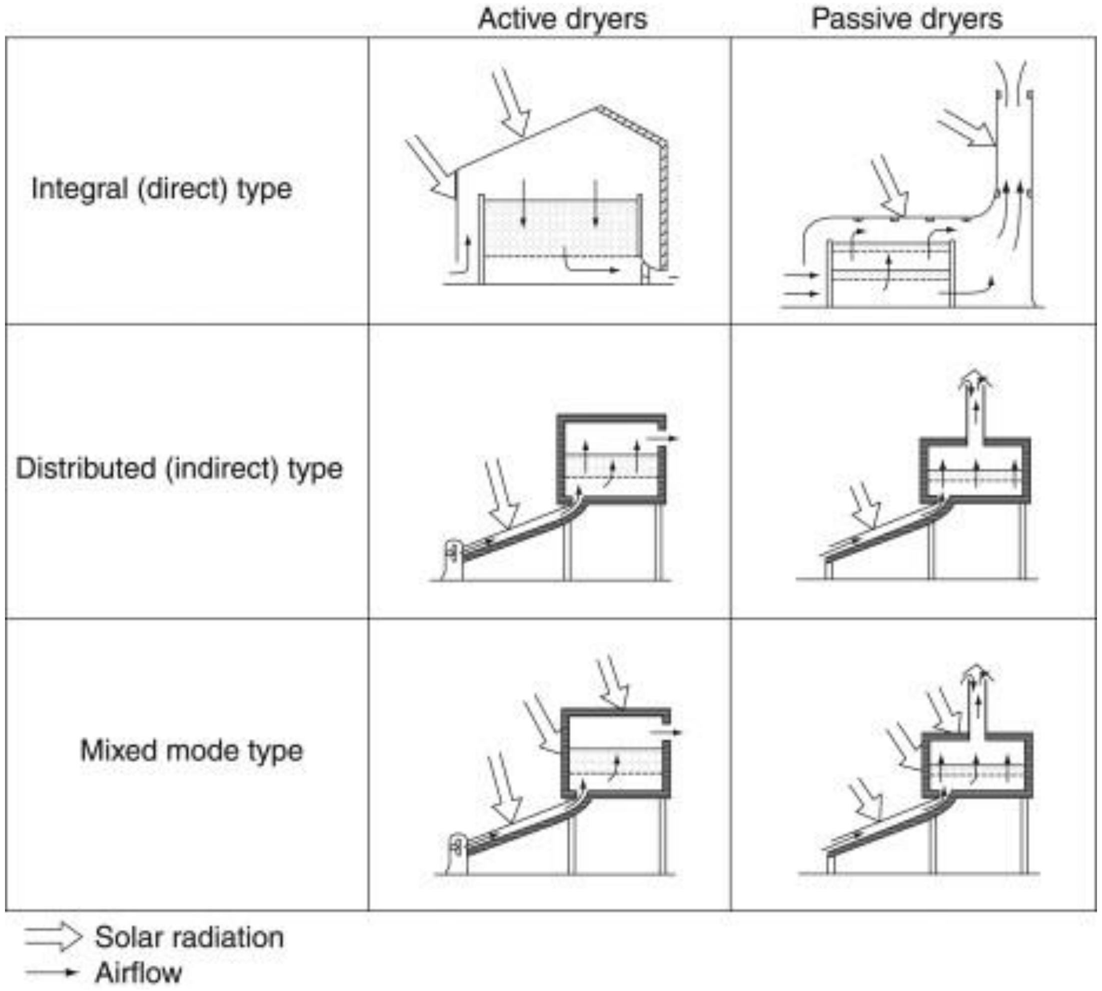
Solar thermal: more applications

- 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



Taxonomy of solar energy dryers

https://www.sciencedirect.com/topics/engineering/solar-dryer



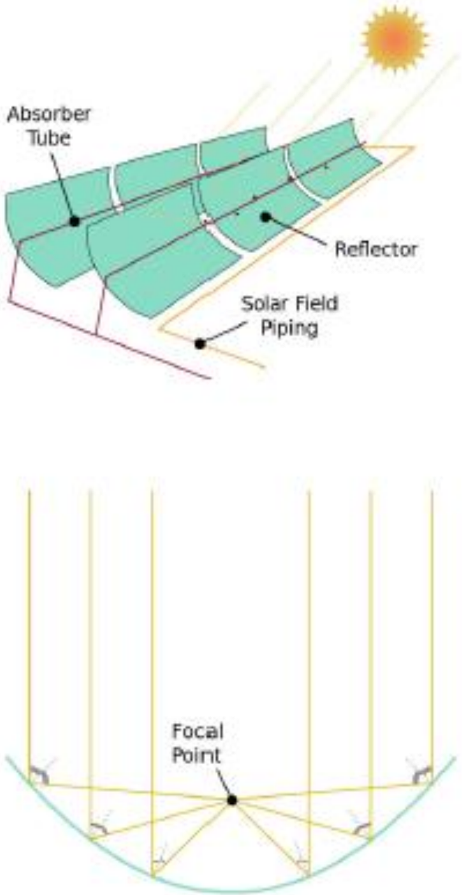
Features of solar energy dryers

(https://www.sciencedirect.com/topics/engineering/solar-dryer)

Solar Thermal Energy: Medium Temperature

- When working temperatures are above 100 ^{o}C, solar thermal energy is normally used for the production of electricity.
- Medium temperature installations are typically formed by parabolic trough mirrors designed to focus all the incoming radiation on a tube located above them.
- 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.

Solar Thermal Energy: Medium Temperature



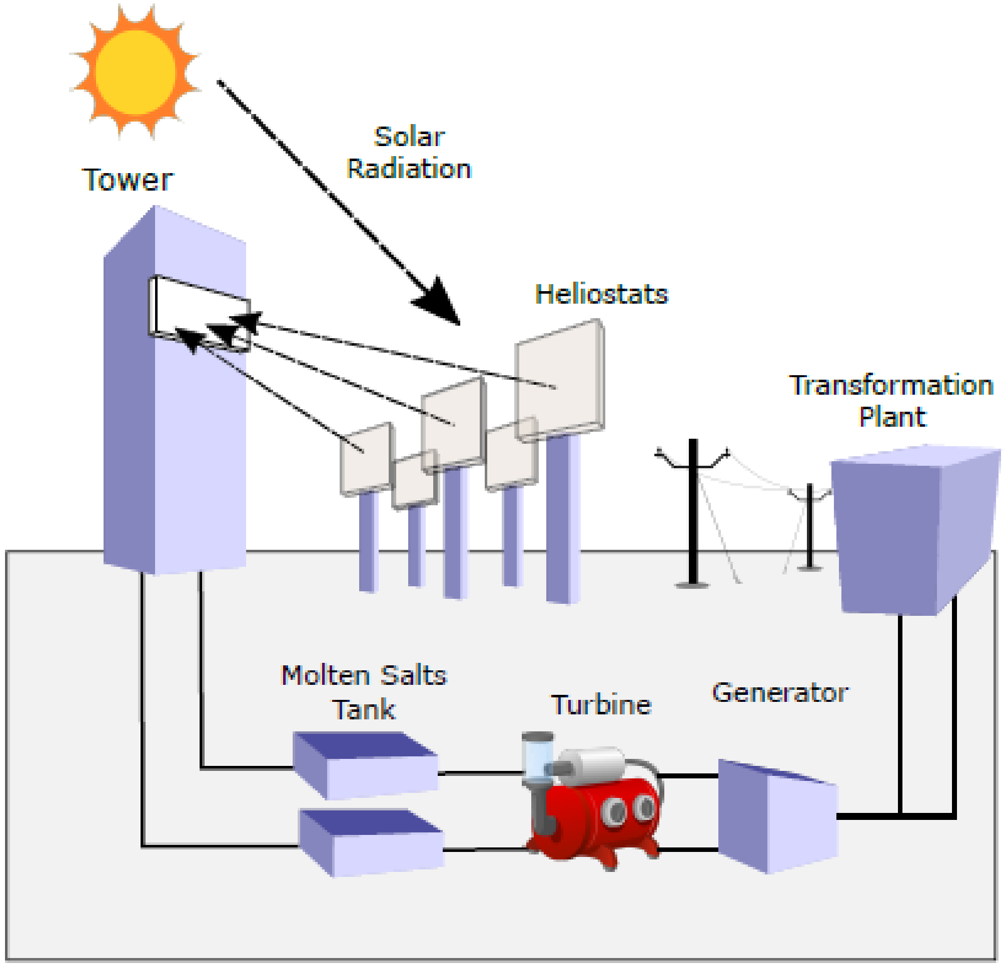
Working principle of a parabolic-trough (left). Parabolic-trough at the Harper Lake plant (California, USA) (right). Source (left)
http://bit.ly/2BxAAFE, License: CC BY-SA 4.0. Source (right): http://bit.ly/2Bx7Gpb (License CC-BY-SA 3.0).

Why are oils chosen as HTF (heat thermal fuel) instead of water? Water has some disadvantages like:

- It is aggressive, oxidant and leads to corrosion
- It gives rise to a high vapor pressure
- Its volume increases at solidification

Solar Thermal Energy: High Temperature / Concentrating Solar Power (CSP)

- High temperature solar thermal energy, also known as **Concentrating Solar Power (CSP)** is typically based on the **power-tower** scheme.
- 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 a computer to track the sun and thus optimize production. As with parabolic-troughs, water is typically avoided as a 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.



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

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

Solar thermal furnace installation in Odeillo (France)

Source: http://bit.ly/2zewRXF. License: CC-BY-SA 3.0

Solar Photovoltaics: A brief history of its evolution

- Solar Photovoltaic (PV) technology converts the sun's energy into direct current electricity by using semiconductors. https://www.youtube.com/watch?v=gl5tY5Noacc
- Solar Photovoltaics (PV) allows direct conversion of solar radiation into electricity, thus being completely different from 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 century, 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.)
- 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

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.

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 100$cm2$ 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.

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.

2002 More than 500 MWp produced that year.

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

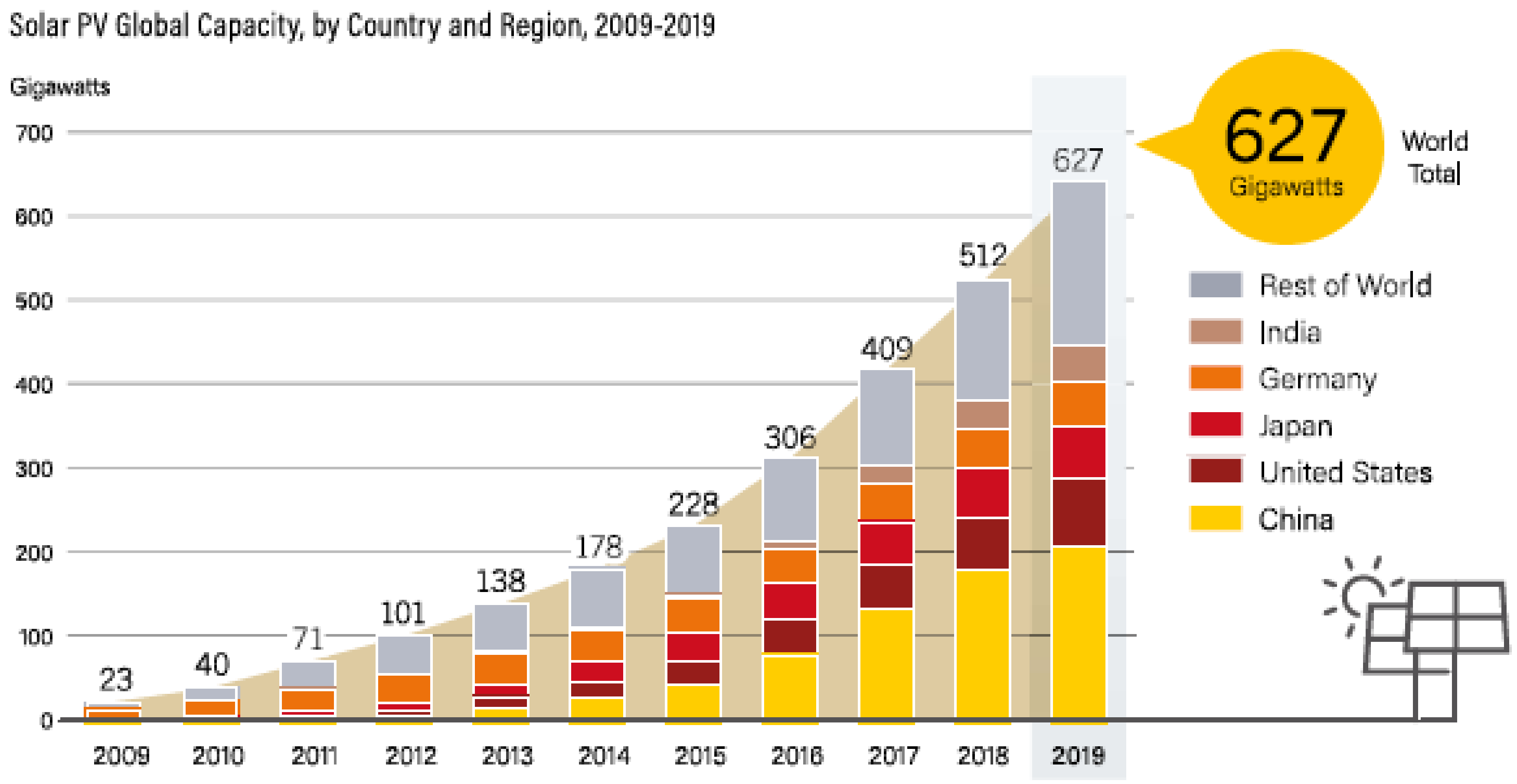
2010 More than 15 GWp fabricated.

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.

Solar PV: Current Situation

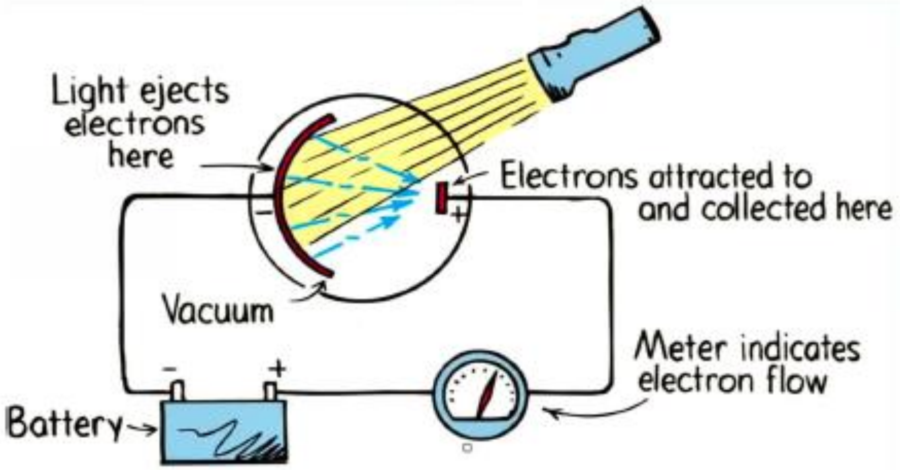
- The rate of growth of PV capacity in recent years is **absolutely remarkable**, showing the highest growth rate (among all RE technologies) in terms of electricity production.
- Within this remarkable rate of growth, the contributions of China, Japan, and the USA in recent years clearly stand out.
- It can also be very interesting to analyze the current situation in terms of the **shares (%) of these technologies with respect to electricity generation**.



Evolution of PV global capacity by country and region (2009-2019)
Source: REN21 (2020 Report). https://bit.ly/39IvYMz

Solar PV Fundamentals: Photoelectric Effect and Solar PV Cell

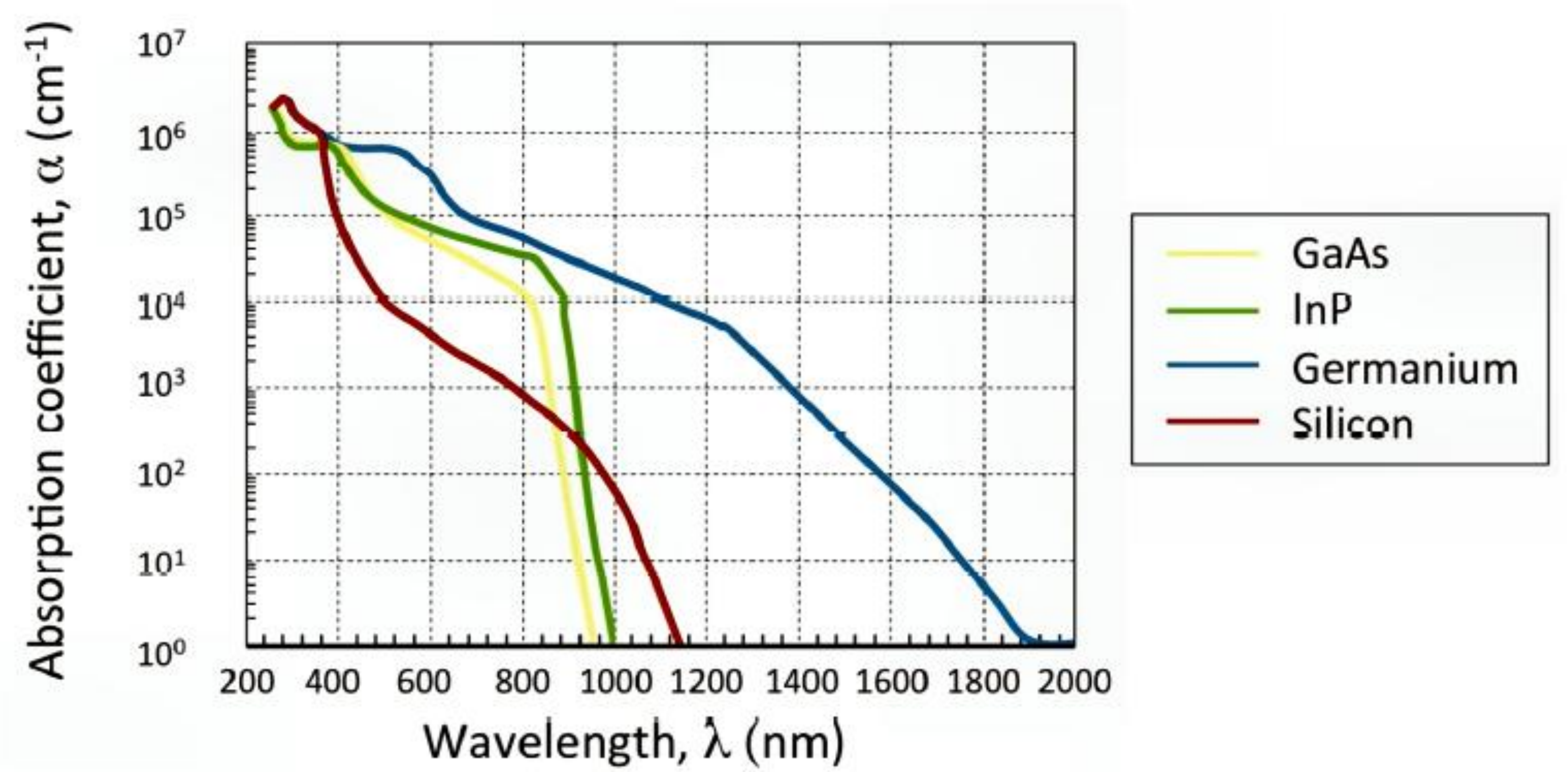
- The **photoelectric effect**, basically explains why some materials (e.g. silicon) are able to produce an electric current when radiated by specific electromagnetic radiation.
- The features of this radiation are a key issue to understand the operation and **efficiency** (actual sticking point of PV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



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

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.
- We know that PN junctions are typically made of **silicon (Si)**, but: why is Si the material of choice for building PV cells? **Is Si the best material for this application?**
- The answer is clear: **NO!**
- **How do Solar cells work?** https://www.youtube.com/watch?v=L_q6LRgKpTw&t=13s



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

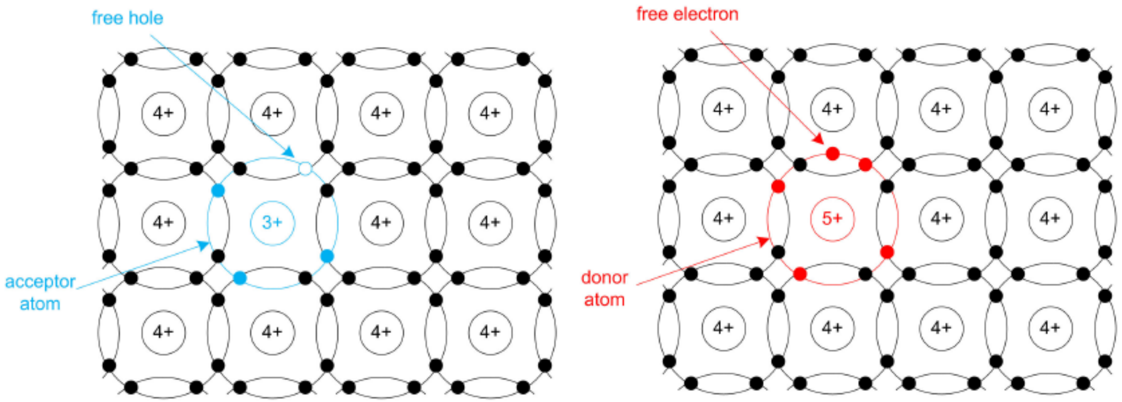
Gallium arsenide (**GaAs**) Indium phosphide (InP)

- Direct Gap:
  - In a direct-gap semiconductor, the electron transition (from the valence to the conduction band (photon absorption) or vice versa (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** (a collective excitation in a periodic, elastic arrangement of atoms or molecules in condensed matter, specifically in solids and some liquids).
- As other particles are involved, these transitions are less likely (in comparison to direct-gap materials).

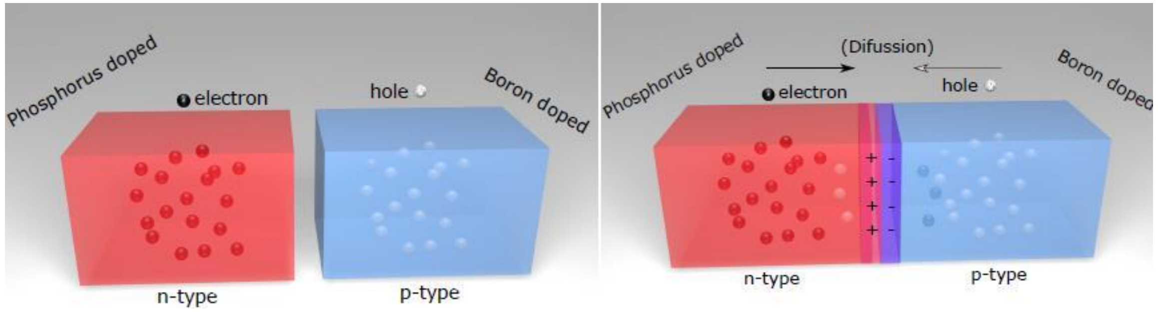
PN Junction

- A solar PV cell is basically a PN junction with some special features.
- A PN junction is based on 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**.

https://www.youtube.com/watch?v=0yyFiJw5emw



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



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

- A PN junction is obviously formed by the union of two (p-type and n-type) semiconductors. 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, 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) 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 vice versa).
- 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.

p and n-type solar cells

- Even if the very first solar cell was **n-type**, **p-type**, 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 their improved efficiency and immunity to the light-induced degradation effect**.
- This is mainly due to the absence of boron, which recombines with oxygen damaging efficiency and performance.

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 to produce electricity in a solar cell.
- It is also important to also know the **Si spectral response**.
- As can be observed, the Si spectrum comes up to around **1100 nm**, with associated gap energy.

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**.

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

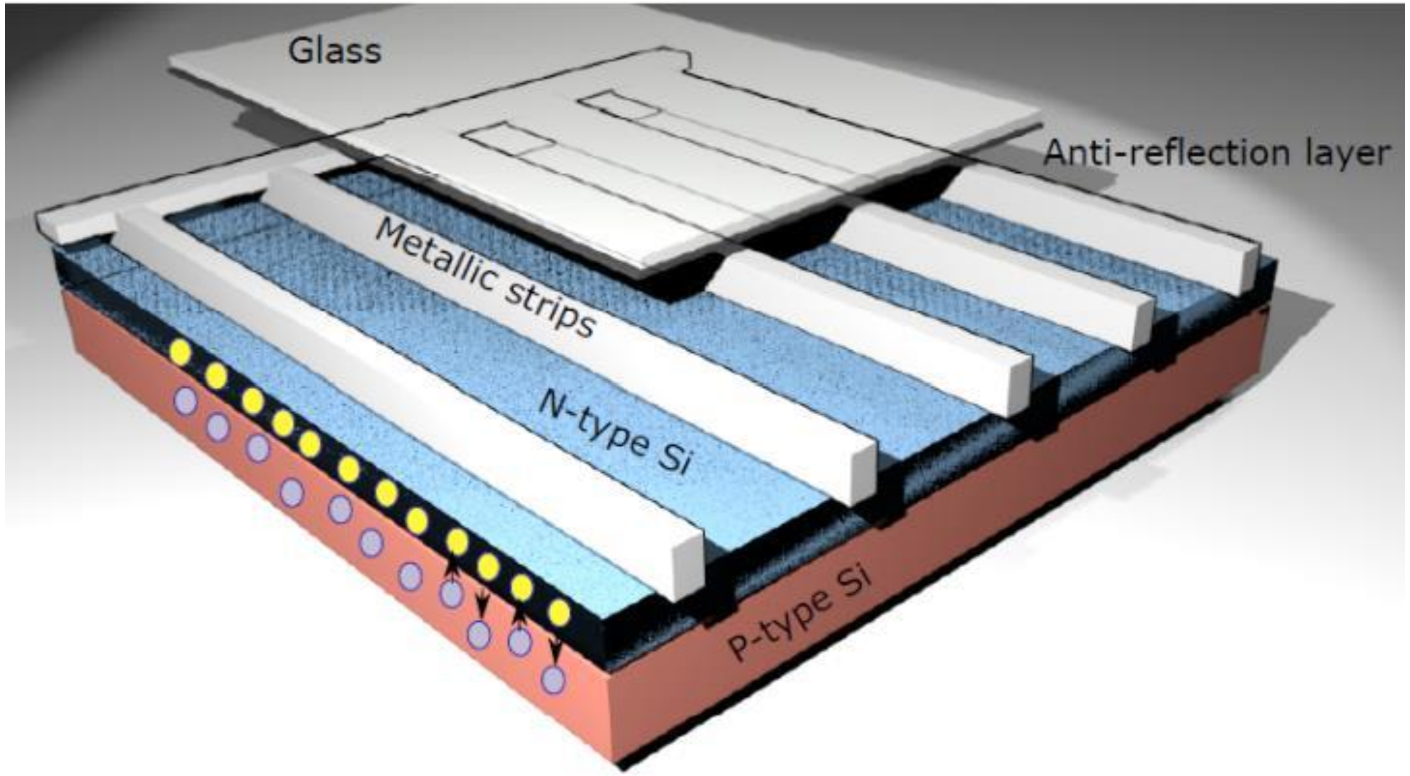
- It is then necessary to measure the electrical power generated by the PV cell/module (watts), as well as the solar irradiance (watts/m^2), considering the surface of the cell/module (m^2).

- 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 surface of the strips is diminished, more photons will reach the n-type region, but the series resistance will increase.
- On the other hand, the Si spectral response limits the amount of photons that can be converted into electricity.
- Finally, recombination and potential barrier losses are intrinsic to the PN junction and, consequently, very difficult to overcome.

Solar PV Cell: Structure

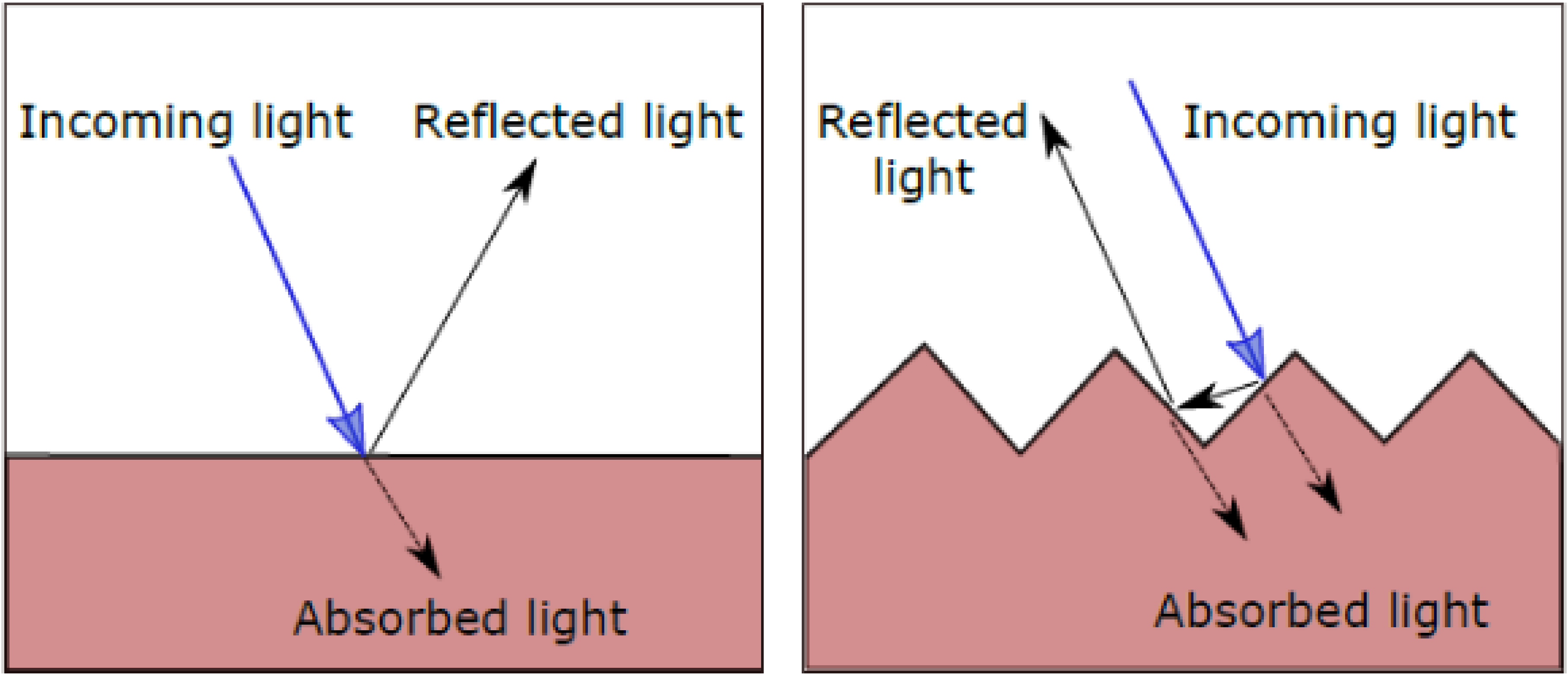
- The “main core” of a solar cell, the so-called PV laminate, is the PN junction.
- However, there are more elements that form a commercial PV cell.
- **Glass layer** The glass layer is used to protect the PV laminate (the PV cells). Special attention must be paid to the optical properties of the glass, 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.



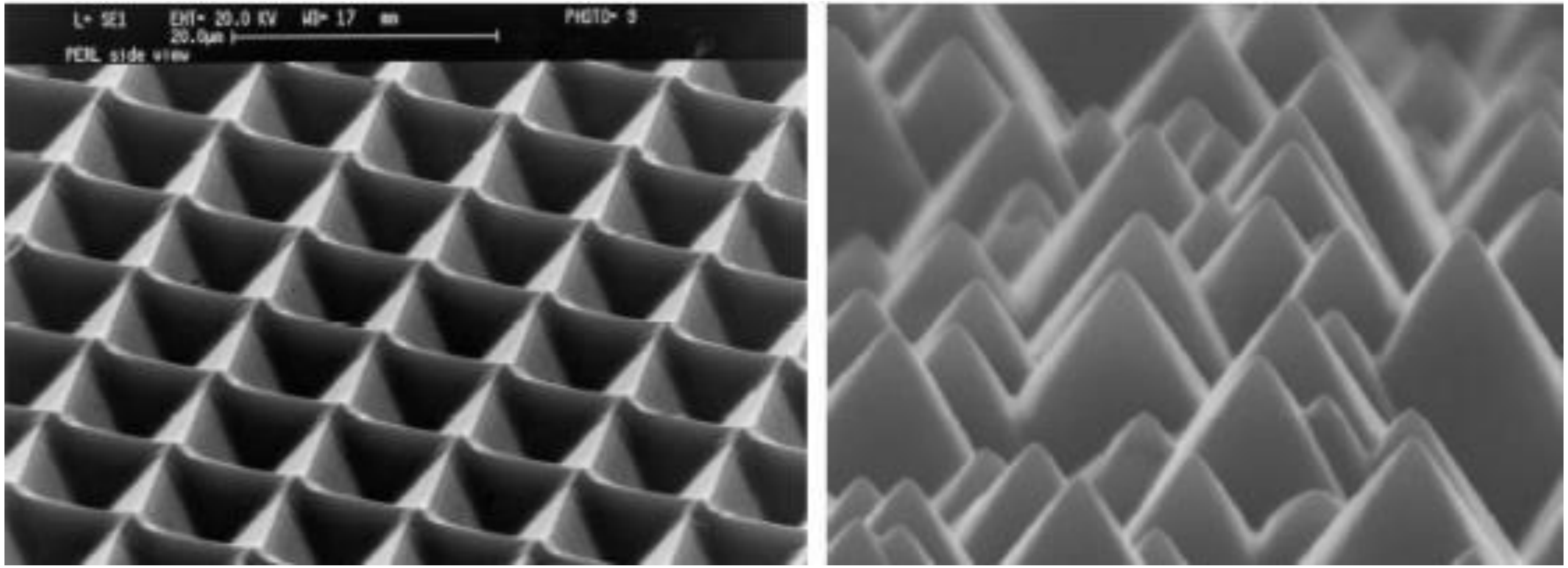
Schematic representation of the structure of a solar cell. Source: Jesus Mirapeix.

Texturization is another key concept in PV technology.

- It is based on giving a certain texture to 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 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.



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

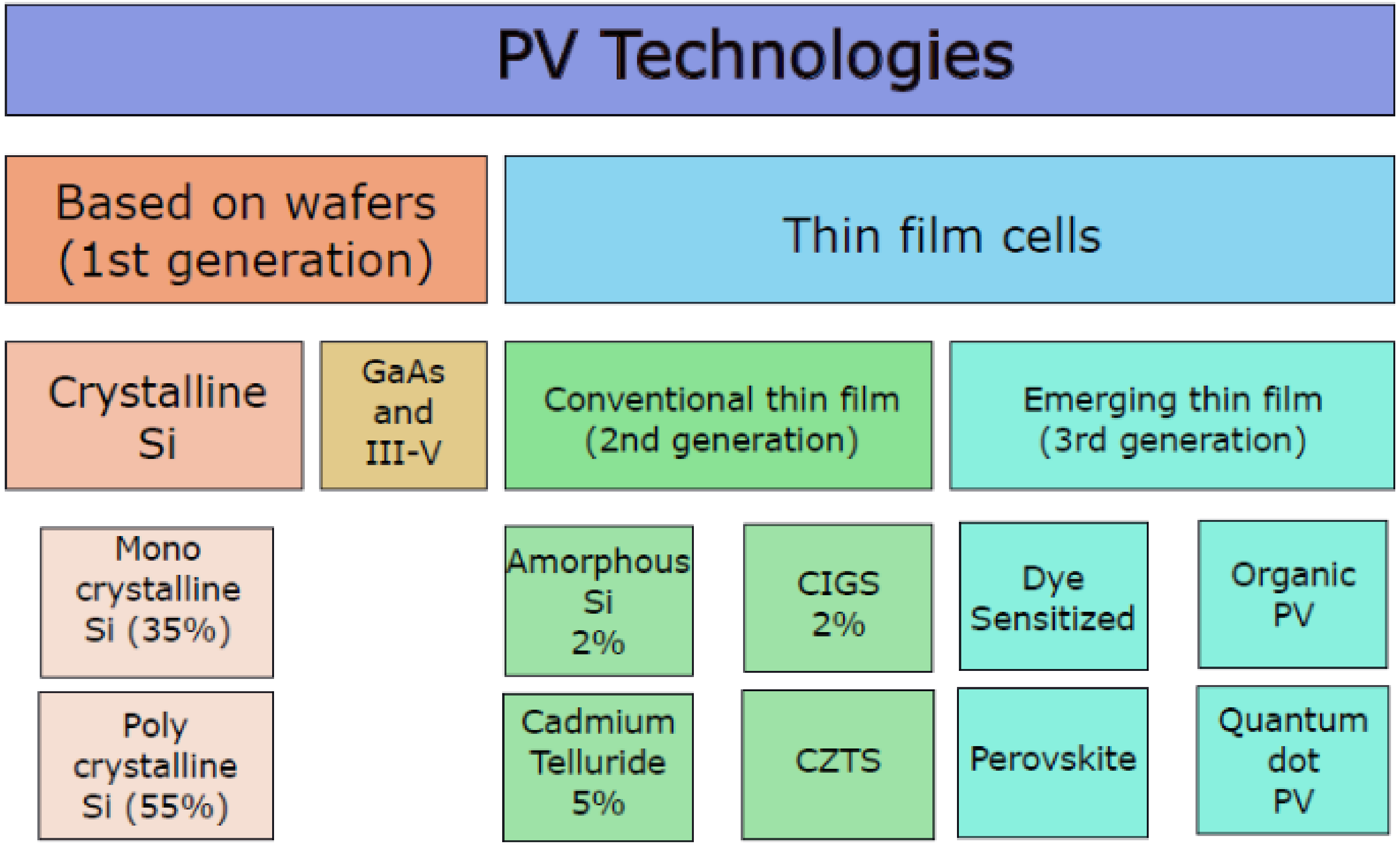


Examples of texturized solar PV cells: inverted pyramid (left) and pyramid (right).
Source: http://bit.ly/2F61VvW. Images by The School of Photovoltaic & Renewable Energy Engineering, University of New South Wales.

PV Technologies

- There are different **PV technologies** classified in terms of the materials used to build the PV cell.
- First of all, they are 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 c**rystalline-Si technology** (mono and poly-crystalline), with a 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 (a material made from the combination of two elements: Cadmium (Cd) and Tellurium (Te)), CIGS (Copper Indium Gallium Di selenide), and CZTS (Copper Zinc Tin Sulfide) cells.
- **3rd generation** solar cells are emerging thin-film technologies such as dye-sensitized, Perovskite, organic, or quantum dot cells.

Everything You Need To Know About Crystalline Silicon VS Thin-Film Solar Cells 2024
https://www.youtube.com/watch?v=vy_p9d-AK4w



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.

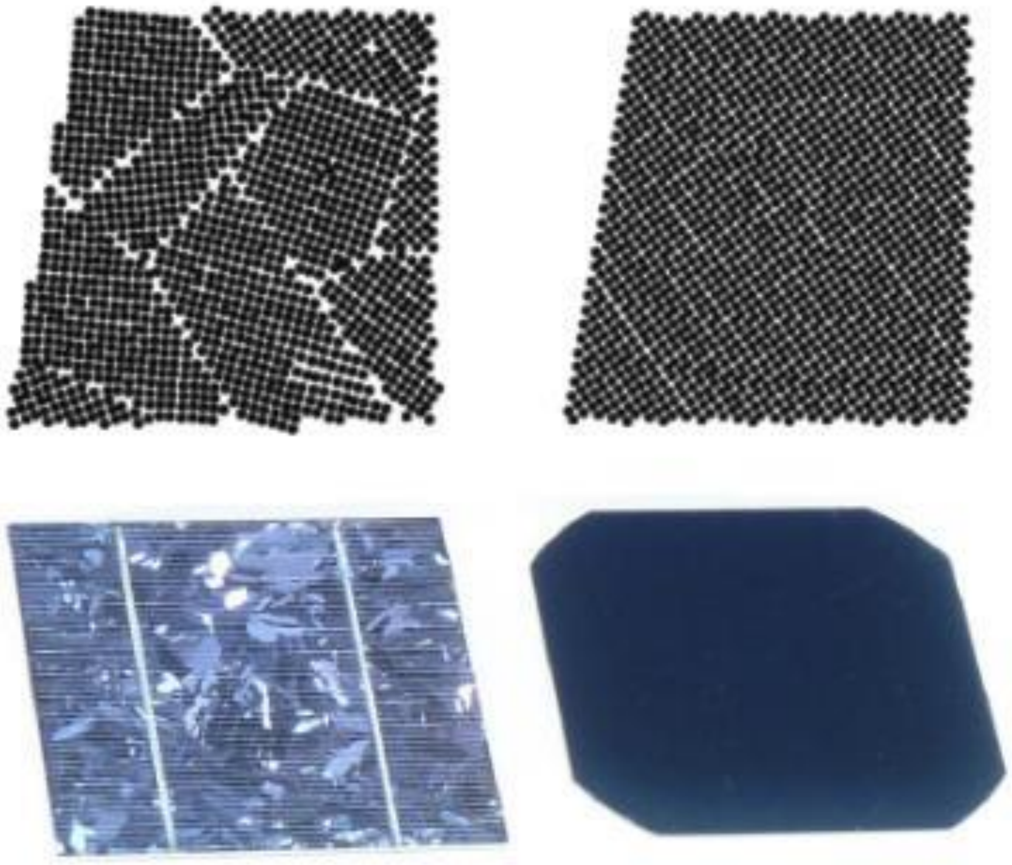
Sustainability Some materials used for PV technologies may impose an environmental risk.

In this regard, technologies without these disadvantages, like organic cells, are more likely to be successful.

- 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**.

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), while poly-crystalline may offer a maximum of 14%.
- The simplest way of telling what kind of crystalline panel are we looking at is by means of a visual inspection.
- Mono-crystalline cells show a uniform black color, whereas polycrystalline 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 higher quality material.



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 BYSA 3.0). Source (top image): Course EdX Solar Energy: 4.1. Properties of Crystalline Silicon. Licencia Atribución de Creative Commons (re-use allowed)

PV Technologies: Thin-film (2nd generation)

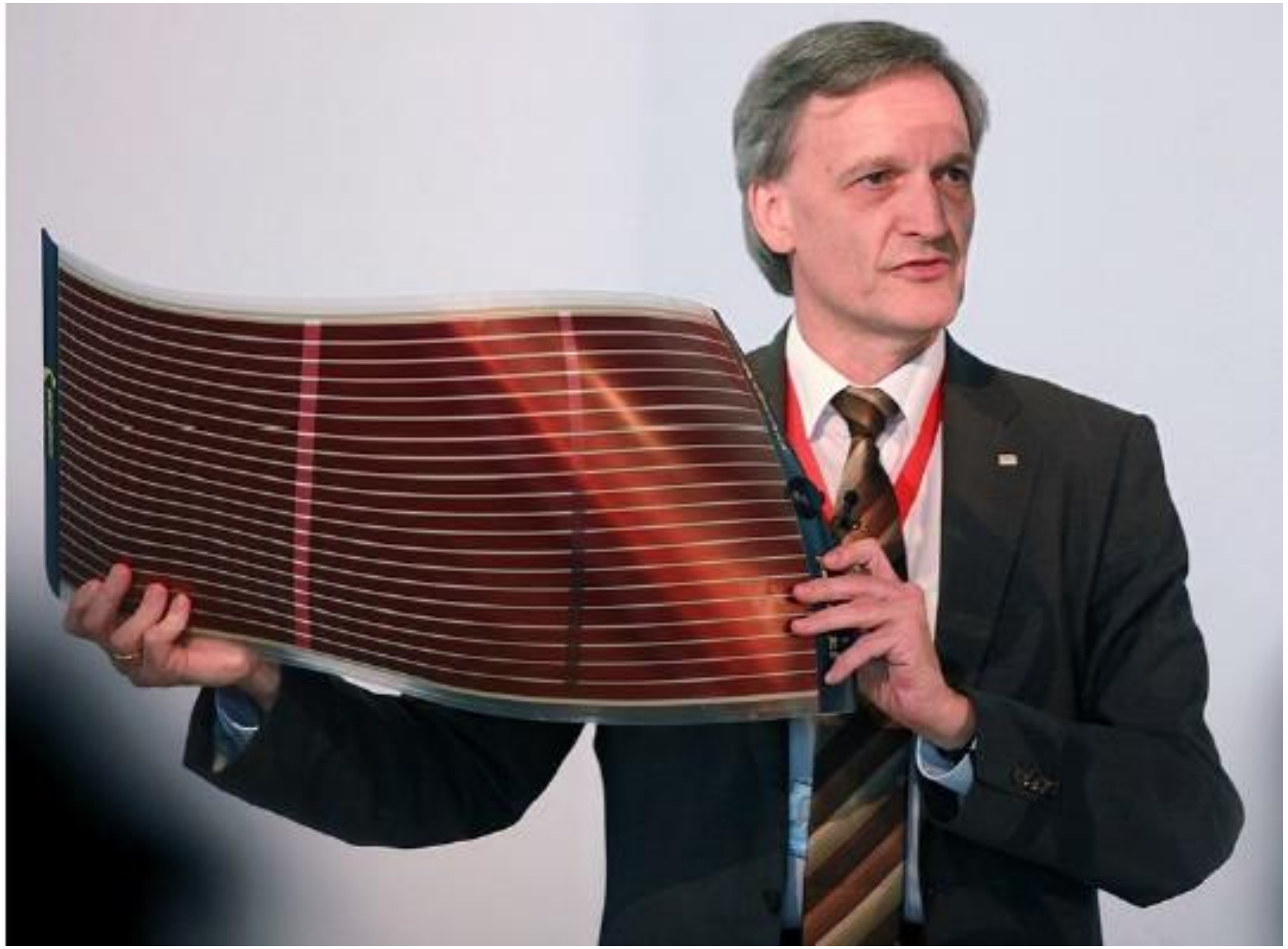
Thin-film PV installation. Source: Fieldsken Ken Fields (CC BY-SA 3.0). http://bit.ly/2lA2plW.

- **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 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.

PV Technologies: 3rd Generation (Organic Cells)

- Within the **3rd Generation** “family”, **organic cells** constitute a very interesting and promising technology.
- An organic solar cell, 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.
- As current disadvantages,
  - low efficiency,
  - low stability, and
  - reduced durability.



Organic solar PV cell. Source:http://bit.ly/2ASKYXO. License: CC BY-SA 3.0

PV Technologies: Comparative

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

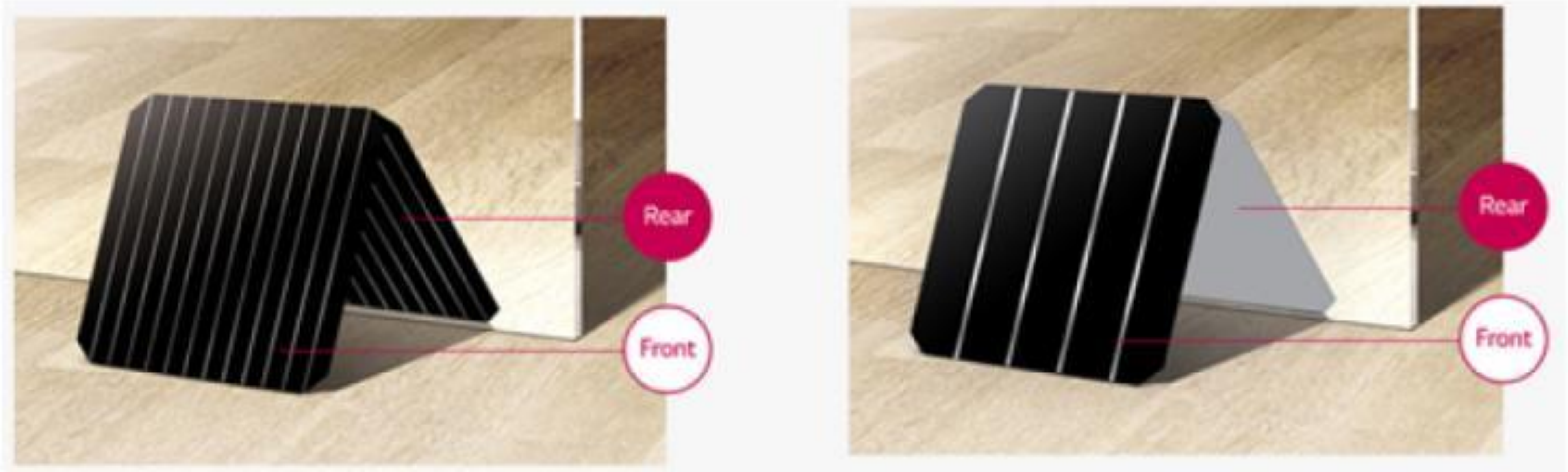
For Additional Reading

Environmental impact (sustainability)

- 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.
- The highest efficiencies achieved with commercial cell/modules
- Presents efficiencies that have been measured in laboratories (non-commercial prototypes).

Bifacial technology

- In recent years, **bifacial technology** seems to be gaining relevance in the photovoltaic sector, **to the point of becoming the new technology most likely to replace conventional crystalline silicon panels**.
- In this sense, it must be pointed out that, in reality, bifacial panels are made up of cells of mono or polycrystalline silicon, so it is not a new technology in the sense of using new materials as occurs with perovskites or cells. organic.
- The **main innovation in bifacial panels lies in their ability to capture radiation from the front and rear faces of the cells**, thus increasing the overall performance of the panel and, with it, the final generation.



Bifacial (left) and monofacial (right) cell designs. Source: LG.

- When introducing the concept of the bifacial cell, it is necessary to clarify the concepts related to **solar radiation**, in particular **direct, diffuse, and reflected radiation**, since the latter two become highly relevant in this new type of cell.
- **Direct radiation** is that received from the Sun without the photons having suffered any interference, in particular any deviation in their path, in the Earth's atmosphere
- **Diffuse radiation** is the radiation that reaches the earth's surface after having undergone a change of direction in the atmosphere, typically by scattering or reflection processes, for example by clouds
- **Albedo (reflected radiation)** which can be defined as the amount of reflected radiation (for example on the surface), versus the incident radiations

Direct, diffuse and reflected radiation. Source: elforoverde.org https://bit.ly/36r5gWV.

In traditional PV,

direct radiation is mainly taken into account, although in locations where diffuse radiation is relevant,

this may have implications regarding the PV technology to be selected,

since some, such as amorphous silicon, present an improved response to this type of radiation.

The design for the bifacial case is complicated, considering that the different types of radiation will vary depending on factors such as:

Meteorology since, as we have just mentioned, in cloudy sky conditions diffuse radiation will predominate (with an irradiance around 100 W / m 2), while on clear days direct radiation will predominate, being able to reach 1000 W / m 2 in optimal conditions

Tilt of the panels the horizontal arrangement maximizes the capture of diffuse radiation footnote For this reason it is possible that if you find yourself with a solar PV installation with solar trackers, you can see on a cloudy day that the trackers have moved to position the modules in a horizontal arrangement, very uncommon on the other hand in traditional PV., but minimizes that associated with reflected radiation (albedo)

Albedo the albedo (and with it the proportion of reflected light) depends on the type of surface as well as its color; For example, ice or snow has a very high albedo, while white concrete will have a higher albedo than grass.

Movement of the Sun with respect to the Earth: the trajectories of the Sun change throughout the year, so this will also influence the estimation of the optimal angle for direct radiation as well as shadows and reflections

Solar PV plant with bifacial modules.
Source: Soltec. https://bit.ly/2Kzy6fh

PV plant with vertically deployed bifacial panels. Source: Next2Sun.

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:

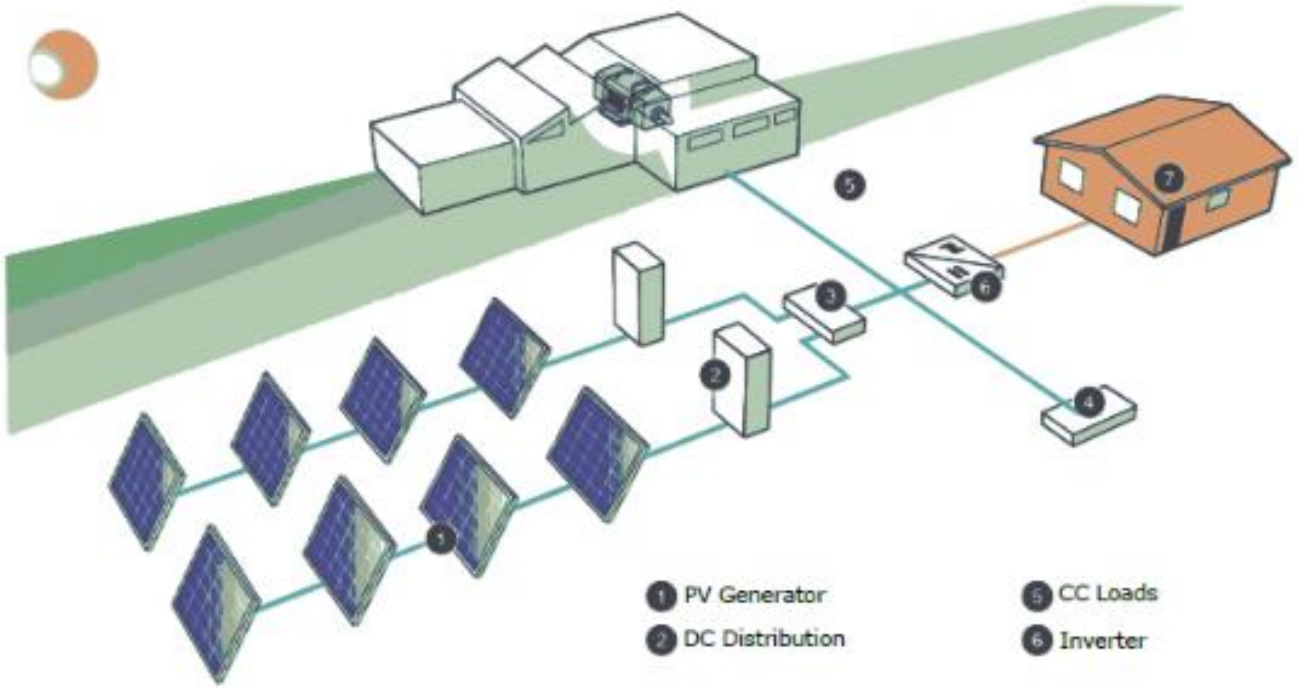
Stand-Alone Systems designed to power supply, independent of the power grid, installations, infrastructures or devices (e.g. homes, Base Transceiver Stations or network sensors).

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

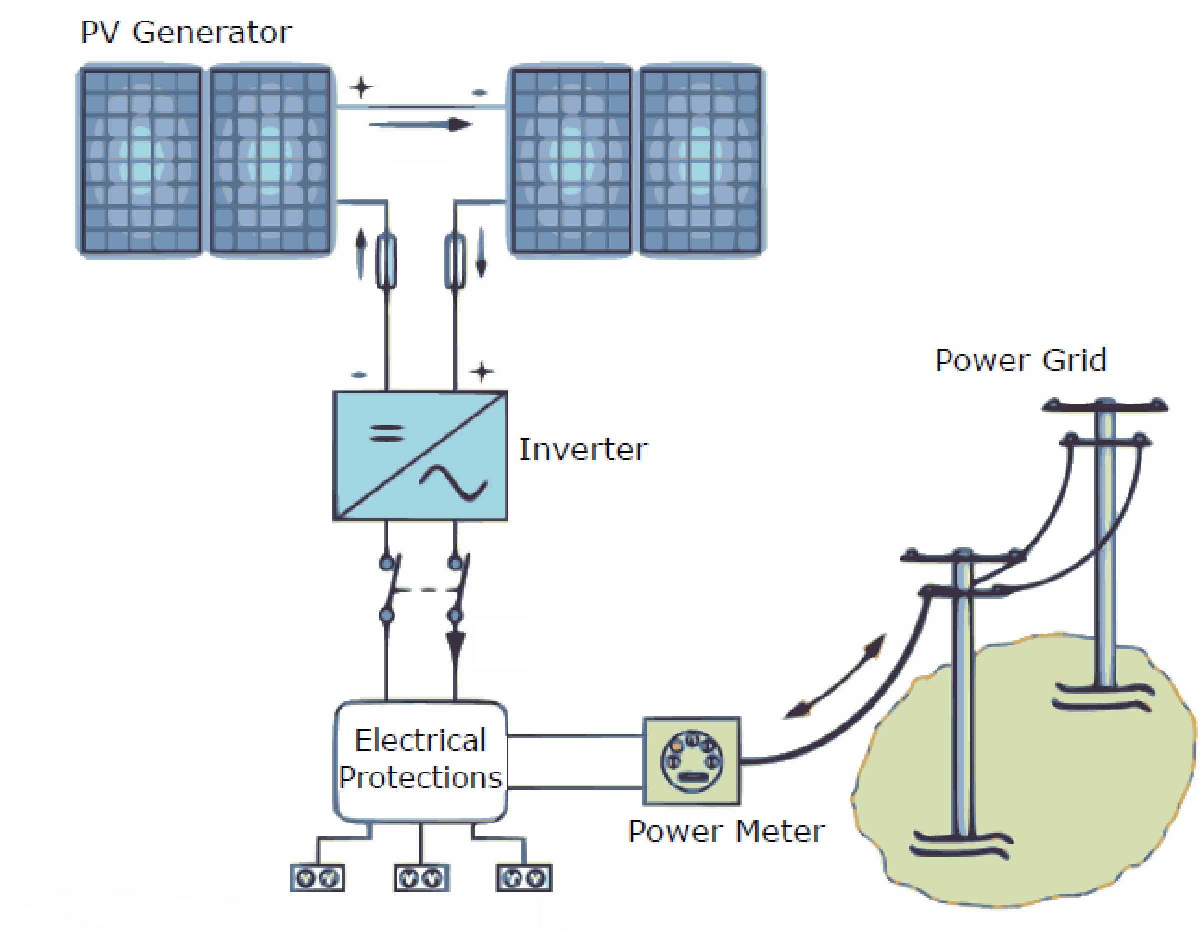
Both systems share many common features, but there are also remarkable differences from the point of view of the chosen devices, as well as of their use and legislation.

PV system: elements

- Start to analyze the elements that form a grid-connected system, which can be considered as the simplest scenario.
- 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**.



Schematic representation of a stand-alone PV system. Source: global electricity http://bit.ly/2mal1Jy.



Schematic representation of a grid-connected PV system. Source: globalelectricity http://bit.ly/2maI1Jy.

Main elements that form a PV system

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.

other important elements whose influence on the final cost may be relevant: cables, module supports, DC-DC converters, etc

https://www.youtube.com/watch?v=ncDGqZeJLqE

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.
- 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

- 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.
- 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%.

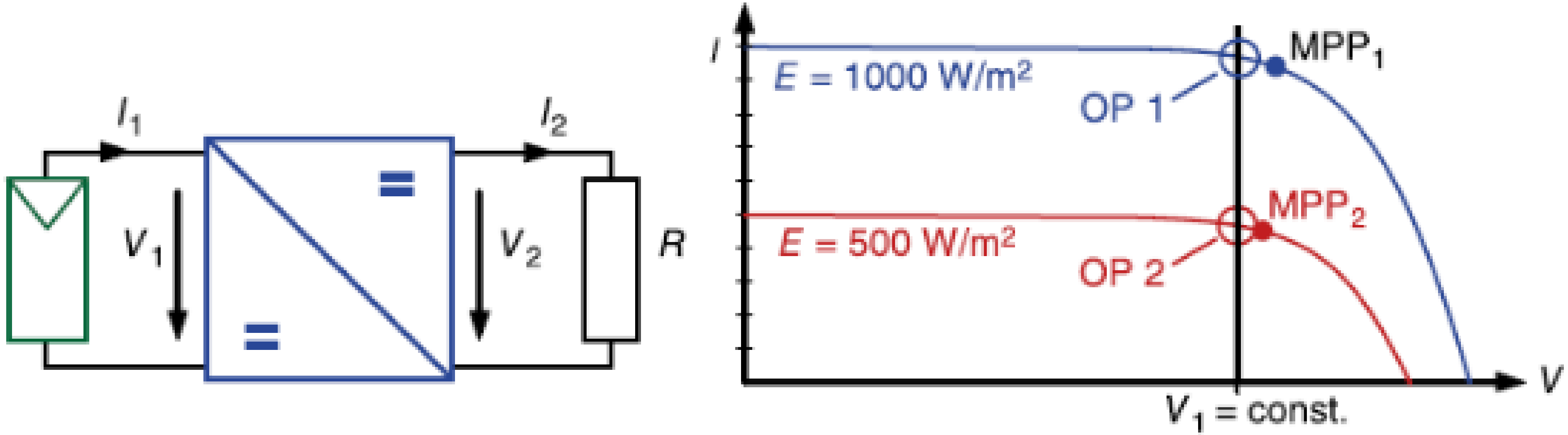


Fig. 45. Example of PV module connected to a resistive load via DC-DC converter: solar irradiances of 500 and 1000*W/m*2. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens]

Inverter

- 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.
- 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).

Fig. 46. Inverter models: (left) Model: SMA SUNNY BOY 1.5/2.5; (right) Model:Solaron 500KW

- Inverters are key elements in a PV system.
- 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 a transformer, with transformer and high-frequency inverters.

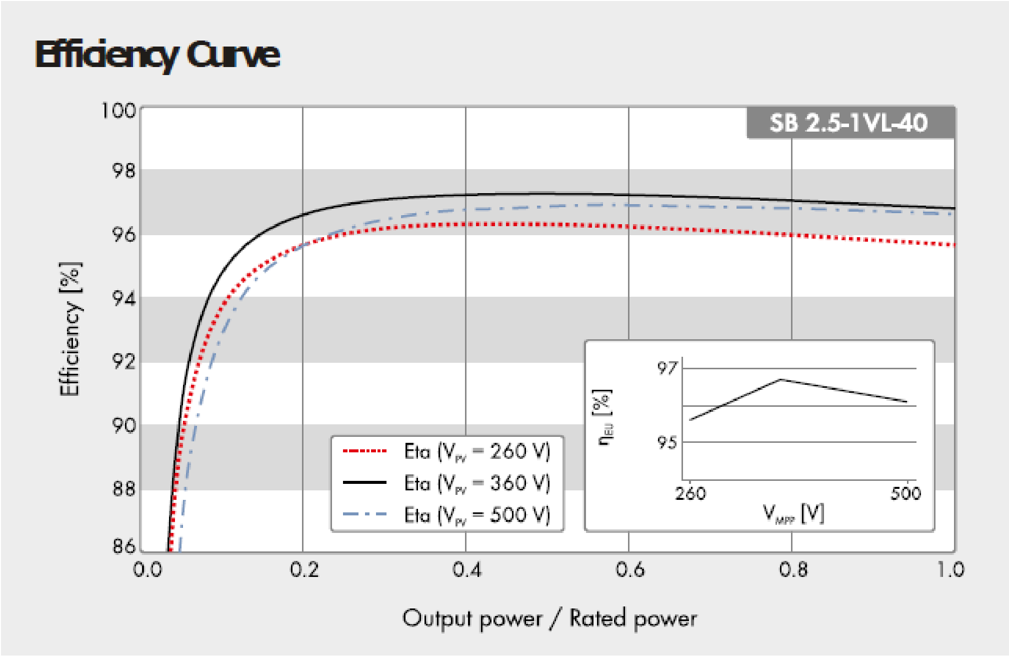


Fig. 47. Efficiency curve for SMA Sunny Boy 1.5/2.5 inverter. Source: Sunny Boy 1.5/2.5 datasheet http://bit.ly/2AICf5W.

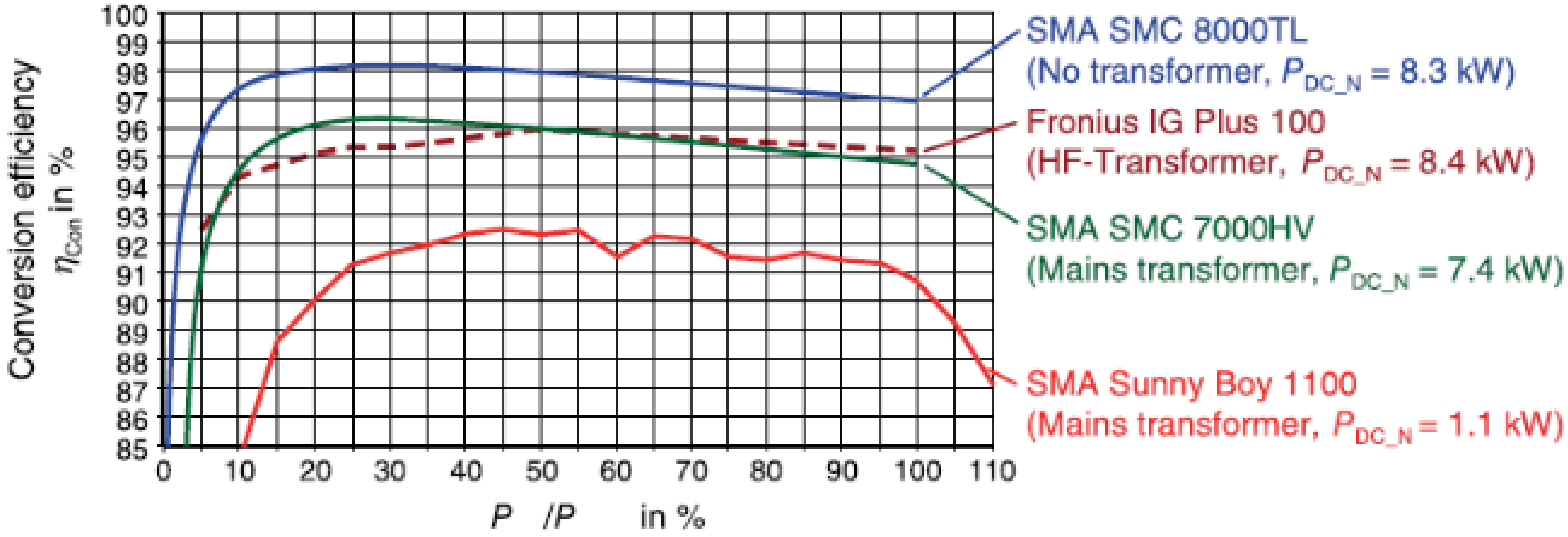


Fig. 48. Efficiencies for different inverter technologies: (*no transformer*), high-frequency (*HF transformer*) and with low-frequency transformer (*Mains transformer*). Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

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.

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 Fig. 49, 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
- The second example, which has been represented in Fig. 50, shows the use of a bidirectional power meter (the "solar energy meter" might be avoided).
- The first situation was typical some years ago in those countries where RE subsidies (feeding 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.

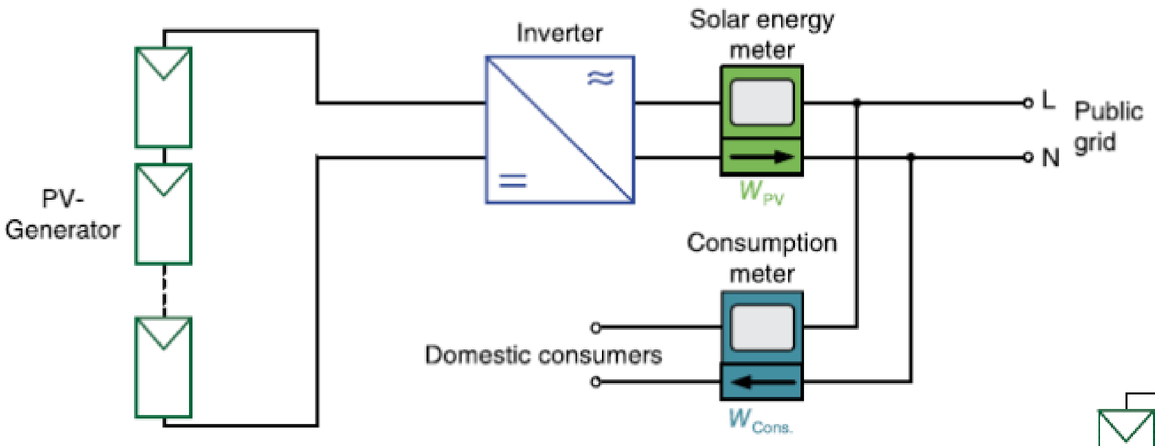


Fig. 49. Example of PV system with uni-directional power meter. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

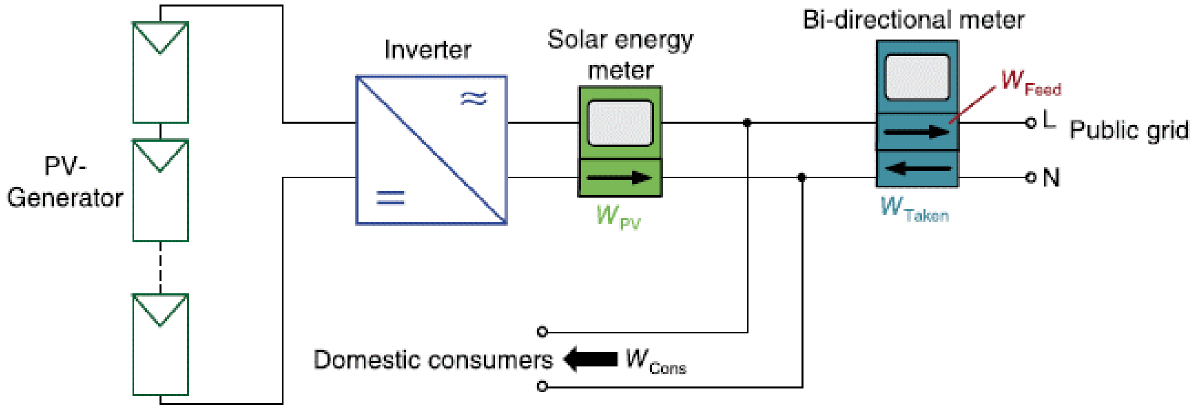


Fig. 50. Example of PV system with bi-directional power meter. Source: *Photovoltaics: Fundamentals, Technology and Practice* [Konrad Mertens].

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

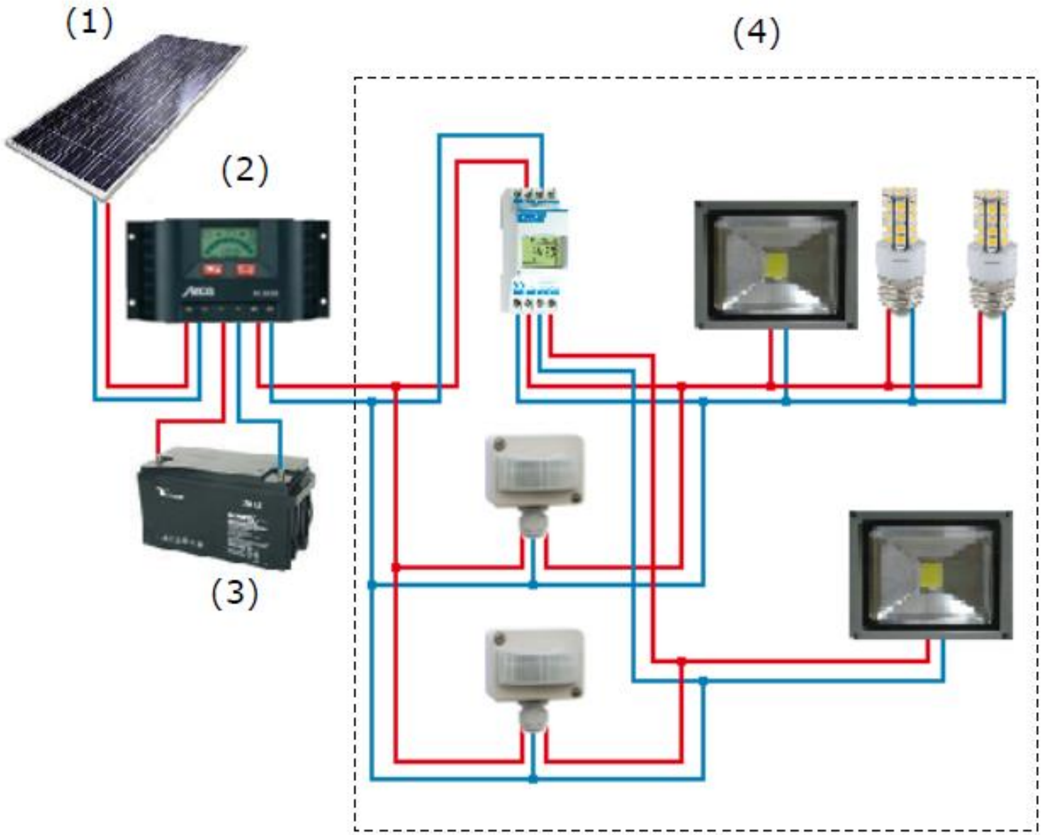


Fig. 51. Example of a stand-alone PV system: (1) PV generator; (2) Charge controller; (3) Batteries; (4) Loads. Source: Jesus Mirapeix.

In Fig. 52 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 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.

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.

Fig. 52. Example of charge controller: Steca PR 3030 LG.

Charge Controllers: PWM and MPPT

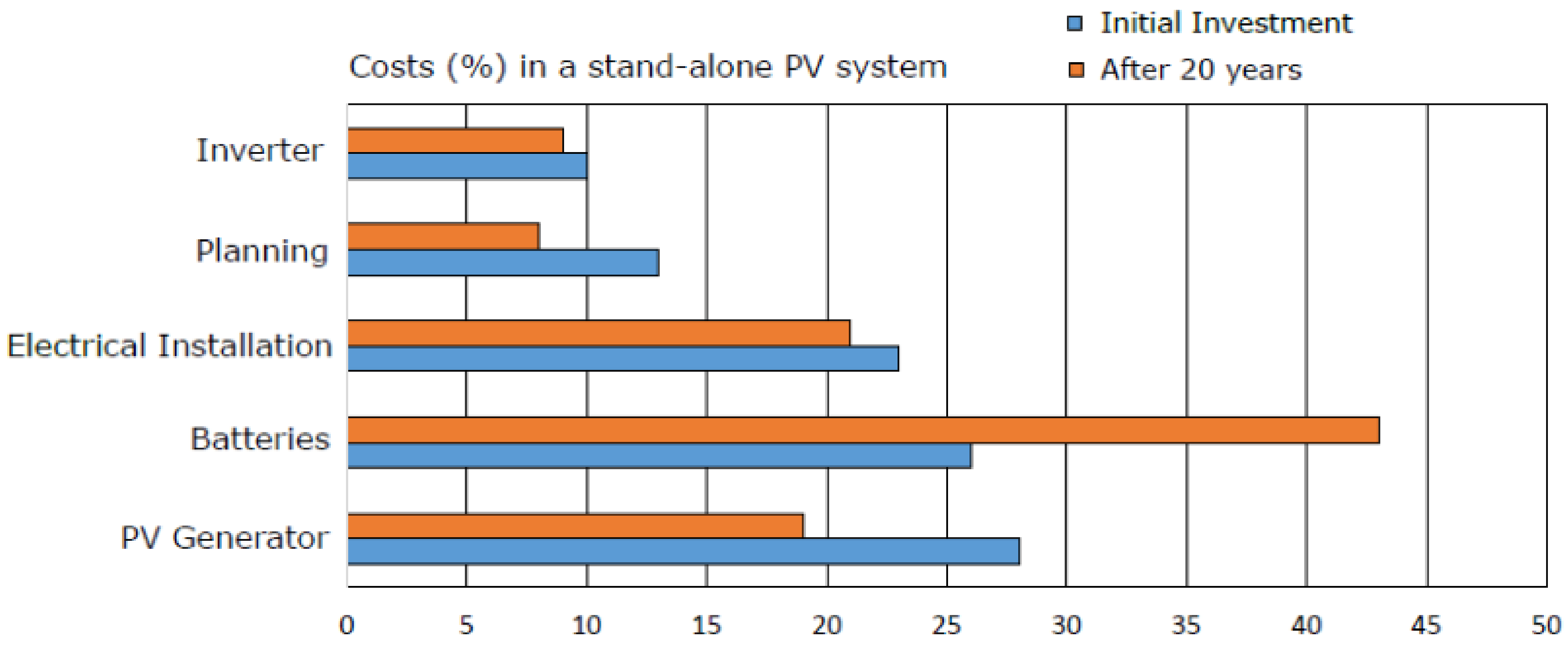
An important decision to make in this regard is the charge controller technology:

- **PWM (**Pulse Width Modulation) **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 (***maximum power point tracking*) **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.

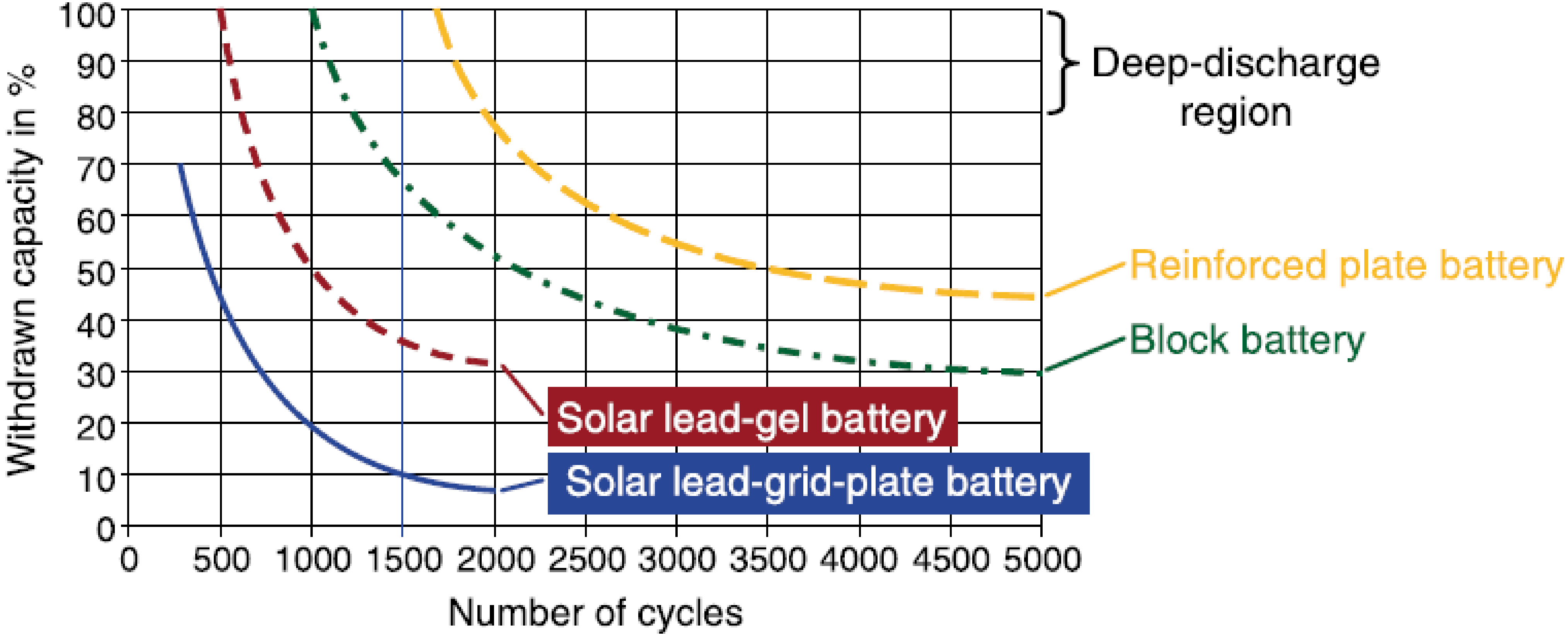
Batteries

- 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, NIMH, Lithium-ion, Lithium polymer, etc. Only lead batteries are used in PV systems, mainly due to their cost, cheaper than the other technologies.



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



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

- 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 (cloud 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 battery autonomy it will be important to take into account the weather conditions where the system is located.

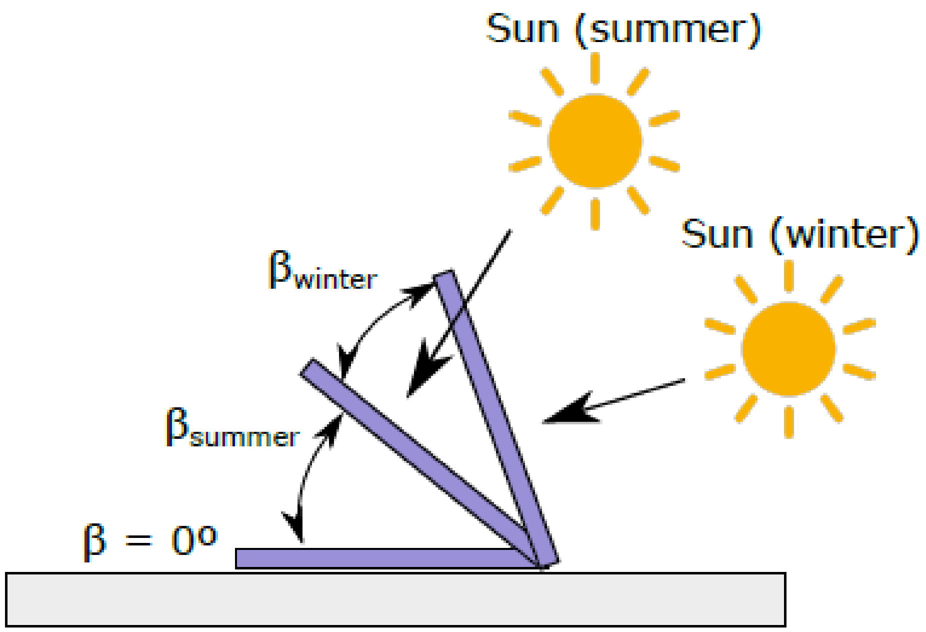
System cabling

- 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.

PV Systems: Dimensioning

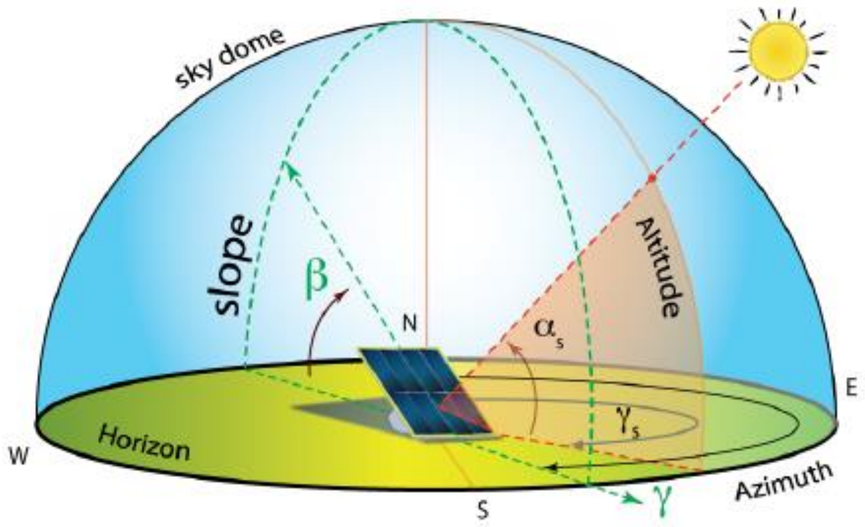
- Having introduced the main concepts of PV technologies and systems,
  - it is now time to analyze some examples of the dimensioning of PV systems.
- However, prior of all, two parameters must be mentioned that may have a huge impact on the system’s performance: the **inclination and orientation** of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

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.



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 (α= 0 means South orientation.)



Tilt β and orientation α of a PV generator. Source: E-Education http://bit.ly/

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.

- 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 *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 *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%**.

Shadowing

- It is important to understand the effect of shadows in a PV system.
- In this 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, losses are significantly higher than if shadows affect several panels of the same string.

Shadowing: Design Recommendations

- 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 amount of strings possible is 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.

Reference

Mirapeix Serrano, Jesús. 2021 . **Energy and Telecommunications.** University of Cantabria

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