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4.1 Basics of PV

4.1.1 Introduction

Photovoltaic solar energy (PV) is the direct conversion of sunlight into electricity. The basic building block of any PV system is the solar module, which consists of a number of solar cells.
The discovery of the photovoltaic effect ("photo" = light, "voltaic" refers to electricity) is usually attributed to Edmond Becquerel, who published a paper in1839[1]. Practical applications for power generation, however, have only come within reach after the successful development in the early 1950s of methods for well-controlled processing of semiconductor silicon, the material that most solar cells are still made of. The research group at Bell Laboratories the USA has played a key role in this development[2]. Although many people immediately saw the great potential of PV for large-scale use, the number and size of applications remained very modest until the 1980s. An exception was the use of PV to power satellites, which started successfully as early as 1958 and has remained the standard ever since.

4.1.2 Basic operation principles

The photovoltaic effect is based on a two-step process [Figure 4.1.01]:

- The absorption of light (consisting of light particles; photons) in a suitable (usually semiconductor) material, by which negatively charged electrons are excited and literally mobilized. The excited electrons leave behind positively charged "missing electrons", called holes, which can also move through the material.
- The spatial separation (collection) of generated electrons and holes at a selective interface, which leads to a build-up of negative charge on one side of the interface and positive charge on the other side. As a result of this charge separation a voltage (an electrical potential difference) builds up over the interface. In most solar cells the selective interface (junction) is formed by stacking two different semiconductor layers: either different forms of the same semiconductor (so-called "p" and "n" type) or two different semiconductors. The first case is referred to as (p-n) homojunction solar cells, the second case as heterojunctions solar cells. Homojunctions can be formed by adding different types of impurities (dopants) to the layers on both sides of the junction. The key feature of a semiconductor junction is that it has a built-in electric field, which pushes/pulls electrons to one side and holes to the other side. When the two sides of the junction are contacted and an electrical circuit is formed a current can flow (i.e., electrons can flow from one side of the device to the other). The combination of a voltage and a current represents electric power. Upon illumination, electrons and holes are generated and collected continuously and the solar cell can thus generate power.

4.1.3 Features of sunlight and solar cell efficiency limits

The total *annual* amount of solar energy per unit area (the *insolation*) varies over the earth's surface and roughly ranges from 700 kWh/m^2 to 2800 kWh/m^2 for horizontal planes. The lowest values correspond to polar regions, the highest to selected dry desert areas[3]. When comparing the insolation on *optimally inclined surfaces* the range becomes smaller, since the lower values increase to roughly 900 kWh/m^2. In other words, the global range of electricity production potentials per m^2 of fixed, optimally inclined surface area roughly spans a factor 3. It is important to note that the maximum *intensity* of sunlight is approximately 1000 W/m^2 everywhere. The differences in insolation primarily result from varying time fractions with low light levels (seasonal, but also daily variations). Whereas daily variations are inherent to the use of sunlight, the magnitude of seasonal variations in the daily (or weekly, or monthly) amount of solar energy received may have important implications for system design and implementation. In the case of grid-connected systems (see "PV systems and systems terminology") the grid acts as a virtual storage and the user is always assured of sufficient electricity, but in the case of stand-alone systems (see "PV Systems and systems terminology) storage has to be part of the PV system to get through hours, days or even months of low insolation.

Sunlight consists of a wide range of colors (from infrared to ultraviolet) and corresponding photon energies; the solar spectrum [Figure 4.1.02]. The details of the shape of the spectrum and the total intensity of the light are dependent on the position of the observer with respect to the sun and the atmospheric conditions. When the sun is exactly overhead and the sky is clear[i], the spectrum is "Air Mass 1", which means that the sunlight has passed the earth's atmosphere in the shortest possible way: it has crossed "1 air mass". Upon passing the atmosphere, some light is absorbed and some light is scattered, leading to characteristic features in the spectrum shape. When the sun is incident at another angle the Air Mass number changes accordingly. For measurement purposes Air Mass 1.5 is often taken as a reference.

The (energy conversion) efficiency of solar cells is defined as the maximum power output $P_{max,electrical}$ of the cell divided by the power input in the form of light P_{light}:

$$\text{efficiency } \eta = \frac{P_{max,\,electrical}}{P_{light}}$$

It is noted that solar cells and modules do *not automatically* operate in their maximum power point; they have to be *set* at that point by selecting the optimum combination of output voltage and output current [Figure 4.1.03]. For reasons of easy (and fair) comparison efficiency values are normally defined and measured under Standard Test Conditions (STC): Air Mass 1.5 spectrum, 1000 watt/m^2 light intensity, and 25 ^oC operating temperature, although other standardized conditions are also useful and necessary for certain types of cells and modules, especially concentrators.

The rated power of PV cells, modules and systems is expressed in terms of watts-peak (Wp). This is the power produced at "full sun", i.e. STC. It is noted that the efficiency of cells, and hence, that of modules and systems is (somewhat) dependent on the operating conditions. Therefore, the average

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[i] Actually, definitions are much stricter than described here, see for instance http://rredc.nrel.gov/solar/spectra/.

efficiency over a year differs from the STC efficiency. In most cases the average value is lower than the STC value, but this is not necessarily so. In particular: higher operating temperatures, lower light intensities and different light spectra lead to deviations from STC efficiency. To calculate the electricity yield the rated power therefore has to be multiplied by the equivalent number of hours full sun (for instance, per year), and corrected for the effects of non-STC conditions. See section 4.1.5 for details.

Semiconductors are, among others, characterized by their light absorption behavior. Each semiconductor has a specific threshold energy above which photons can be absorbed and below which the material is basically transparent. This threshold energy is the so-called bandgap energy[ii] and can be understood as the minimum energy it takes to free an electron from its original position in the crystal lattice of the material. The bandgap energy varies substantially from one semiconductor to another and determines which part of the solar spectrum can be absorbed. Low bandgap materials absorb more of the solar spectrum than high bandgap materials and can thus generate more current (assuming that each absorbed photon yields one electron to contribute to the current). However, the output voltage of a solar cell is also related to the bandgap: the higher the bandgap, the higher the voltage (at least for ideal devices). This implies that to achieve *maximum efficiency* it is important to choose an *optimum bandgap*.

In any cell made of a single semiconductor (i.e. one bandgap) there are large spectral losses, see Figure 4.1.04. Part of the spectrum cannot be absorbed at all and the rest of the spectrum can only be utilized partially. The latter results from the fact that photons with energy higher than the bandgap are readily absorbed, but only the energy needed to cross the bandgap can be used. The excess energy (photon energy minus bandgap energy) is lost in the form of heat in all current solar cells. The combined spectral losses add to more than 50% even for the optimum bandgap and perfect material, see the non-shaded area in Figure 4.1.02 for the case of silicon used a semiconductor. In addition to the spectral losses, any cell (even an ideal cell) suffers from fundamental losses related to the inverse process of light absorption and electron-hole pair generation, i.e. recombination of electrons and holes, and the specific properties of the device structure used (often a p-n junction)[iii]. For cells made from one type of material and operating under natural, i.e. unconcentrated, sunlight, the efficiency is therefore limited to value of roughly 30% at maximum[4]. The best single-material solar cells made so far have an efficiency of 25-26%[5], indicating that these devices are already close to perfect. Commercial solar cells and modules have significantly lower efficiencies for several reasons, see next sections.
There are two commonly used ways to move the efficiency beyond the limit discussed in the previous paragraph: (1) using multiple materials (bandgaps) for light absorption and (2) using concentrated sunlight. By stacking solar cells with different absorption characteristics it is possible to achieve a better

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[ii] The bandgap energy, but also photon energies, are usually expressed in electron-volts (eV). This is the energy an electron takes up when it passes a 1 volt (V) potential difference: $1.6\ 10^{-19}$ joule (J). The eV is a convenient unit in relation to the behavior of single electrons, such as light absorption. Bandgap energies are typically between a few tenths of an eV and a few eV. Solar photon energies are in the same range.
[iii] A full explanation of these losses requires a more rigorous and complex treatment, but is beyond the scope of this chapter. Many textbooks give excellent descriptions of the physics of solar cells.

coverage of the solar spectrum and to reduce the spectral losses. These are called multi-junction, multigap, multilayer, or tandem solar cells. Obviously, such devices are more complex that single-material cells. By using concentrated sunlight (up to 1000x) the effects of recombination can be reduced and the output voltage can be increased. This requires a dedicated device design, because the currents generated by concentrated sunlight are large and significant amounts of heat need to be extracted. The combination of these two approaches is particularly effective to achieve high efficiencies and pushes the fundamental limit up to approximately 85%[4] for direct sunlight, using an infinite number of bandgaps and the highest achievable concentration ratio (≈46,000). It also lies at the basis of the January 2009 world record (as well as most previous records): 41% for a triple-junction cell under ≈450x concentrated sunlight[6]. Although practical efficiencies may never approach the extremely high value of 85% there is still room for a large further increase of the record value; perhaps to 60% or even higher.

Recently there is a growing interest in other approached towards very high efficiencies than the one described here. These fall in the category of what is commonly referred to as “third generation photovoltaics”. Some of these concepts offer fundamental efficiency limits up to 85%[7], but they are all still in a very early stage of development. See “Novel approaches”, next section.

4.1.04 Practical solar cells and modules

Flat-plate and concentrator modules

Solar modules are commonly divided into two categories:
- *flat-plate* modules, in which the active cell area is roughly equal to the light-harvesting area;
- *concentrator* modules, in which a small-area solar cell is illuminated by sunlight collected on a (much) larger area. These modules have a lens and/or a mirror to focus sunlight onto the solar cell behind it.

Concentrator modules need to track the sun, since the optical system requires the light to come from a well-defined angle to produce a high-quality focus on the cell. For similar reasons, concentrator modules can only use the direct (i.e. not the diffuse) part of the sunlight and work best in regions where the fraction of direct radiation is high (“sunbelt” countries, typically countries with an insolation of 1500 kWh/m^2 per year or more). The required tracking accuracy increases with the concentration factor (typically in the range of 100x to 1000x). Low-concentration-factor modules with special (“non-imaging”) optics that do not require tracking have also been developed. “Flat plate concentrators” or “luminescent concentrators[8]” also fall in this category. These may therefore also be integrated into buildings, which is quite difficult, if not impossible for normal concentrators. Obviously concentrating systems *can* be used on flat roofs of buildings, for instance. Recently a new type of concentrator module has been developed which does involve tracking, but in an unconventional way. The tracking (i.e. moving) and focusing elements are integrated into a shallow, dish-shaped module which does not move itself. One may call this “internal tracking”. These modules may also be integrated into buildings.

Apart from the fact that tracking of the sun is essential for concentrators to operate, it also yields a higher electricity output compared to systems without tracking. For flat-plate modules, where the comparison between fixed operation and tracking can be made, it has been calculated that the gain of two-axis tracking ranges from 25% to as much as 70%[9]. Although the relative gains are highest in regions at higher latitudes, the absolute gains are highest in regions at lower latitudes (sunbelt regions).

Cell and module technologies

It is common to categorize cell and module technologies according to the active material(s) used for the solar cells; the semiconductors. At the highest level, cell and module technologies can thus be divided into wafer-based technologies and thin-film-technologies. Although the term “wafer-based” usually refers to flat-plate technologies, also concentrator cells may be (and usually are) wafer-based. The wafer may be silicon, germanium, or gallium arsenide (the latter two only for concentrator applications). In the following, the term “wafer-based” is only used for silicon technology. The individual cells produced from wafers are electrically connected before or upon encapsulation in a module [Figure 4.1.05]. In the case of thin-film technologies, the cells are deposited on a substrate (glass or metal foil) or a superstrate (glass) in the form of a very thin layer. Typical thicknesses are in the order of 1 micron (0.001 mm). The individual cells are usually elongated areas, running from one side of the module to another, and monolithically connected in series in the other direction.

In the framework of the preparation of a Strategic Research Agenda[10], the European Photovoltaic Technology Platform (EU PV TP) has made a survey and an overview of the present state and expected future developments of cell and module technologies. The technology categories and types distinguished are summarized in Table 4.1.01. Although record efficiencies for small-area laboratory cells (typically 1 cm^2) are useful indicators for PV development, it is even more important to consider the development of large-area commercial module efficiencies (typically 1 m^2). These are significantly lower than record cell efficiencies, because they result from a performance/price optimization rather than an efficiency maximization. Moreover, for technical reasons efficiencies of small-area devices are *necessarily* lower than those of large-area devices. Although it is difficult, if not impossible to make accurate statements about the potential and future development of commercial PV technologies, it is may be useful to describe the typical expert expectations, based on a survey made in the context of the earlier mentioned Strategic Research Agenda. Efficiency values for laboratory cells as well as current and possible future commercial modules are summarized in Table 4.1.01.

It is noted that the table lists data for “PV technologies”, “PV conversion concepts” and “PV efficiency boosters”. The first refers to existing cells (and modules, where applicable), the second to cell yet to be demonstrated in practical form, the third to “add on” elements that may enhance performance of existing or future cells and modules.

Table 7.01. Overview of PV technologies, PV conversion concepts and PV efficiency boosters.

State of development	Category	Technology type	Record cell efficiency (rounded figures); status 2008	Typical commercial module efficiency (aperture area); status 2008	Potential future commercial module efficiency (aperture area)
Commercial	**Flat plate**	Wafer-based crystalline silicon (Monocrystalline, cast multicrystalline, ribbon)	25% (mono) 20% (multi)	12-20%	18-23%
		Thin-film silicon (amorphous, nano- & microcrystalline)	12% (stabilized)	6-9%	15%
		Thin-film cadmium telluride (CdTe)	17%	9-11%	15%
		Thin-film copper-indium/gallium-diselenide/sulphide (CIGS)	20%	11-13%	18%
	Concentrator	Silicon-based	27%	?	?
		Compound semiconductor-based	41%	20-25%	40%
Emerging (typically advanced laboratory or pilot production)	**Flat plate**	Polymer cells and modules	6%	n.a.	Primarily aimed at very low costs and/or new application possibilities, long-term efficiency potential still unclear
		Dye-sensitized cells and modules	11%	n.a.	
		Alternative forms of inorganic thin films (e.g. printed CIGS) and hybrid materials	?	n.a.	
	Concentrator (low concentration)	Luminescent concentrators employing silicon or compound semiconductor cells)	7%	n.a.	
Novel concepts (laboratory only – research or proof-of-principle phase)	**Not yet known**	Intermediate band semiconductors ("intrinsic multi-junction materials"	n.a.	n.a	Primarily aimed at very high efficiencies; cost potential still unclear
		Spectrum converters ("external efficiency boosters)	n.a.	n.a.	
		Various electronic and optical applications of quantum dots (e.g. "all-silicon tandems")	n.a.	n.a.	
		Plasmonic structures for light management	n.a.	n.a.	
		Hot-carrier devices	n.a.	n.a.	

		Other	n.a.	n.a.	

The data in Table 4.1.01 shows that existing flat-plate PV technologies have an efficiency potential in the range of 15% to 23%, not taking into account the possible effects of add-on “efficiency boosters”, such as spectrum converters. Currently the only proven approach towards very high efficiencies (>>20%) is the use of multi-junction cells in concentrator modules. However, a variety of alternative device concepts for very high efficiencies are under development. On the longer term these concepts may also yield possibilities for very high efficiency flat-plate modules. It is nevertheless emphasized that it is expected[10] that all PV cost targets for the short and medium term (at least up to 2020) can be reached by ambitious further development of proven and emerging technologies. In other words, there is no need for a disruptive technology or a breakthrough in the traditional sense of the word to reach these targets.

4.1.05 PV systems and systems terminology

Complete PV systems[4,11,12] consist of modules (also referred to as panels), which contain solar cells, and the so-called Balance-of-System (BoS). The BoS mainly comprises electronic components, cabling, support structures and, if applicable, electricity storage, optics & sun trackers, and/or site preparation. The BoS *costs* also include labor costs for turn-key installation.

PV systems are often divided into the following categories [Figure 4.1.06]:
- grid-connected systems (integrated of ground-based);
- stand-alone (autonomous) systems.

PV systems feeding into, or connected to a minigrid fall in between these categories.

Systems are built of modules which are electrically connected in series and/or in parallel. A number of modules connected in series are called a *string*. A number of strings connected in parallel are called an *array or subarray*. A number of arrays that belong together are called a *system or a subsystem*.

Here we only consider grid-connected systems, because for the short and medium term this is the most likely application form of PV in the urban environment. Although grid-connected systems normally do not include electricity storage (the grid acts as virtual storage capacity) it is noted that grid-connected systems *with* a small (battery) storage may perhaps enter the market in some situations. By adding storage it becomes possible to supply electricity to the grid at moments when the value is highest rather than only when the sun shines. This advantage always has to be counterweighted against the obvious cost increases and energy losses associated with adding storage.

Grid-connected systems

To be able to quantify the performance of PV systems and to make comparisons with other electricity generating technologies it is important to introduce some terms and definitions.

System power

The (nominal, nameplate, rated) **Power** of PV cells, modules and systems is expressed in watt-peak (Wp]. This is the power produced under Standard

Test Conditions (see section 4.1.04). The power of complete systems is often simply expressed as the sum of the powers of the individual modules that build the systems. Although the actual DC power of many modules connected in series and in parallel will never equal the sum of the individual powers, this is still a very useful practice, since it puts all system-related losses (and possible gains) into one lumped parameter, the Performance Ratio.

Performance ratio
The (dimensionless) **Performance Ratio (PR)** of PV systems is defined as:

$$\mathbf{PR} = \frac{\text{average AC system efficiency}}{\text{STC module efficiency}}$$

in which: AC = alternating current, DC = direct current.

The PR can be defined over any period of time, but usually the average is taken over a year. In the PR the effects on efficiency of very different factors are taken together. Most importantly: module mismatch due to series and parallel connection of modules with (slightly) different characteristics, cabling and inverter (DC/AC conversion) losses, cell/module operating temperatures, light intensities, light spectra and angles of incidence that deviate from the STC conditions of 25^{o}C, 1000 W/m^2, AM1.5, and perpendicular incidence. Typical PR values for well-functioning recent systems are in the range of 0.70 ~ 0.85[13]. The PR may have a modest upward potential to 0.9, for instance due to further improvements of average inverter efficiencies and to the introduction of modules with a lower temperature sensitivity of the efficiency.

It is noted that also system outages, if they occur, influence the PR. However, as discussed in the section “PV system performance in practice”, the number and duration of systems outages decreases as the PV sector matures.

Capacity factor
The (dimensionless) **Capacity Factor** of a PV system is determined by the insolation (in the plane of the modules) at the location of the system and the system PR:

$$\mathbf{CF} = \frac{\text{N } x \text{ PR}}{8760}$$

In which 8760 is the number of hours in a year and N the equivalent number of hours full sun in a year:

$$\text{N} = \frac{\text{insolation (in kWh/m2·yr)}}{\text{intensity of full sun (1 kW/m2)}}$$

It is noted that numeric value of N is equal to the insolation because on earth “full sun” can defined as 1 kW/m^2. The latter may be considered a fortunate coincidence.

Taking the range of insolation values (in the plane of the modules, for optimally inclined modules) as 900 to 2800 kWh/m^2 per year (see section 4.1.03), and the range of PR’s as given, the global range of CF’s becomes 0.06 to 0.27, with upward potential to 0.29. It is important to note that these values refer to systems without sun tracking. If tracking is applied, N increases, depending on the specific climatic condition at the location considered[9]. For a modest increase of 20%, the CF of systems in high insolation regions reaches values well over 0.30.

For PV modules integrated into buildings and especially for PV modules integrated into façades, the insolation values may be significantly lower than for optimally inclined and oriented modules. The ratio of the amount of solar radiation received on a façade to the maximum that could be obtained at the same location for an optimum inclination and orientation varies strongly with the geographical region considered and –of course- with the orientation. Note that "inclination" refers the angle with the horizontal surface, while "orientation" refers to the angle with respect to "South-facing". Simple as well as more sophisticated tools are available for estimation or calculation of the amount of solar energy to be expected.

Specific electricity yield
The **specific final AC electricity Yield** of a system $\mathbf{Y_f}$ is defined as the AC output per unit of installed power:

$$\mathbf{Y_f} = \frac{\text{annual AC electricity output}}{\text{system power}} = \frac{P\ x\ N\ x\ PR}{P} = N\ x\ PR \quad [\text{kWh}_{AC}/\text{kWp}\cdot\text{yr}]$$

Again taking the ranges as discussed above, the global range of Y_f-values is 600 to 2400 kWh/m^2·yr, with upward potential to 2500 kWh/m^2·yr, excluding yield gains by sun tracking. *With* tracking (which is especially likely to be applied for all ground-based desert systems), Y_f could go up to well over 3000 kWh/m^2·yr.
For PV systems in the urban environment it is often not possible to use the exact optimum angle and orientation. This leads to lower amounts of sunlight harvested and hence, to lower specific electricity yields than the (maximum) values indicated here. Moreover, urban areas are usually not located in the sunniest parts of the world, i.e. deserts, which implies that the upper part of the range may not occur in practice. Most urban areas are located in regions where yields well below 2000 kWh/m^2·yr are achievable for optimally inclined and oriented systems.

PV system performance in practice
A very important parameter determining the actual output of PV systems is the absence or occurrence of partial or complete shading. This may occur due to the presence of trees, buildings, or other "external" objects, or as a result of the design features of the building where the PV system is integrated into or mounted onto. Shading inherently varies with the time of the day and the time of the year. Generally speaking shading should be avoided as much as possible since the output loss may even be larger than expected on the basis of the lower amount of solar energy captured only. The latter is especially the case when partial shading occurs. In any case it is important to be aware of these effects already in the design phase and to optimize the electrical system design (e.g., parallel and series connections of modules) for the specific situation to be expected. Fortunately it is possible to make quite accurate calculations of shading-related losses in advance of actual system operation[14].

Extensive data on the performance of PV systems in different countries is collected in the framework of IEA-PVPS Task 2[13]. It is found that in the period from 1991 to 2005 the typical system performance ratio has improved significantly from 0.64 to 0.74, among other as a result of higher inverter efficiencies, fewer and shorter system outages and more accurate module rating (the latter may perhaps be considered an artefact in this context). This trend does not appear to saturate yet. In 2005 the best systems had a PR in the range of 0.80 to 0.85.

4.1.06 Economic aspects of PV systems

Although PV modules are the most visible part of PV systems, the economics of PV is obviously dependent on (among others) the price and the performance of *complete, turn-key systems*, since these are the units that actually produce electricity to the user or the grid. The price (or alternatively: the cost) of a turn-key PV system is the sum of the price of the modules and the price of the Balance-of-System (BoS), see 4.1.05. It is expressed in $, €, ¥, etc., per Wp of system power. It also contains labor costs related to engineering, installation, etc.

Module price development
The price evolution of photovoltaic modules can be described well by a price-experience curve (also called "learning curve"), in which the average selling price is plotted as a function of the cumulative production, on a double logarithmic scale[15], see Figure 4.1.07. A straight line indicates that prices decrease by a fixed percentage for each doubling of the cumulative production (or shipments). The progress ratio is defined as 100% minus this percentage.

Since crystalline silicon accounted for more than 90% of all modules produced over the past decades, the experience curve for this technology gives a reliable picture of the entire PV sector in that period. Figure 4.1.07 shows that the average selling price of modules has decreased by more than 20% for each doubling of the cumulatively shipped volume. The flattening of the curve over the past few years is a direct result of a temporary shortage of high-purity silicon; feedstock for the wafer-based silicon PV industry. Note that the curve shows prices, not costs. Because existing feedstock production capacities are being expanded and new capacity is under construction in several parts of the world, it is expected that this problem will soon be solved. Since technology development has continued (and partly even accelerated, e.g. by using much thinner wafers and increasing output in terms of Wp per gram silicon used) price reduction can then continue the historic trend. In other words, selling prices may then follow manufacturing costs again.

A question yet unanswered is what the experience curve for thin-film PV modules will look like. Since thin-film manufacturing processes differ substantially from that in the wafer-based silicon industry is expected that these technologies follow their own curve (i.e. the thin-film PV volumes produced should not be simply added to those produced by the wafer-silicon PV industry to extend the curve in Figure 4.1.07. Now that the market share of thin-film PV may increase[16] from approximately 10% in 2007 to 15~25% in a few years, it is important to closely follow both developments.

The value of efficiency

It is noted, however, that turn-key system prices of a PV technology are a better indicator of the competitive position than module prices as such. Since the BoS-part of system prices consists of a power-related part (e.g. the inverter) and an area-related part (e.g. the mounting or support structure), module efficiency has an influence on system price $/Wp. Systems based on higher efficiency modules are more compact (lower m^2/Wp) than systems based on lower efficiency modules. One could turn this around and say that for an equal turn-key system price higher efficiency modules are generally allowed to be somewhat more expensive than lower efficiency modules. The numbers behind this statement may vary substantially depending on the system type and should be evaluated on a case-by-case basis.
Just to illustrate the argument, Figure 4.1.08 gives a comparison between two systems with an equal price of 4 €/Wp. One system uses 20% efficient modules at 3 €/Wp, the other 10% efficient modules at 2.5 €/Wp. In this particular example, the “value” of 20% over 10% efficiency is thus 0.5 €/Wp

System price development
System prices vary much more than module prices. Reasons for that are the wide variety of system types and sizes, country-to-country differences in experience and installation practice, etc. For systems that can be compared, a European study has indicated that the BoS-part of system prices may follow an experience curve with a progress ratio similar to that of modules, although the uncertainties are much larger[17]. Moreover, it is uncertain whether this trend can be maintained on the longer term, because drastic possibilities for price reduction are perhaps less obvious for the BoS than for the modules. Therefore it has been argued that the progress ratio for the BoS on the longer term may be 0.85 or even 0.90 rather than 0.80 like for the modules.

The evolution of system prices is monitored by IEA PVPS[18]. It is noted that prices of building-integrated systems vary even more than those of add-on or ground-based systems. This is even further complicated by the fact that it is not straightforward to attribute certain price components to either the building of the PV system. Therefore this topic is not dealt with further here.

Although turn-key system prices can be determined rather easily and accurately on a case-by-case basis, they are of limited practical use. Therefore is becoming common practice to translate the turn-key system price to electricity generation costs. This is for instance done using a so-called Levelized Energy Cost (LEC) method (also referred to as Levelized Cost of Energy, LCoE). Although the calculation involved is very straightforward, it requires assumptions and estimates of parameters which may not be made in a straightforward manner. More precisely, besides the turn-key investment price, we need a value for the operation & maintenance costs (normally expressed as a % of the investment per year), the system economic lifetime (depreciation period), the discount rate (interest rate) and the specific electricity yield (kWh per year per watt-peak of system power). Without explicit information on the assumptions made, comparisons between different PV systems and between PV and other energy technologies are quite meaningless. Moreover, it is difficult to “standardize” the parameters used in the calculation, because they may vary substantially depending on, among others, the type of technology and system, the geographical location and the type of ownership.

Table 4.1.02 presents a set of calculation examples to show the effect of typical ranges of parameters. Turn-key prices of grid-connected systems in 2008 ranged from less than 4 € per watt-peak to 8 € per watt-peak or more, for different system types and sizes, and countries. A value of 5 € per watt-peak was sometimes used as a reference. It is expected that system prices will drop to (less than) 2 € per watt-peak in 2020, (less than) 1 € per watt-peak in 2030 and perhaps even less in the longer term, see ref. 5. Specific electricity yields for high-quality, well-oriented systems roughly range from 0.8 kWh/watt-peak per year for NW Europe to 1.6 kWh/watt-peak per year for the most Southern parts of Europe; values used as examples here. Combining a low (future) system price with a high insolation and reasonable values for other parameters gives an indication of what PV may be capable of in the longer term: electricity generation at 5 eurocents per kWh. Clearly, if this can be reached PV will be competitive with almost all other electricity options.

Table 4.1.02. *Levelized cost of electricity for a range of turn-key system prices, geographical locations and other parameters. Numbers serve as examples to illustrate dependencies only. See text for details.*

Turn-key system price (€/Wp)	Depreciation time (yrs)	Energy yield (kWh/Wp.yr)	Interest rate (%)	O&M + other costs (% of initial investment/yr)	Levelized electricity cost (€/kWh)
5,00	20	0,80	4	1	0,52
2,00	20	0,80	4	1	0,21
1,00	20	0,80	4	1	0,10
5,00	**30**	0,80	4	1	0,42
5,00	**20**	0,80	4	1	0,52
5,00	**10**	0,80	4	1	0,83
5,00	20	**0,80**	4	1	0,52
5,00	20	**1,20**	4	1	0,35
5,00	20	**1,60**	4	1	0,26
5,00	20	0,80	**8**	1	0,70
5,00	20	0,80	**4**	1	0,52
5,00	20	0,80	**2**	1	0,44
5,00	20	0,80	4	**0,5**	0,49
5,00	20	0,80	4	**1**	0,52
5,00	20	0,80	4	**2**	0,58
1,00	20	1,60	4	1	**0,05**

Grid parity

The term of "grid parity[19]" is used to describe the situation where the generation cost of PV is equal to the price of electricity at the point of connection. When this situation is reached, and under the condition that "net

metering"[iv] applies the owner of a PV system can recover the entire investment by the earnings of selling e Note that it is common practice to speak about the cost of electricity from PV, because the point of grid parity does not assume a profit margin for the owner, while the comparison is made with the price of electricity from the grid, which again makes sense from the perspective of the owner/consumer.
At 2009 price levels, electricity from PV cannot yet compete with electricity from the grid, except in selected situations like peak power consumption. This, however, will soon change and grid parity with retail electricity will be reached in sunny regions like Southern Europe or Southern USA. The situation of grid parity with retail prices is of course highly relevant for PV applications in the urban environment in general and for PV on private houses in particular. It is expected that by 2020 grid parity will have been reached in most of the urban environments (i.e., also in regions with a moderate insolation).

4.1.07 Sustainability issues

A persistent misconception about PV systems is that it would require more (fossil) energy to manufacture and install them, than the (renewable) energy they generate over their lifetime. Although this may have been true for the first generation systems built decades ago, the current generations have a so-called energy pay-back time (not to be confused with economic pay-back time) of typically 1.5 to 2 years in relatively sunny regions (insolation 1700 kWh/m^2 per year) and 2.5 to 3.5 years in regions with moderate insolation (1000 kWh/m^2 per year), see Figure 4.1.09[20]. These values may be compared with system technical lifetimes of 25 years or more, implying that PV systems are indeed excellent net producers of renewable energy. Moreover, the energy pay-back times decrease constantly and may soon be shorter than one year.

In addition to the *energy* needed to manufacture and install PV systems also the *materials* used should be considered in a sustainability analysis. For PV systems to be used on a very large scale it is important that they are based on "earth-abundant" materials. If that turns out to be impossible for all materials, closing the materials cycles is the next best solution, although this would not solve availability restrictions in the long term.

[iv] "Net metering" refers to the situation where (solar) electricity may be sold *to* the grid at the same price as the price paid for (conventional) electricity purchased *from* the grid. When the electricity consumption is higher than the production (either e.g. on an annual basis or at a particular moment), so that there are *no net* sales, "net metering" in fact refers to avoided purchase of electricity.

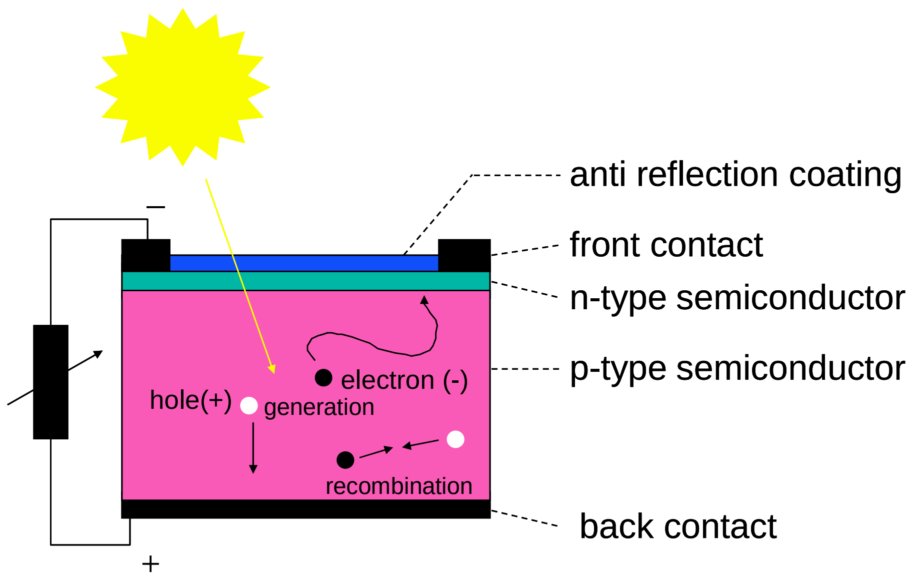
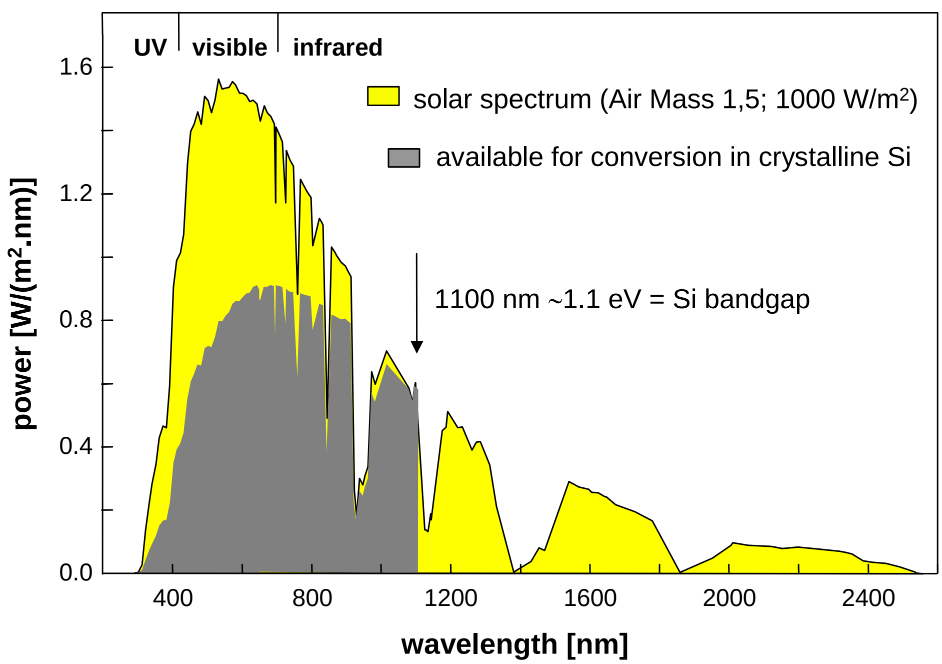


Figure 4.1.01. Schematic cross-section of a typical solar cell, showing the basic steps in the conversion of light (photon) energy to electrical energy: (1) generation of electron-hole pairs by the absorption of light and (2) spatial separation of (negative) electrons and (positive) holes. See text for details.



courtesy John Schermer, KUN

Figure 4.1.02. Air Mass 1.5 solar spectrum, showing the power density versus the wavelength (color) of the light. The shaded area indicates the fraction that can be converted by a silicon (Si) solar cell, see text. Courtesy John Schermer, Radboud University, Nijmegen, The Netherlands.

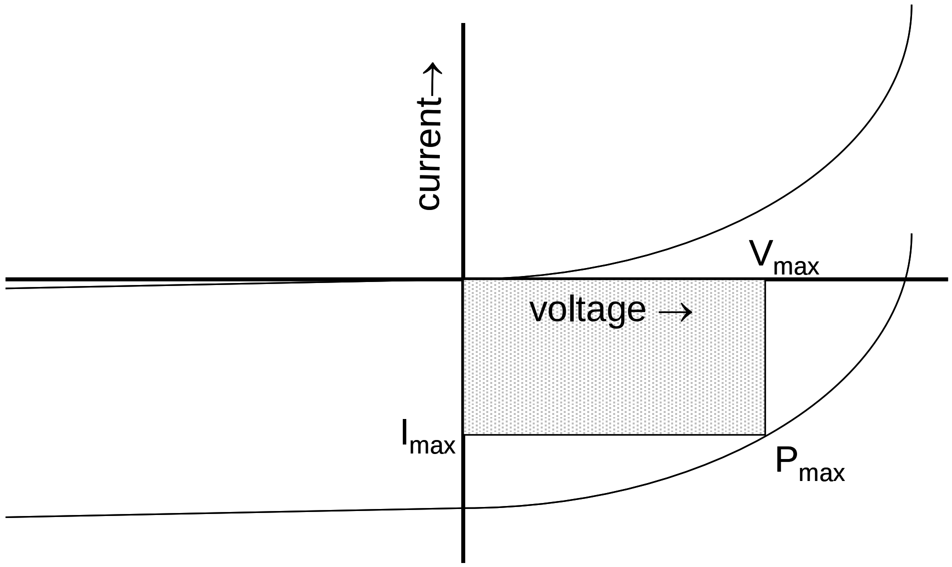


Figure 4.1.03. Schematic electrical (current-voltage) characteristic of a solar cell in the dark (upper) and under illumination (lower). $P_{max} = I_{max} \times V_{max}$ is the so-called maximum power point. See text.

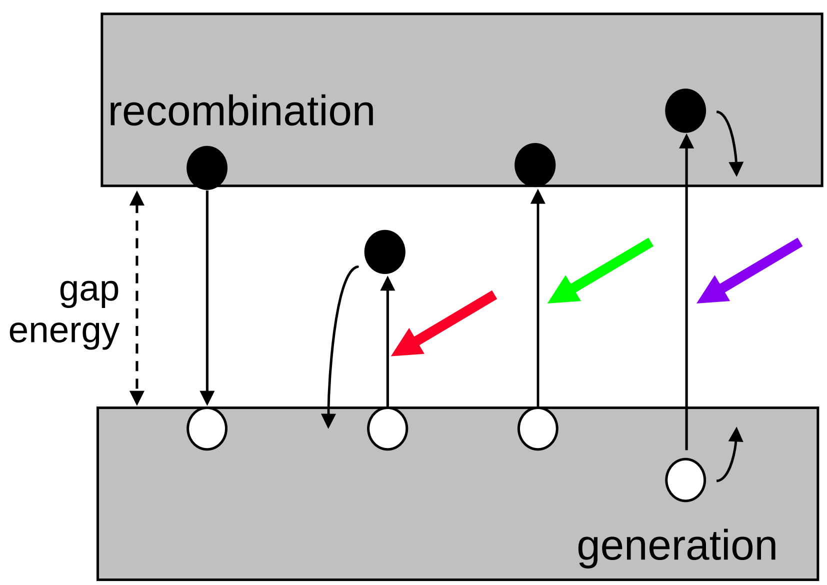


Figure 4.1.04. Schematic representation of two key processes in a solar cell: light absorption leading to electron-hole pair generation, and recombination leading to loss of electron-hole pairs. The vertical scale is the electron energy. Photons with insufficient energy ("too red") are not absorbed. Grey areas refer to the main energy levels in the semiconductor that the solar cell is made of. The "energy gap" (or "bandgap") is a property of the semiconductor and a major variable in solar cell design and optimization.

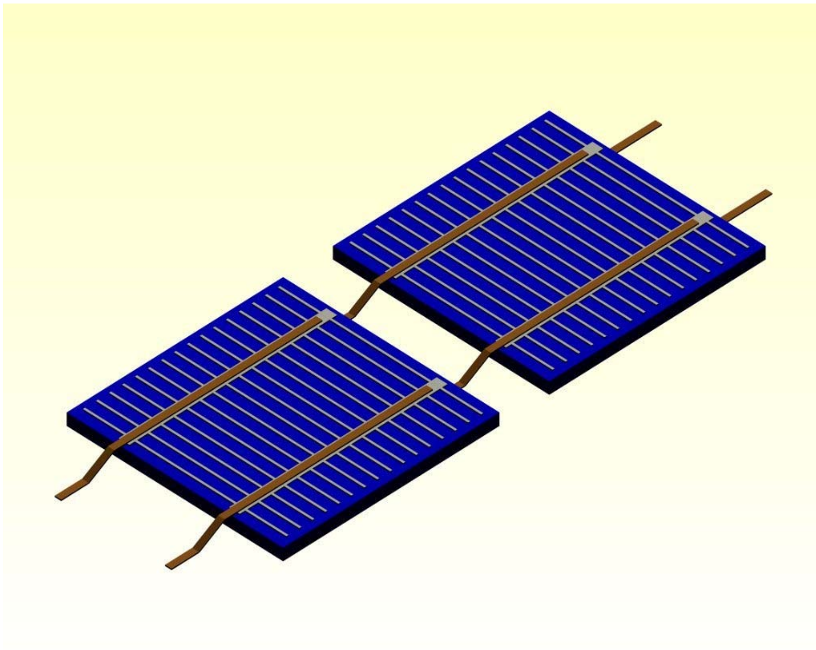


Figure 4.1.05. Series interconnection of silicon solar cells in a module.

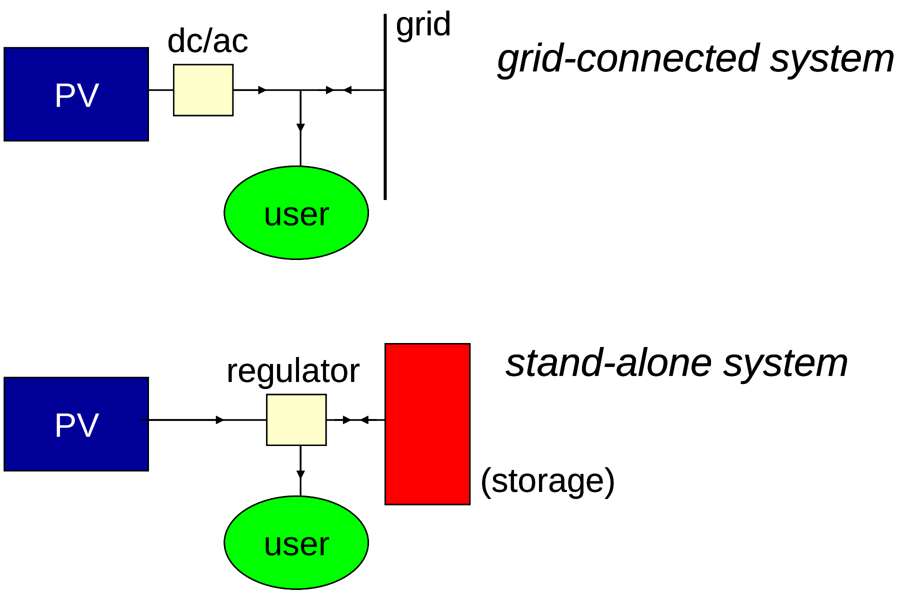


Figure 4.1.06. Block diagram of grid-connected and stand-alone PV systems. The blue block "PV" represents the PV modules, strings and arrays (see text).

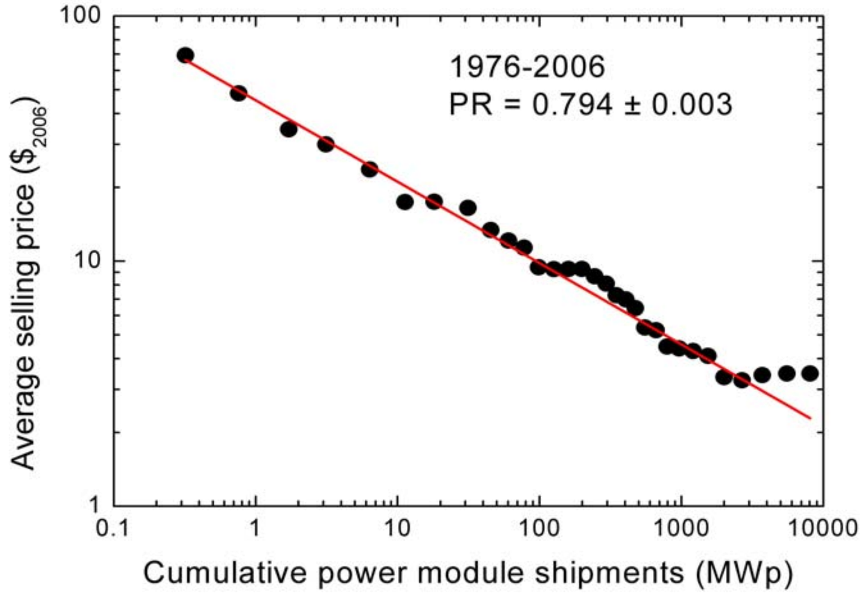


Figure 4.1.07. Crystalline silicon PV module experience curve showing average module price in 2006 US$ as a function of cumulative power module shipments. Taken from Van Sark et al. [15], see that reference for details and information on the data compiled in this graph.

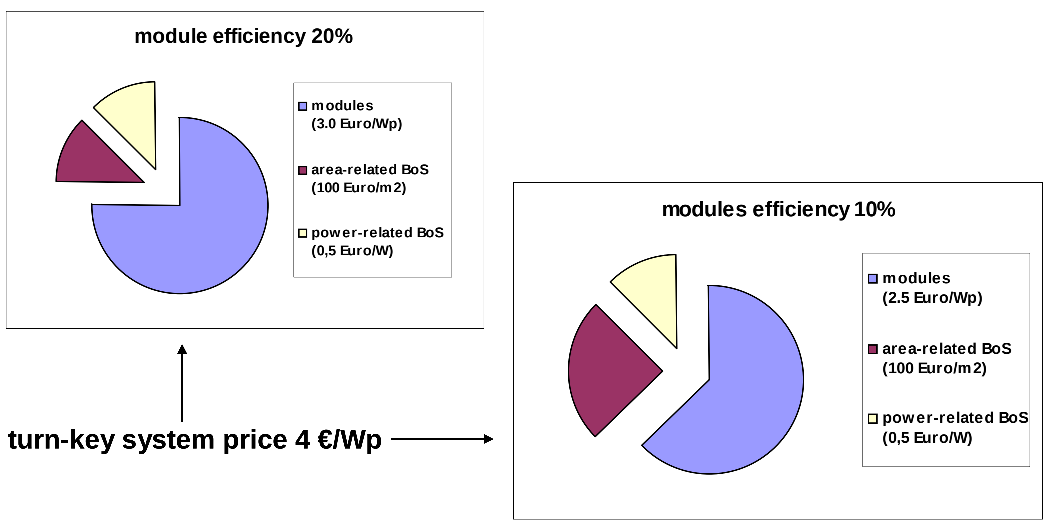


Figure 4.1.08. Comparison of two systems with the same overall price, but different price components, illustrating the influence (value) of module efficiency. *Numbers serve as examples only.* See text for datails.

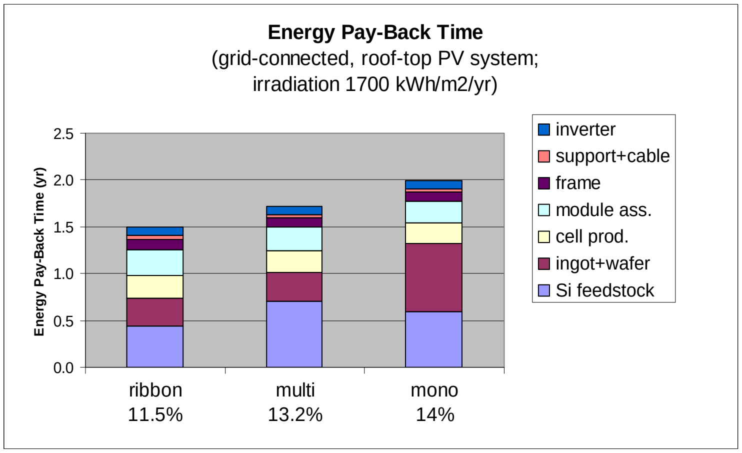


Fig. 4.1.09: Energy pay-back time of PV systems (state-of-the-art 2006)[19].

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