

7. Electric Characteristics of Photovoltaic Cells and Modules

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Learning outcomes

After studying this chapter, the reader should be able to:

- Comprehend the electric characteristics of photovoltaic cells and modules
- Perform mathematical calculations to assess figures such as the voltage, current and power of a PV cell or module
- Realise the concept of Peak Power and be able to mathematically assess it
- Understand the concept of Fill Factor, the quality figure of PV cells
- Be able to assess the output of a module based on the manufacturer's STC figures
- Understand the influence of temperature on the performance of PV cells
- Understand the aging process of PV cells

Electric Characteristics of a photovoltaic cell

A PV cell is in fact a well-known electronic component called “LED” (Light Emitting Diode), a component that lets pass the electric current in one direction (with a voltage drop of about 0.6 volt) and that blocks its passage in the other direction.

In the case of a PV cell, we try to keep the surface of the junction as wide as possible to collect the maximum of solar energy.

The simplified electric diagram of such a PV cell is shown in the following figure:

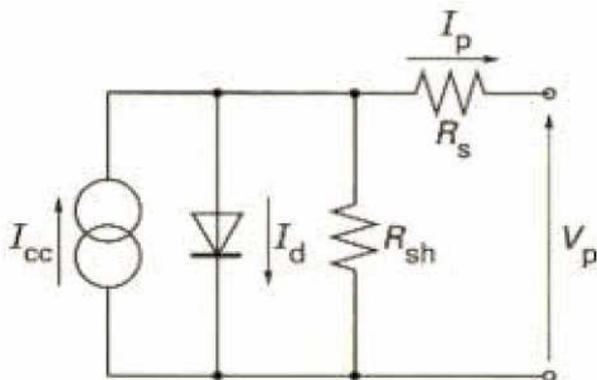


Figure 1: electrical scheme of a PV cell

One recognizes the symbol of the diode (crossed by the current I_d), in parallel with the generator of current I_{CC} , which corresponds to the flow of electrons generated by the flow of photons from the light (solar or otherwise) within the junction of the diode. Also in parallel to the diode there is the resistance R_{sh} (shunt resistance), which corresponds to the direct losses through the junction. In series towards the V_p and I_p usage, is the resistance R_s (series resistance) that corresponds, amongst other things, to the Joule losses in the wires.

At the two poles of photovoltaic cell, electrical energy is recovered under the form of a voltage V_p and of a current I_p .

The equation between I_p and V_p is the following:
$$I_p = I_{CC} - I_s \left(e^{\frac{V_p + I_p R_s}{kT/q}} - 1 \right) - \frac{V_p + I_p R_s}{R_{sh}}$$

Where: I_{CC} = variable generated current according to light radiance

T = temperature in K

$k = 1.38 \cdot 10^{-23}$ J/K (Boltzmann constant)

$q = 1.6 \cdot 10^{-19}$ C (electron charge)

I_s = some nA (own characteristic of each charge diode)

The layout of the equation $I_p = f(V_p)$ looks like:

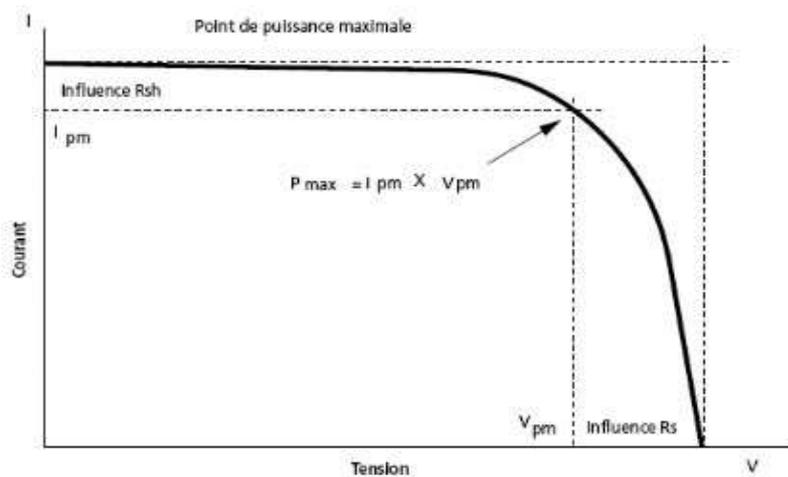


Figure 2: equation $I_p = f(V_p)$

On this curve, one can recognize the curve of the diode (to the bottom because of the sign - in the equation) and shifted to the top of the value I_{CC} from the current generated by luminous radiance.

Characteristic Points on this curve for a crystalline silicon cell:

No-load Voltage ($I_p = 0$ A) $V_{oc} = 0.6$ V (power $P = 0$ W)

Short-circuit current ($V_p = 0$ V) = I_{CC} (variable according to radiance, power $P = 0$ W)

Charging Voltage $V_{pm} = 0.5$ V at the point of operation where the power is maximum

Current I_{pm} (variable according to radiance) at the point of operation where the power is maximum

Maximum power : $P_{max} = I_{pm} \times V_{pm}$

Note that, while varying V_{pm} from 0 to V_{oc} (or I_p from 0 to I_{CC}), the power starts from 0W to go up to reach P_{max} , then to go down again to 0W.

The output of luminous energy conversion in electrical energy of a photovoltaic cell of surface S , of a P_{max} power under a luminous radiance I_{rrad} is the following:

$$R_{cell} = \frac{P_{max} (W) / S(m^2)}{I_{rrad} (W/m^2)}$$

One define also a factor of form (or fill factor), noted FF , representing the quality of a photovoltaic cell:

$$FF = \frac{V_{pm} \times I_{pm}}{V_{oc} \times I_{CC}}$$

The typical factors of form for various photovoltaic technologies are the following:

Crystalline silicon (m-Si): $FF = 0.83$

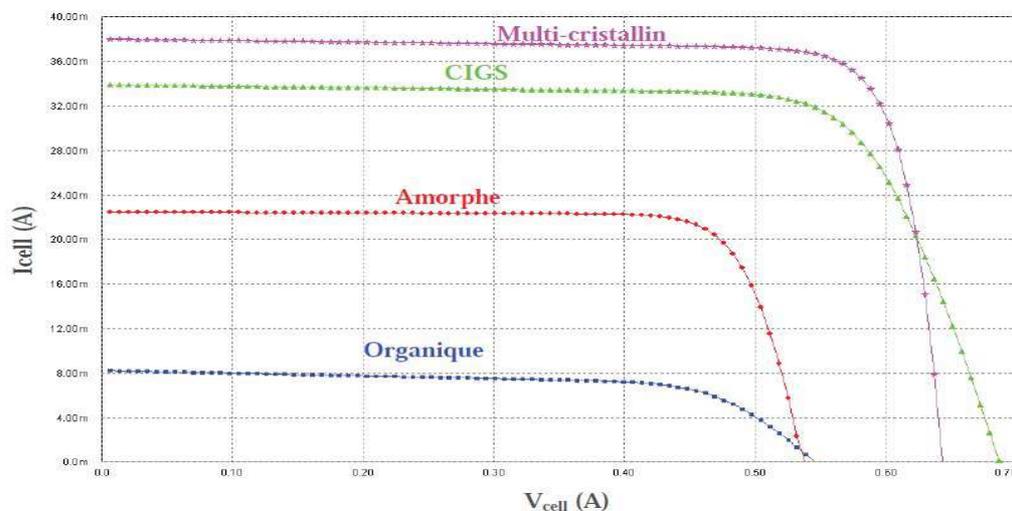
Amorphous silicon a-Si : $FF = 0.7$

Cadmium Tellurium (CdTe): $FF = 0.76$

Copper Indium Selenium: $FF = 0.78$

According to photovoltaic technologies of cells, the layout of the equation $I_p = f(V_p)$ keeps the same form but the values of no-load voltage are slightly different and especially, for the same surface, the currents of short-circuit are different because the output conversion yields are different for each technology.

Layout of the equation $I_p = f(V_p)$ for different photovoltaic technology of cells:



(Source: INES RDI/CEA)

Figure 3: layout of the equation $I_p = f(V_p)$ for the different PV kind of cells

Here are the typical conversion efficiencies for various photovoltaic technologies:

Crystalline silicon (m-Si): from 15 to 17%

Amorphous silicon (a-Si): 6 to 8%

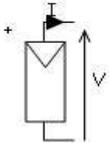
Cadmium Tellurium (CdTe): 11 to 12%

Copper Indium Selenium: 12 to 13%

Organic cell (still at research level): 5% (record at 11%)

Electric Characteristics of a photovoltaic module

The voltage of 0.5 V delivered by a photovoltaic cell is much too weak for most implementations. To increase the voltage, the photovoltaic modules are composed of photovoltaic cells assembled in series to increase the voltage.



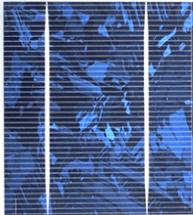
The electric symbol of a photovoltaic module:

Historically, the first photovoltaic modules included 36 PV cells in series (0.5 V). They were used in isolated sites to charge the 12 volts lead-acid batteries and, because of that, these modules are known as the 12V type. The voltage of 18 volts makes it possible to charge 12V batteries until fully charged (typically 14.8 volts), even with a weak irradiation (where the voltage slightly drops).

Currently, there is no market for battery chargers since most of the photovoltaic installations in the world are connected to grid, so the number of the cells in series can be higher, in general of 48, 54, 60, 72, 96 cells (standard of 60 cells).

In short, the photovoltaic cells are assembled in series to create photovoltaic modules, then the modules are assembled in series and in parallel to form photovoltaic fields.

PV Cell



PV Module



PV Field



The characteristic curve of a photovoltaic module (for various radiances) for the output current and power (i.e. product Voltage-Intensity) according to the output voltage are represented in the following figures for a 12V photovoltaic module:

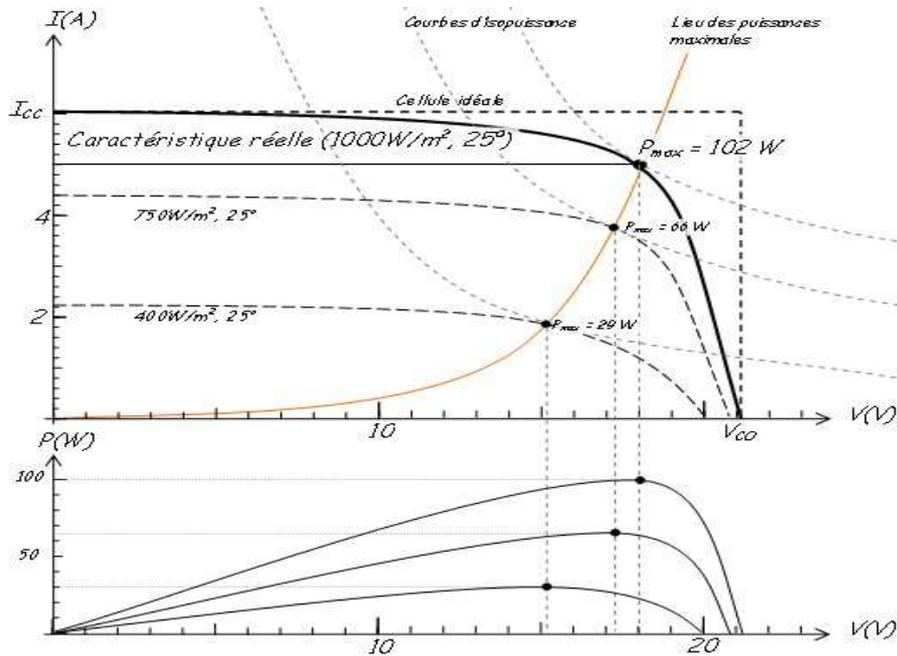


Figure 4: Intensity versus voltage curve for 12 V PV module.

The electric characteristics of PV modules are given into one point of operation described under the term of STC (Standard Test Conditions), which are:

- solar irradiation of $1,000 \text{ W/m}^2$
- solar spectrum AM 1.5
- temperature of 25°C

- V_{OC} , No-load Voltage (Intensity = 0A) in volt (21 volts on the curve)
- Short-circuit Intensity I_{CC} (tension = 0V) in A (6A on the curve)
- typical voltage of use at the point of maximum output V_{typ} in volt (18 volts on the curve)
- typical Intensity of use at the point of maximum output I_{typ} in A (5.6 A on the curve)
- the point of maximum output, P_{max} in W (102 W on the curve)

At the point of function described as STC conditions ($1\,000 \text{ W/m}^2$, spectrum AM1.5 and 25°C), the maximum capacity is the peak power P_c of the photovoltaic module, this peak power is expressed in Watts Peak.

According to the curves plotted above for various radiances (1000 , 750 and 400 W/m^2 , and a surface cell temperature of 25°C), one notes that the optimum point of operation in power is variable in current and voltage. That means, for the load connected to a module (or a photovoltaic field) to function at this optimum power, the installation will have to include an electronic device that will search for this point of maximum power. This system is called MPPT (for Maximum Power Point Tracking). Typically, inverters include this function.

Relation between surface S (in m^2), the output of luminous energy conversion into electrical energy (R_{mod}) and the peak power of a photovoltaic module (in W_p).



On the basis of the formula for the output of a cell: $R_{cell} = \frac{P_{max}(W)/S(m^2)}{I_{rrad}(W/m^2)}$ already considered before and by remembering that the power peak P_c is defined under conditions STC, we can write:

$$P_c(\text{in } W_p) = S(\text{in } m^2) \times R_{module} \times 1000 W/m^2$$

or

$$P_c(\text{in } kW_p) = S(\text{in } m^2) \times R_{module} \times 1 kW/m^2$$

For example, a module of two m^2 with an output of 0.15 (or 15%), it has a peak power of:

$$P_c(\text{in } W_p) = 2 m^2 \times 0.15 \times 1000 W/m^2 = 300 W_p$$

Or

$$P_c(\text{in } kW_p) = 2 m^2 \times 0.15 \times 1 kW/m^2 = 0.3 kW_p$$

Note: the output of a photovoltaic module is generally slightly lower than the output of the cells it is made of, because surface is lost between the cells and it is also necessary to count the surface of the framework. For example, a photovoltaic module with an output of 12% may contain cells with an individual output of 14%.

Influence of the solar radiance on the curves voltage-intensity for a given photovoltaic module:



(Source PHOTOWATT)

Figure 5 : Influence of the solar radiance on the curves voltage-intensity for a given photovoltaic module. Example for a module from PHOTOWATT company, type PW6-110

The intensity is a linear function I of radiance (and the surface of the cells), the voltage is a logarithmic function of the radiance (and of the number cells in series) but relatively near to the value under STC conditions.

So at first approximation, we can write that the electric output is a linear function of radiance, which makes possible to calculate the electric output (at the point of maximum power) for any radiance.

$$\text{Electric Output: } E_p \text{ (in W)} = C_p \text{ (out of } W_p) \times I_{\text{rrad}} \text{ (in kW/m}^2\text{)}$$

$$\text{Or Electric Output: } E_p \text{ (in kW)} = C_p \text{ (in kW}_p\text{)} \times I_{\text{rrad}} \text{ (in kW/m}^2\text{)}$$

These formulas do not seem homogeneous but it should be remembered that “Watt peak” is not a SI unit and that it expresses the electric power recovered under a luminous radiance of 1 kW/m^2 .

For example, a PV module of 300 W_p under a radiance of 600 W/m^2 will produce an electric output of $E_p = 300 \text{ W}_p \times 0.6 \text{ kW/m}^2 = 180 \text{ W}$ (attention, it is a first approximation).

The graph below represents the standardized output at the point of STC conditions (thus a radiance of 1000 W/m^2) according to radiance for various technologies of photovoltaic modules.

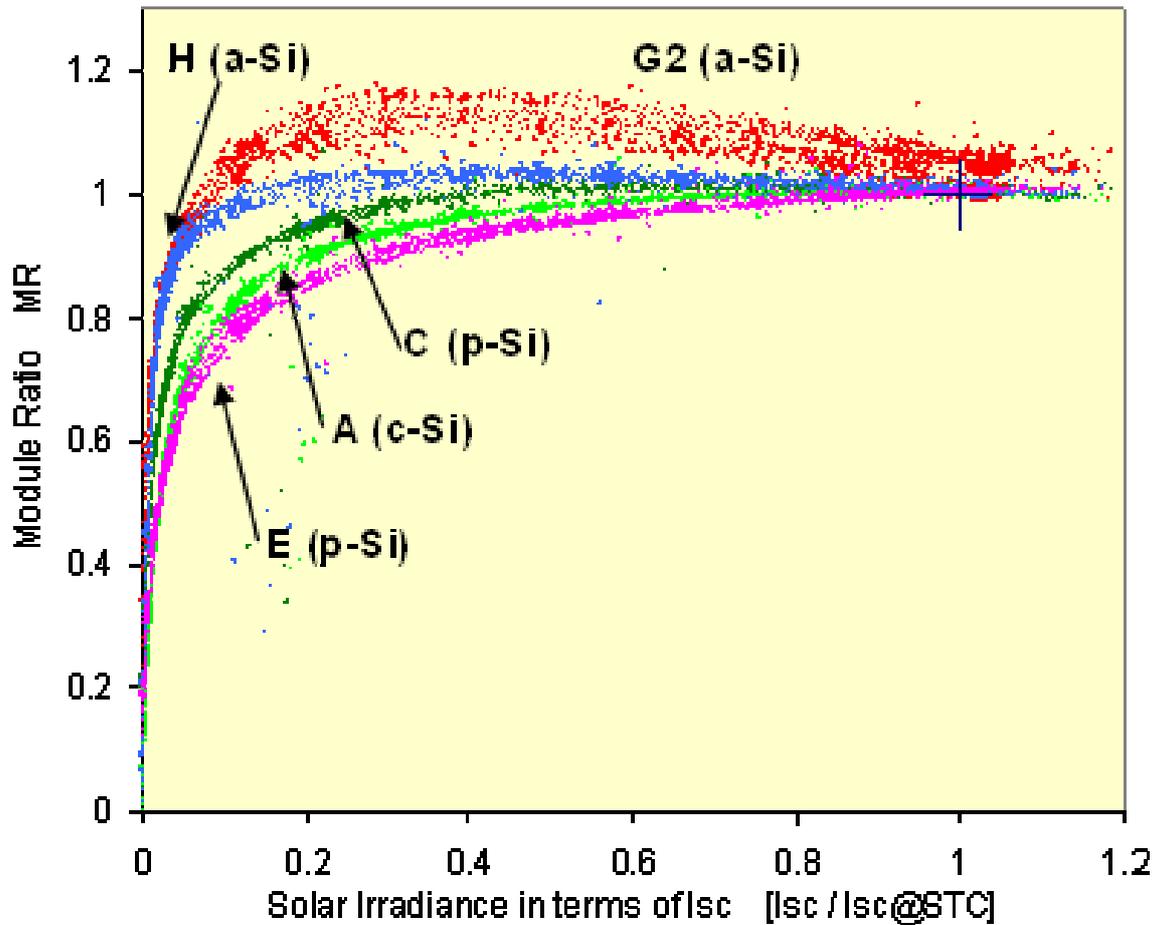


Figure 6: Standardized output at the point of STC conditions (radiance of 1000 W/m^2) according to radiance for various technologies of photovoltaic modules for different technologies.

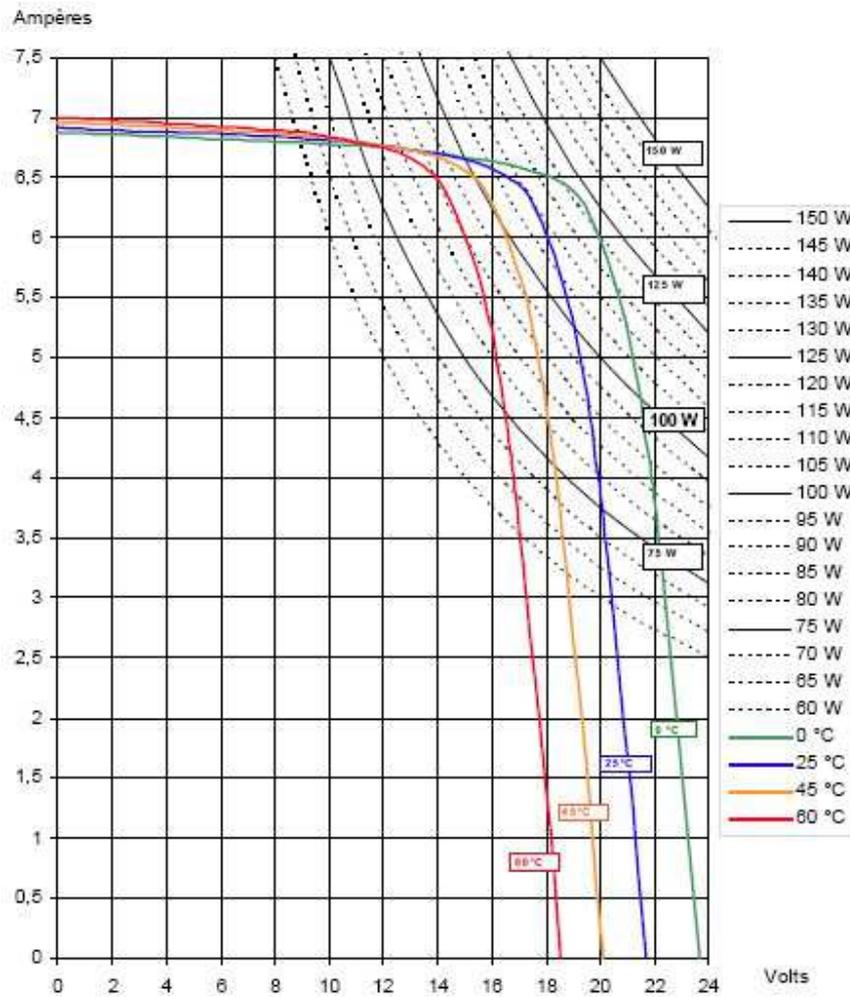
(Source: INES RDI/CEA)

On these curves, it has to be noted that for amorphous technology silicon (a-Si, in red and blue), the output is slightly higher than the output standardized for most radiances, but near 1, except when they are weak where the output falls. For crystalline technologies (C-Si and P-Si, green and pink), the output is slightly lower than the output standardized for most radiances, but near to 1, except when the radiance is weak, where the output falls.

This shows that the formula used to calculate the electric output according to radiance is valid as a first approximation for radiances ranging between 100 and 1000 W/m^2 . Software for photovoltaic simulation (such as the well-known PVsyst and PV-SOL) make it possible to perform more precise calculations because they take into account all of these losses by calculating them.

Influence of the temperature on the electric characteristics

Influence of the temperature on the voltage-intensity curves of a photovoltaic module:



(Source PHOTOWATT)

Figure 7: Influence of the temperature, Example for a module from PHOTOWATT Company, type PW6-110

From these curves, it is noted that the intensity increases slightly according to the temperature (+2 mA per °C, so +0.028% per °C).

One notes that the voltage decreases significantly according to the temperature (-79 mV per °C, so -0.47% per °C).

Consequently, the power at the point of maximum power decreases by -0.43% per °C.

For example, this 110 W_p photovoltaic module, under a radiance of 800 W/m² and with a cell temperature of 55 °C will produce an electric output P_e of:

$$P_e = 110 \times 0.8 \times (1 - (55-25) \times 0.0043) = 88 \times 0.871 = 76.65 \text{ W}$$

To define the temperature of a photovoltaic module, one used the **TUC** (Temperature of use of cell) or the **NOCT** (Nominal Operating Cell Temperature).

Here are the characteristics of PHOTOWATT Company PW1650 module :

PW1650						
CARACTÉRISTIQUES TECHNIQUES						
Encapsulation	Verre / TPT ou PVDF					
Taille des cellules	125 X 125 mm					
Nombre de cellules	72					
Tension	24 V					
Diodes by-pass	4					
Tolérance électrique	0 / + 5 Wc					
Puissance typique	Wc	165	170	175	180	185
Tension à la puissance typique	V	34,4	34,7	35	35,3	35,6
Intensité à la puissance typique	A	4,8	4,9	5,0	5,1	5,2
Tension en circuit ouvert	V	43,2	43,3	43,4	43,5	43,6
Intensité de court circuit	A	5,1	5,2	5,3	5,4	5,5
Tension maximum du circuit	V	1000V DC				
Coefficient de température	α (Isc) = +0,034%/°C					
	β (Voc) = -0,36%/°C					
	δ (Pm) = -0,43 % /°C					
NOCT	47,1°C ± 2					
Spécifications de puissance en STC (Standard Test Conditions 1000 W/m ² ; 25°C ; AM 1,5)						

Figure 8: characteristics of a PHOTOWATT Company PW1650 module

The NOCT of this module is at 47.1 °C

The TUC or the NOCT represents the temperature reached by a cell encapsulated in a module in open circuit, under an irradiation of 800W/m², an ambient temperature of 20°C, an angle of 45° and a wind speed of 1 m/s.

From the TUC or NOCT figures, it is possible to approximately calculate the temperature reached by a cell in a module (T_{cell}) according to solar radiance (I_{rad}) and the ambient temperature (T_{amb}).

$$T_{cell} (en\ ^\circ C) = T_{amb} (en\ ^\circ C) + (TUC (en\ ^\circ C) - 20^\circ C) \times \frac{I_{rad} (en\ W/m^2)}{800\ W/m^2}$$

For example, a photovoltaic module of TUC = 47°C, under a radiance I_{rad} of 1,000 W/m² and with an ambient temperature $T_a = 30^\circ C$, the temperature of cell will be :

$$\text{Temperature of cell, } T_{cell} = 30 + (47-20) \times 1000/800 = 64^\circ C$$

Note, the TUC and NOCT are given for free field conditions: for an integration on a roof, the temperature will be higher and hard to estimate, according to the type of integration.

Evolution of the temperature coefficient on the power for different technologies:

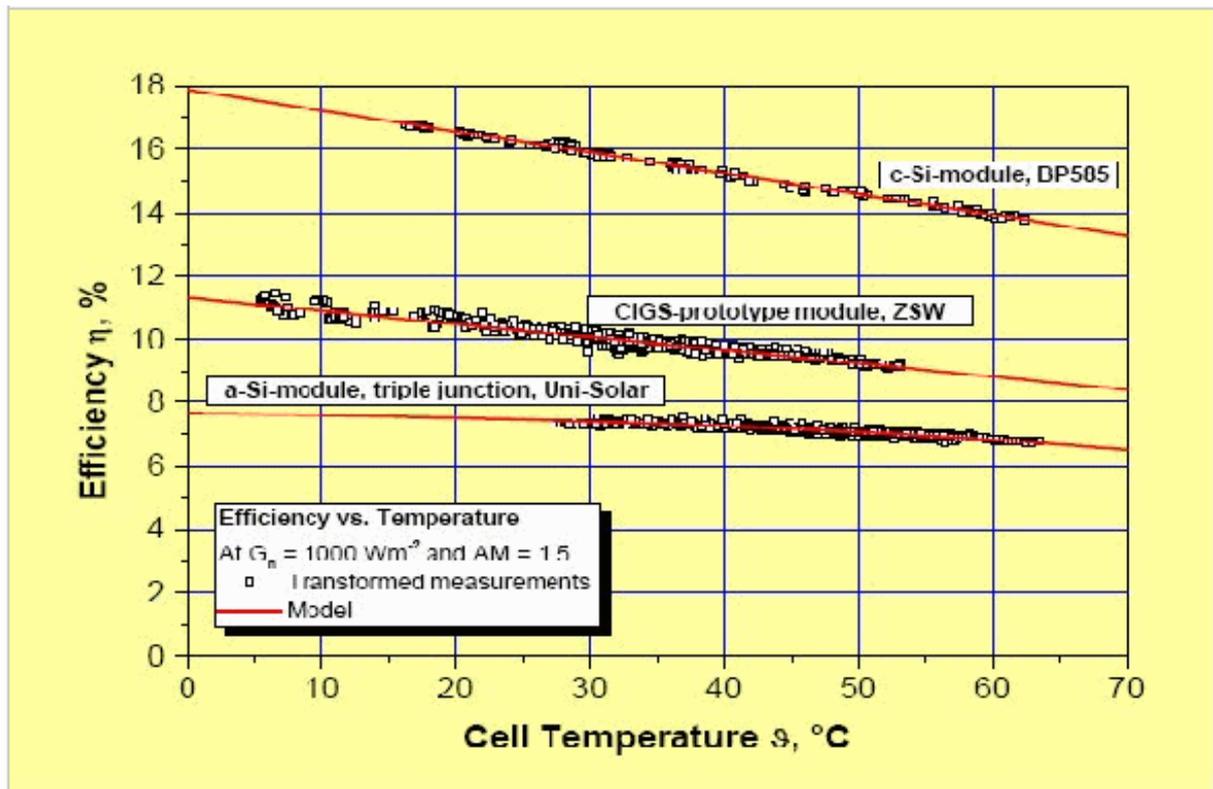


Figure 9: Effect of the temperature on a PV module

The effect of the temperature coefficients on the power for various technologies are the following:

Technology crystalline silicon (C-Si): $-0,45\%/^{\circ}\text{C}$

Technology Copper Indium Selenium: $-0,35\%/^{\circ}\text{C}$

Technology amorphous silicon (a-Si): $-0,2\%/^{\circ}\text{C}$

Technology Cadmium Tellurium (CdT): $-0,25\%/^{\circ}\text{C}$ (not presented in the above graph)

One notes that technologies having a relatively low output also have low temperature coefficients, therefore lower losses due to the temperature increase of the module under the effect of solar radiance. Thus, they will have lower losses for the same power peak with higher efficiency technologies but, on the other hand, it will be necessary to install a larger surface, which is a disadvantage.

Another point, in spite of the lowest loss ratio for poor yield technologies, at a temperature of 70°C , it is always the crystalline silicon technology that maintains the best conversion efficiency.

Time-related degradation of crystalline silicon PV modules

This study originates from LEEE TISO, performed in Switzerland on 288 modules ARCO Solar ASI 16-2300 m-Si of 37 W_p each, installed on May 13th, 1982.



The results were:

Year	Measured plant power	N° of modules	Module mean power [W]
Nominal	10.7 kW	288	37.1
1983	9.8 kW	288	34.0
2002	8.3 kW	252	32.9
Δ module power _{2001_1983}			- 3.2%
détérioration de la puissance du module (depuis 1983)			- 0.2%

Annotations: A blue box highlights Δ = -8.4% next to the 37.1 W value. Blue arrows indicate the flow of power from 37.1 W to 34.0 W, and from 34.0 W to 32.9 W. A dashed circle highlights the 34.0 W value.

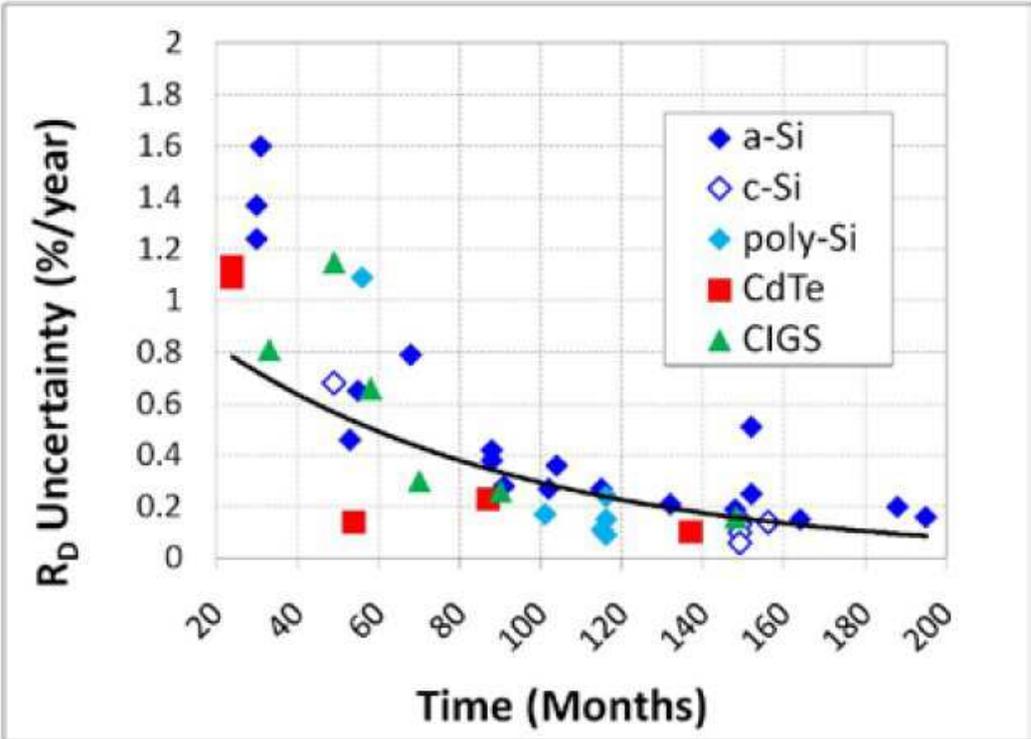
Figure 10: time effect on the performances of a PV module.

It is noted that among the 288 modules, 252 are still functional, which corresponds to a loss of 12.5% after 20 years.

In addition, over the 252 functional modules remaining, the production loss is 0.2% per annum, which is very low.

To all appearances, these modules that were manufactured in 1983 were proven to be reliable.

According to a study made by the US NREL, 'Outdoor PV degradation comparison' in June 2010, studying the degradation rate uncertainty vs observation time for different PV technologies, the results were:



(Source: www.nrel.gov/docs/fy11osti/47704.pdf and <http://www.nrel.gov/docs/fy11osti/47596.pdf>)

Figure 11: Rate of uncertainty versus time for different PV technologies.

It is noted that the production loss in photovoltaic energy is roughly not significant during the first years of use, especially for amorphous silicon technology. After a few years, the annual loss on the photovoltaic production is stabilized to 0.2% per annum, which is very low. To compare with the 20% maximum loss guarantee after 20 years given by the majority of the PV module manufacturers, that is to say 1% per annum, far greater than the research results. PV modules are proven highly reliable on this point.

Comparison of production between various technologies

A study performed by the University of Stuttgart on the energy production of 13 sites in Germany and in Cyprus using various technologies.

ANNUAL ENERGY YIELD OF 13 PHOTOVOLTAIC TECHNOLOGIES IN GERMANY AND IN CYPRUS



module type	Stuttgart			Nicosia		
	AC-yield kWh/kW _{Prated}	PR %	T _{mod} °C	AC-yield kWh/kW _{Prated}	PR %	T _{mod} °C
A-170M 24V tracked	-	-	-	2039	76.9	25.8
A-170M 24V	1163	79.7	16.0	1593	79.8	23.8
BP7185S	1158	79.3	17.0	1463	73.3	24.2
HIP-205NHE1	1189	81.5	15.8	1630	81.7	24.0
STM 200 FW	1253	85.8	15.9	1692	84.7	23.9
ASE-165-GT-FT/MC 170	1180	80.9	15.9	1588	79.5	23.5
ASE-260-DG-FT 250	1147	78.5	15.9	1562	78.2	24.2
SW165 poly	1180	80.8	16.1	1573	78.8	24.4
P220/6+	1199	82.1	16.1	1567	78.5	24.3
MA100T2	1113	76.2	15.8	1573	78.8	23.3
ASIOPAK-30-SG	1257	86.1	16.1	1472	73.7	24.1
FS60	1193	81.7	16.4	1599	80.1	24.8
WS 11007/75	1292	88.5	16.7	1653	82.8	24.9
average without tracked	1194	81.8	16.1	1580	79.2	24.1

Figure 12: Comparison of different technologies, under different climate conditions.

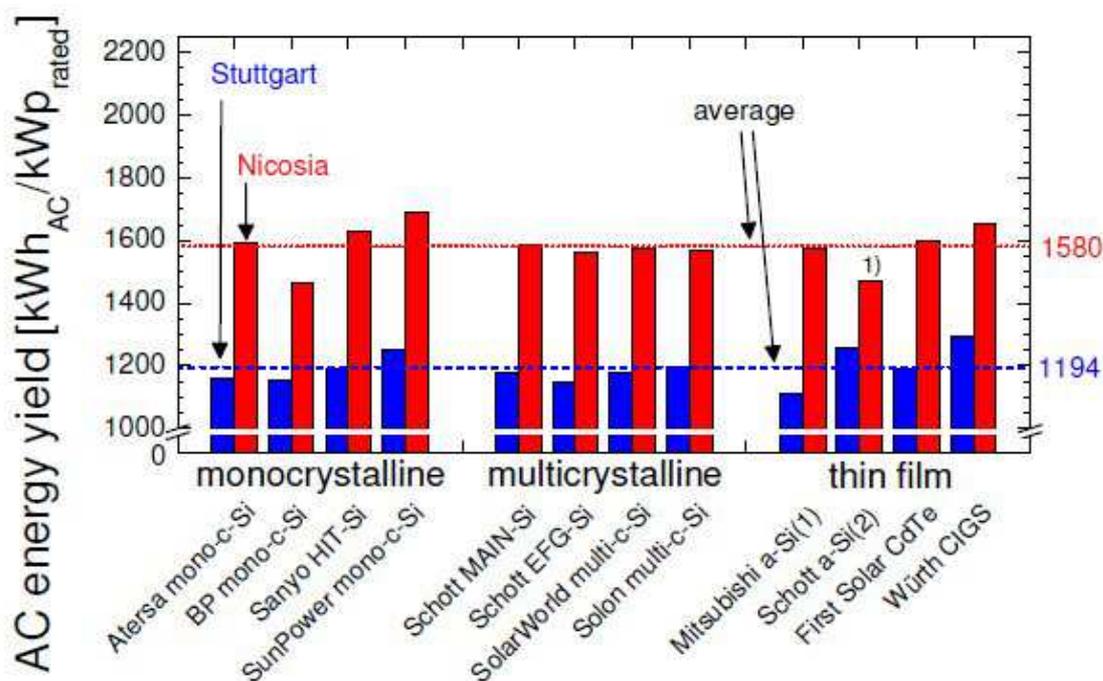


Figure 13: Energy yield for different technologies.

From the graph above, one notes that no technology is frankly more advantageous than another (it is said that amorphous silicon is better in the countries with strong nebulosity but that is not confirmed), and that dispersion within the same technology seems larger than that between technologies.

Advantages and disadvantages of solar photovoltaic

Advantages:

- Free resource and enormous potential distributed on the planet
- Decentralized means of production, autonomy
- Great reliability and little maintenance (no moving parts)
- No pollution during the use on site
- Great flexibility of production, from milliWatt to MegaWatt

Disadvantages:

- High investment cost, need for subsidies, dependence on political decisions and policies
- Intermittent availability (auxiliary electrical network or storage needed)
- Diffused source, large surface of sensors, difficulty of integration (building/landscape)
- High-end manufacturing technology, energy intensive, use of chemical products
- Difficulty to recycle components that must resist more than 20 years even in bad weather conditions

Bibliography

Stuart R Wenham (Editor), Martin A Green (Editor), Muriel E Watt (Editor), Richard Corkish (Editor), "Applied Photovoltaics", Routledge, 2013.