The Photovoltaic Solar Panel

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May 2024

HESAM UNIVERSITÉ

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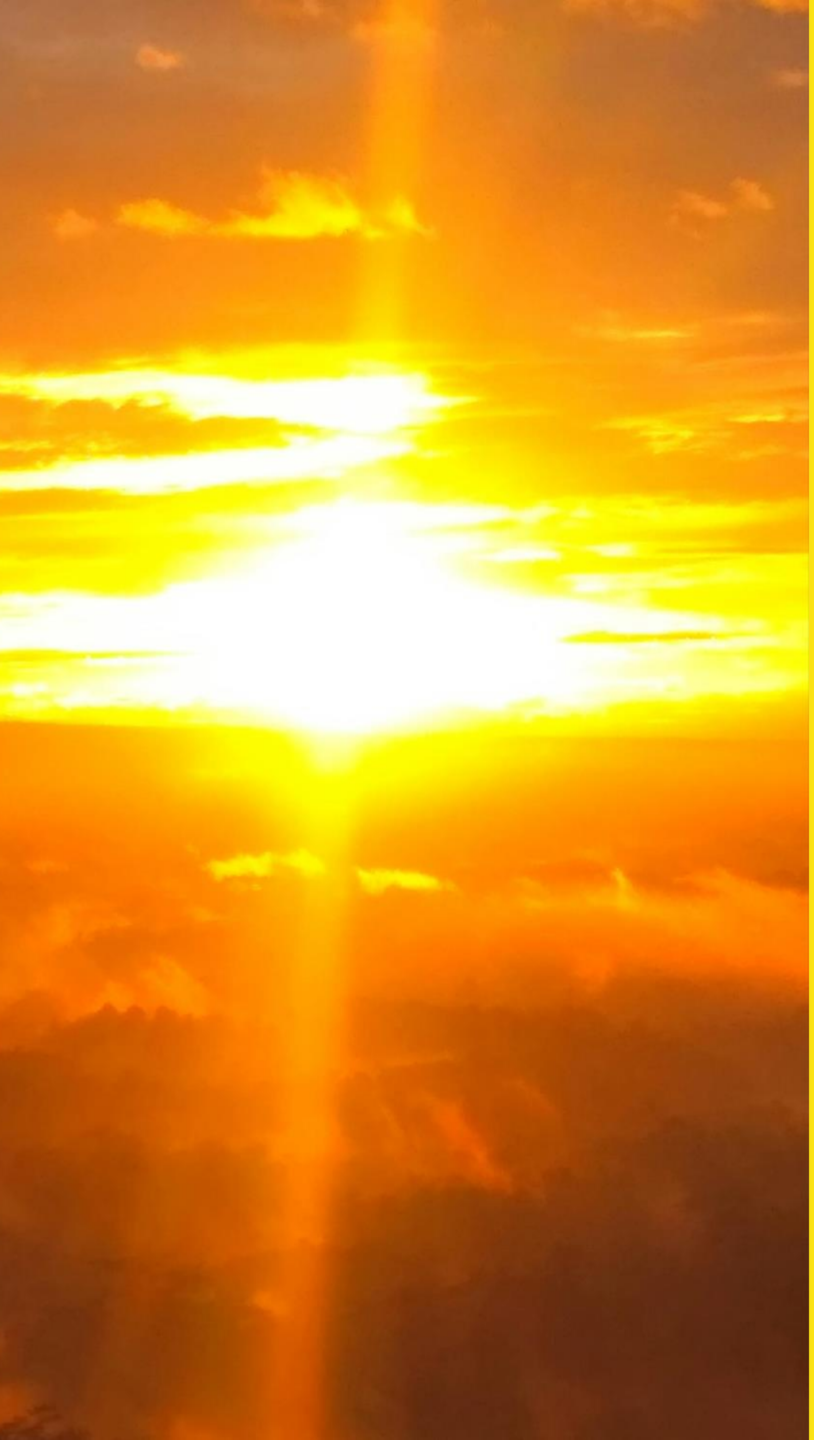
Table of Contents



1. Solar radiation

I. Solar radiation
I.1 Brief history

19th Century
In 1839, the French scientist Edmond Becquerel, who was 19 years old at the time, discovered the photovoltaic effect.

1883
First production of a photovoltaic cell, the core unit of a solar panel. This feat was achieved by the American inventor Charles Fritts.

1905
Albert Einstein published a very conclusive paper on the photoelectric effect potential. He won a Nobel Prize in 1921 for his work.

1941
R. S. Ohl described the first creation of a P-N junction in silicon, with a photovoltaic effect.

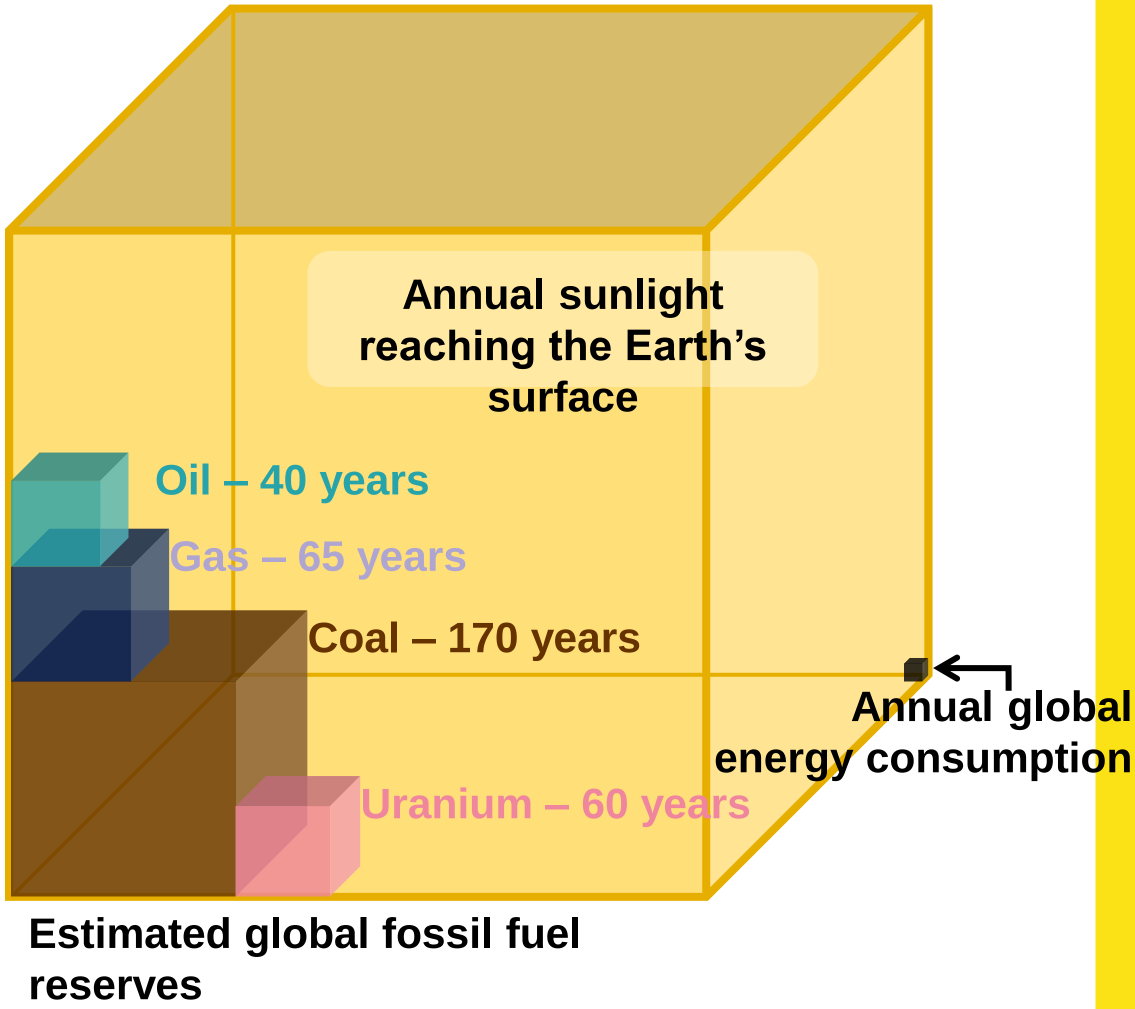
1970
Solar panels began to be marketed.

1984–1996
15 % annual increase in solar power production.

I. Solar radiation
I.2 Solar potential

The energy received on Earth each year is 8,000 to 10,000 times the human energy consumption.

This source of energy will be around for another 5 billion years.

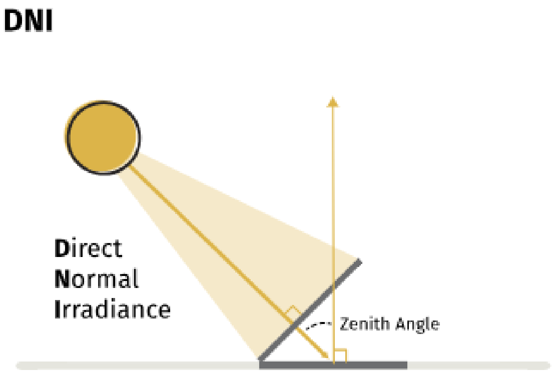


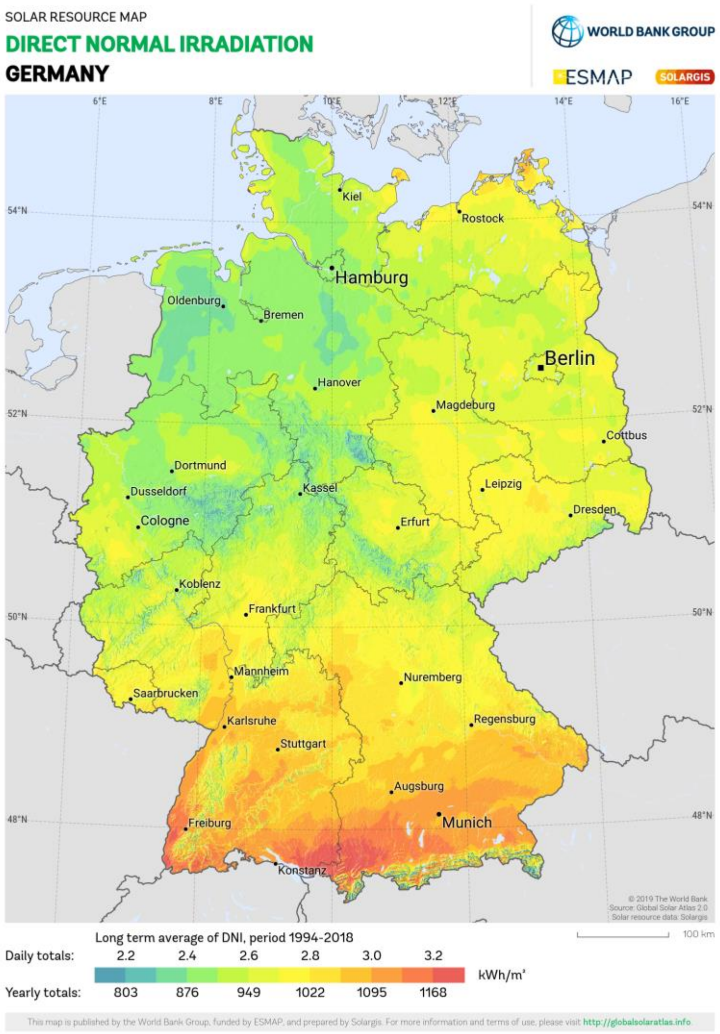
Reference : https://www.asder.asso.fr/wp-content/uploads/2018/12/Solaire-thermique-22-11-18.pdf:

I. Solar radiation
I.2 Solar potential

The sun is a renewable energy source that has been underestimated for a long time.

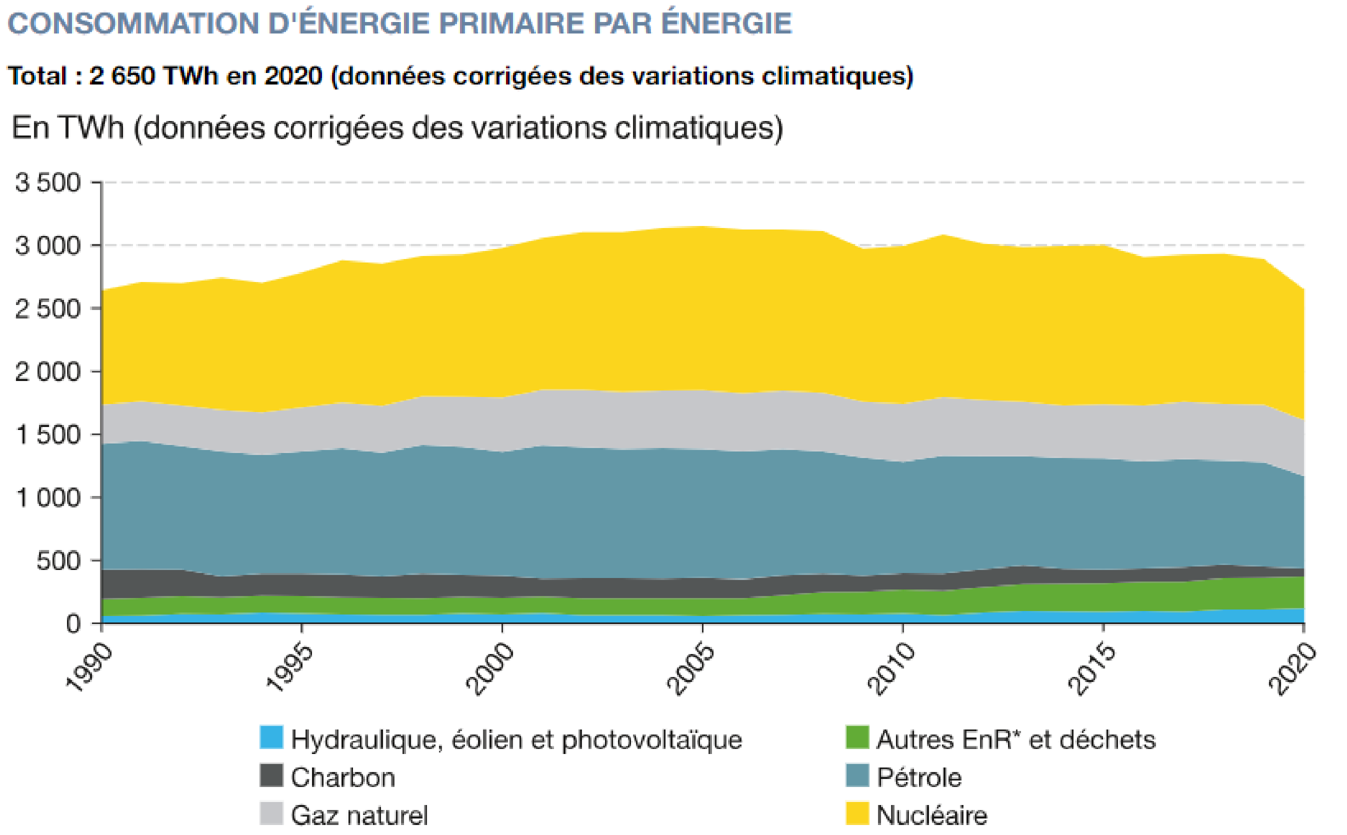
- The average solar *irradiance outside the Earth's atmosphere* is 1367 W/m²
- In France the average irradiance over the year varies between 139 W/m² (about one tenth of the solar constant) and 200 W/m²





https://globalsolaratlas.info/download/germany

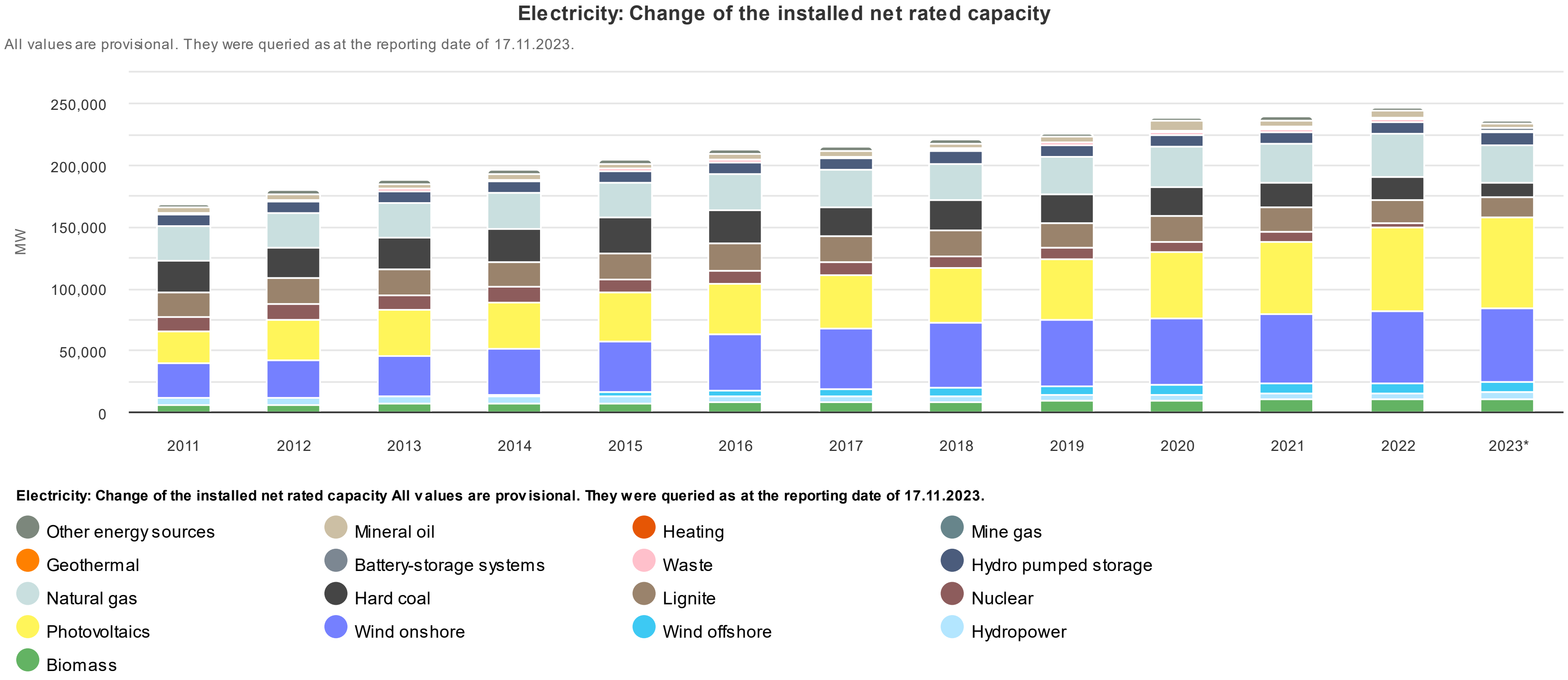
Energy mix in France and Germany



French electrical production (instantaneous output) :

https://www.rte-france.com/eco2mix/la-production-delectricite-par-filiere

Energy mix in France and Germany



[German electrical production :](https://www.smard.de/home/energiedaten-kompakt/energiedaten-kompakt)

https://www.smard.de/home/energiedaten-kompakt/energiedaten-kompakt

I. Solar radiation
I.3 Notions of Physics

In the 20th Century, beyond the wave or particle aspects of light, it was established that the amount of energy carried by light is quantified ➔ the photon.

The energy carried by a photon is expressed by the Planck-Einstein relation:

$$E = h\nu = \frac{hc_0}{\lambda}$$

with

- h Planck's constant, $h = 6.63 \times 10^{-34}$ J·s
- ν the frequency of light, in hertz (1 Hz = 1 s^{-1})
- λ the wavelength, in m
- c_0 the speed of light in vacuum, $c_0 = 2.998 \times 10^{8}$ $m \cdot s^{-1}$

The quantum of energy that the photon represents is obviously small, but given the number of incident photons, this energy should be strongly considered.

I. Solar radiation
I.3 Notions of Physics

The radiative power emitted at the wavelength λ by unit area of a black body at temperature T is given by Planck's law (*not to be learnt*):

$$M_\lambda = \frac{2\pi h c^2 \lambda^{-5}}{\exp\left(\frac{hc}{k\lambda T}\right) - 1} \quad \text{(spectral emittance in W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}\text{)}$$

with

- h Planck's constant, $h = 6.63 \times 10^{-34}$ J·s
- k the Boltzmann constant, $k = 1.38 \times 10^{-23}$ J·K^{-1}
- λ the wavelength, in m or µm
- c_0 the speed of light in vacuum, $c_0 = 2.998 \times 10^{8}$ m·s^{-1}
- $c = c_0/n$ the speed of light in the propagation medium of the radiation, where n is the index of refraction of the medium
- T the temperature of the body causing the radiation, in K

I. Solar radiation
I.3 Notions of Physics

The radiative power emitted at the wavelength λ by unit area of a black body at temperature T is given by Planck's law (*not to be learnt*):

$$M_\lambda = \frac{2\pi h c^2 \lambda^{-5}}{\exp\left(\frac{hc}{k\lambda T}\right) - 1} = \frac{A\lambda^{-5}}{\exp\left(\frac{B}{\lambda T}\right) - 1} = f(\lambda, T)$$

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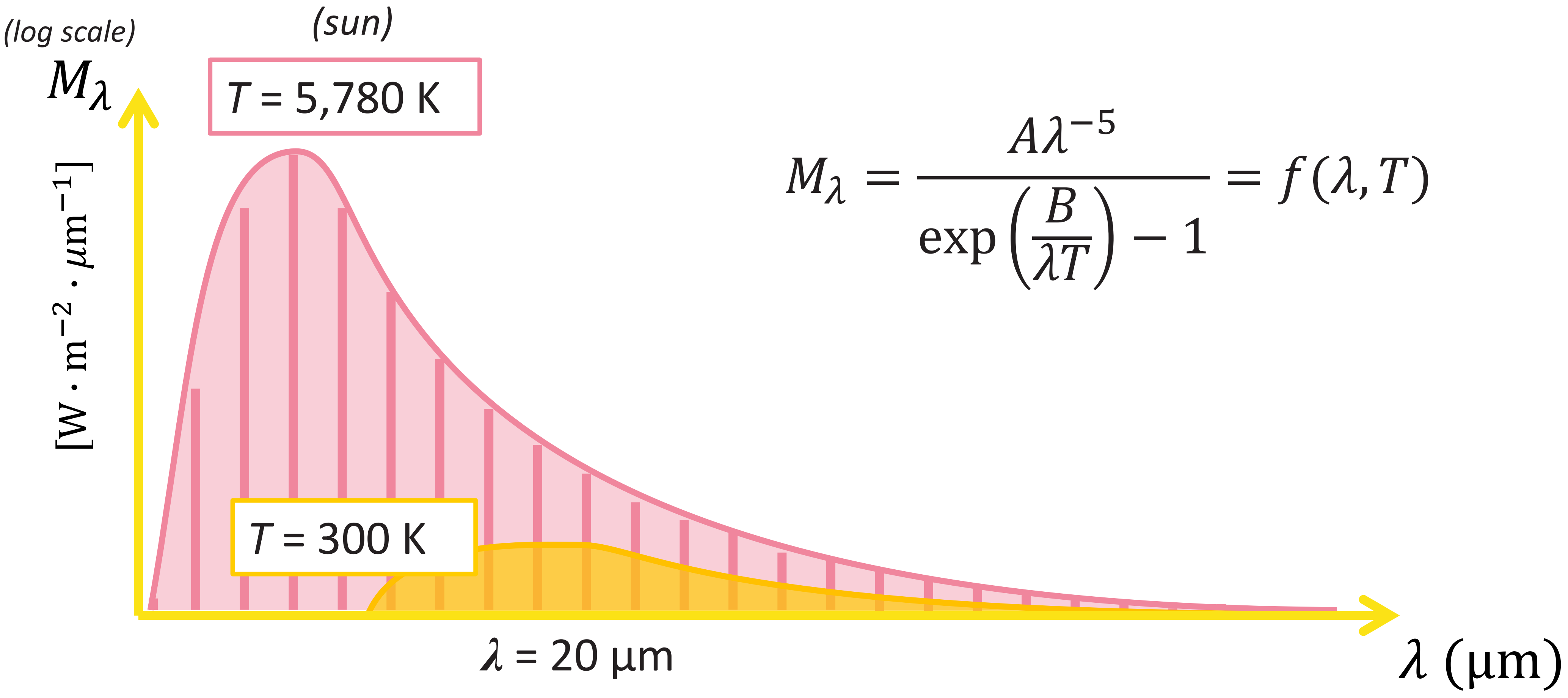
I. Solar radiation
I.3 Notions of Physics



$$M_\lambda = \frac{A\lambda^{-5}}{\exp\left(\frac{B}{\lambda T}\right) - 1} = f(\lambda, T)$$

2. Photovoltaic technologies

II. Photovoltaic technologies
1. Environmental context

- Scarcity of fossil fuels
- Strong increase in energy needs
- Increase in energy prices
- Fit to 55 : Under the European Climate Law, the EU committed to reduce its net greenhouse gas emissions by at least 55% by 2030. The ‘Fit for 55’ package of legislation makes all sectors of the EU’s economy fit to meet this target. It sets the EU on a path to reach its climate targets in a fair, cost-effective and competitive way.

https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal/fit-55-delivering-proposals_en

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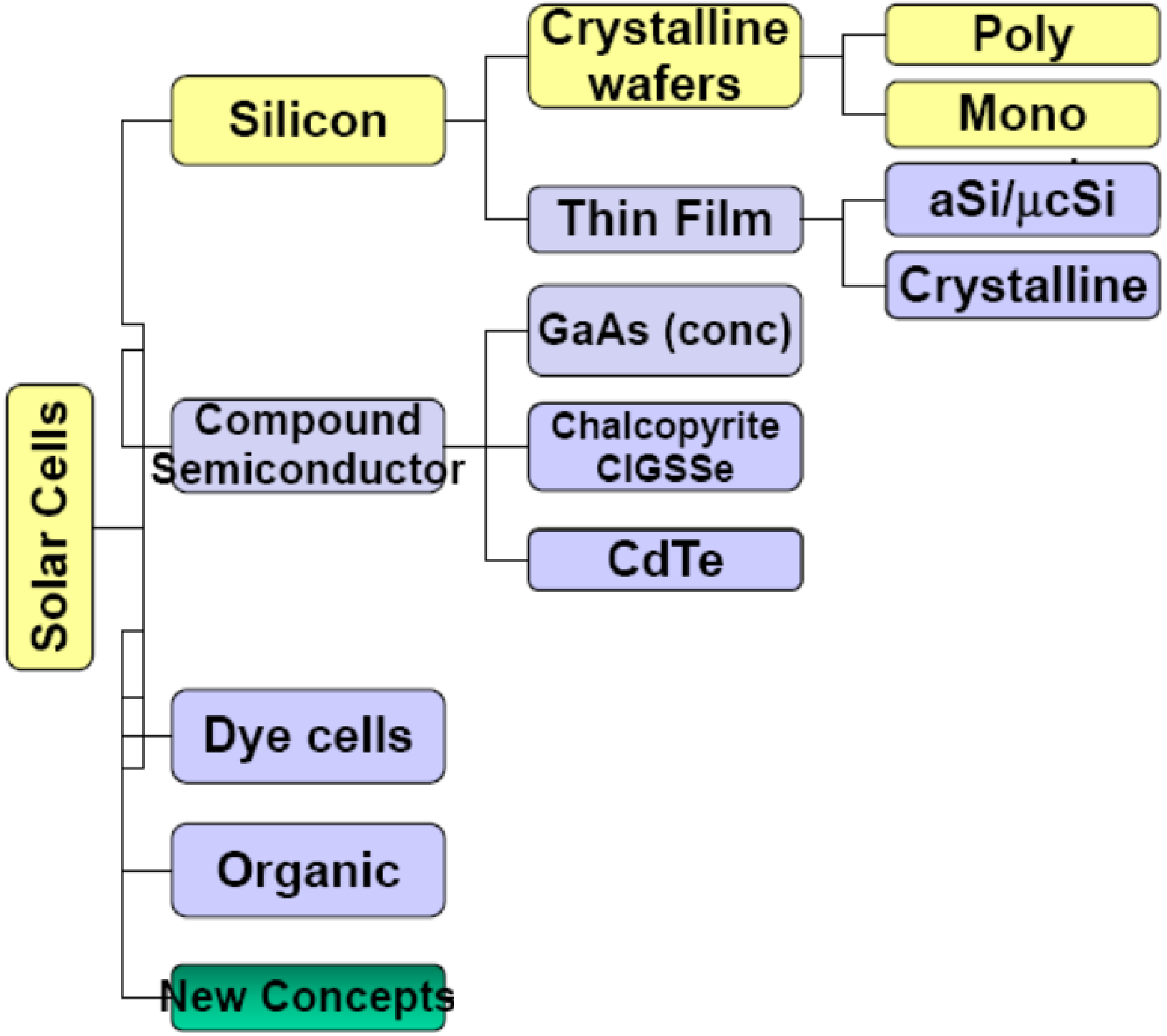
II. Photovoltaic technologies

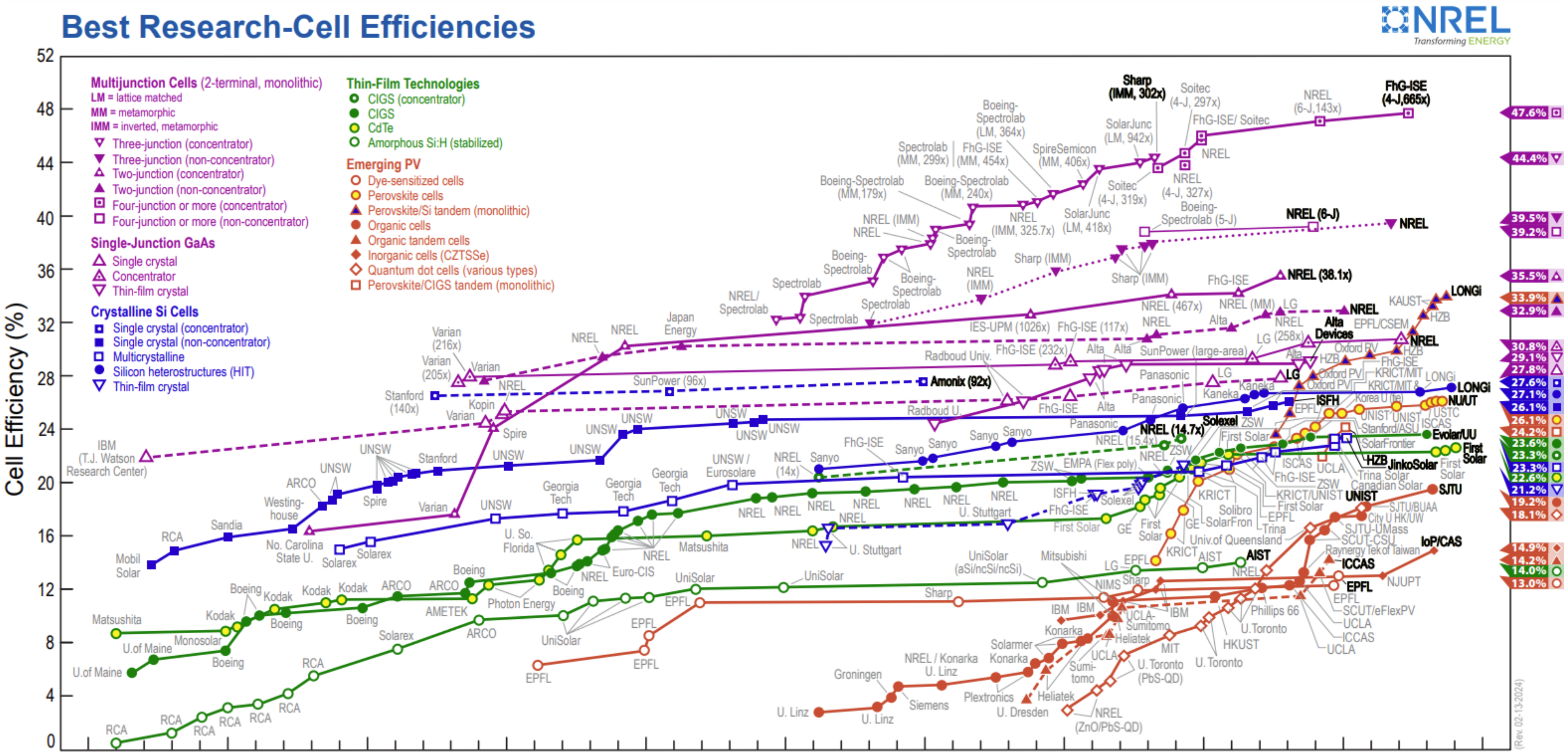
2. Materials & Technology for Photovoltaic Panels



Based on M. Powalla,ZSW

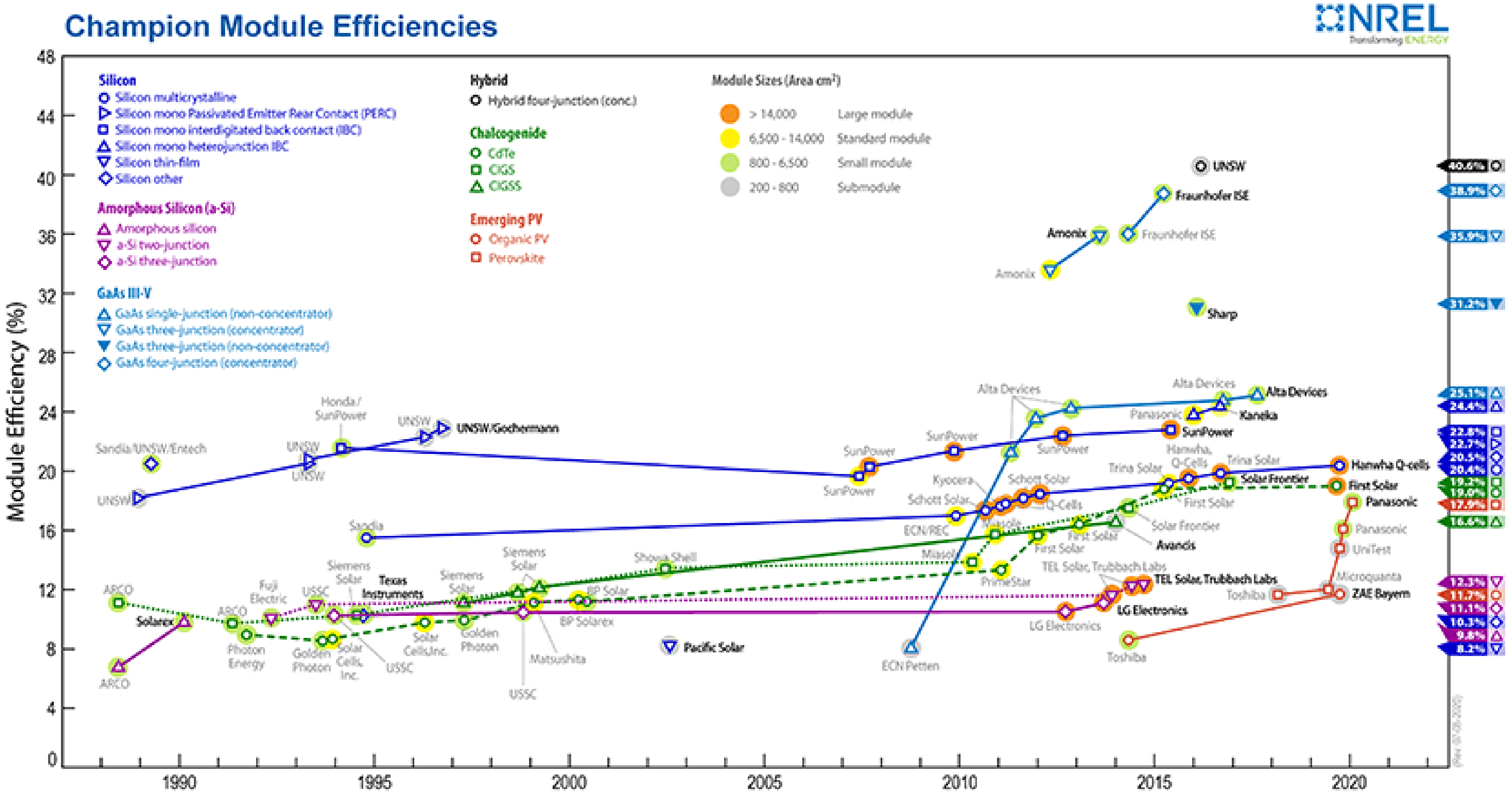
II. Photovoltaic technologies
3. Existing photovoltaic technologies

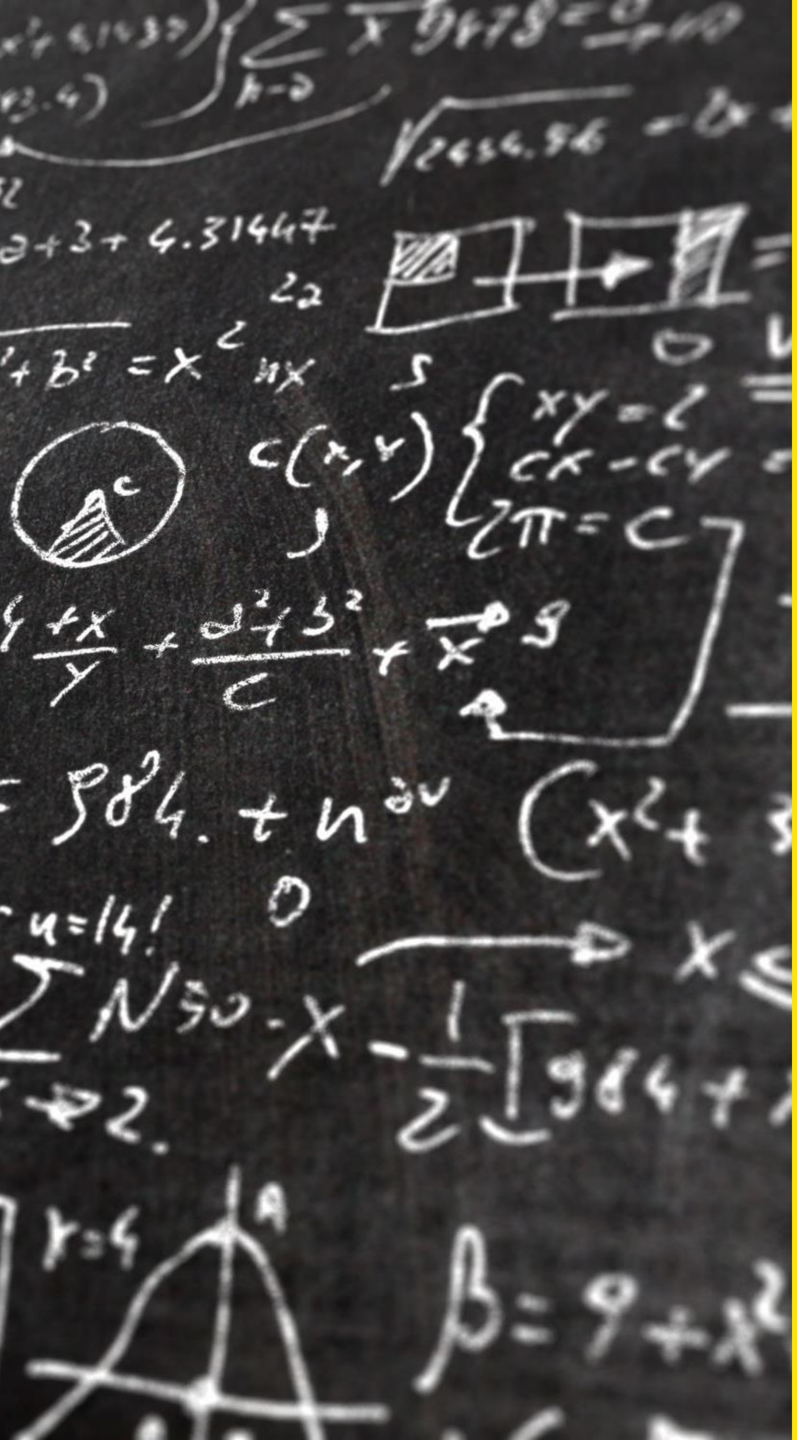
- ❑ Continuous R&D efforts on several sectors in parallel
- ❑ Maturity requires time and resources; potentials have not been



II. Photovoltaic technologies

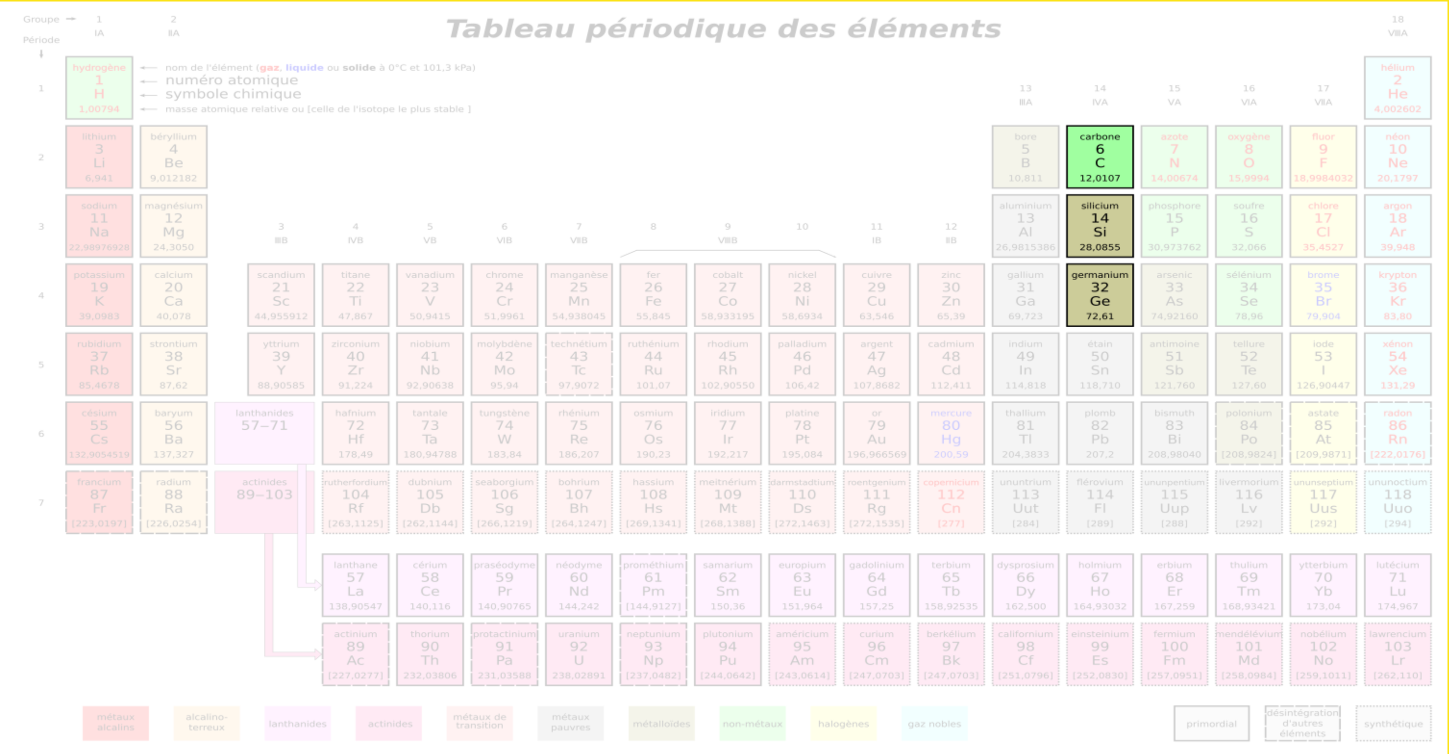
3. Existing photovoltaic technologies





3. Operating principle

III. Operating principle
1. Semiconductors

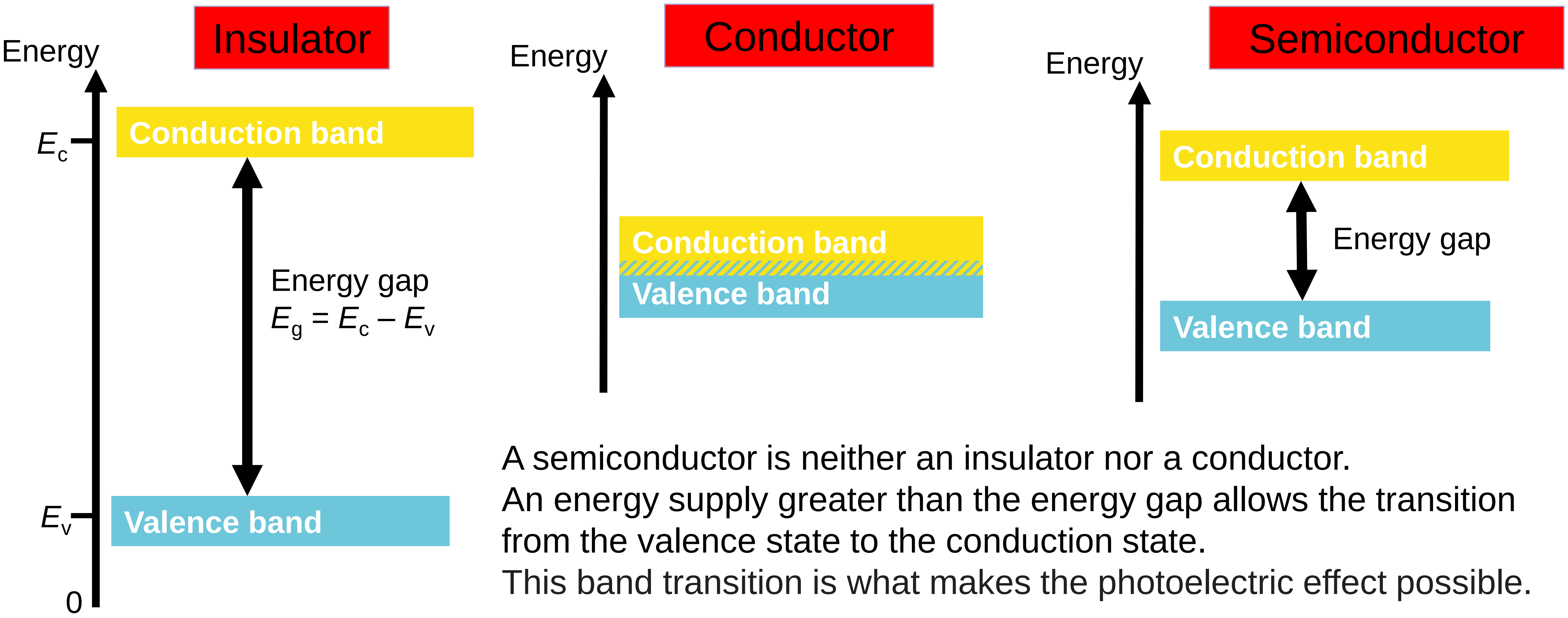


An (electrical) semiconductor is a material that falls between the conductor and the insulator. A semiconductor in its pure state is neither a good conductor nor a good insulator. The most commonly used single elements for semiconductors are germanium (Ge), carbon (C), and especially silicon (Si), which accounts for 90 % of the PV market.

In matter (large number of atoms), electrons are confined to energy layers, or bands. The outermost band of an atom is called the ***valence band***.

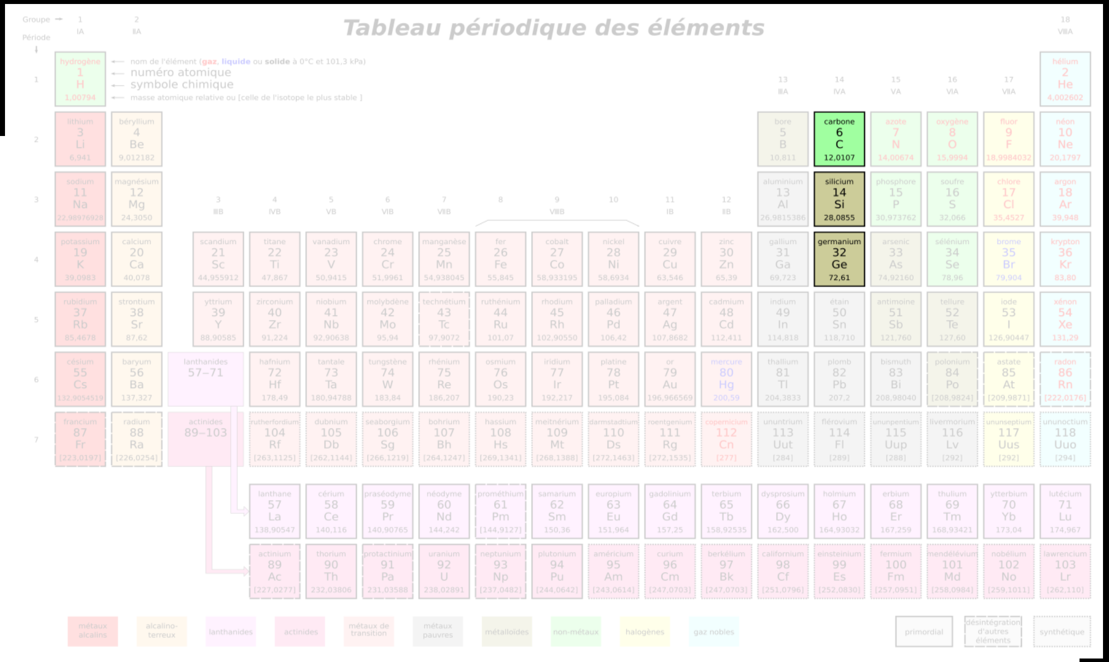
When an electron in the valence band receives energy from outside, it can leave the valence band to become a free electron and exist in the ***conduction band***.
It can move from atom to atom and is no longer bound to a specific atom.

III. Operating principle
1. Semiconductors



A semiconductor is neither an insulator nor a conductor.
An energy supply greater than the energy gap allows the transition from the valence state to the conduction state.
This band transition is what makes the photoelectric effect possible.

III. Operating principle
2. P-type and N-type doping



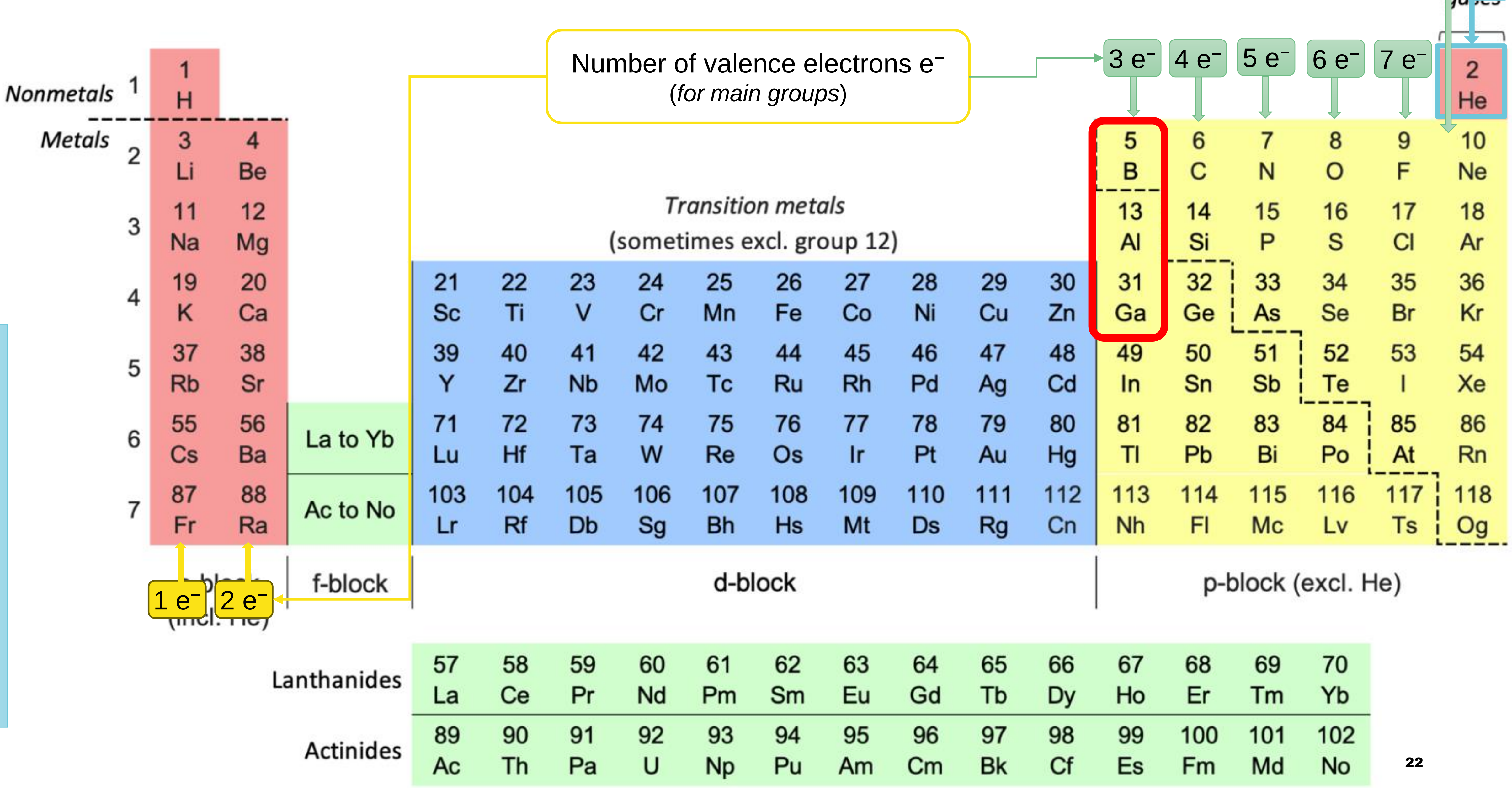
Silicon comes in several forms:
- Amorphous silicon
- **Crystalline silicon**

Crystalline structure = organisation of atoms
→ regular repetition in a crystal
Amorphous compound = no crystalline structure

Semiconductor conductivities can be modified by adding impurities to the crystal lattice. This means that we change the amount of carriers (electrons, holes) in matter and energy levels.

III. Operating principle
2. P-type and N-type doping

Periodic table

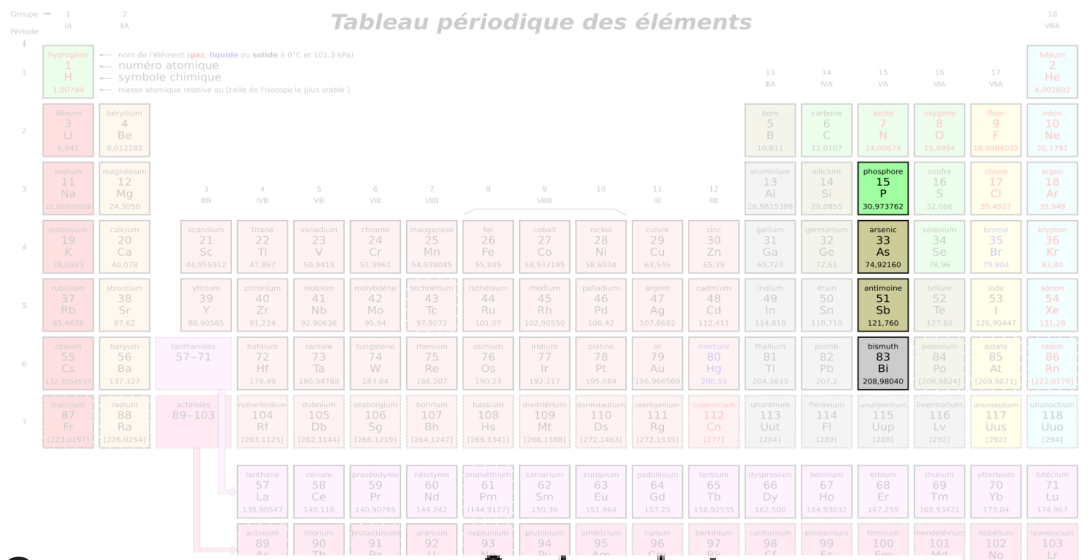


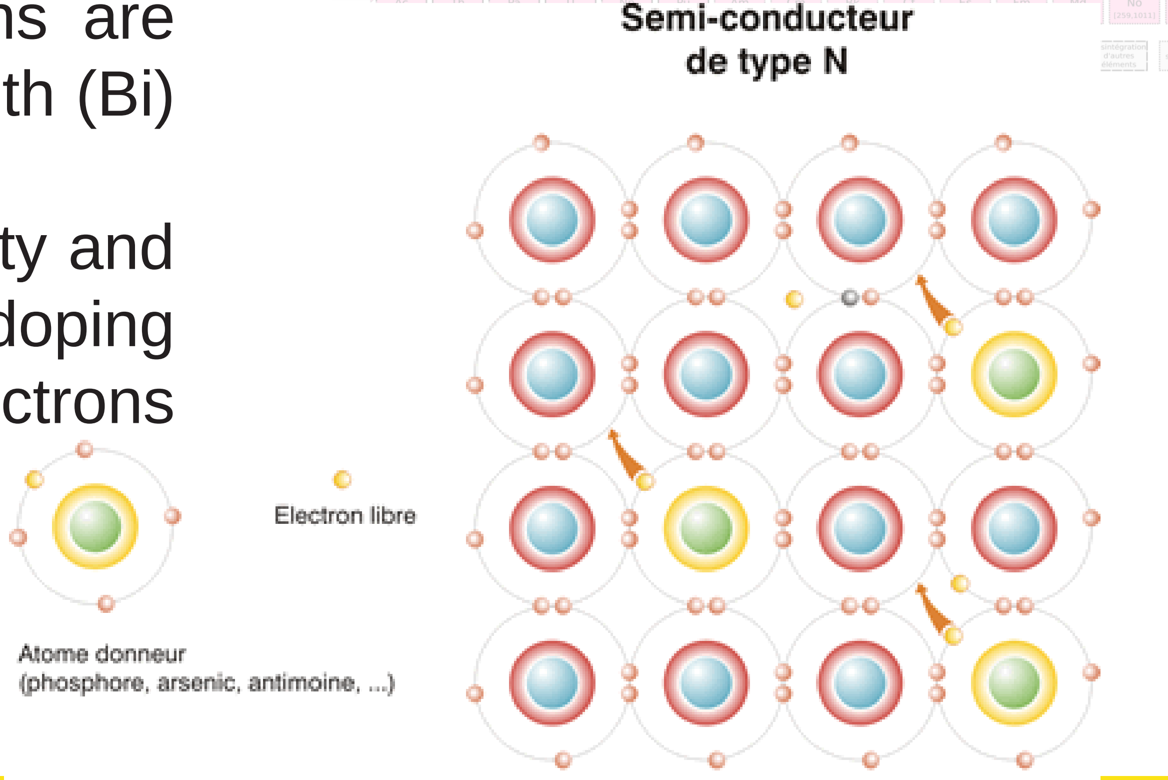
III. Operating principle
III.2 P-type and N-type doping

N-type doping:

- Impurities with 5 valence electrons are added: arsenic (As), phosphorus (P), bismuth (Bi) and antimony (Sb)

➔ therefore, electrons constitute the majority and holes the minority. N-type doping (N = ***N****egative*) increases the number of electrons in the conduction band.



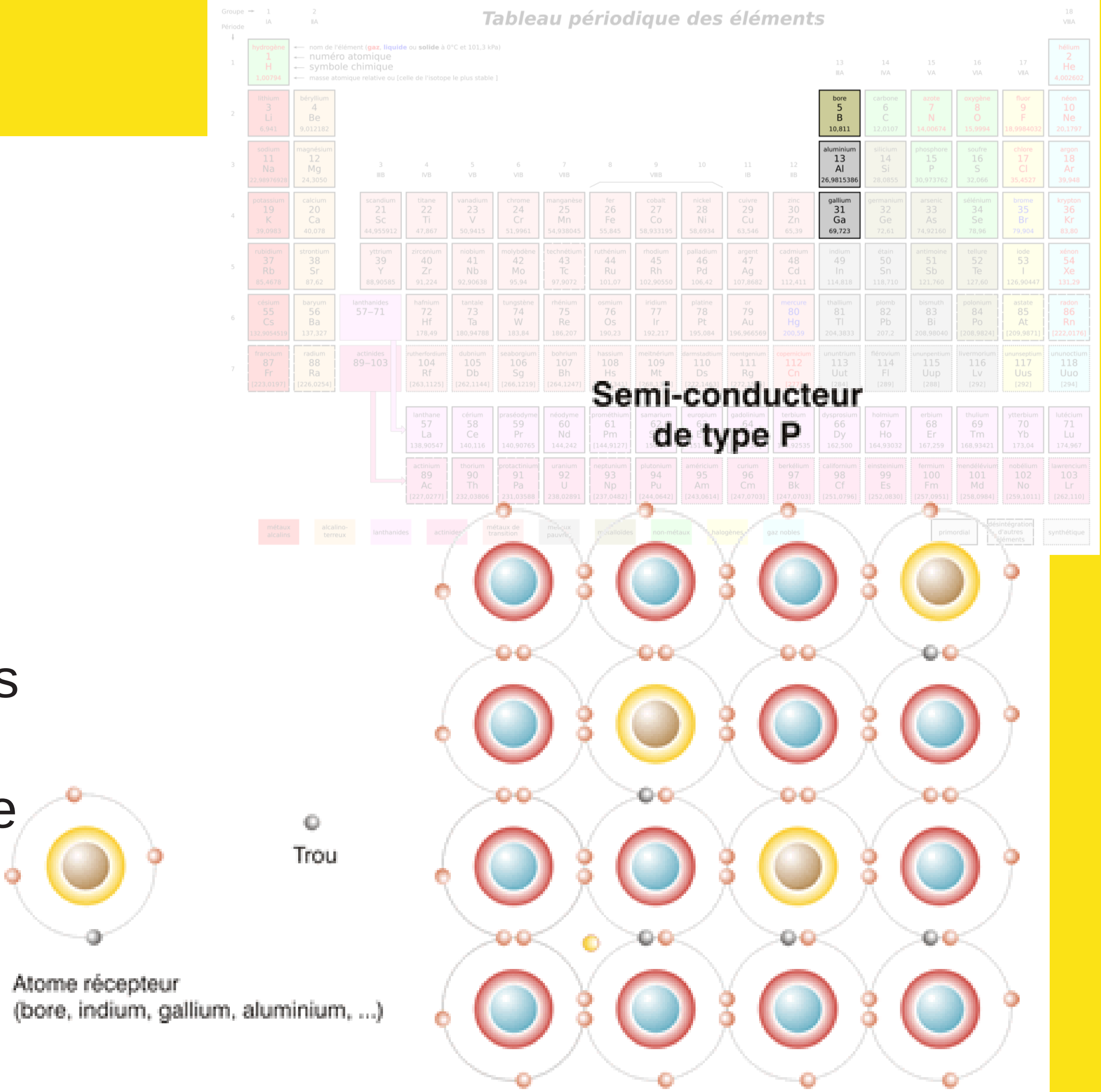


III. Operating principle
III.2 P-type and N-type doping

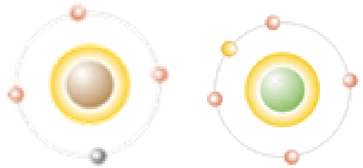
P-type doping:

- Impurities with 3 valence electrons are added: aluminium (Al), boron (B) and gallium (Ga) ➔ therefore, electrons constitute the minority and holes the majority.

P-type doping (P = ***Positive***) increases the number of holes (electron acceptors) in the conduction band.



III. Operating principle
2. P-type and N-type doping



Acceptor atom

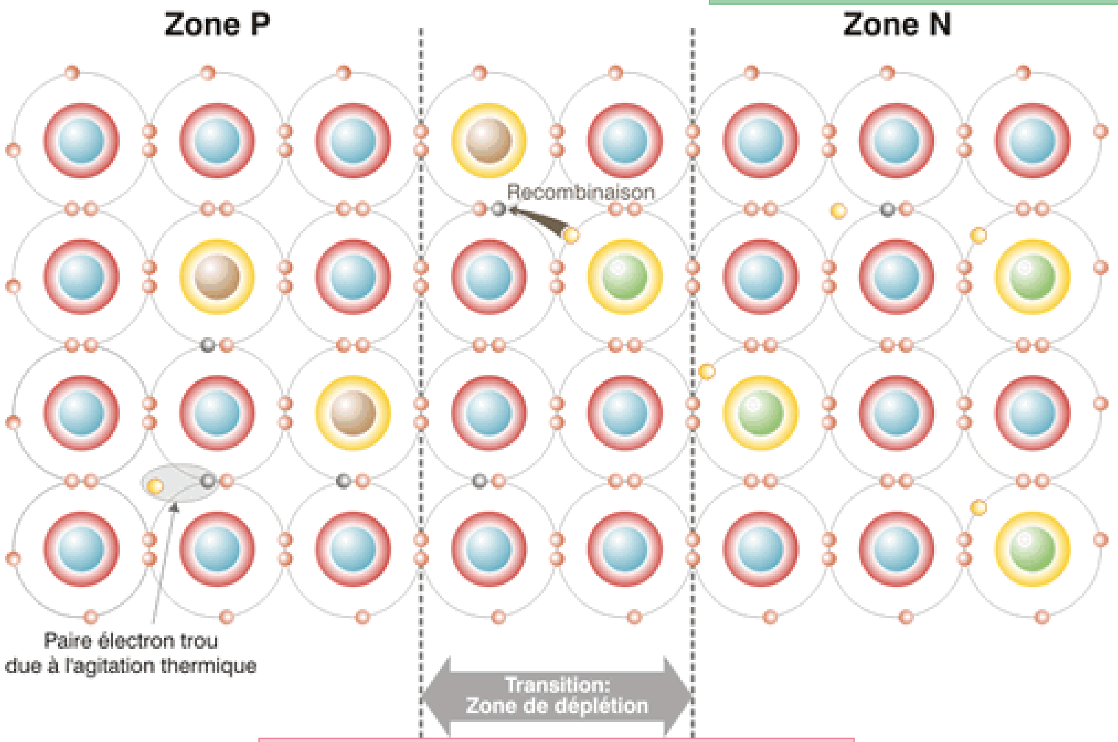
Donor atom

A solar photovoltaic cell is composed of a P-N junction. The top layer will be N-type and the bottom layer will be P-type.

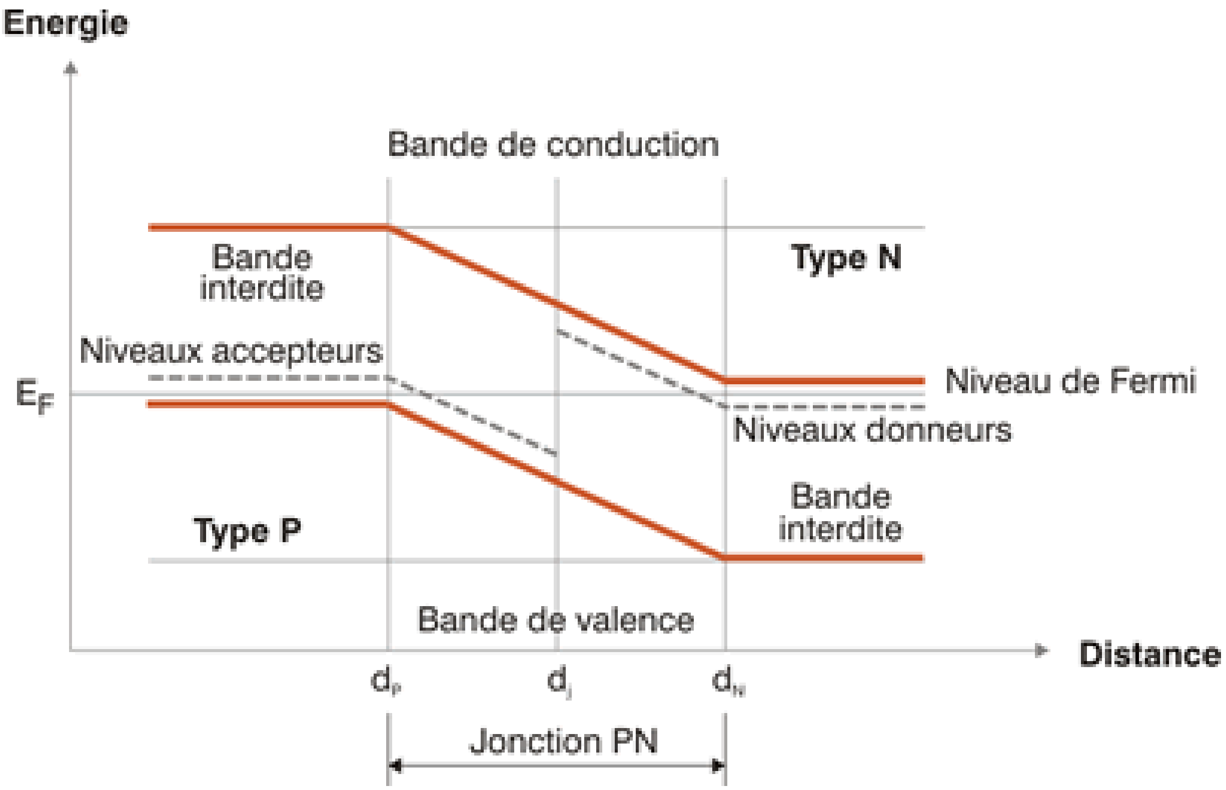
(free ***P****ositive* charge carriers)

Jonction PN

(free **N**egative charge carriers)

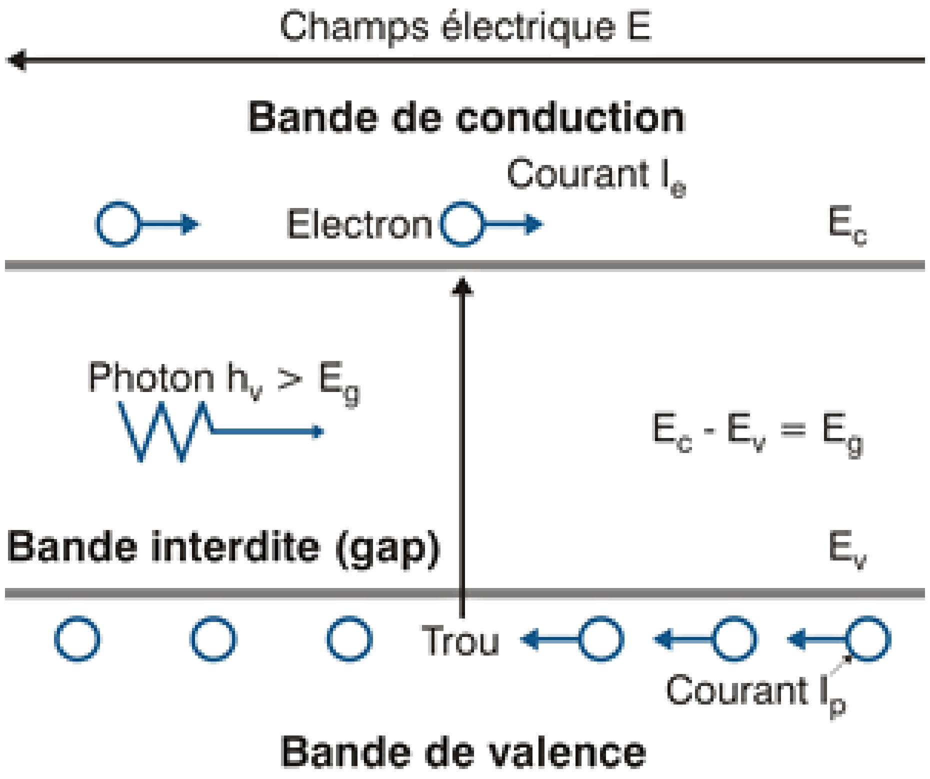


Depletion zone
zone **without** free carriers
(positive = holes, or negative = electrons)



III. Operating principle
2. P-type and N-type doping

The photoelectric effect in a P-N junction:



All it takes is for a photon whose energy is greater than the energy gap to be absorbed to cause an electron to move from the valence band (thus creating a hole) to the conduction band. This electron-hole pair is what leads to the photoelectric effect.

A semiconductor material with a forbidden gap between 0.4 eV and 0.7 eV is a so-called solar spectrum photovoltaic material.

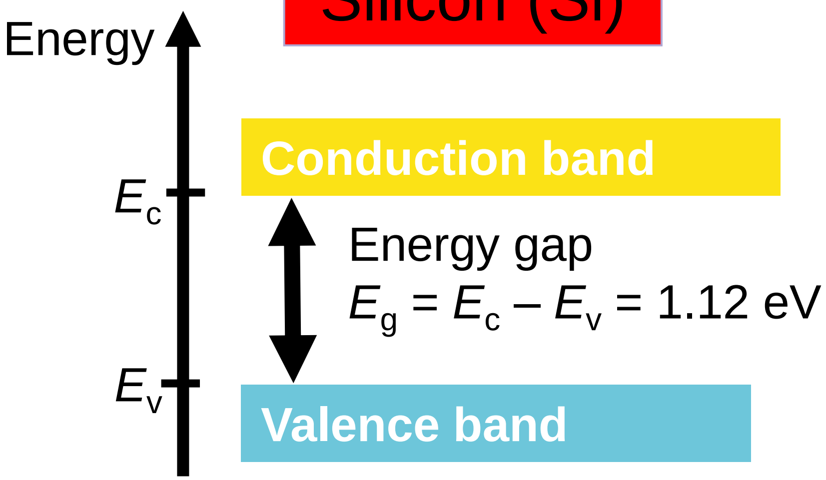
III. Operating principle
2. P-type and N-type doping

cut-off wavelength

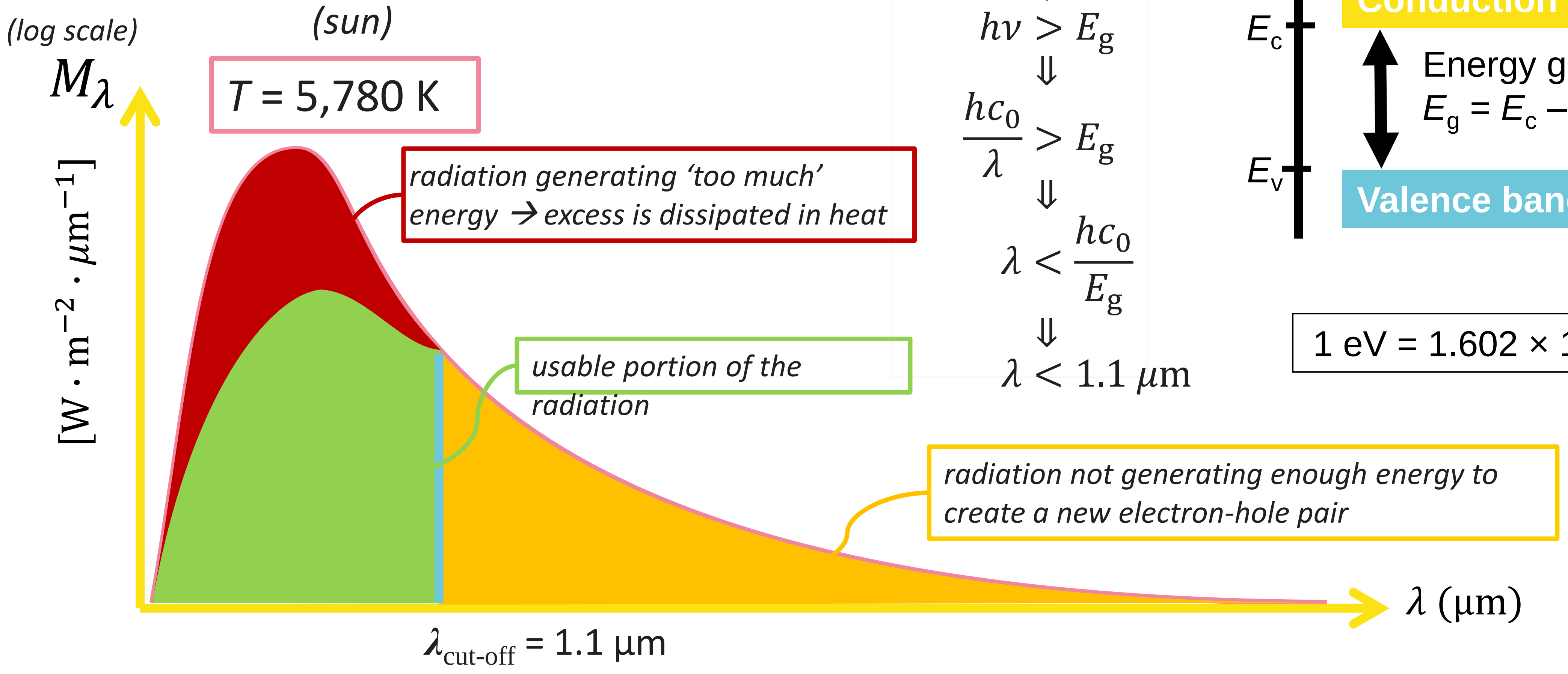
$\lambda_{\text{cut-off}}$

$$E_\nu > E_g$$
$$\Downarrow$$
$$h\nu > E_g$$
$$\Downarrow$$
$$\frac{hc_0}{\lambda} > E_g$$
$$\Downarrow$$
$$\lambda < \frac{hc_0}{E_g}$$
$$\Downarrow$$
$$\lambda < 1.1\ \mu m$$

Silicon (Si)



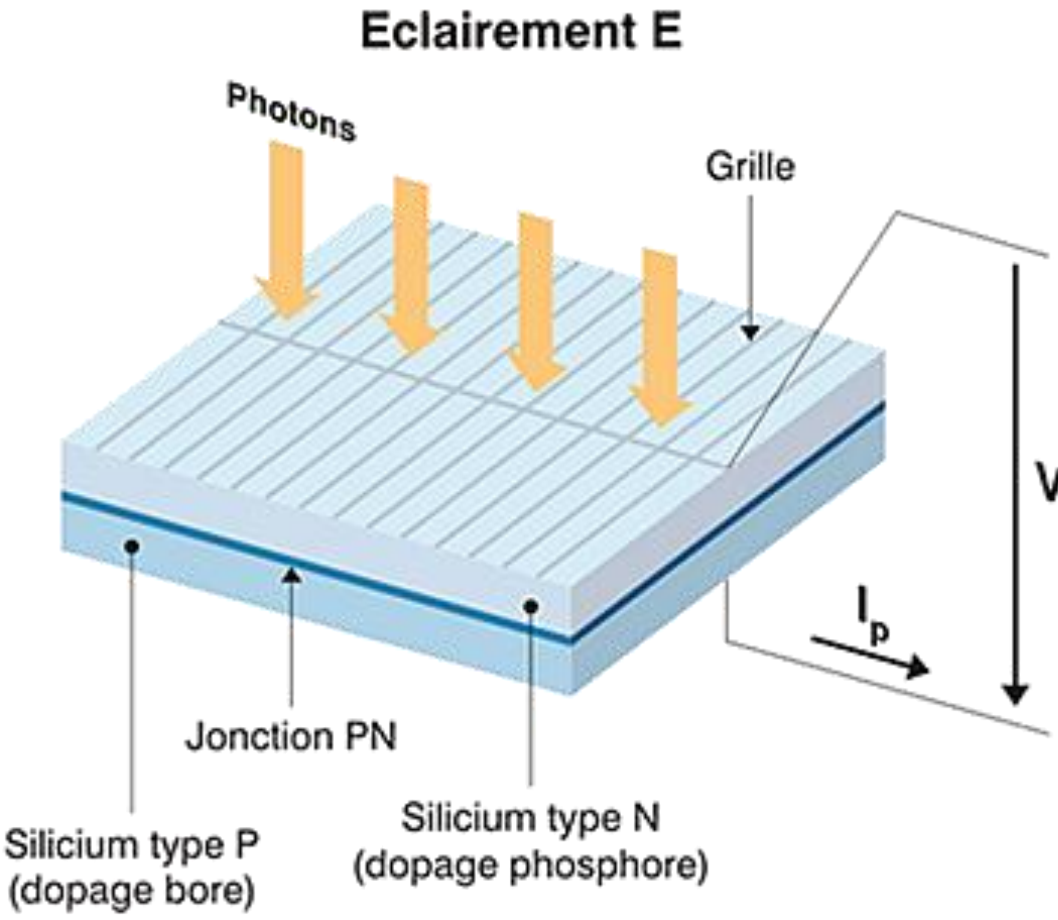
1 eV = 1.602 × 10^{-19} J



III. Operating principle
3. Characteristics of PV cells

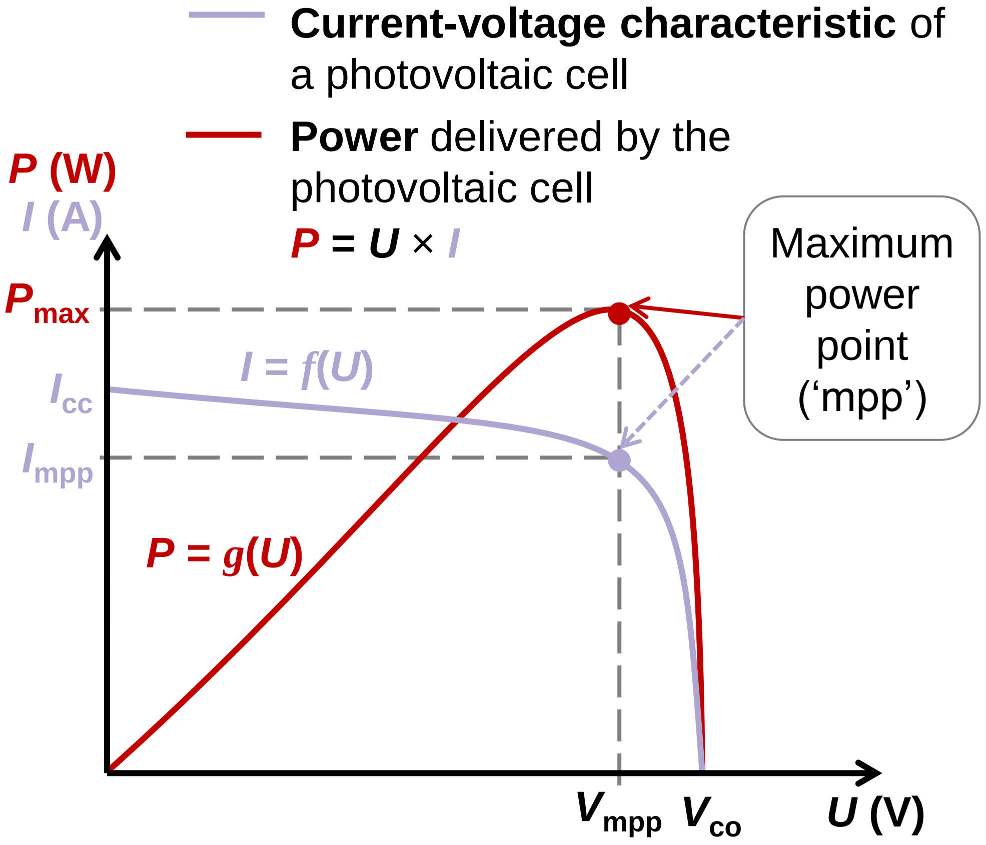
If we place electrodes on each side of the photovoltaic element, we will see a voltage and a current appear.

Direct Current : DC



III. Operating principle
3. Characteristics of PV cells

In the case of an ‘ideal cell’ in generator mode:

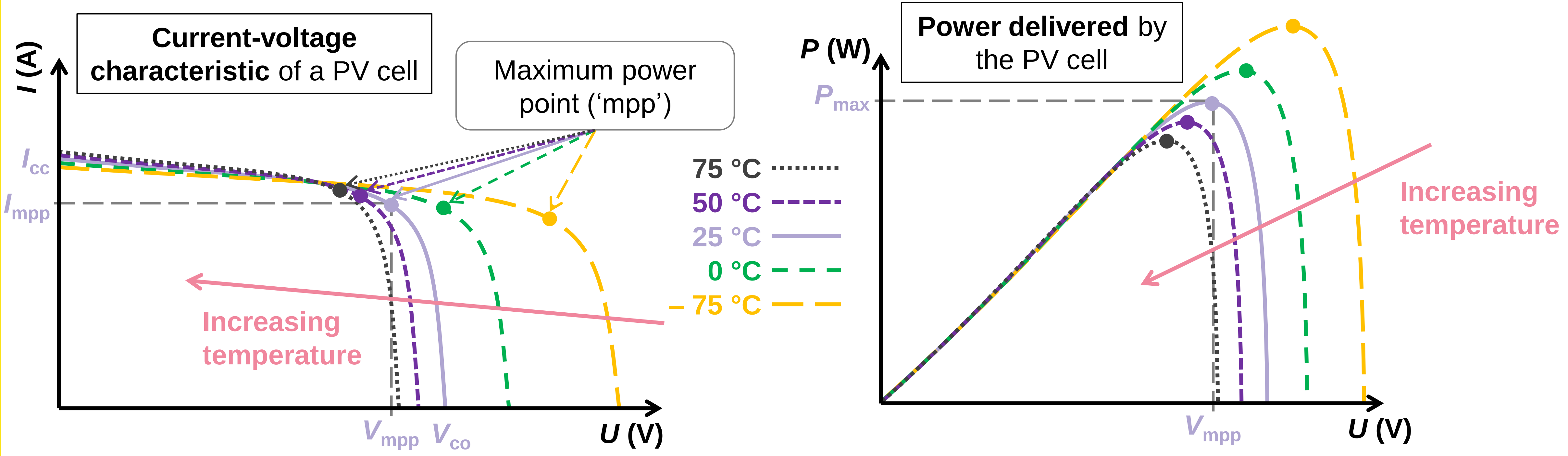


I_{cc}: Short-circuit current
V_{co}: Open-circuit voltage
P_{max} or P_{mpp}: Maximum power point
V_{mpp}: Voltage at the maximum power point
I_{mpp}: Intensity at the maximum power point

III. Operating principle
3. Characteristics of PV cells

I_{cc}: Short-circuit current
V_{co}: Open-circuit voltage
P_{max} or P_{mpp}: Maximum power
V_{mpp}: Voltage at the maximum power point
I_{mpp}: Intensity at the maximum power point

Temperature strongly influences performance

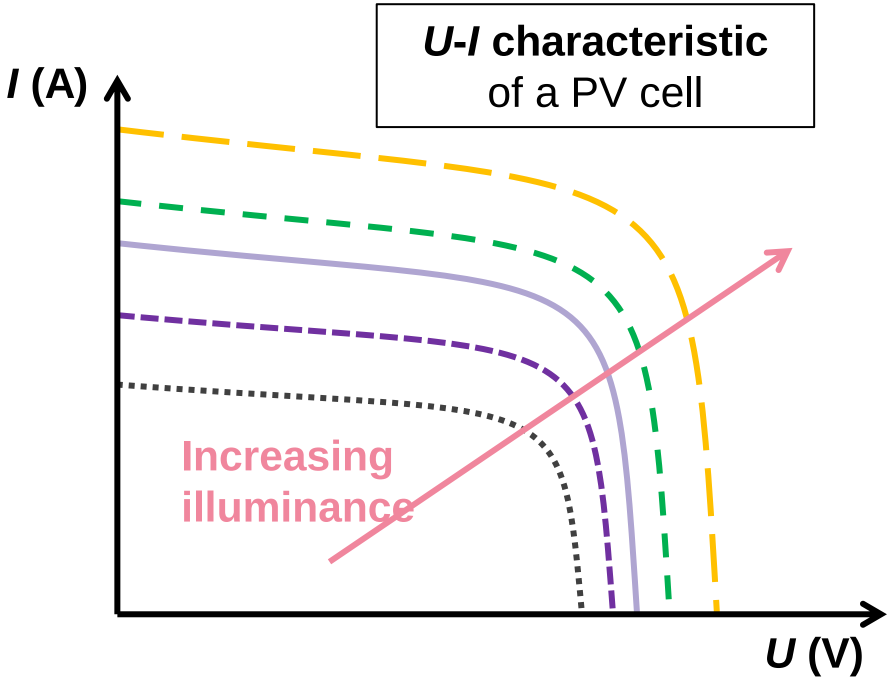


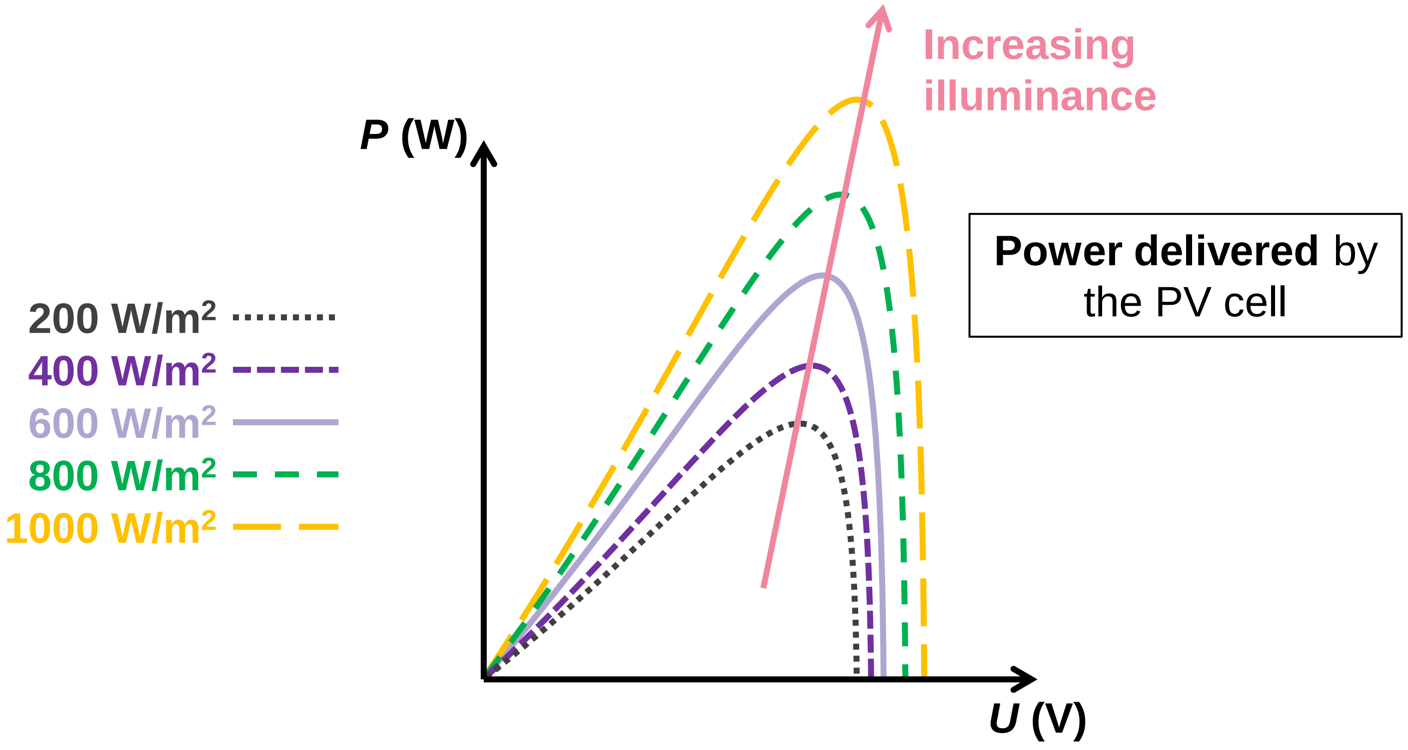
The more *T* increases ➔ the more P_{max} decreases
Therefore, it is necessary to ensure that the panel is well ventilated.

Power temperature coefficient ≈ −0.47%/K

vs. 25 °C (STC conditions, see slide No. 32)

III. Operating principle
3. Characteristics of PV cells

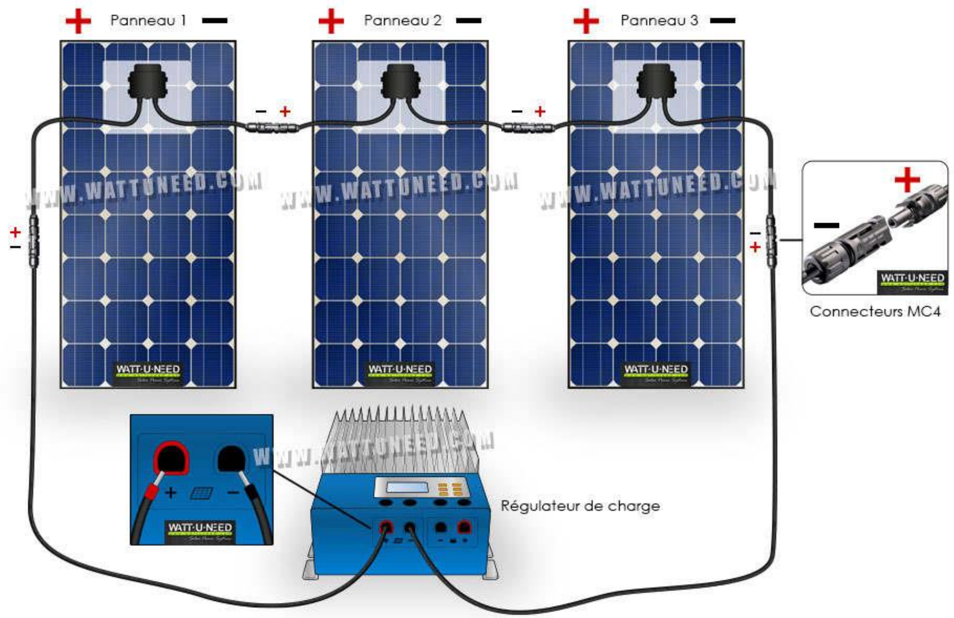




III. Operating principle
3. Characteristics of PV cells

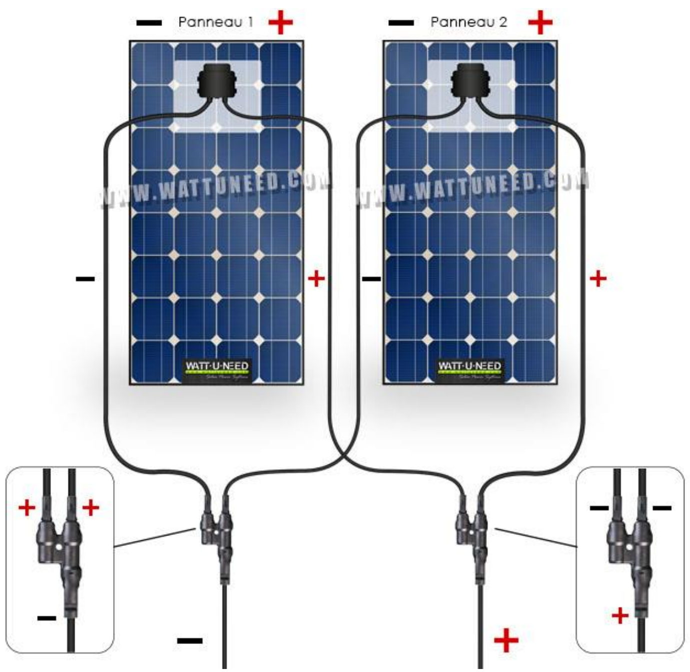
PV cells are installed in **series** or in **parallel**.

Installation of n_s cells in series



www.wattuneed.com (accessed on 09/09/2021)

Installation of n_p cells in parallel



wattuneed.com (accessed on 09/09/2021)

III. Operating principle
3. Characteristics of PV cells

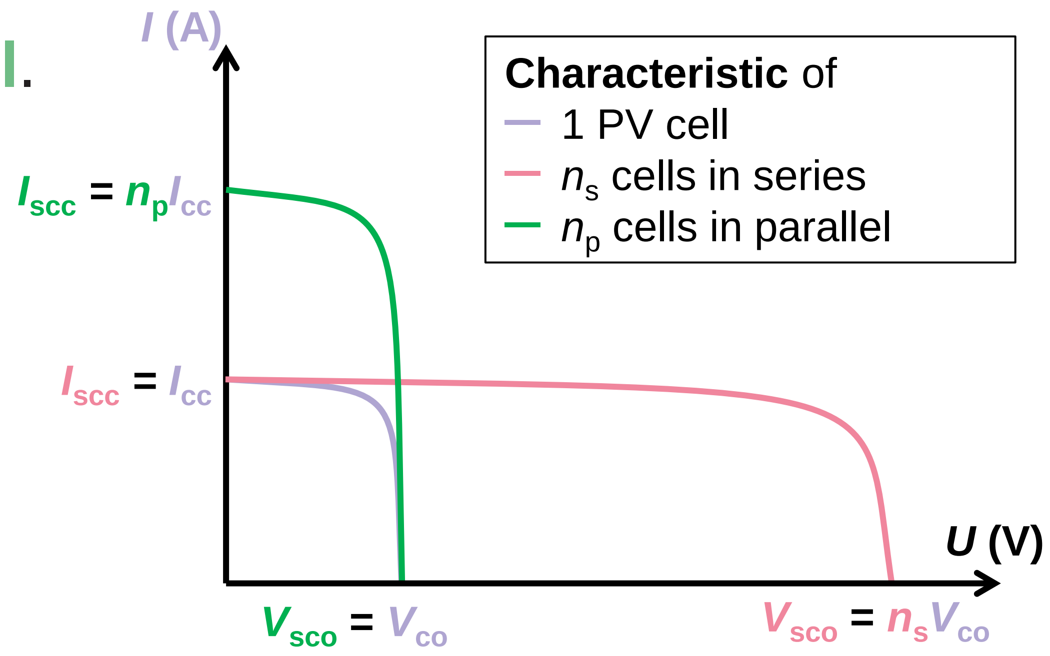
PV cells are installed in **series** or in **parallel**.

Installation of n_s cells in series

here n_s = 4 identical cells

Installation of n_p cells in parallel

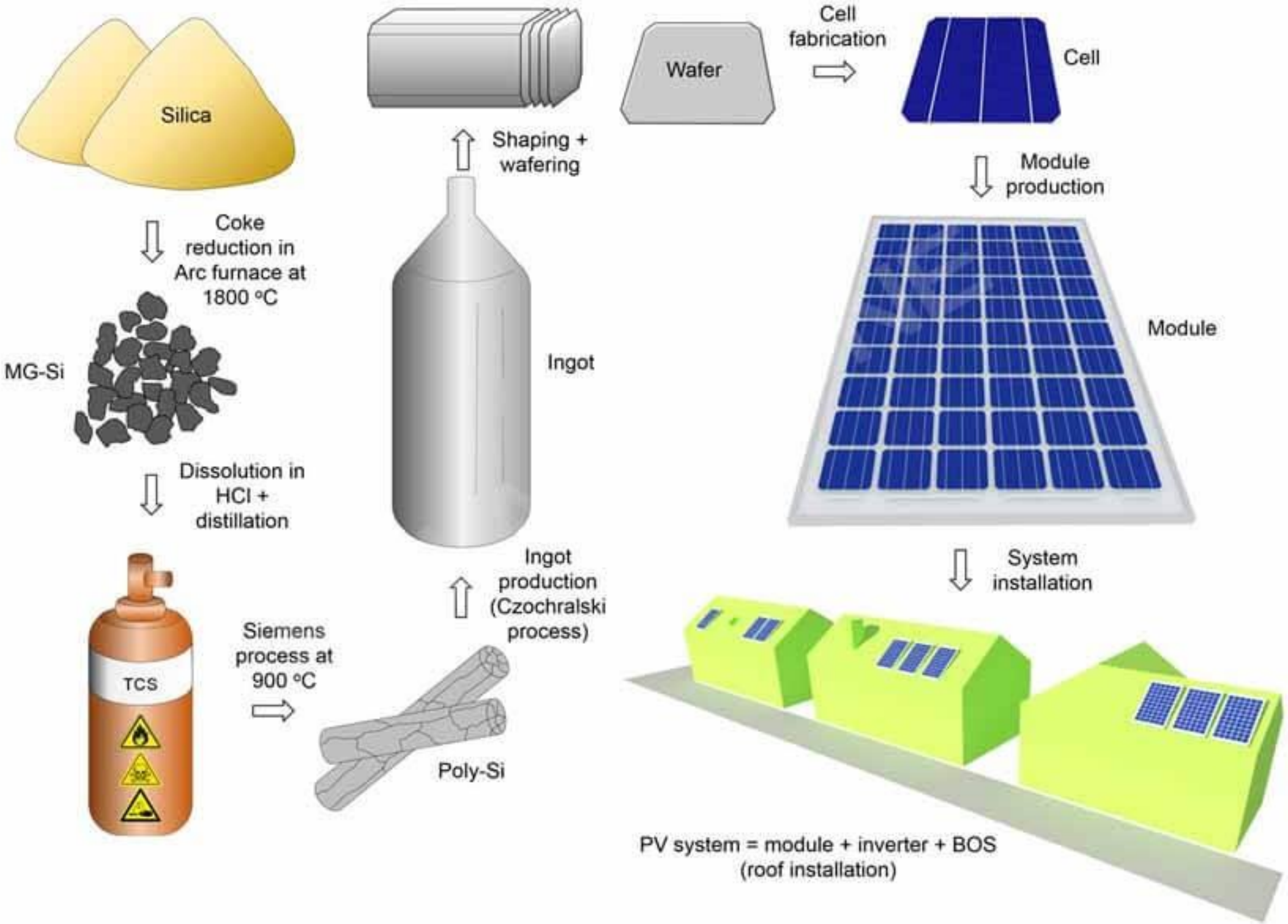
here n_p = 2 identical cells



If a cell installed in series does not provide the same power (due to shading, accumulation of dirt, defects, manufacturing...), it might operate in receiver mode against other more powerful cells. Therefore, the risk is to dissipate the transformed power. Faced with a loss of performance risk, we add bypass diodes that solve this problem.
As a rule, cells are installed in series inside a module to access the desired voltage, and then the modules (= panels) are installed in parallel to avoid voltage sag problems.

III. Operating principle
4. Types of panels

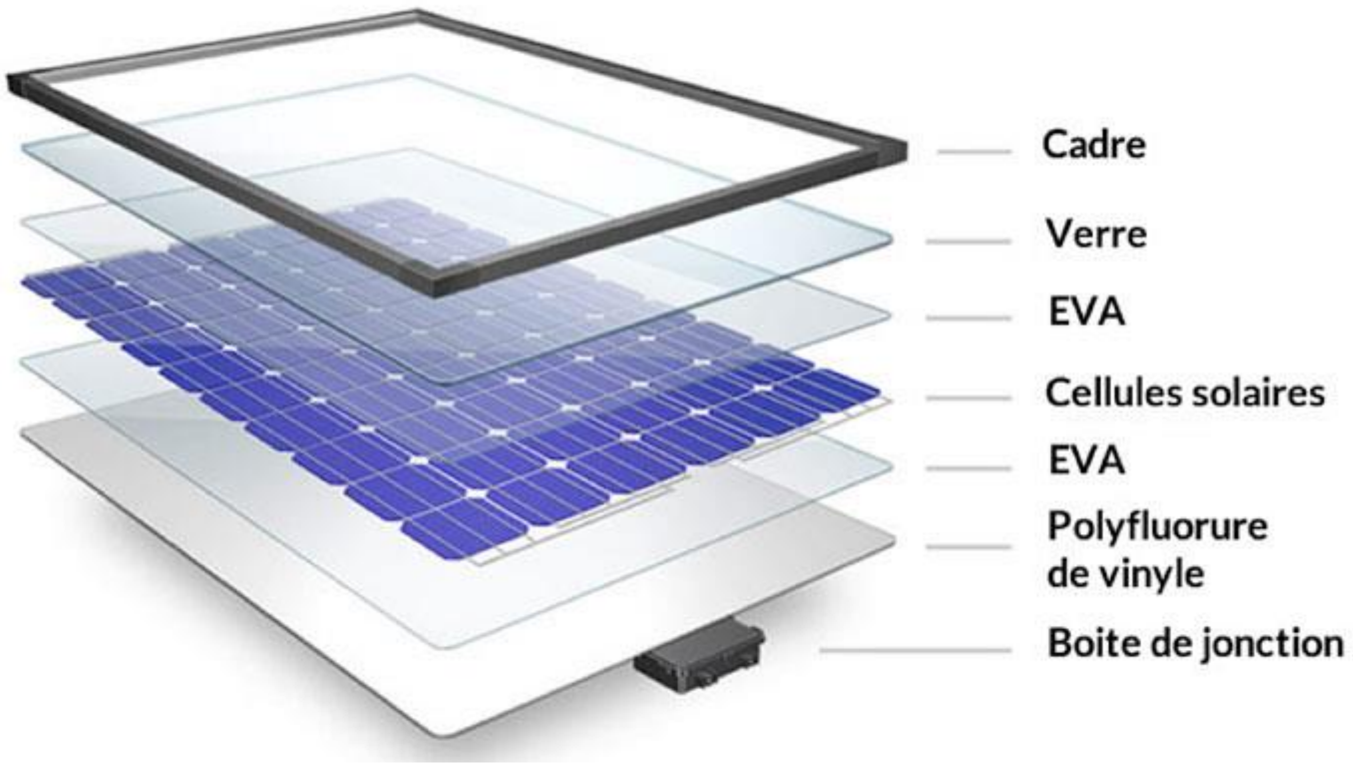
The manufacture of silicon-based photovoltaic panels goes through several stages:



https://www.linkedin.com/pulse/manufacturing-process-silicon-solar-cell-solar-panel-products/ (14/03/2024)

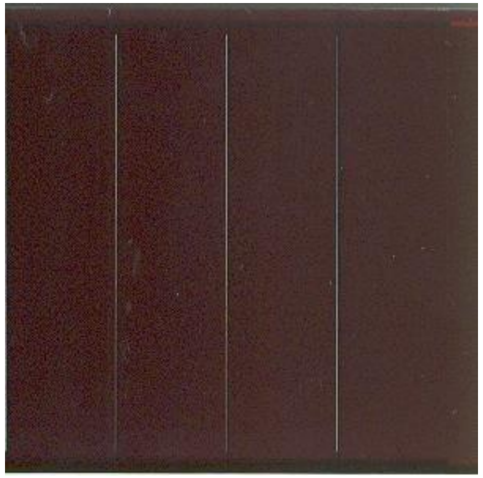
III. Operating principle
4. Types of panels

Composition of a silicon photovoltaic module



www.encyclopedie-energie (accessed on 09/09/2021)

III. Operating principle
4. Types of panels



There are different types of panels:

Efficiencies, but also prices, will vary according to their nature.

Amorphous panels

During its transformation, silicon produces a gas that is projected onto a sheet of glass. These panels are very dark grey or brown. This is the technology used in the so-called ‘solar’ calculators and watches. There is no crystalline structure/form (amorphous).

They are very affordable and even work in low light conditions. The only disadvantage is that their efficiency is very low, between 5-9 %. As a result, they are less and less used, except when certain advantages are sought : flexible membrane, lightness,...

III. Operating principle
4. Types of panels

Polycrystalline panels

When silicon is cooling down, several crystals are formed. This kind of panel has blue cells, but they are not evenly distributed; we can distinguish patterns created by the different crystals.

Their efficiency is 11-15 %.

Being more expensive than amorphous panels but cheaper than monocrystalline ones, they represent a good value for money.

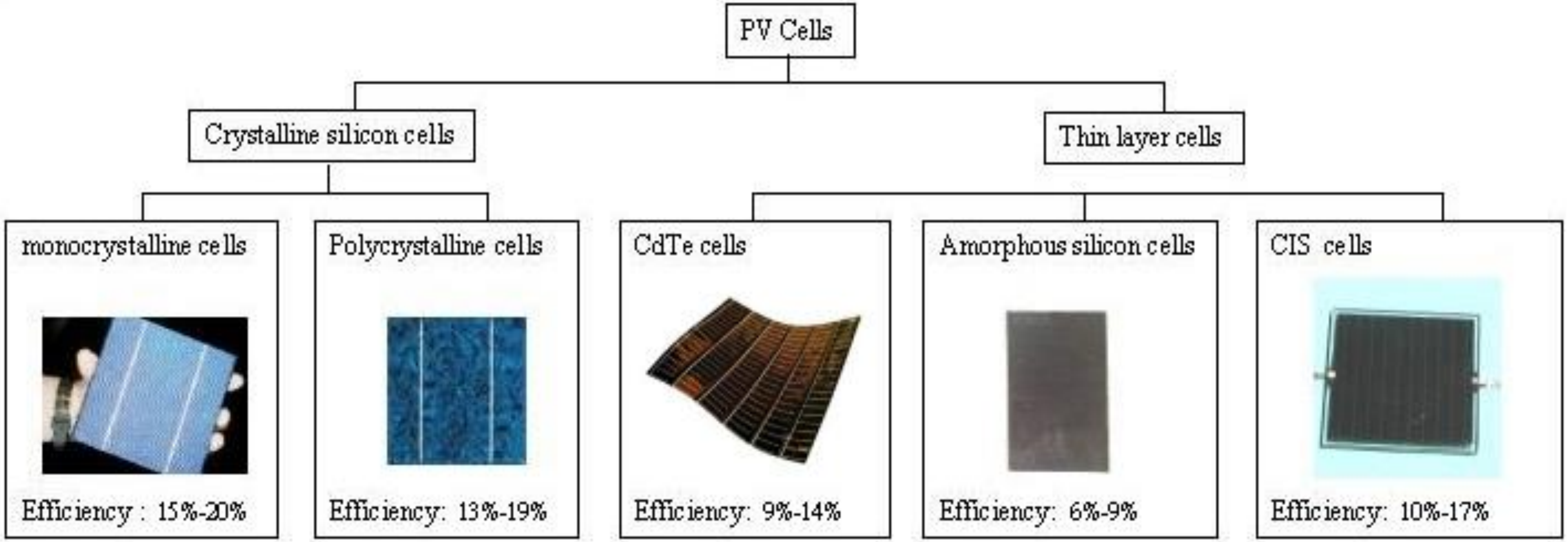
III. Operating principle
4. Types of panels

Monocrystalline panels

During the cooling process, the molten silicon solidifies into a single large crystal. The crystal is then cut into thin slices that will turn into cells. Usually, these cells have a consistent blue colour.

Their efficiency is 12-20 % but their cost is relatively high.

III. Operating principle
4. Types of panels



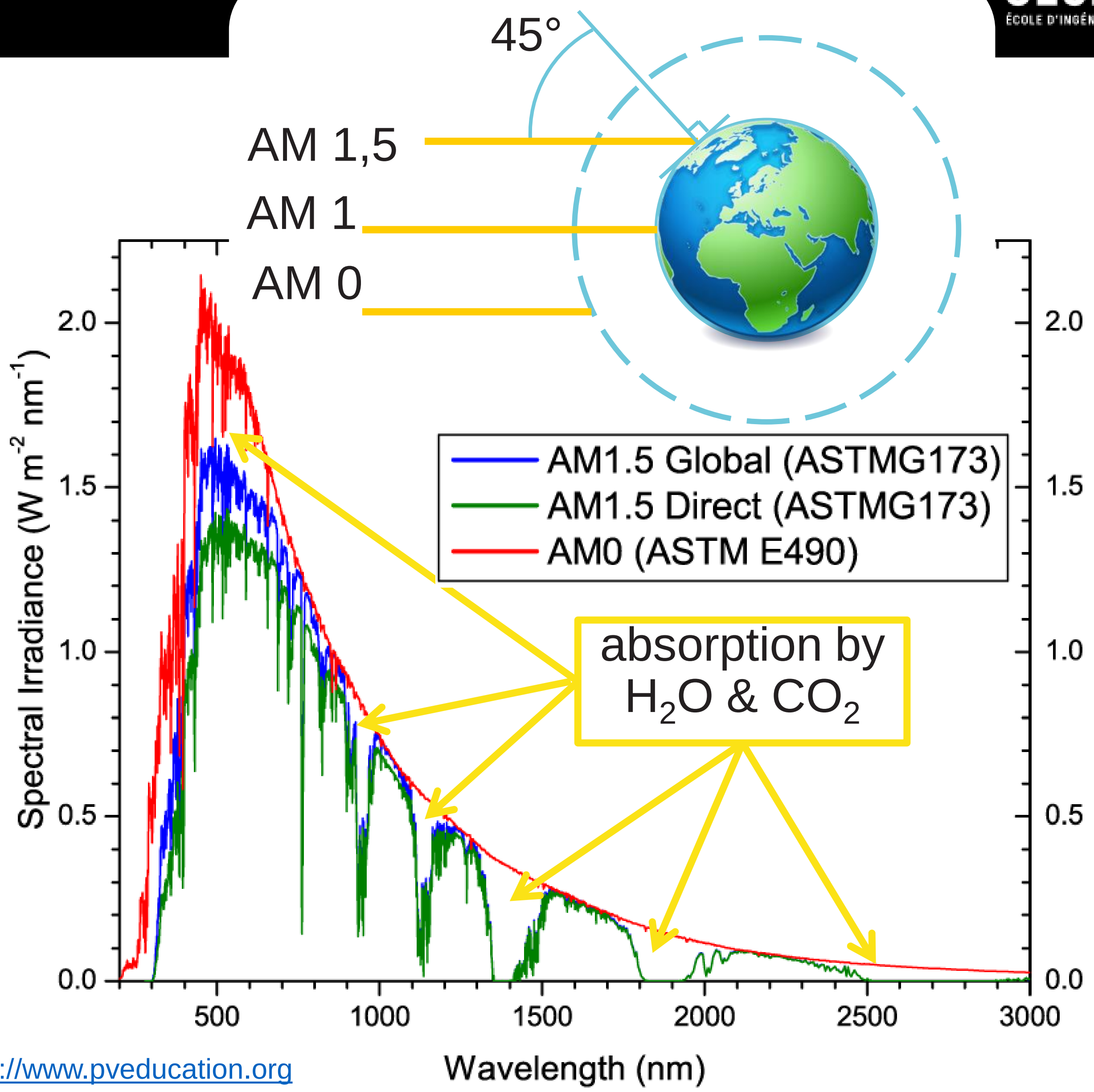
(Sources for above: Monocrystalline cells - Fraunhofer Institute for Solar Energy Systems)
Polycrystalline cells - Lanitis Solar
CIS cells - Solar World)

III. Operating principle
III.4 Types of panels

To compare the performance of different panels
→ Standard Test Conditions (**STC**):

- Panel temperature of 25 °C
- Irradiance of 1000 W·m^{-2}
- Spectral distribution of radiation AM 1.5
  AM = Air Mass
  - ➥ corresponds to the spectrum of solar radiation that reaches the ground after passing through the atmosphere at an angle of 45°

➔ Power rating under these STC conditions expressed in W_p (Watt-peak)

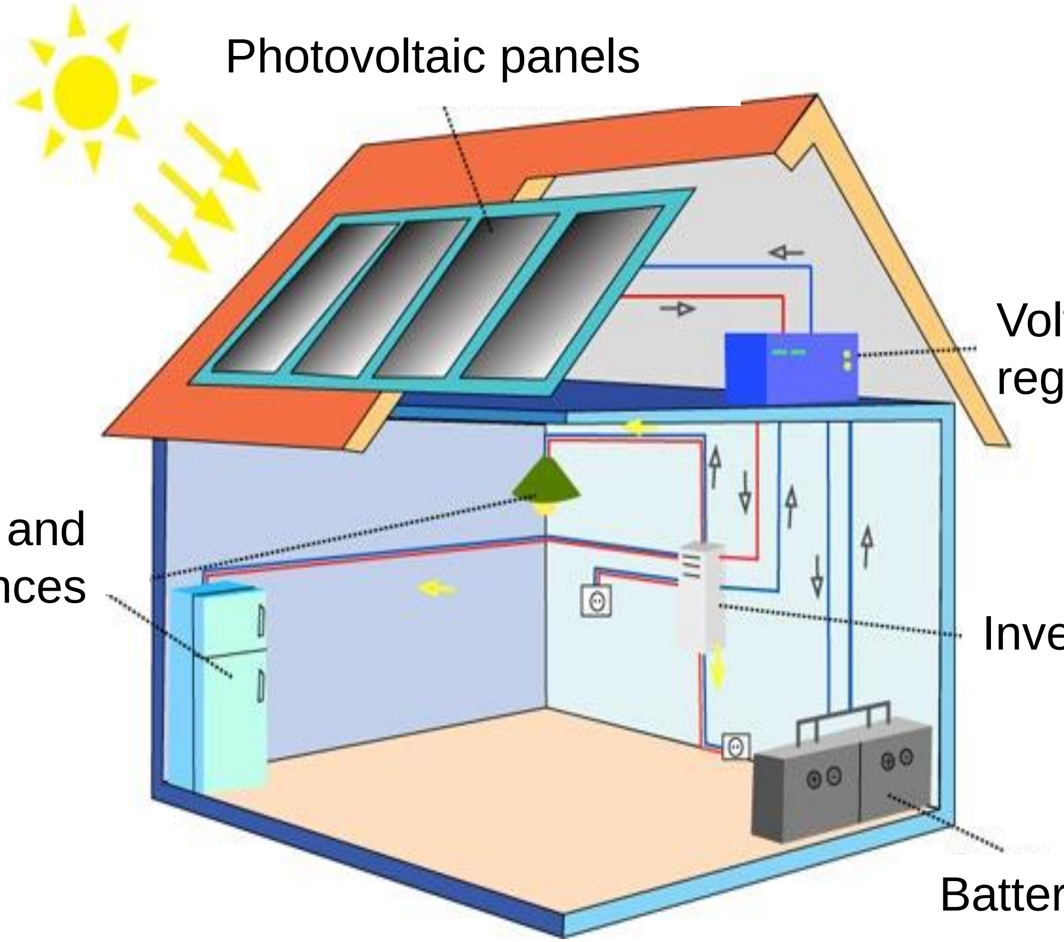


Source: https://www.pveducation.org

III. Operating principle
5. Segments and standard assemblies

Some standard assemblies:

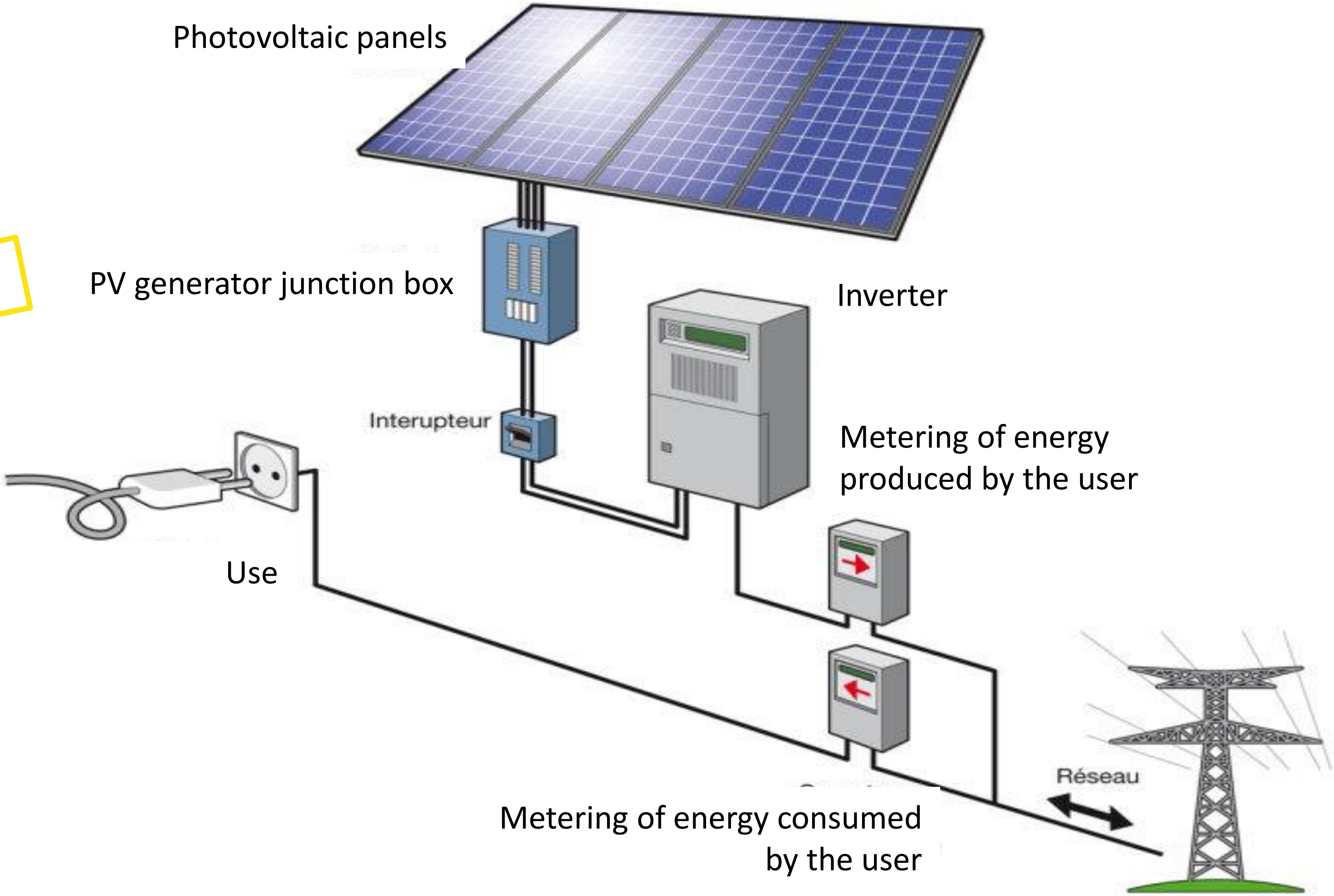
– Segment from 1 W_p to 10 kW_p
➔ off-grid households.



III. Operating principle
5. Segments and standard assemblies

– Segment from 1 W_p to a few h
  ➔ connected to the grid.

DC current → inverter → AC current



4

4. Sizing a PV system according to the example

IV. Sizing
IV.1 Example

1 – Defining the needs: stand-alone system (meets local consumption needs) or grid-connected system (best (production, efficiency)/cost ratio).

2 – Choosing the location:

– Available area: maximize it

– Orientation and inclination:

Depends on usage and production periods. Usually in France (or equivalent latitudes) an angle of 35° is recommended.

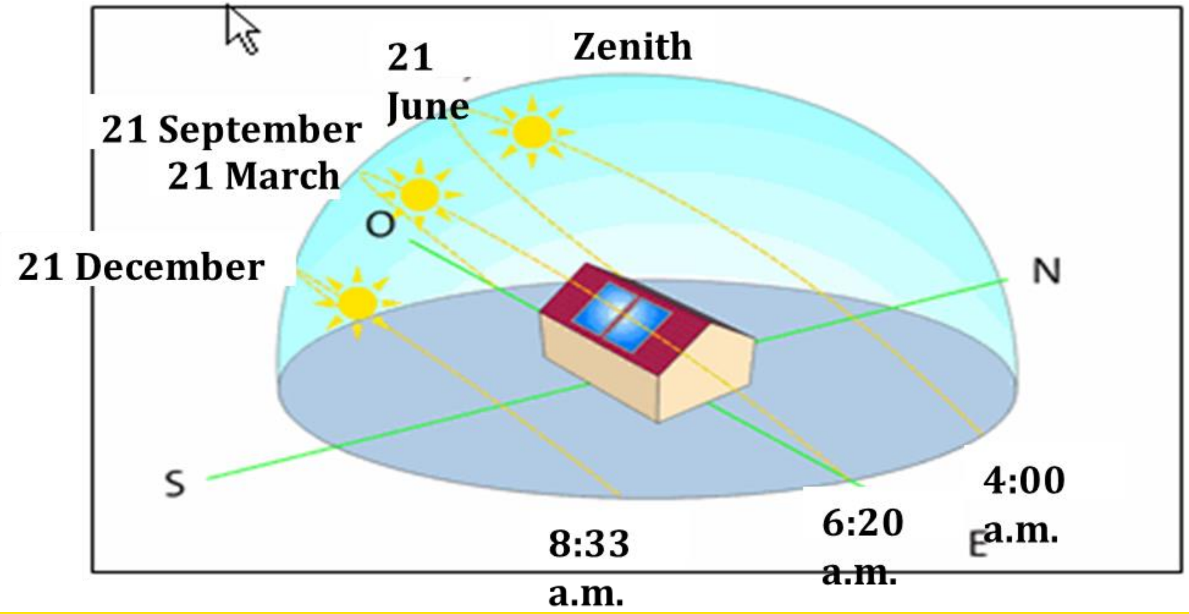
However, if the panel is motor-driven it can follow the following tilt angle curve.

IV. Sizing
1. Example

The sun's position in the sky depends on the date, time and latitude of the observer.

Latitude: allows us to position a point on Earth in the north-south axis with reference to the equatorial plane, and is expressed in degrees. It's the angular distance of a location in relation to the equatorial plane of reference.

E.g.: Perpignan 43° north



Latitude

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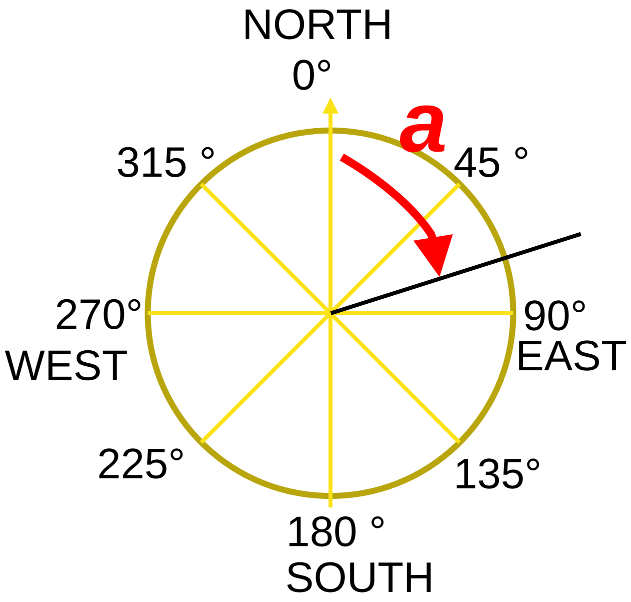
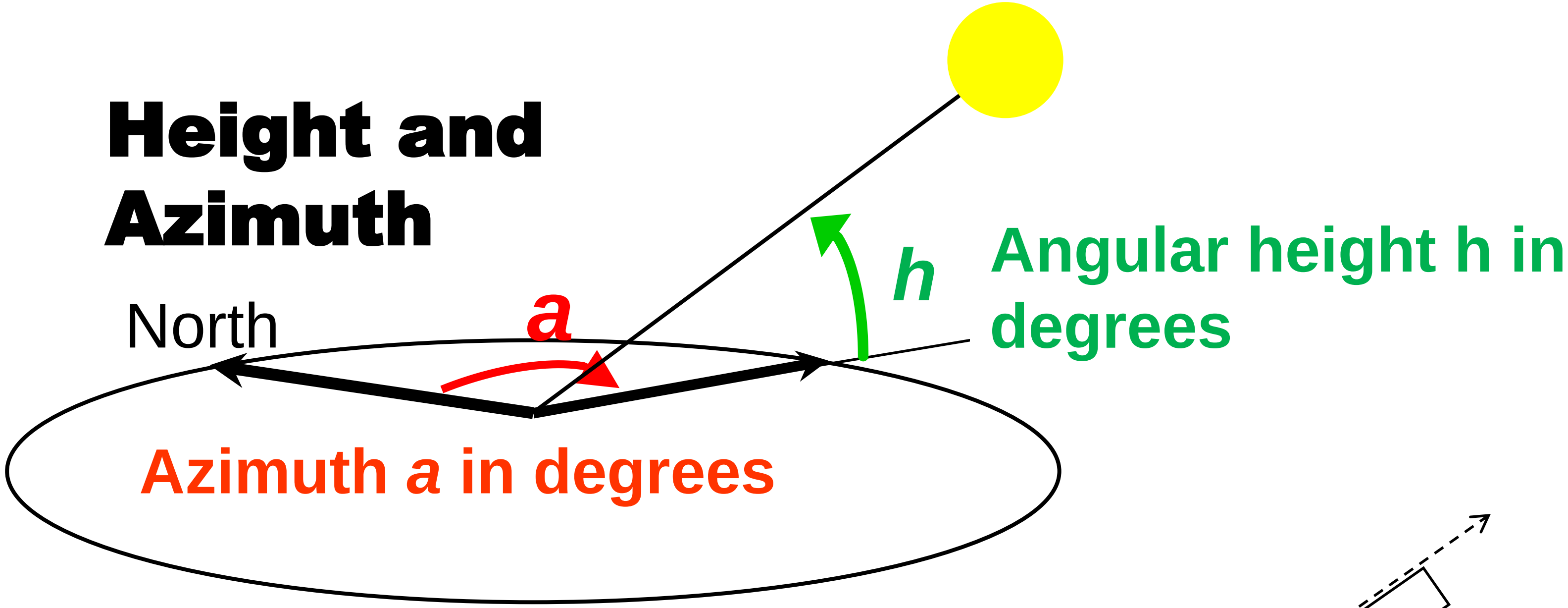
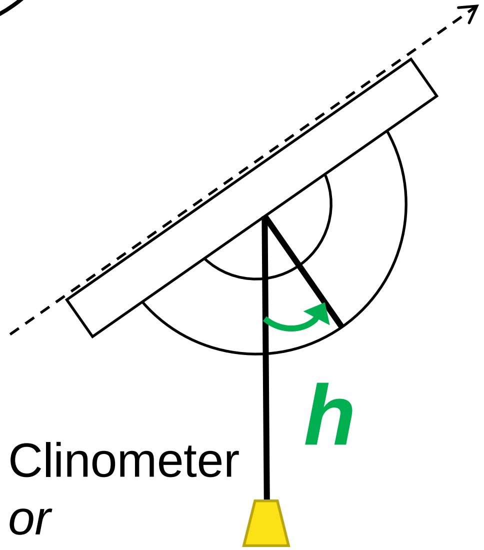
IV. Sizing
1. Example



Height and Azimuth



Compass

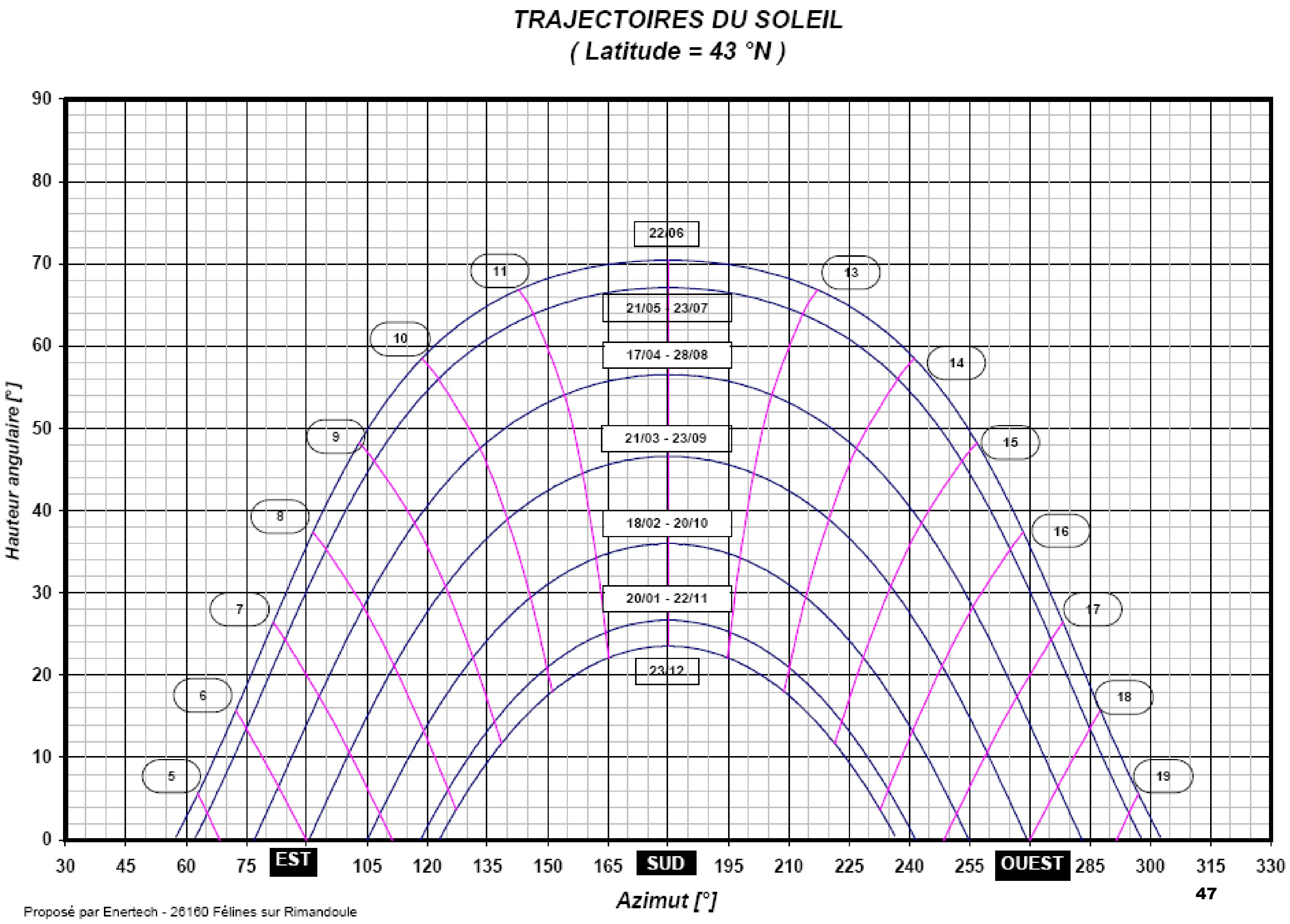


Clinometer
or
Inclinometer

IV. Sizing
1. Example

Exercise on how to locate the sun

1) Give the sunshine duration on 21 March
2) Give the angular height and azimuth of the sun on 23 July at 11 a.m.



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IV. Sizing
1. Example

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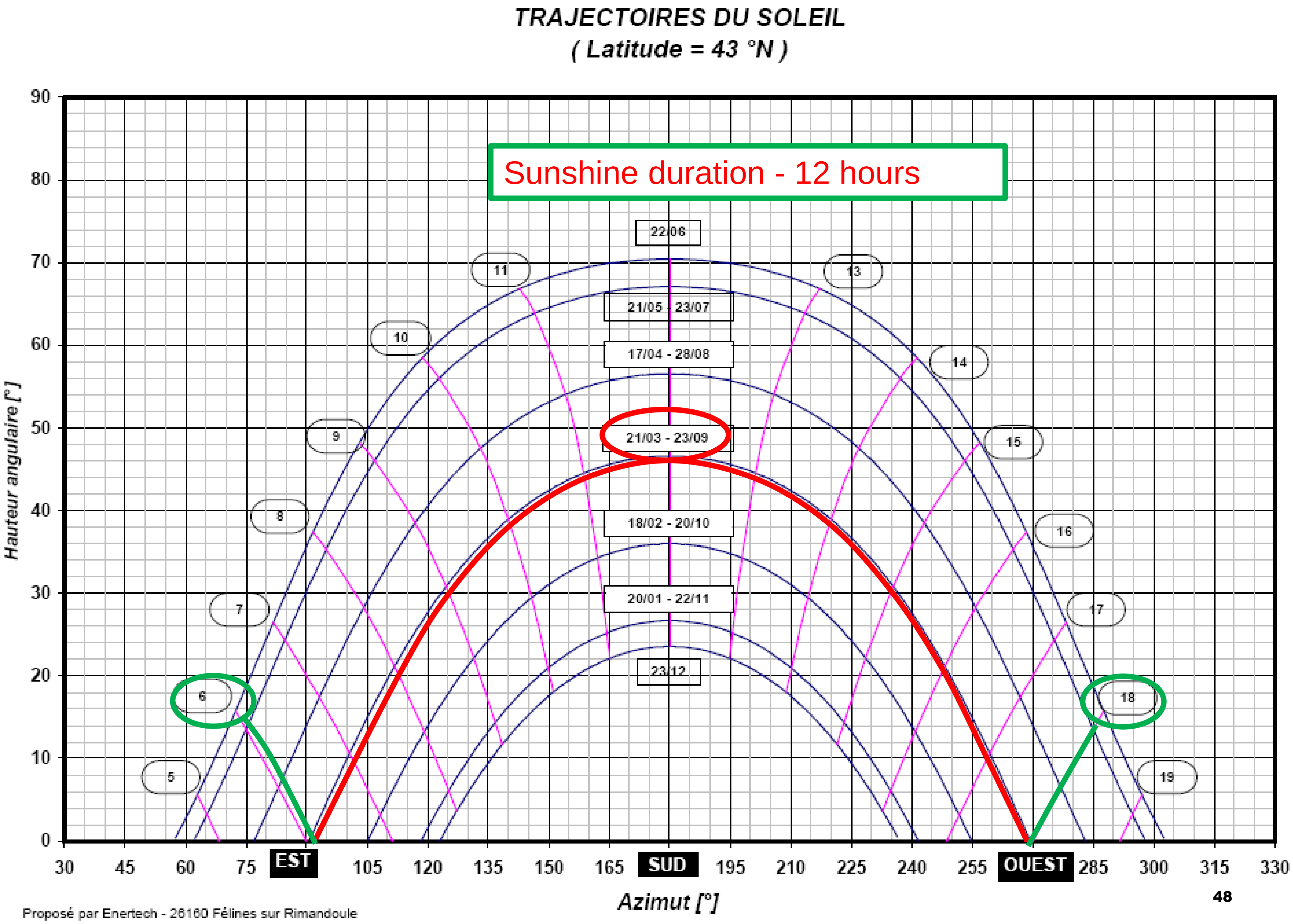

IV. Sizing
IV.1 Example

Exercise on how to locate the sun

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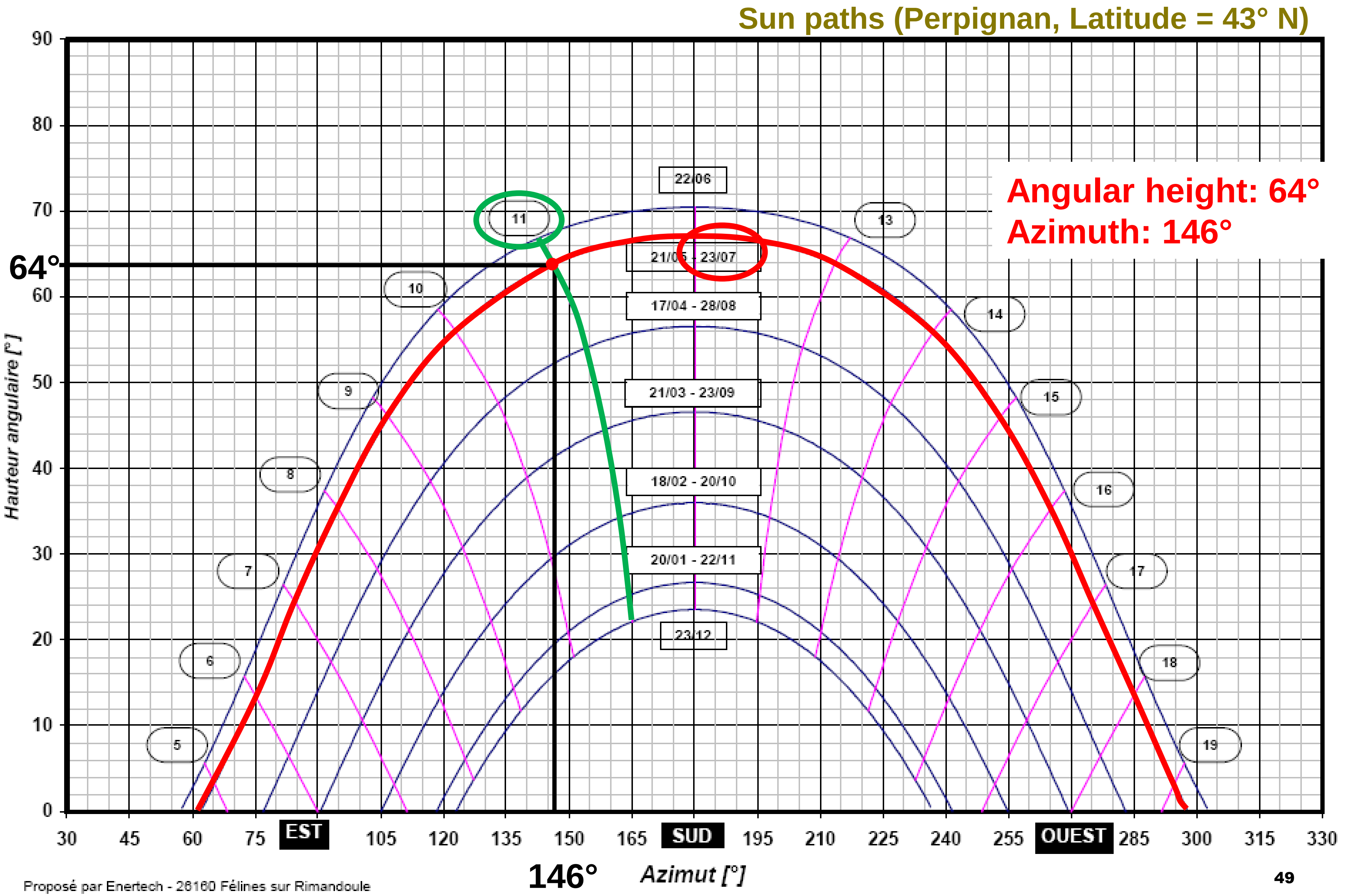
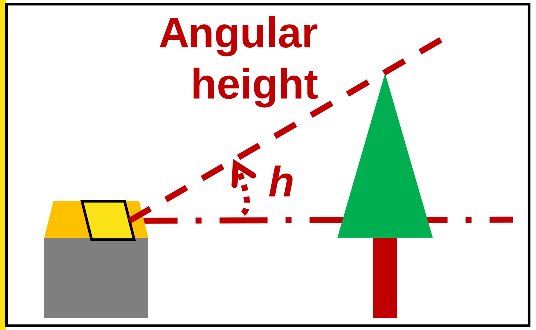
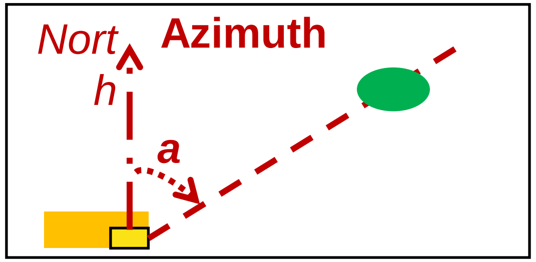


IV. Sizing
1. Example

Shading can be included in these curves to take into account the associated decrease in production.

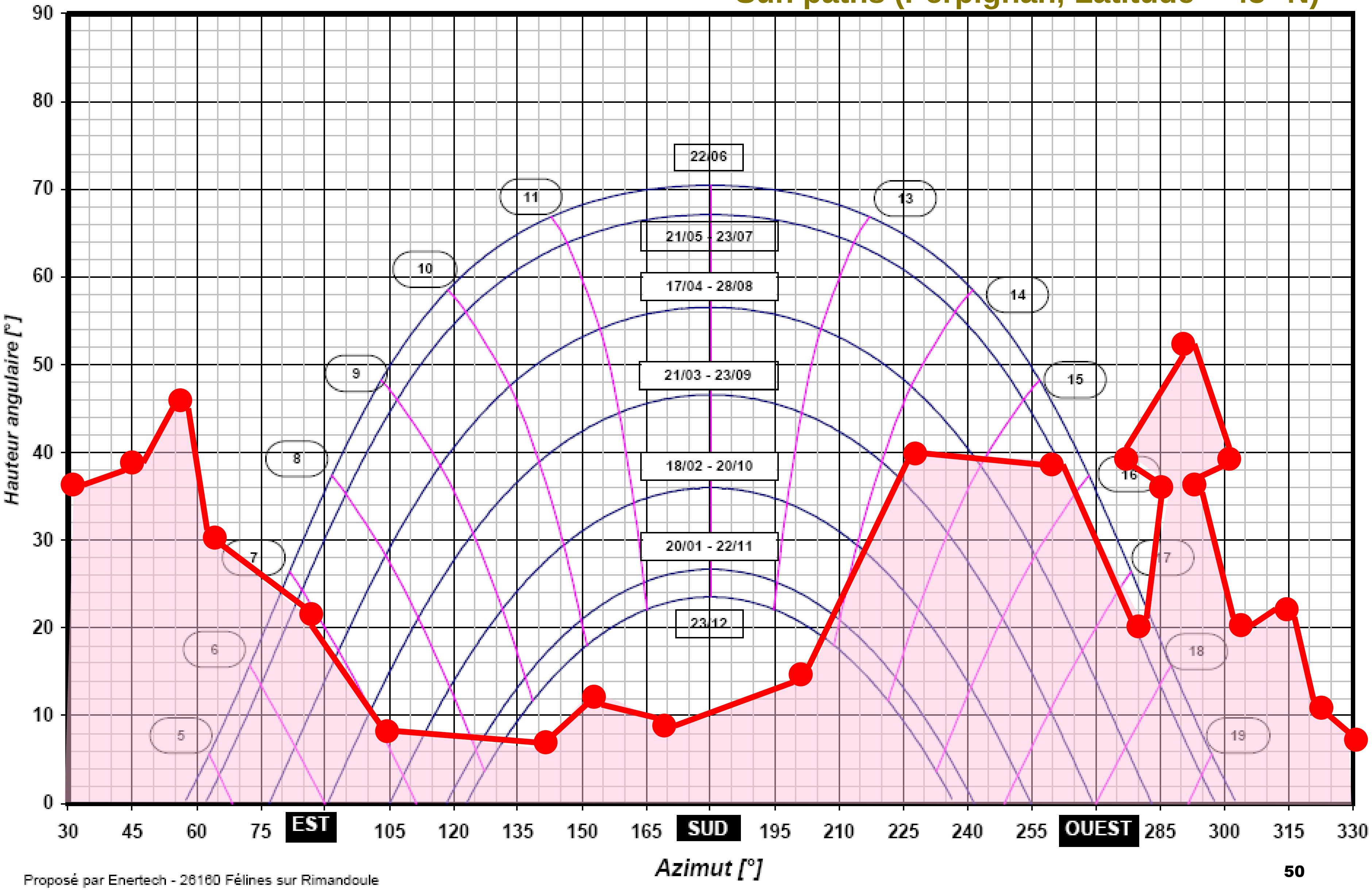


Side view



Top view

Sun paths (Perpignan, Latitude = 43° N)



IV. Sizing
1. Example

– Type of installation:

There are many possibilities depending on the location chosen: sloping roof (overlay or integration), flat roof (on a support or integrated into the roof covering), façade-mounting, glass roof-mounting, on a solar shading system, or even on the ground...

Care must be taken to consider the accumulation of dirt, shading or rising temperatures (the colder the panel, the more efficient it will be).

IV. Sizing
1. Example

2 - Choosing the module:

– make the optimum choice in terms of efficiency and price.

An example for a production of 1 kW_p (value for reference only):

– 6 m² of monocrystalline cells (considering a peak power of 165 W_p/m^2),

– 8 m² of polycrystalline cells (considering a peak power of 125 W_p/m^2),

– 15 m² of amorphous cells (considering a peak power of 66 W_p/m^2).

In series (homogeneous installation): easy/fast assembly. Small number of connections. Beware that in case of shading, defects or accumulation of dirt, one cell will affect the entire module.

In parallel (heterogeneous installation): allows for better compliance with the assembly voltages, but junctions lose more energy.

IV. Sizing
IV.1 Example

Example of electrical characteristics provided by a data sheet

Atakama by siliken

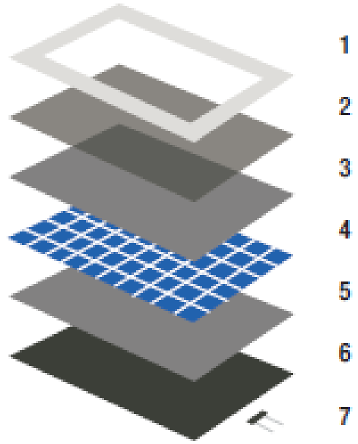
220 Wc - 245 Wc

Les panneaux solaires Atakama permettent d'obtenir d'excellentes performances à un prix très compétitif. Les processus et le contrôle qualité très rigoureux de Siliken assurent la rentabilité et une fiabilité éprouvée du produit avec une garantie de production d'énergie de 25 ans.

- Excellente tolérance de puissance ±3 %
- Garantie matériel 10 ans
- Garantie de 25 ans pour la puissance de sortie
- Comportement optimal à faible luminosité
- Certification TÜV pour une utilisation internationale
- Modules avec un rendement pouvant atteindre 15,1 %

Description des composants

1 CADRE
2 VERRE
3 et 5 EVA
4 CELLULES
6 FACE ARRIÈRE
7 BOÎTIER DE CONNEXIONS



Modules solaires polycristallins

IV. Sizing
1. Example

Electrical characteristics provided by a data sheet

Different Peak Power values available for this module range

1 = Peak power
2 = STC efficiency
- irradiance of 1000 W/m²
- T_{panel} = 25 °C
- AM 1.5

3 = this factor is the Peak Power ratio to the product of $V_{co} \times I_{cc}$
4 Power Temp. Coefficient
5 = Nominal Operating Condition Temperature (NOCT)
- 800 W/m² & AM 1.5
- T_{room} = 20 °C
- wind at 1 m/s
- 'free back' assembly

Caractéristiques électriques

1	Puissance maximale sous conditions STC (±3 %)	Pmp (Wp)	220*	225*	230	235	240	245*
2	Rendement sous conditions STC	η (%)	13,5	13,8	14,1	14,4	14,8	15,1
3	Facteur de forme	FF	0,733	0,734	0,737	0,738	0,740	0,741
	Tension au point de puissance maximale	Vmp (V)	28,7	28,9	29,0	29,2	29,3	29,4
	Courant au point de puissance maximale	Imp (A)	7,67	7,79	7,93	8,05	8,19	8,33
	Tension de circuit ouvert	Voc (V)	36,8	36,9	37,0	37,1	37,2	37,3
	Courant de court-circuit	Isc (A)	8,16	8,31	8,43	8,58	8,72	8,86
	Tension maximale UL/IEC	Vmax (V) UL/IEC	600 / 1000					
4	Coeff. température au point maximal de puissance	TkPmp (%/°C)	-0,47					
	Coeff. température de tension de circuit ouvert	TkVoc (%/°C)	-0,340					
	Coeff. température de courant de court-circuit	TkIsc (%/°C)	+0,07					
5	Temp. nominale de fonctionnement de la cellule	NOCT (°C)	48±2					

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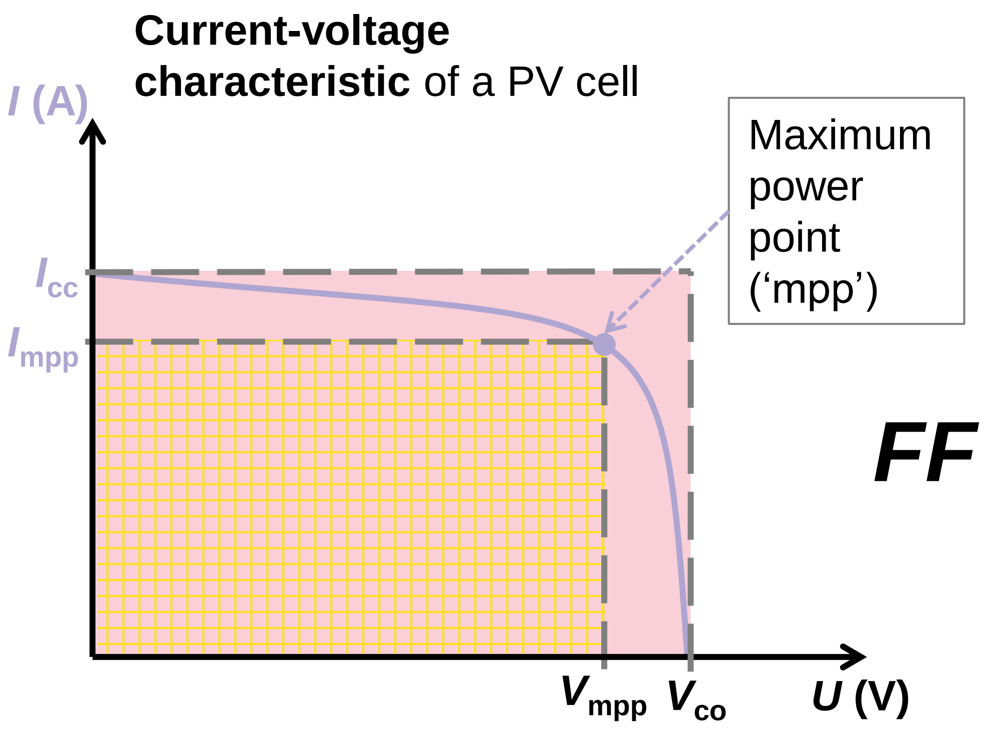
IV. Sizing
1. Example

Form Factor *FF*



$$FF = \frac{V_{mpp} \times I_{mpp}}{V_{co} \times I_{cc}}$$

Efficiency

$$\eta = \frac{P_{max}}{P_i \times S}$$

P_{max} = panel power at max power point (mpp) [W]

P_i = irradiance [W·m^{-2}]

S = panel area [m^2]

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IV. Sizing
1. Example

The electric power generation of a stand-alone PV system is calculated as follows:

$$E_{e\mathrm{elec}} = \frac{P_\mathrm{C}}{P_\mathrm{i}} \times E_\mathrm{i} \times PR$$

with:

E_{elec} = *Electric power potentially generated daily by the PV system (in* kW·h·j^{-1}*)*

P_c = *Peak power of the PV field (in* kW → *this is the maximum power reached for a radiant power density of* 1000 W/m²*)*

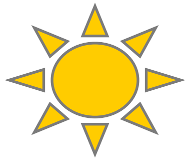
P_i = *Irradiance under STC (in* kW·m^{-2}*)*

→ **P_i = 1000 W·m^{-2}**

E_i = *Actual daily solar irradiance received per* m² *by the PV field, taking into account this PV field's orientation + inclination (in* kW·h·m^{-2}·j^{-1})

PR = *Performance ratio of the PV system (without unit of measurement)* → it characterizes the various losses

IV. Sizing
1. Example



Sun ‘at infinity’ → parallel rays

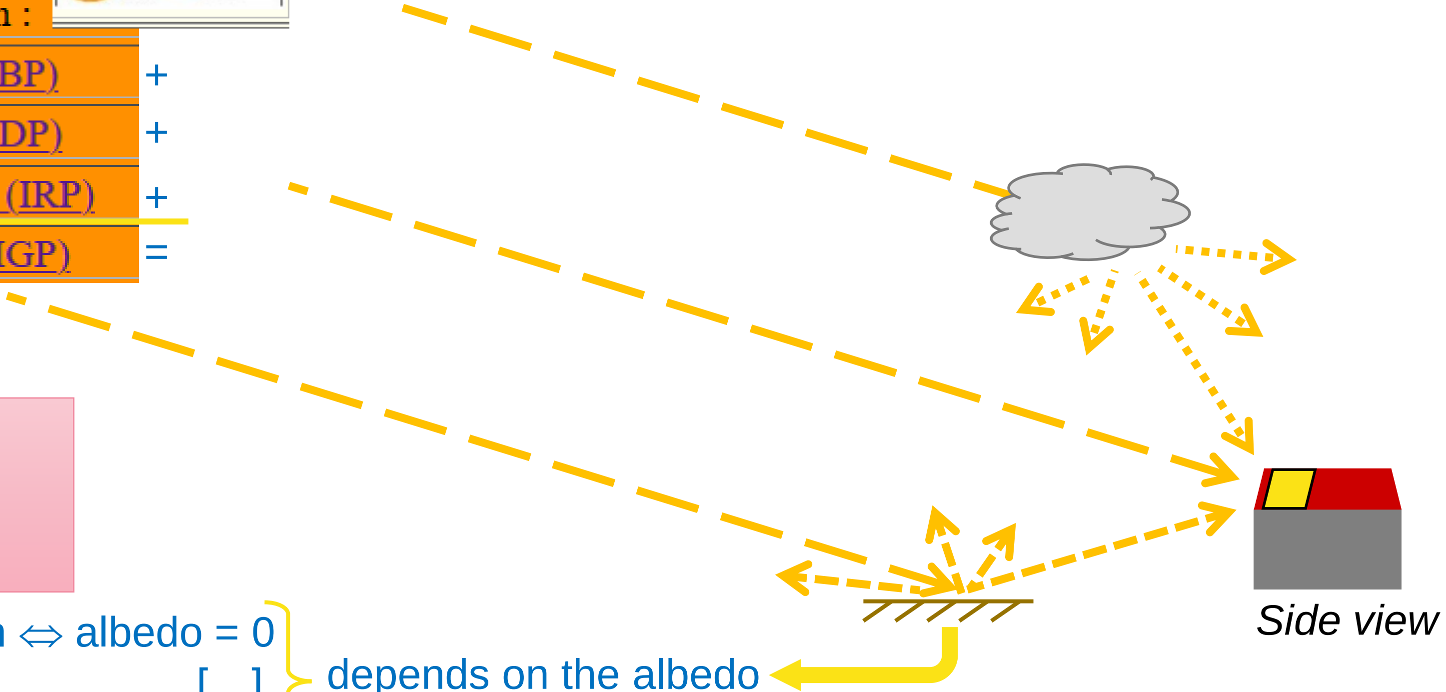
E_i = **Overall** actual daily solar irradiance received per m² by the PV field (facing a given direction); this includes:

in $kW \cdot h \cdot m^{-2} \cdot j^{-1}$

CalSol

Irradiation :	
Directe (IBP)	+
Diffuse (IDP)	+
Réfléchie (IRP)	+
Σ Globale (IGP)	=

- Direct radiation
- Diffuse radiation
- Reflected radiation



German Institut for Solar Energy System
https://www.ise.fraunhofer.de/en.html

no reflection ⇔ albedo = 0
[…]
total reflection ⇔ albedo = 1

depends on the albedo

Questions/Answers

Thank you for your attention.

MERCI

Do you have any questions?

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