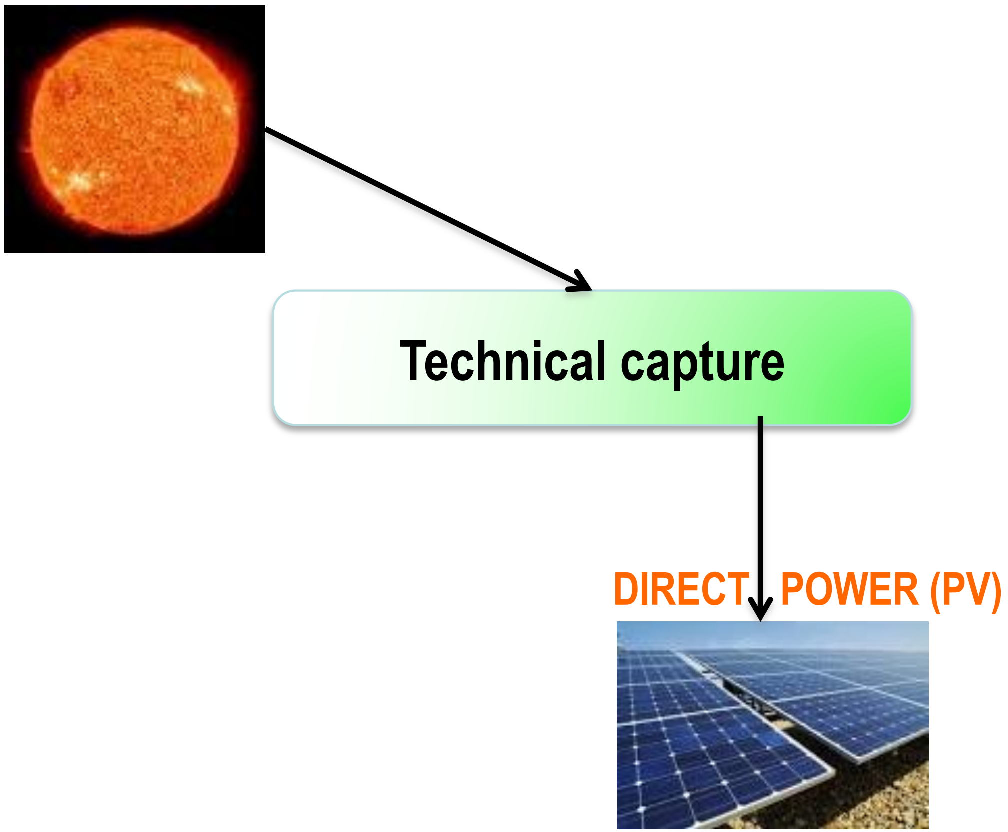
SOLAR ELECTRIC:

PHOTOVOLTAÏCS (SOLAR CELLS)



Technical capture

DIRECT POWER (PV)

Learning objectives in this chapter

- Explain the operating principle of a solar cell
- Know the efficiency and power density of PV.
- Know different PV technologies
- Know to apply basic formulas (p. 38)

Principle of operation

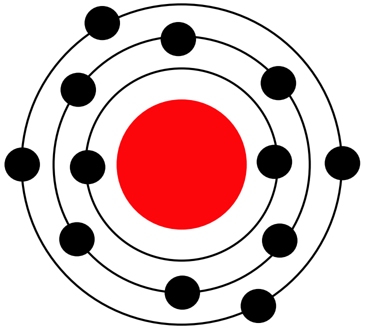
The operating principle of a solar cell relies on the **direct** conversion :

1) of incident energy of photons (=solar irradiation spectrum, see ‘Solar basics’ chapter) on a semiconductor (s.c.)

2) in electricity, by creation of charge carrier pairs (electrons (n^-) and holes (p^+)) in the s.c.

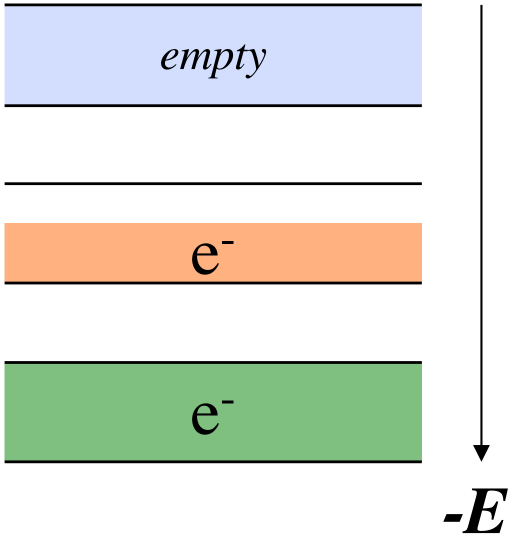
3) and separation of these thanks to a p-n junction

Reminder of semiconductor physics



- in atoms, electrons (= ***particle*** **+** ***wave***) are found on precise and confined energy levels (= *s, p, d, f* orbitals => quantum mechanics)

- when closely arranging many identical atoms in a solid (=a crystal), these energy levels combine to form continuous **energy bands** between 2 energy values; these bands are one of the following:
  - ***filled*** (shell electrons, close to the nucleus),
  - ***partially filled*** (valence electrons, far from the nucleus)
  - ***empty*** (allowed energy levels, but without electrons)



Fermi distribution:

→ all these electrons in the solid crystal interact

(i) with each other

(ii)with the nuclei

and due to the **Pauli exclusion** principle

(= no 'free' occupation on the available energy levels, and maximum 2 electrons (of opposite spin) on each level),

the density of authorised energy levels for the electrons in the confined crystal volume is given by the Fermi distribution

(different from that of 'free' molecules in a gas, which is given by the Maxwell-Boltzmann distribution)

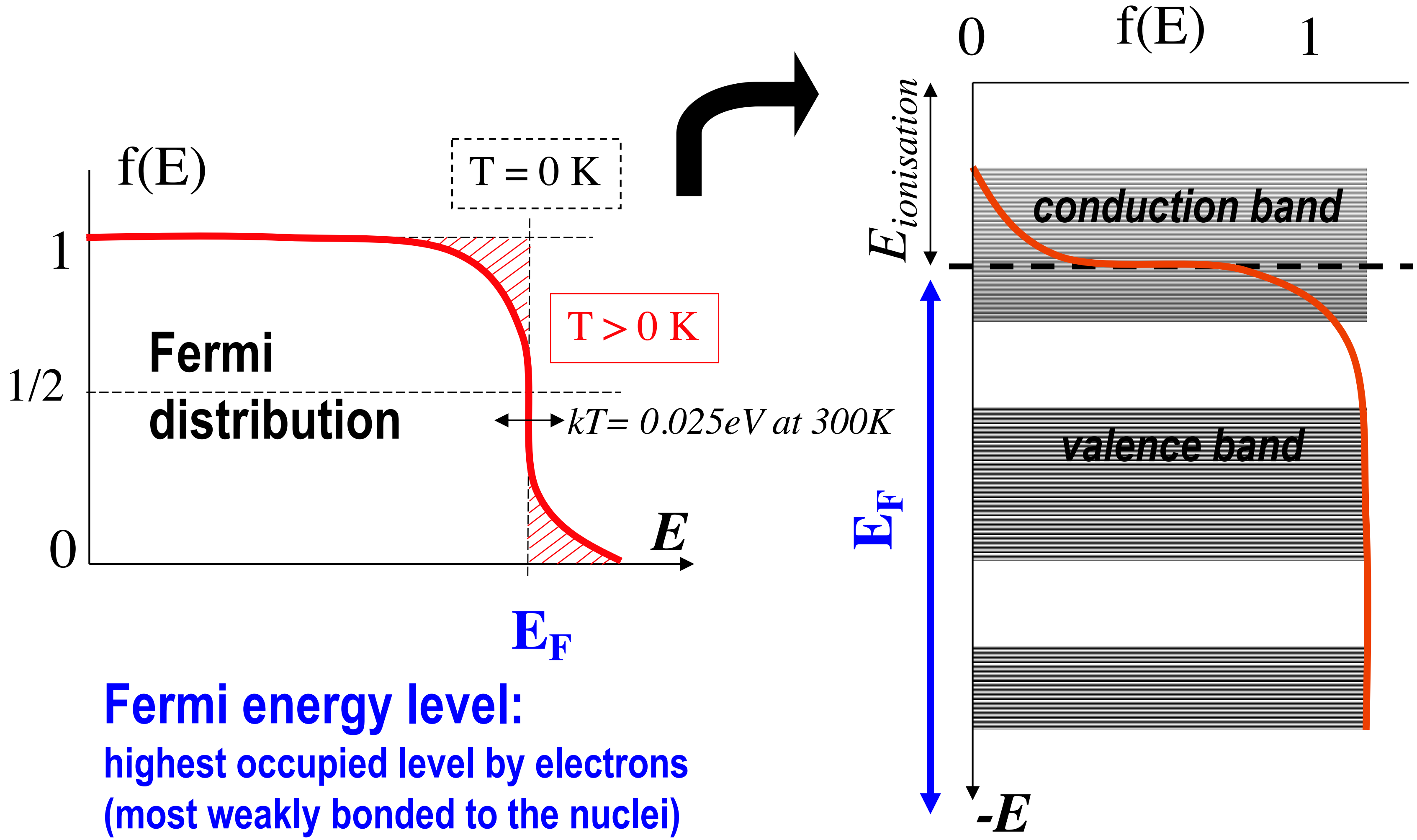
→ number dN of electrons in the energy level interval E+dE :

$$dN = N_0 f(E)dE \quad \text{avec} \quad f(E) = \frac{1}{1+\exp\left[\frac{E-E_F}{kT}\right]}$$

Fermi distribution

↓

N_0: total number of e-



Fermi energy level:

highest occupied level by electrons

(most weakly bonded to the nuclei)

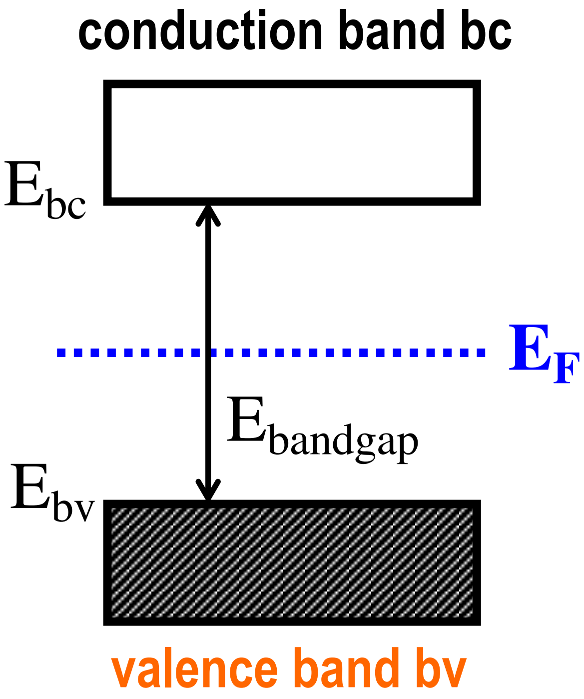
Electrical conduction in a solid

When an electric field acts on a solid, only electrons close to the Fermi level (= weakly bonded) acquire energy (kinetic, translational), and can hence conduct electricity, but only when they are in a partially filled energy band, and if the Fermi level is located in this band (which is the typical case for a **metal**; which is why metals conduct electricity)

Semiconductor

- for a semiconductor (f.ex. Silicium, Si), the Fermi level E_F is located between 2 bands
- above E_F = **conduction** band bc (*empty*), 3sp^{3*}
- below E_F = **valence** band bv (*full*)

  (filled with the **4** valence (=outer) electrons of each Si atom) $1s^2\ 2s^2\ 2p^6\ \mathbf{3s^2\ 3p^2}$



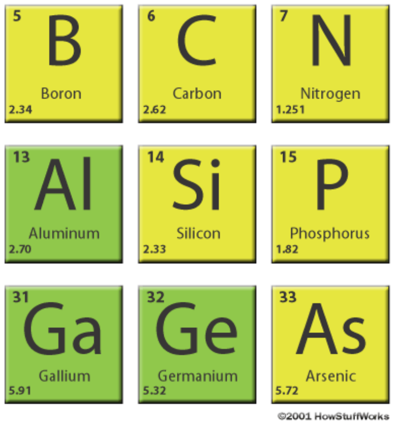
→ electrical conductivity of semiconductors

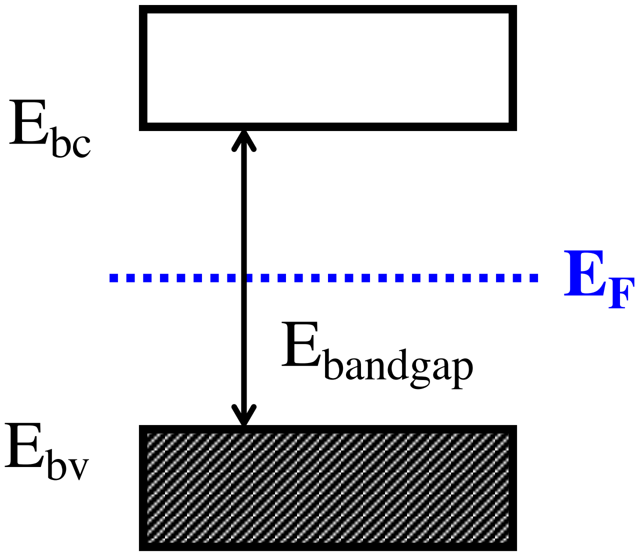
= 10^5-10^{10} times lower than metals (the bv is already full)

= increases with temperature (contrary to metals)

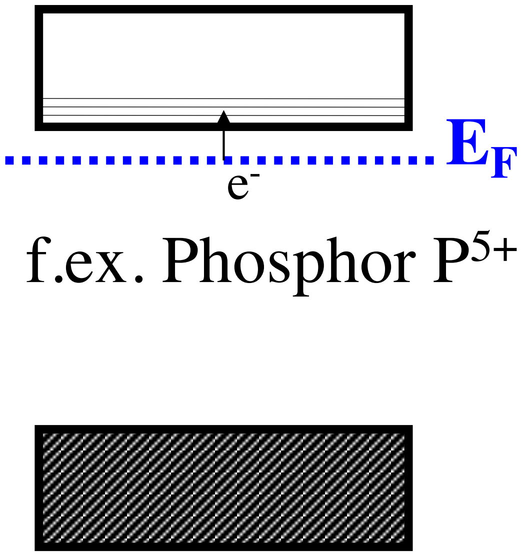
(since some electrons will populate the free bc when they acquire thermal energy)

Fermi level / *intrinsic* semiconductor vs. *doped* semiconductor



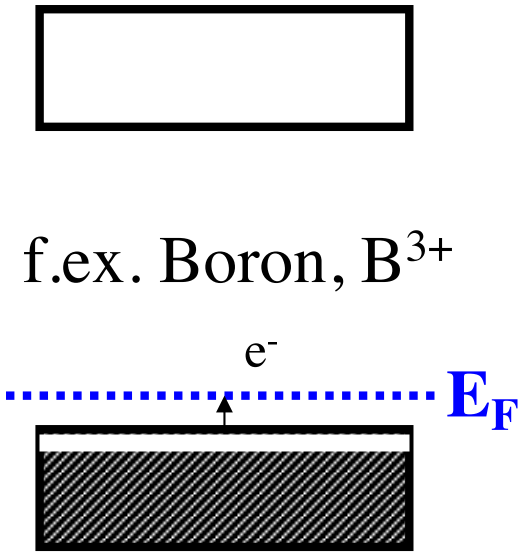


s.c. **intrinsic**



f.ex. Phosphor P^{5+}

s.c. **doped "n"**
(donor of e^-)

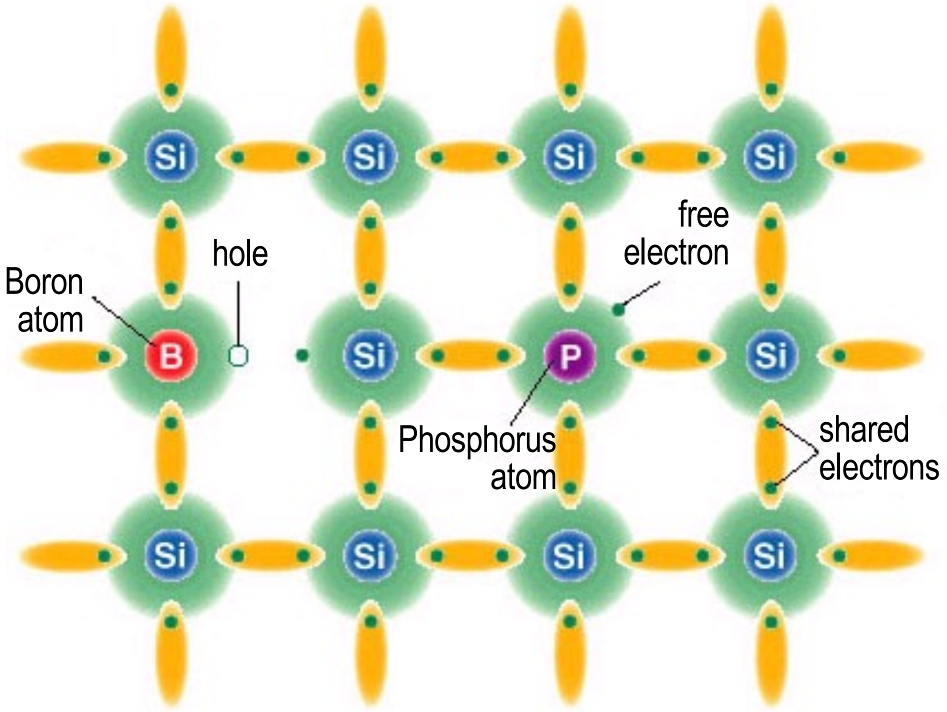


f.ex. Boron, B^{3+}

s.c. **doped "p"**
(acceptor of e^-)

Example of silicon doping of p-type and n-type

Both p- and n-layers are electrically neutral, yet n-type silicon has excess ***mobile*** electrons and p-type silicon has excess ***mobile*** holes



Sandwiching the two layers together creates a **p-n junction** at their interface, which creates an internal electrical field, necessary to keep electrons and holes separated => P.V.

Let n_c be the number of **mobile electrons**,
p_v the number of **mobile holes**,
N_c the number of levels for electrons e^-,
P_v the number of levels for holes p^+

2 electrons per orbital (downspin/upspin)

g: degenerescence of the orbital energy level

$$n_c = \int_{E_c}^{\infty} 2g_c(E)\frac{1}{1+\exp\left[\frac{E-E_F}{kT}\right]}dE \quad \text{et} \quad p_v = \int_{-\infty}^{E_v} 2g_v(E)\frac{1}{1+\exp\left[\frac{E_F-E}{kT}\right]}dE$$

$$n_c = \int_{E_c}^{\infty} 2g_c(E)\exp\left[\frac{-(E-E_F)}{kT}\right]dE = \underbrace{\int_{E_c}^{\infty} 2g_c(E)\exp\left[\frac{-(E-E_C)}{kT}\right]dE}_{N_c}.\exp\left[\frac{-(E_C-E_F)}{kT}\right]$$

$$n_c = N_c.\exp\left[\frac{-(E_C-E_F)}{kT}\right] \quad \text{et analogue} \quad p_v = P_v.\exp\left[\frac{-(E_F-E_V)}{kT}\right]$$

$$n_c p_v = N_c P_v \exp\left[\frac{-Egap}{kT}\right] = \text{const} = n^2_{\text{intrinsèque}}$$

$$\frac{n_c}{p_v} = \frac{N_c}{P_v}\exp\left[\frac{-(E_C-E_F)}{kT} + \frac{-(E_F-E_V)}{kT}\right] = \frac{N_c}{P_v}\exp\left[\frac{2E_F-E_C-E_V}{kT}\right]$$

$$E_F = \frac{E_C+E_V}{2} + \underbrace{\frac{kT}{2}\ln\left(\frac{n_c}{p_v}\right)}_{} + \underbrace{\frac{kT}{2}\ln\left(\frac{P_V}{N_C}\right)}_{}$$

for s.c. intrinsic:1 1

The Fermi level is located exactly midway between bv and bc

$\Rightarrow$ an intrinsic semiconductor is a poor electrical conductor

f.ex. Silicon : $n_{intrinsic} = 10^{10}$ e^-/cm^3, but 5.10^{22} atoms/cm^3, hence 2.10^{-13} mol e^-

=> $\rho = 10$ kΩcm

Doping of a semiconductor

Doping **n** : $n_c >> p_V$

$$n_c = N_c.\exp\left[\frac{-(E_C - E_F)}{kT}\right] \quad \text{donc} \quad E_F = E_C + kT\ln\left(\frac{n_c}{N_c}\right)$$

The Fermi level is very close to the **conduction** band bc

Doping **p** : $p_V >> n_c$

$$p_v = P_v.\exp\left[\frac{-(E_F - E_V)}{kT}\right] \quad \text{donc} \quad E_F = E_V - kT\ln\left(\frac{p_v}{P_V}\right)$$

The Fermi level is very close to the **valence** band bv

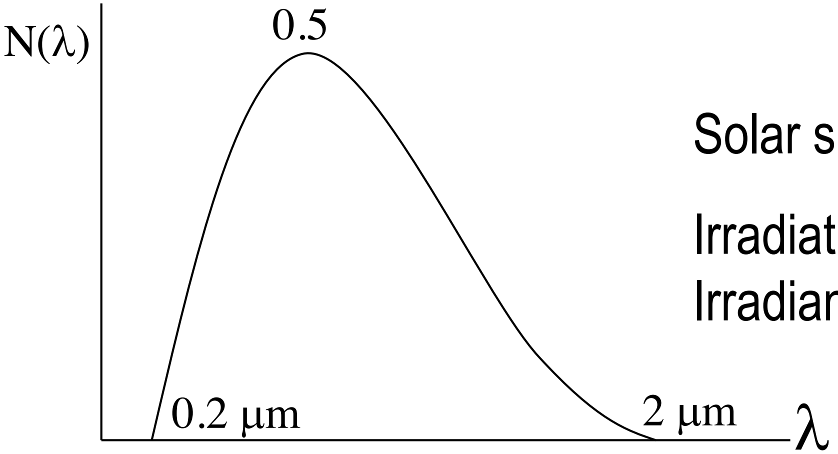
f.ex. **2 ppm** P^{5+} or B^{3+} = 10^{17} atoms/cm^3 = 10^{17} e^-/cm^3

=> $\rho = 0.3$ Ωcm

→ … which is why we need clean rooms in s.c. manufacturing!

Solar spectrum - see 'Solar basics' chapter

- Energy of photons is given by the Planck equation : $E_{photon} = h\nu = hc/\lambda$
  h = Planck's constant = $6.6262\ 10^{-34}$ Js
  c = speed of light = 3.10^{8} m/s
  λ = wavelength (m) and ν = frequency (s^{-1})



Solar spectrum on Earth= 49% IR, 46% VIS, 5% UV

Irradiation from the sun on earth = 178.10^{15} Wyr/yr
Irradiance = **1367 W/m²** ± 3% (Solar constant)

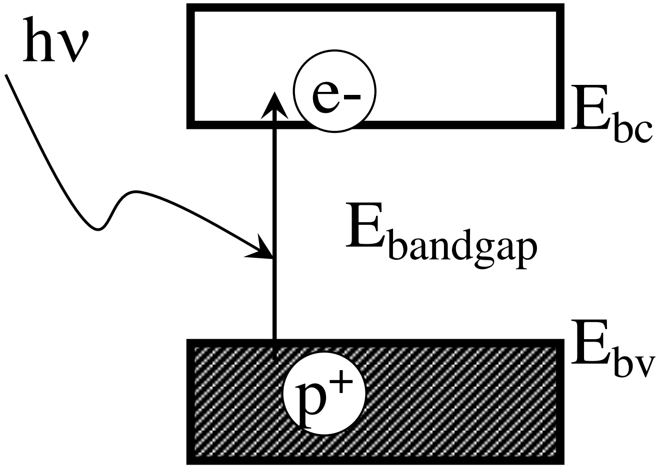
- From this irradiance, 29% is reflected, the rest absorbed (38% by oceans, 24% by atmosphere, 9% by continents) => **1 kW/m²** at the zenith
- depends on latitude + season: for Lausanne: 750 W/m² in summer, 360 W/m² in winter
- solar energy is *direct* (=sunny weather) and *diffuse* (=cloudy weather)
- Swiss year average : 140 W/m² (day and night)

Band-gap

- When irradiating a semiconductor, photons with energy $E_{photon} \geq E_{bandgap}$ excite electrons from bv to bc, thereby creating a charge carrier pair (e^-, p^+)

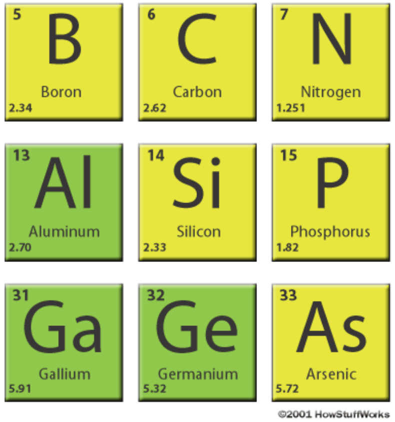
- The following relation applies :

  λ (nm) * $E_{bandgap}$ (eV) = 1240



Different PV materials have different energy band gaps (E_{gap})

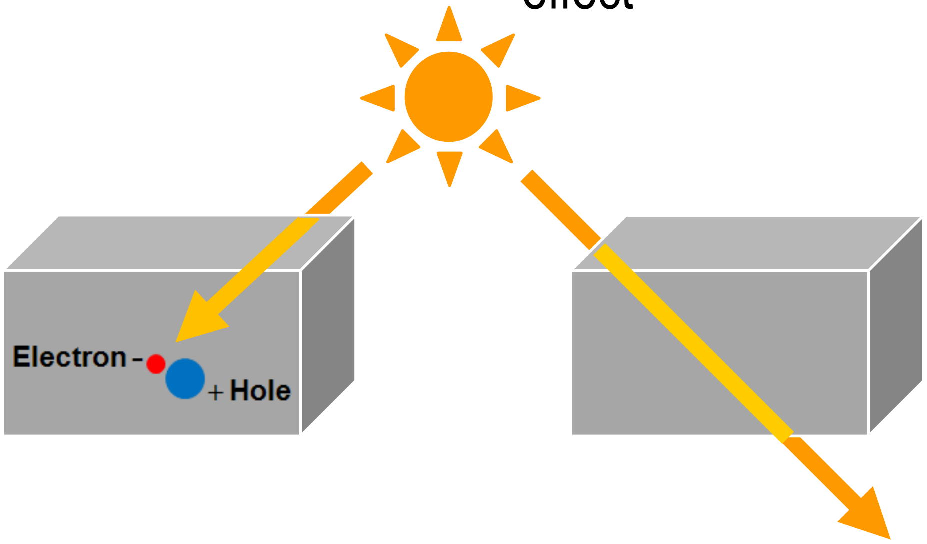
Material	**E_{gap} [eV]**
Silicon	**1.11**
Gallium arsenide	**1.43**
Aluminium-Gallium arsenide	**1.70**



©2001 HowStuffWorks

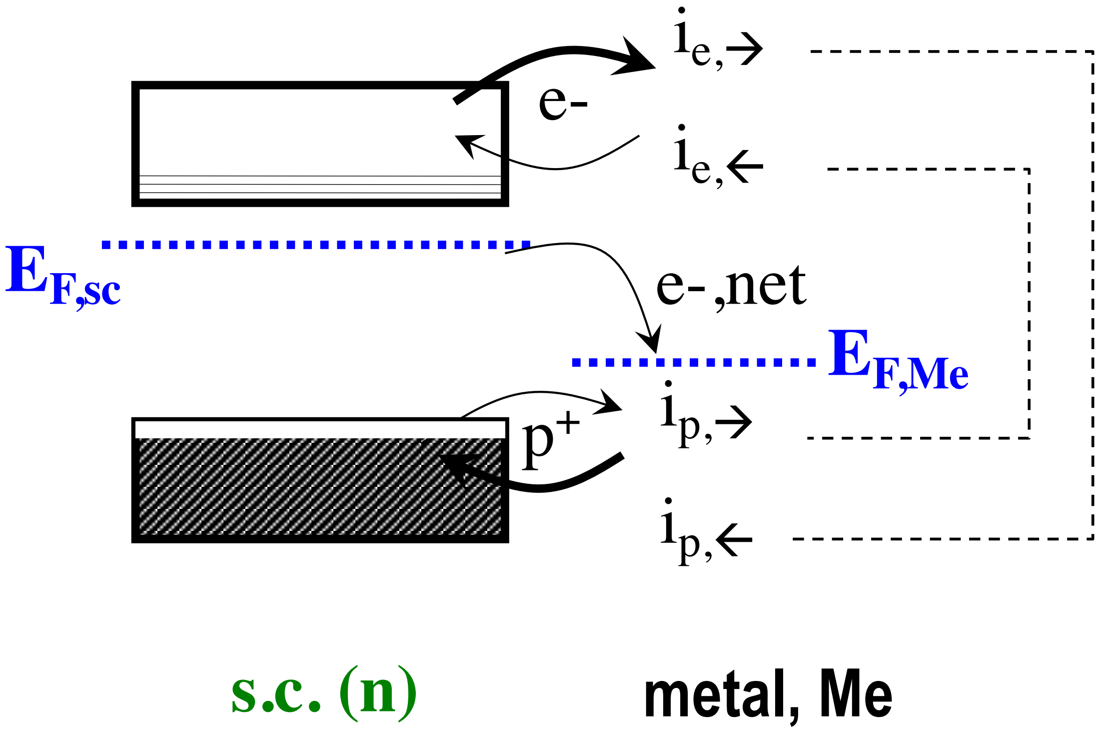
Photons with energy > the band gap energy are absorbed to create free electrons and holes

Photons with less energy pass through the material without PV effect

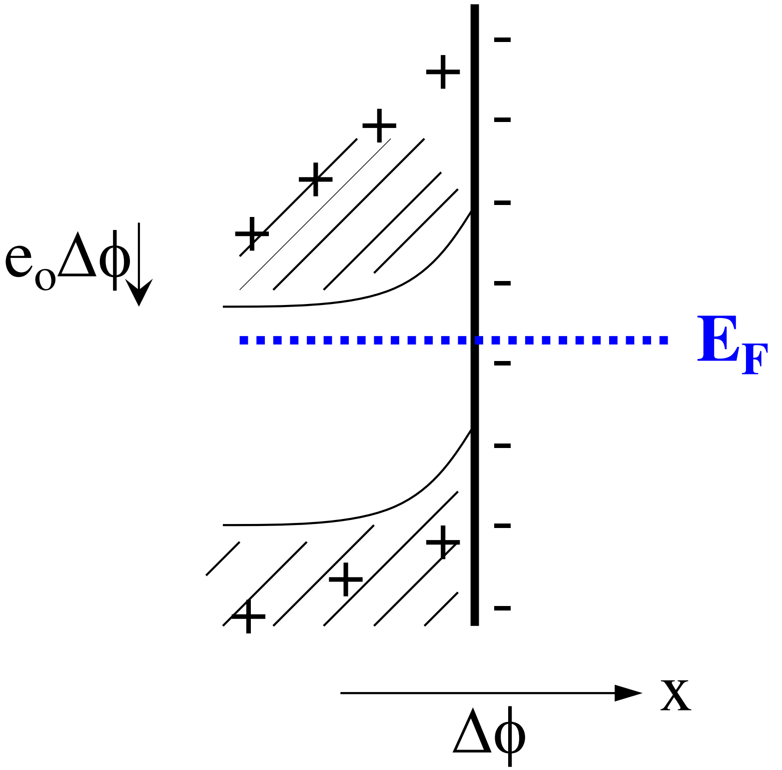


Band *bending*:

(1) junction between s.c. and metal



before junction



(inner electrical field)

after junction

Explanation:

- charge exchange between **Me** and **s.c.** until equilibrium
- compensation by an **internal electrical field**
- a **single Fermi level** exists at equilibrium
- a charge "double layer" develops, with potential difference $\Delta\phi = \phi_{Me} - \phi_{sc}$
- from Poisson's equation, we know that:

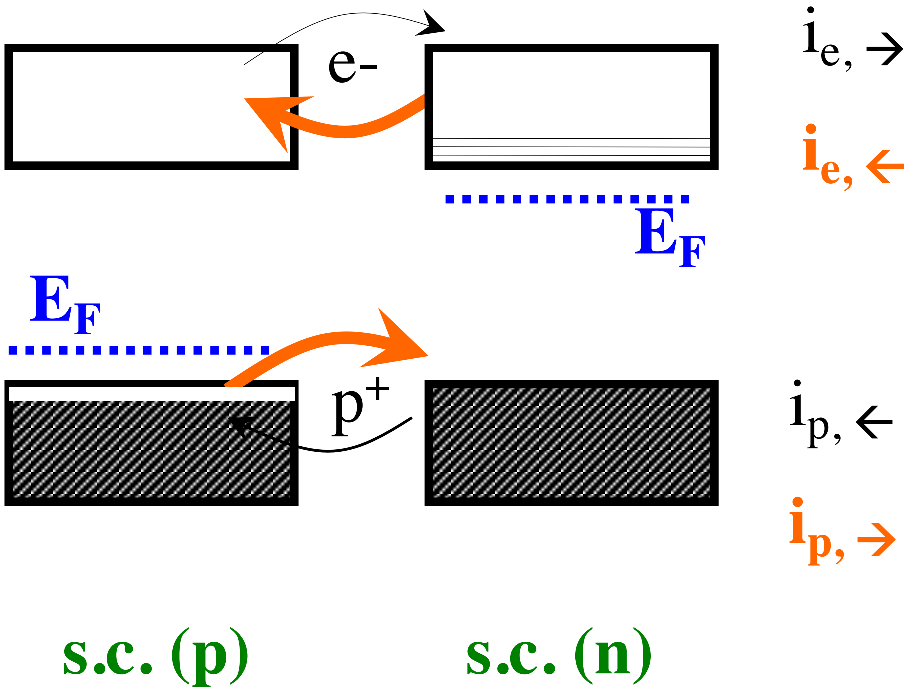
  $\nabla\phi = d\phi^2/dx^2 = -4\pi q(x)/\varepsilon_0$ (ε_0 = dielectric constant), i.e.

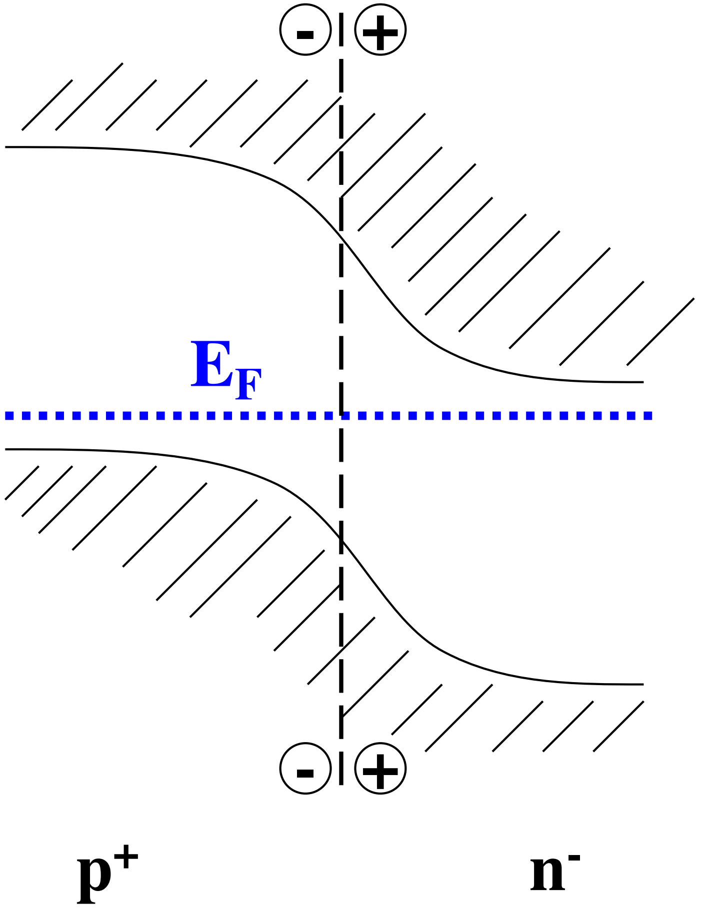
  a charge distribution q(x) is associated to this potential difference, which extends solely into the s.c. (=space charge layer)

  (since the metal conductivity is much higher)

  => ***band-"bending"***

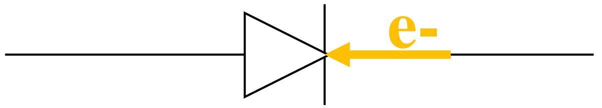
Band *bending*:
(2) junction s.c / s.c (p-n, diode)





before junction

after junction



- charge exchange (e-,p+) occurs across both bands bc, bv until equilibrium is reached (=the Fermi levels equalize)

- an internal field exists (=a voltage barrier) which opposes the natural charge flows of e^- (←) and p^+ (→)

With an applied voltage V, it follows:

elementary charge

dynamic exchange current across the junction

thermal agitation (Arrhenius)

$$i_{p,\rightarrow} = i_{p,0} \bullet \exp\left[\frac{e_0 V}{kT}\right] \quad \textit{and} \quad i_{p,\leftarrow} = i_{p,0}$$

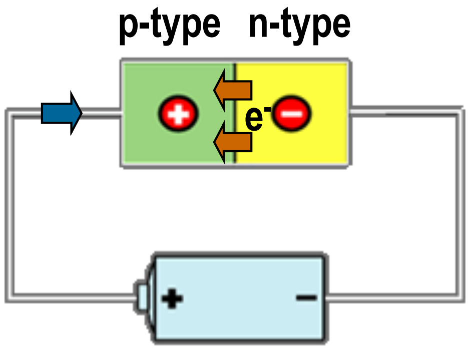
$$i_{tot} = i_e + i_p = i_{e,\rightarrow} + i_{e,\leftarrow} + i_{p,\rightarrow} + i_{p,\leftarrow}$$

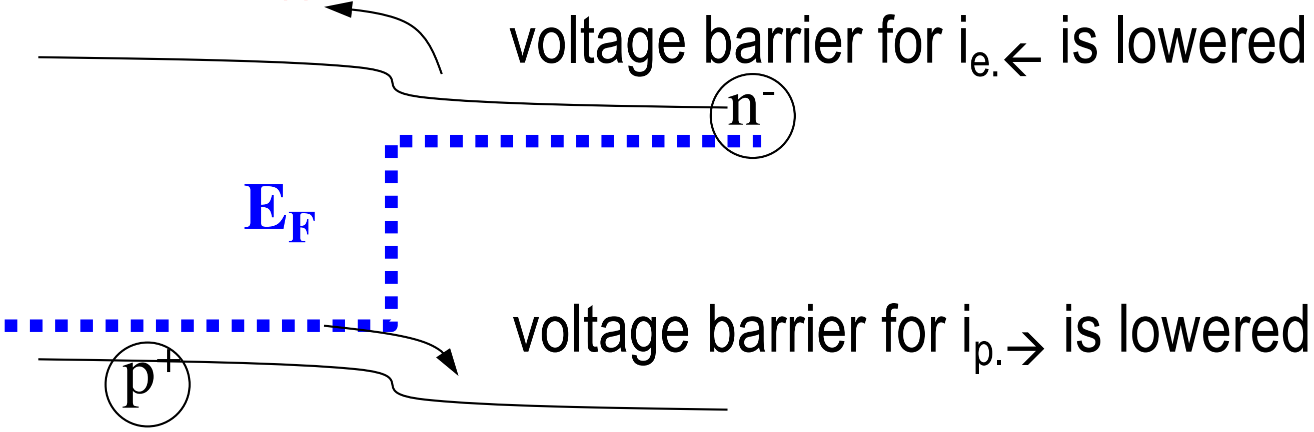
$$i_{tot} = i_{e,0} \bullet \left(1 - \exp\left[-\frac{e_0 V}{kT}\right]\right) + i_{p,0} \bullet \left(1 + \exp\left[\frac{e_0 V}{kT}\right]\right)$$

Forward bias (direct bias)

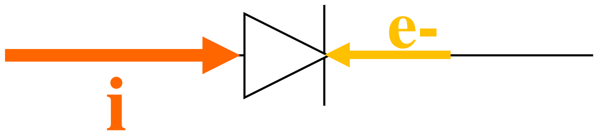
- $V_{applied}$ = positive between p and n (=anodic)
  (= counteracting the band bending, reducing the internal electric potential)
- electrons from s.c. (**n**) are drawn into s.c. (**p**) (= the natural charge flow)
- => conducting diode

  (above a threshold value, $V_{applied}$ ≈ the internal electric potential)



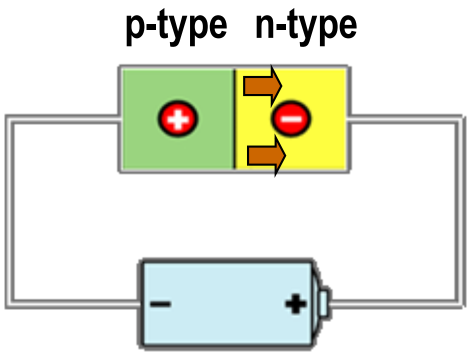

voltage barrier for $i_{e.\leftarrow}$ is lowered

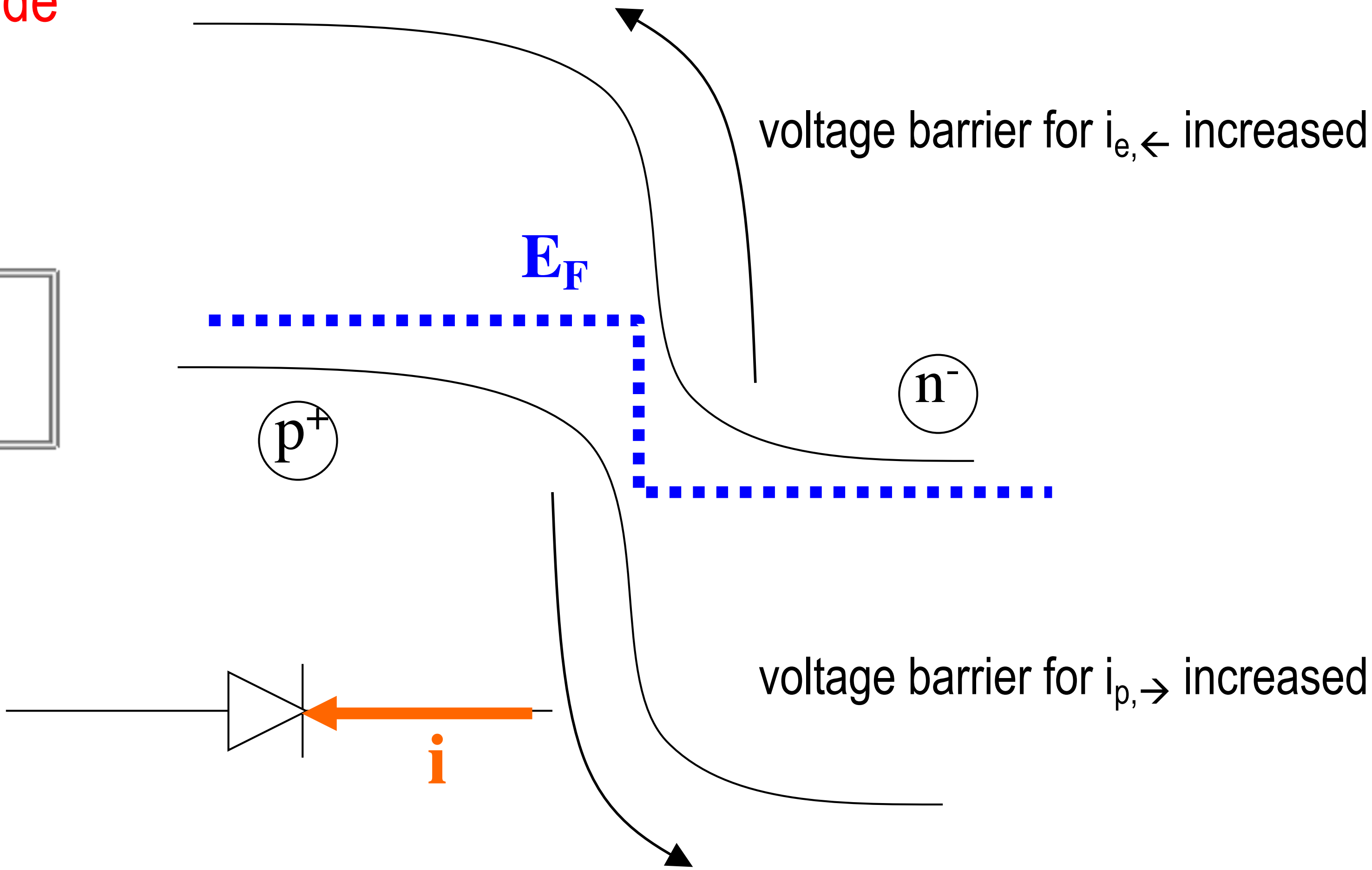
voltage barrier for $i_{p.\rightarrow}$ is lowered



Reverse bias (indirect bias)

- $V_{applied}$ negative between p and n (= cathodic)
  (= amplifying the band bending, increasing the internal electric potential)
- electrons from s.c. (**p**) are forced into s.c. (**n**) (= counternatural charge flow)
- => blocking diode





CHARACTERISTIC i-V (current-voltage curve) OF A DIODE

$$i_{p,\rightarrow} = i_{p,0} \bullet \exp\left[\frac{e_0 V}{kT}\right] \quad and \quad i_{p,\leftarrow} = i_{p,0}$$

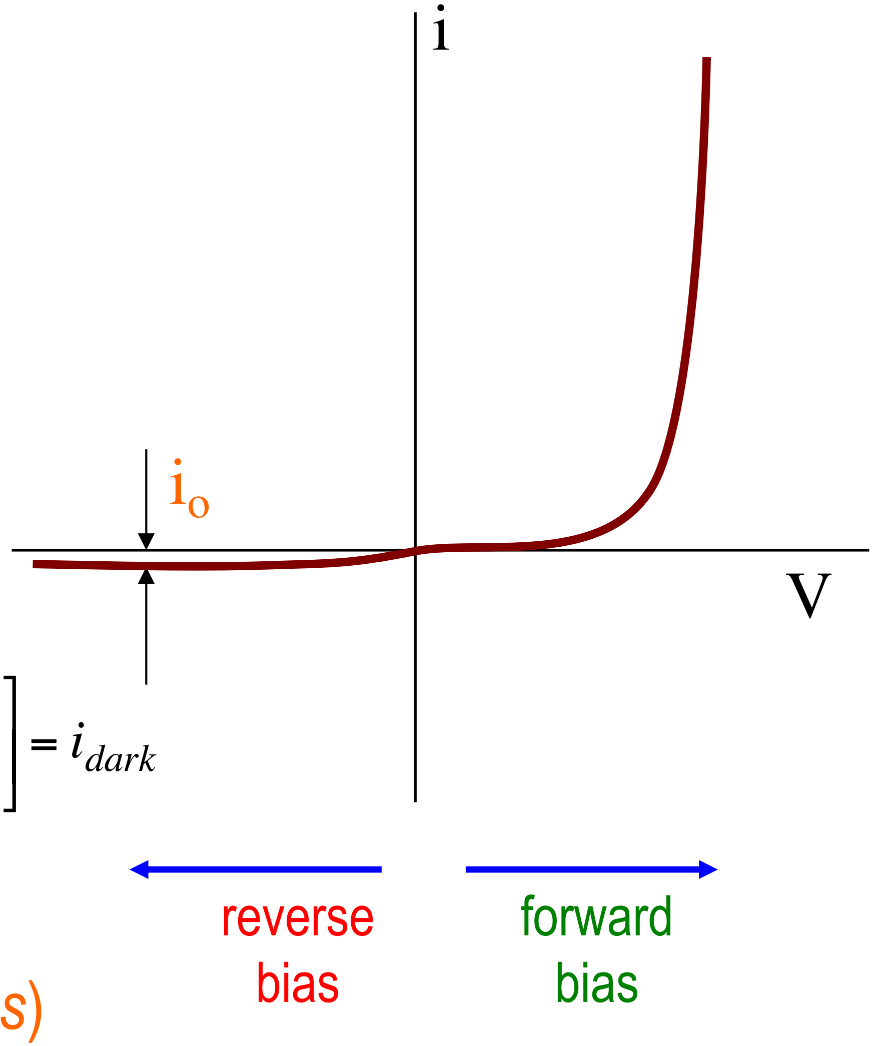
$$i_{e,\leftarrow} = i_{e,0} \bullet \exp\left[\frac{e_0 V}{kT}\right] \quad and \quad i_{e,\rightarrow} = i_{e,0}$$

$$i_{e,tot} = i_{e,\leftarrow} - i_{e,\rightarrow} = i_{e,0} \bullet \left[\exp\left[\frac{e_0 V}{kT}\right] - 1\right]$$

$$i_{p,tot} = i_{p,\rightarrow} - i_{p,\leftarrow} = i_{p,0} \bullet \left[\exp\left[\frac{e_0 V}{kT}\right] - 1\right]$$

$$i_{tot} = i_{e,tot} + i_{p,tot} = \underbrace{\left(i_{e,0} + i_{p,0}\right)}_{i_o} \bullet \left[\exp\left[\frac{e_0 V}{kT}\right] - 1\right] = i_{dark}$$

saturation or leakage current (< *picoAmps*)

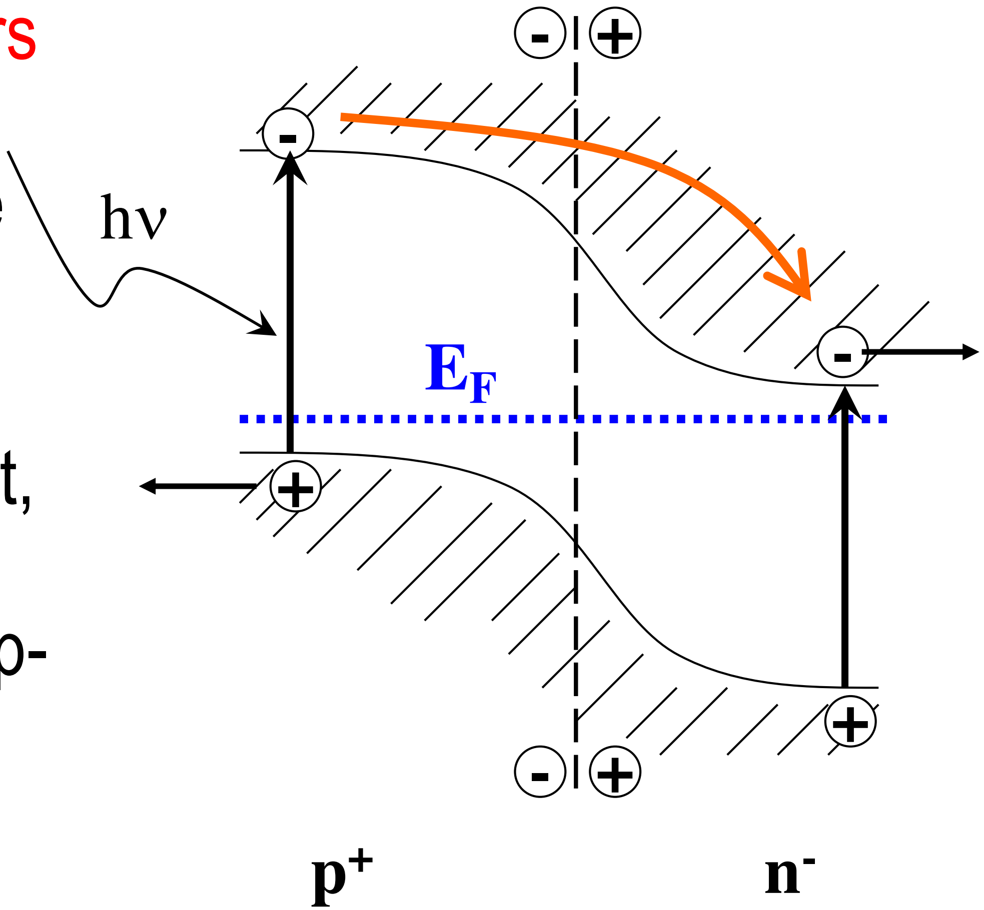


Illumination of a p-n diode (= PV solar cell)

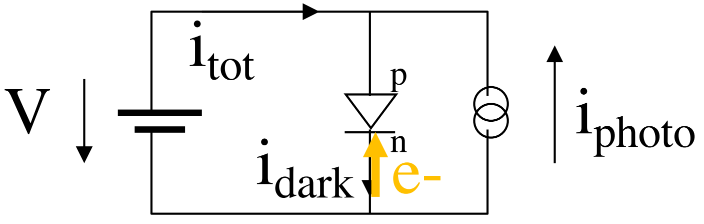
- The photon energy $h\nu$ promotes electrons from bv to bc across the band gap.

- generation of charge carrier pairs (e^-, p^+) in the bv and bc bands, **and separation of these** by the **internal voltage barrier** (band bending) at the **p-n-junction**
- electrical current created by light, $h\nu$(‘i_{photo}’), is thus **opposite to the natural charge flow** of the p-n diode (‘i_{dark}’)

$$i_{tot} = i_{dark} - i_{photo}$$

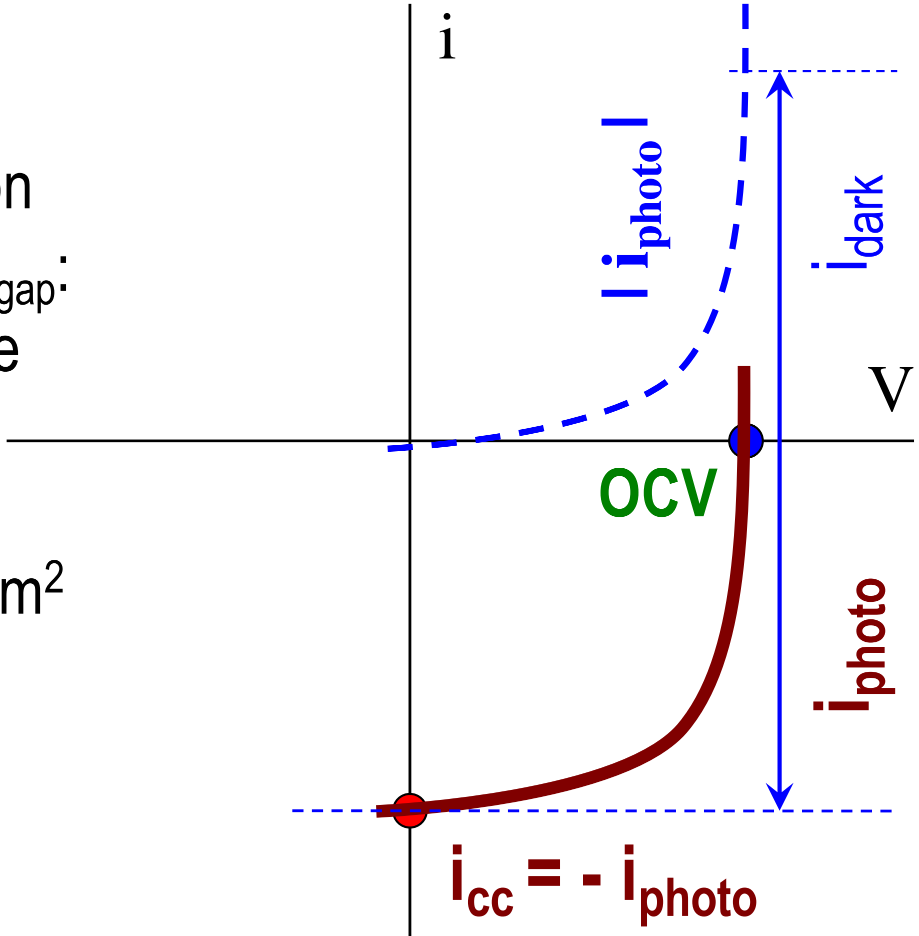


$$i_{tot} = \overbrace{i_0\left(\exp\left[\frac{e_0 V_{appl}}{kT}\right]-1\right)}^{i_{dark}} - i_{photo}$$



'current source' = hν

1. for **V_{appl} = 0, i_{tot} = - i_{photo} = i_{cc}** :
the short circuit current (i_{cc}) depends on the irradiance IRR and the bandgap E_{gap}:
i_{cc} = sensibility S (mA/mW) * IRR * surface
→ 42 mA/cm² in research,
→ 30 mA/cm² in practice
for IRR = 50-100 mW/cm² = 0.5-1 kW/m²



2. for **i_{tot} = 0 (V_{OCV}), i_{dark} = i_{photo} :**

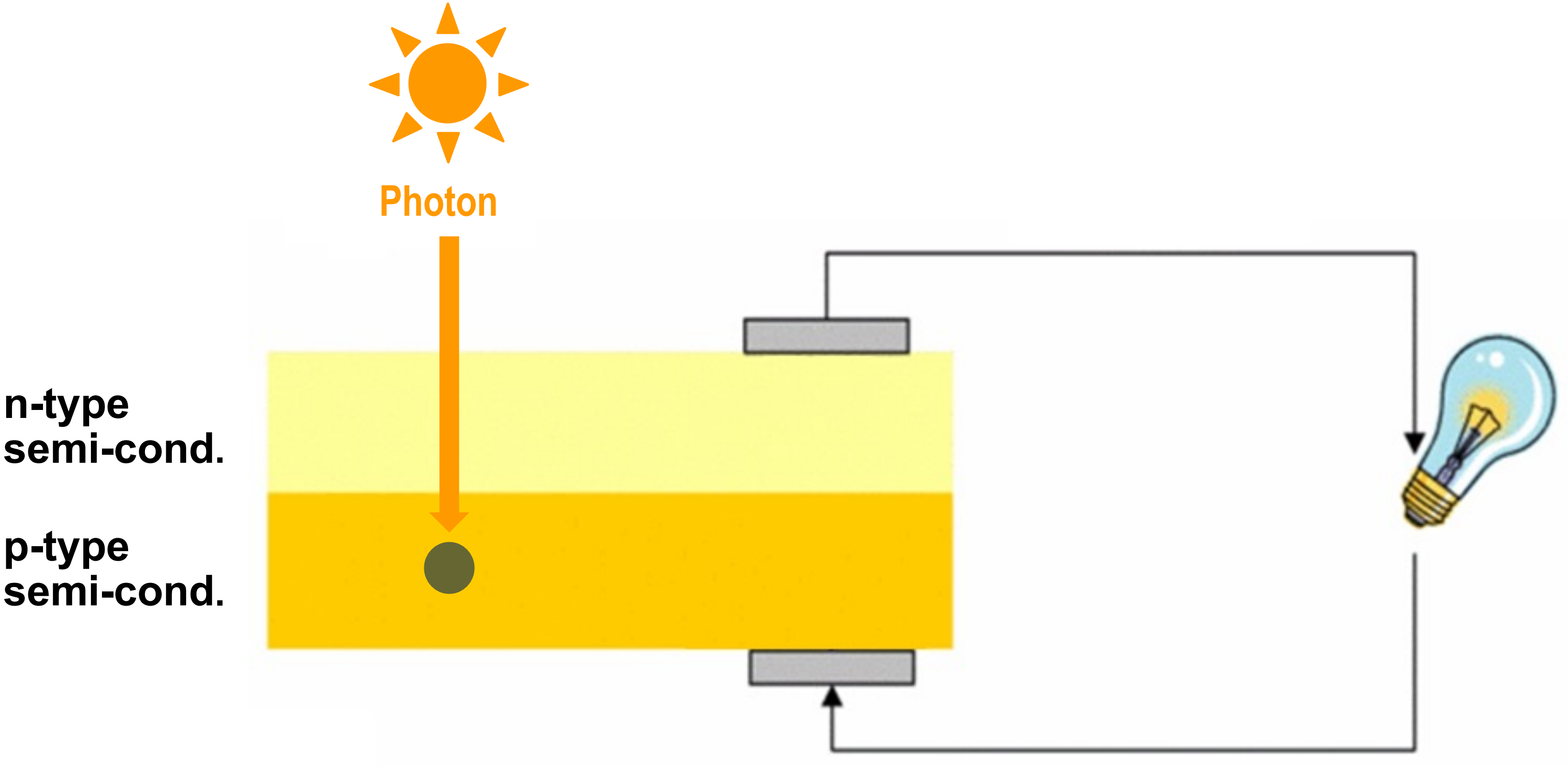
$$i_0\left(\exp\left[\frac{e_0 V_{OCV}}{kT}\right]-1\right) = -i_{cc}$$

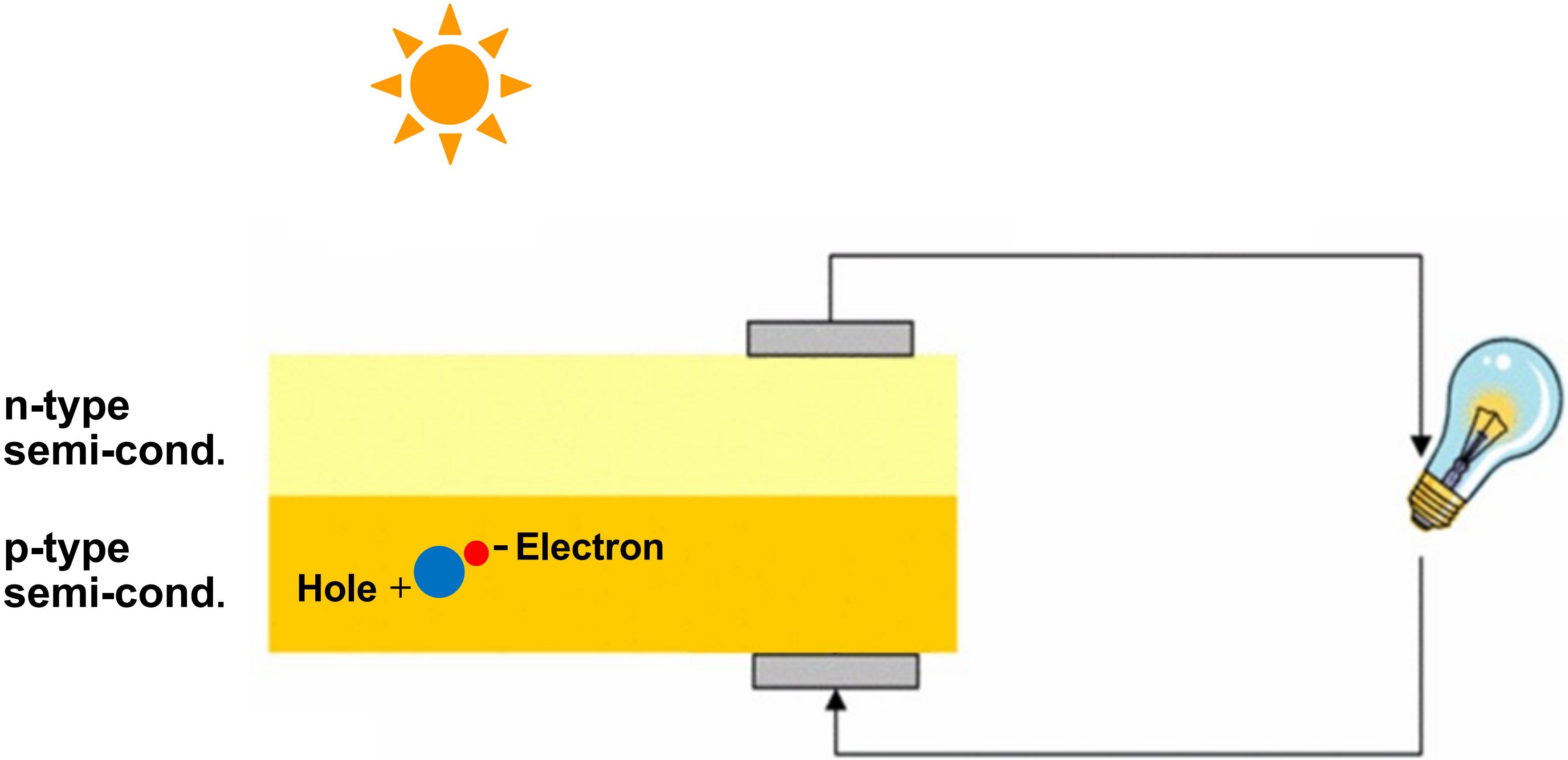
$$V_{OCV} = \frac{kT}{e_0}\ln\left(1-\frac{i_{cc}}{i_0}\right) = V_T\ln\left(-\frac{i_{cc}}{i_0}\right)$$

→ 0.7 V in research
→ 0.6 V in practice

"thermal voltage": 25.7 mV @ 298K

Animation:



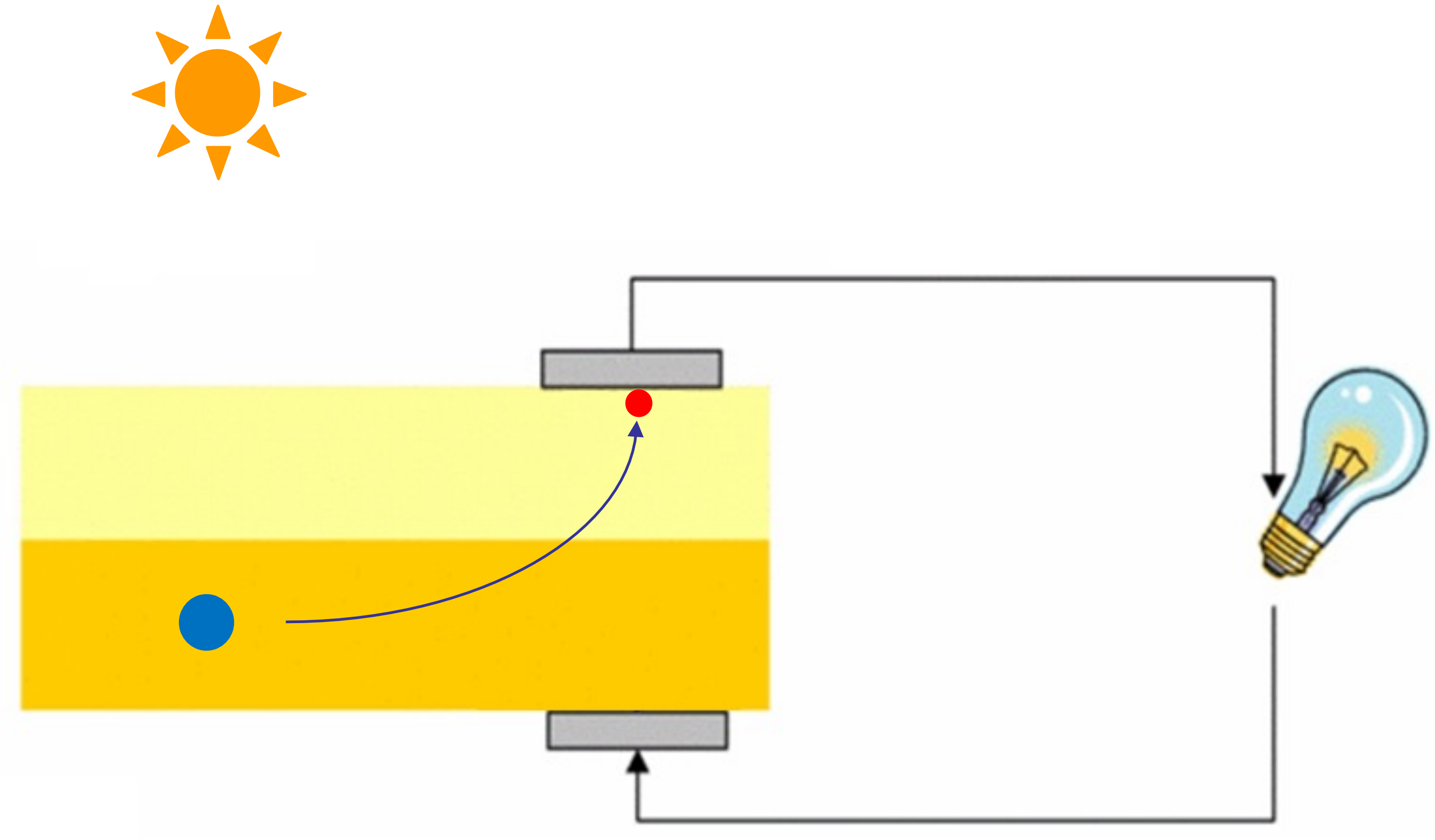


n-type
semi-cond.

p-type
semi-cond.

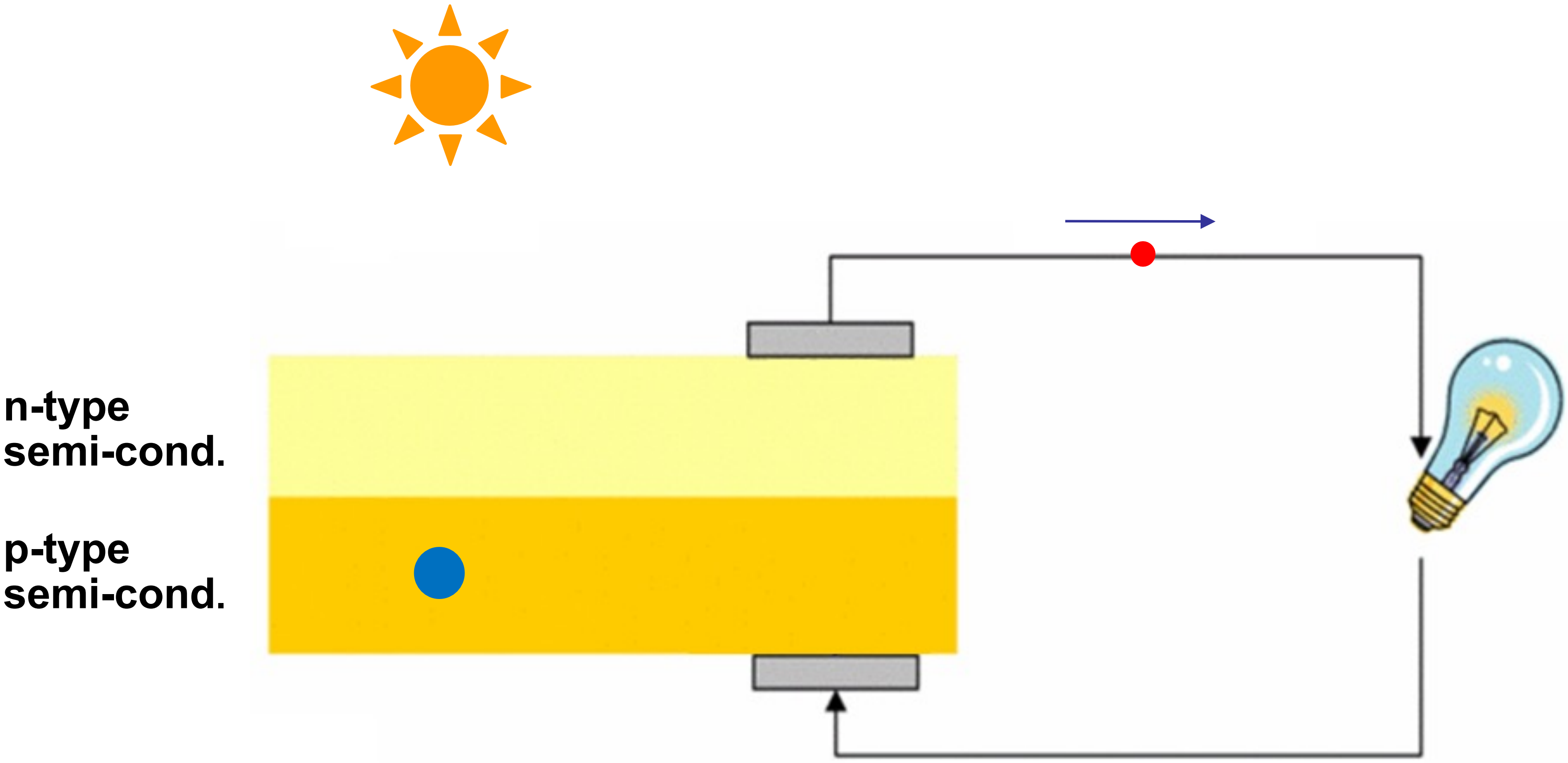
Hole +

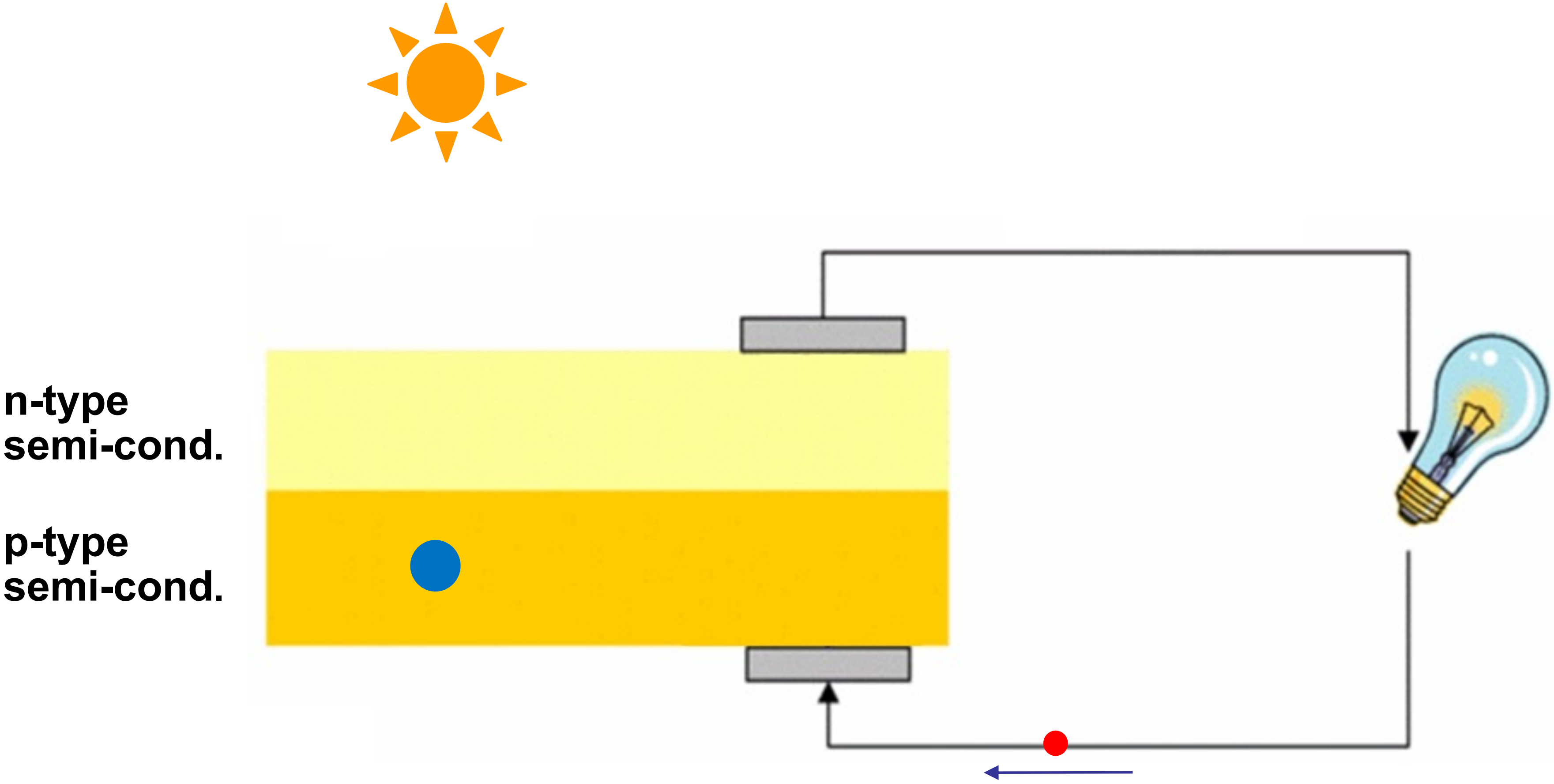
- Electron

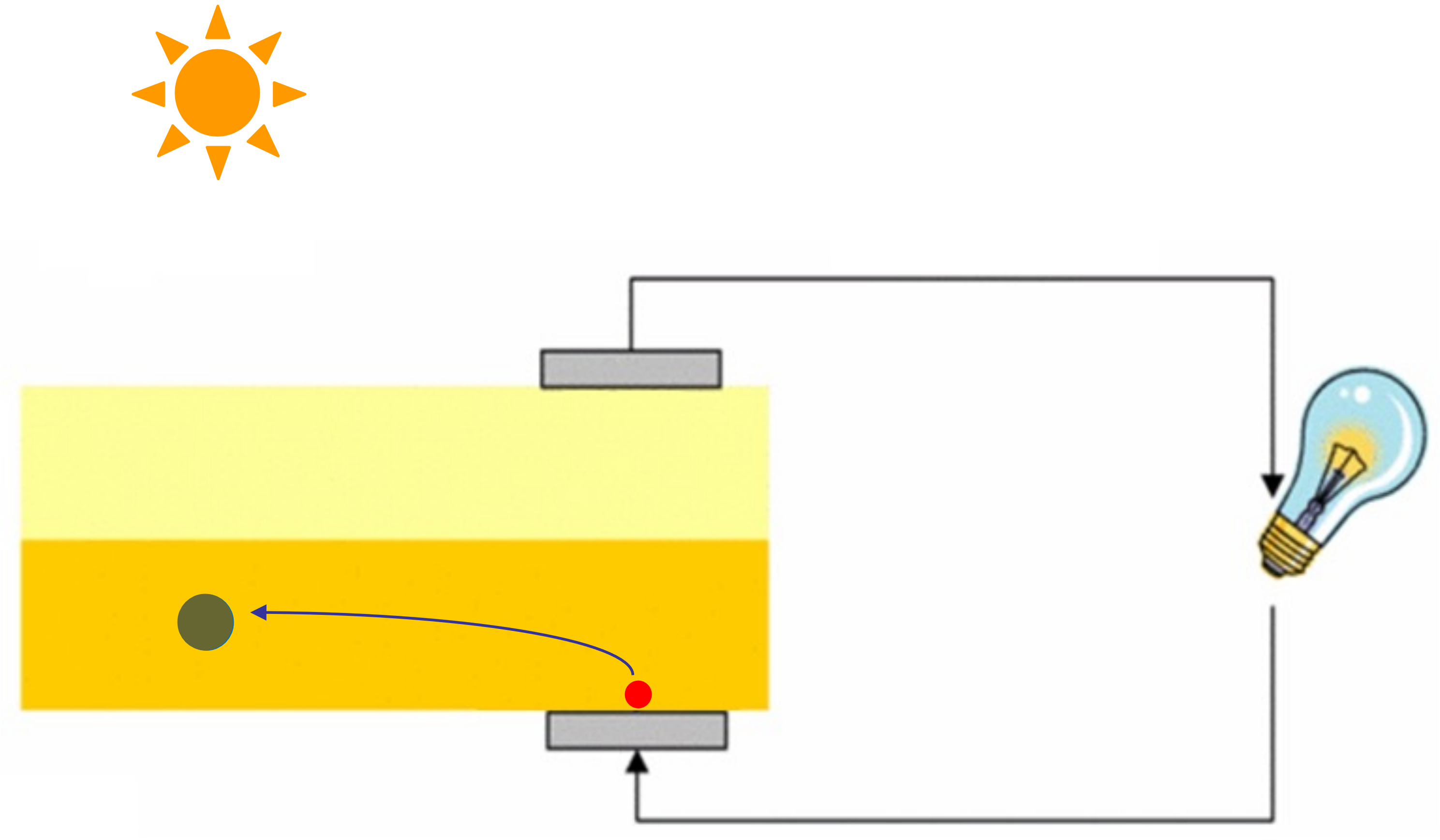


n-type semi-cond.

p-type semi-cond.


n-type
semi-cond.
p-type
semi-cond.

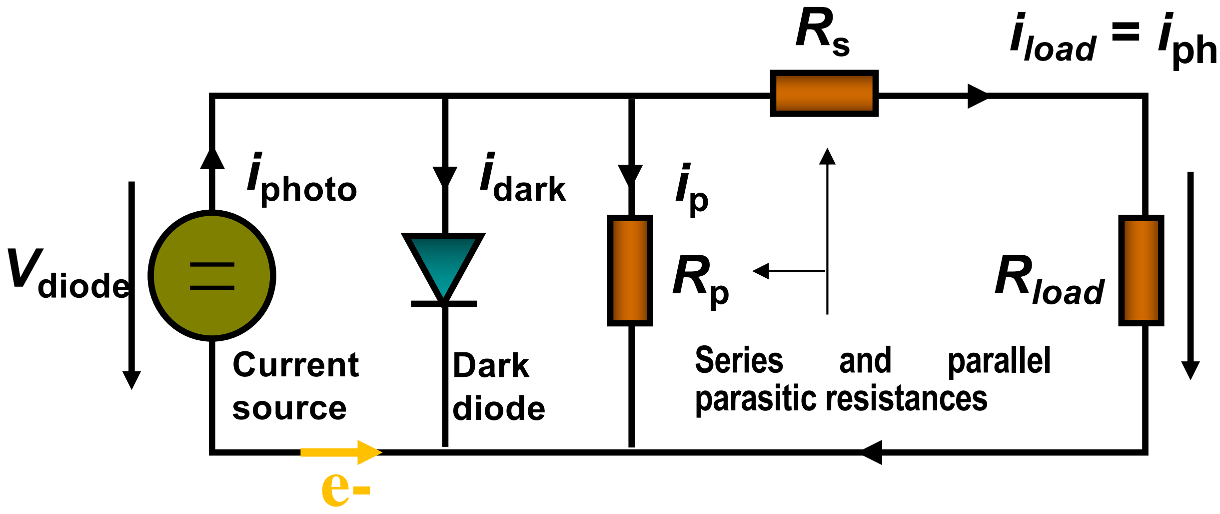

n-type
semi-cond.
p-type
semi-cond.



n-type semi-cond.

p-type semi-cond.

Equivalent electrical circuit, with a consumer (=load)



$$i_{load} = i_{photo} - i_{dark} - V_{diode} / R_p$$

$$V_{user} = V_{diode} - \underbrace{R_s \cdot i_{load}}_{\text{normally very small}}$$

Diode characteristic: $i_{dark} = i_0 \,.\, [\exp(e_0 V/kT) - 1]$

short-circuit current $(V_{user} = 0 \Rightarrow V_{diode} = R_s \cdot i_{load} \Rightarrow i_{load} = i_{photo} - i_{dark} - (R_s / R_p).i_{load}$

$\Rightarrow i_{load}\,(1+(R_s / R_p)) = i_{photo} - i_{dark}$

V_{OCV} $(i_{load} = 0$; and $i_p \approx 0)$:

$$i_{photo} = i_{dark} = i_0\left(\exp\left[\frac{e_0 V_{OCV}}{kT}\right] - 1\right)$$

$$\downarrow$$

$$i_{photo} + i_0 = i_0 \exp\left[\frac{e_0 V_{OCV}}{kT}\right] \longrightarrow V_{OCV} = \frac{kT}{e_0} \bullet \ln\left[\frac{i_{photo}}{i_0} + 1\right] = V_T \bullet \ln\left[\frac{i_{cc}}{i_0}\right]$$

Power from a solar cell (‘fill-factor’)

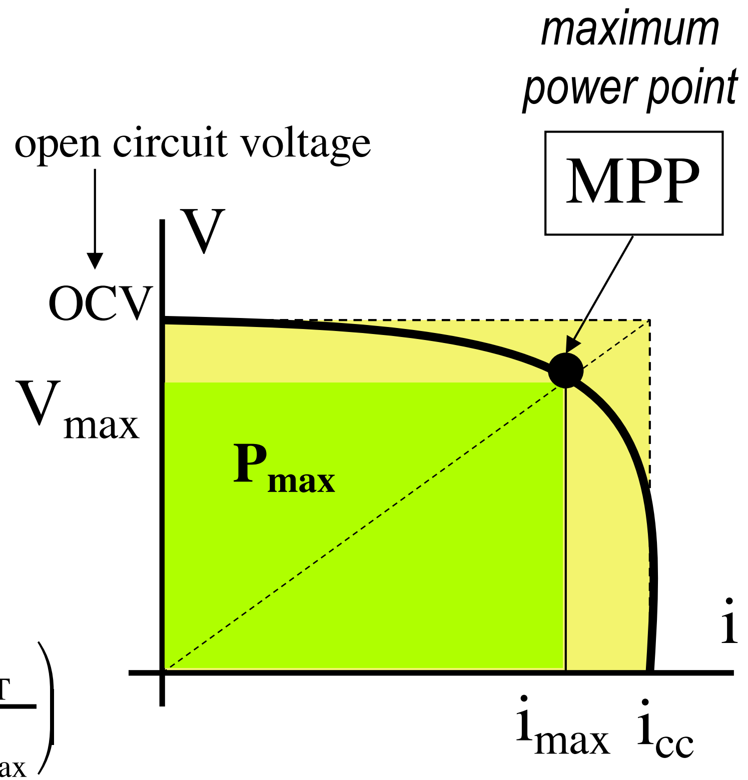
- Power P = I.V

$$P = V * \left[i_{cc} - i_0 \left(\exp\left[\frac{e_0 V}{kT} \right] - 1 \right) \right]$$

- Fill-factor FF (%): 🟩/🟨

$$FF = \frac{P_{max}}{V_{OCV} . I_{cc}} \qquad V_{max} = V_{OCV} + V_T \ln\left(\frac{V_T}{V_{max}} \right)$$

$$FF = \frac{V_{max}}{V_{OCV}} \left[1 - \frac{\exp\left(\frac{V_{max}}{V_T} \right) - 1}{\exp\left(\frac{V_{OCV}}{V_T} \right) - 1} \right]$$



→ FF = 0.83 in research

→ FF = 0.70 in practice

Solar cell efficiency

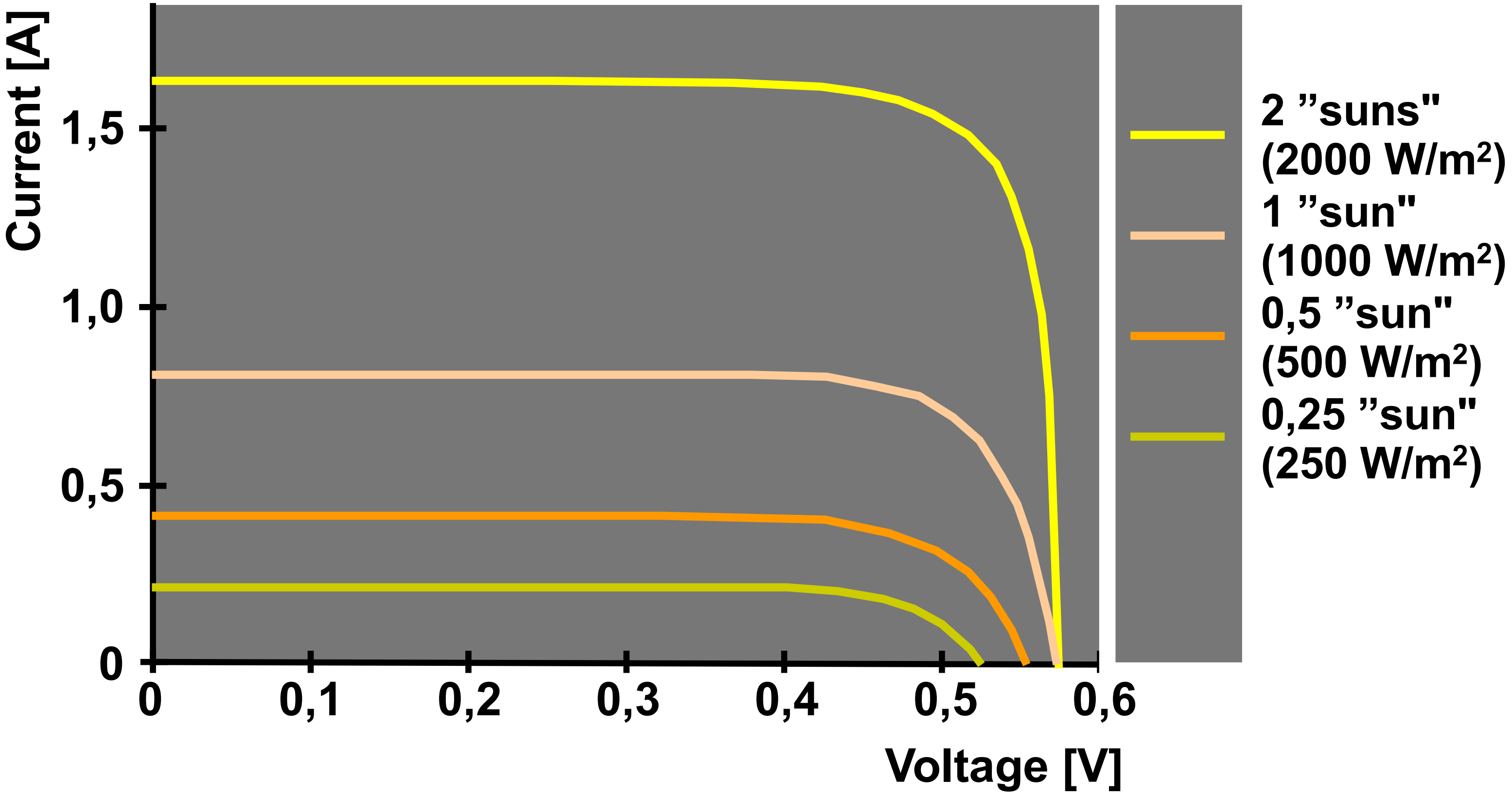
$$\eta = \frac{P_{\max}}{irradiance\left[\frac{W}{cm^2}\right] * surface} = \frac{P_{\max}}{i_{cc}\left[\frac{A}{cm^2}\right] \Big/ sensibility\ S\left[\frac{A}{W}\right]} = S.FF.V_{OCV}$$

in research: η = 29% (Si), in practice: η = 15%

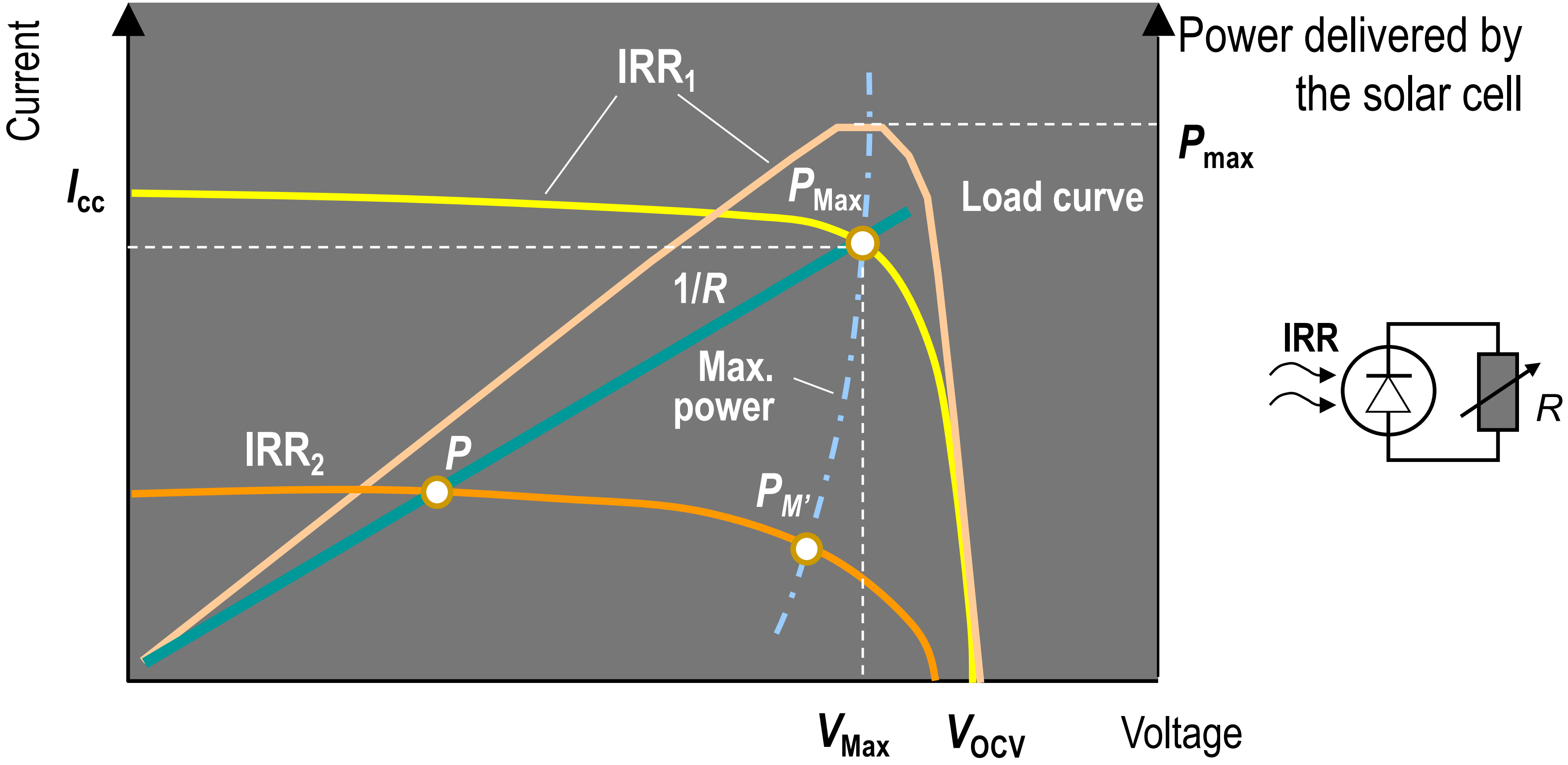
Effect of temperature :

- dV/dT = ca. -2 mV/K
- very small effect on i_{cc} (IRR is more important)
- best location for solar panels = high mountain area (cold; snow albedo ($IRR_{effective} = IRR_{incident}$*1.3))

i-V characteristic under variable irradiation



Real operation with consumer (=load R)



=> **MPP : maximum power point tracking**

Summary of useful formulas

$$V_{OCV} = \boxed{\frac{kT}{e_0}} \bullet \ln\left[\frac{i_{photo}}{i_0} + 1\right] = \boxed{V_T} \bullet \ln\left[\frac{i_{cc}}{i_0}\right]$$

$$\mathrm{V_{max}} = \mathrm{V_{OCV}} + \mathrm{V_T} \ln\left(\frac{\mathrm{V_T}}{\mathrm{V_{max}}}\right)$$

$$i_{\mathrm{max}} = i_{cc}\left(1 - \frac{V_T}{V_{OCV}}\right)$$

$$\mathrm{FF} = \frac{\mathrm{P_{max}}}{\mathrm{V_{OCV}} . \mathrm{I_{cc}}}$$

$$\eta = \frac{P_{\mathrm{max}}}{irradiance\left[\frac{W}{cm^2}\right] * surface}$$

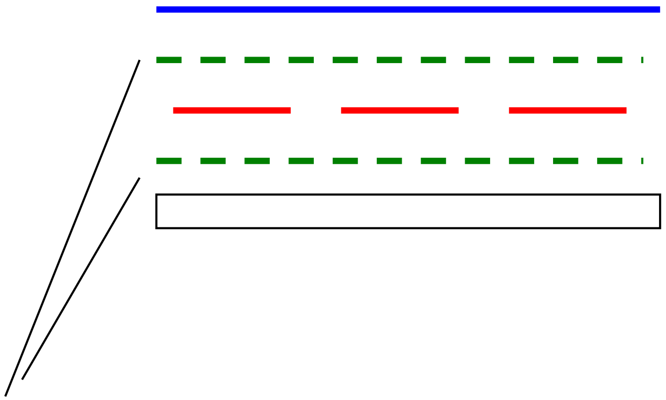
Solar panels

- series + parallel connection of cells (each cell = 100 cm^2), f.ex. 30 in series (30 mA/cm^2 @ 0.5 V) → 15 V x 3 A
- cells are *classified* according to their i_{cc} - value
- **MPP : maximum power point tracking**
- to avoid "hot spots" (= a cell in reverse bias), *shunt* diodes are used to deviate excess current

f.ex. a tree leaf falls on a cell and blocks the sunlight

P.V. module assembly

series of cells in 4 x 8 or 3 x 12 arrangement
(classified by the i_{cc} - value)

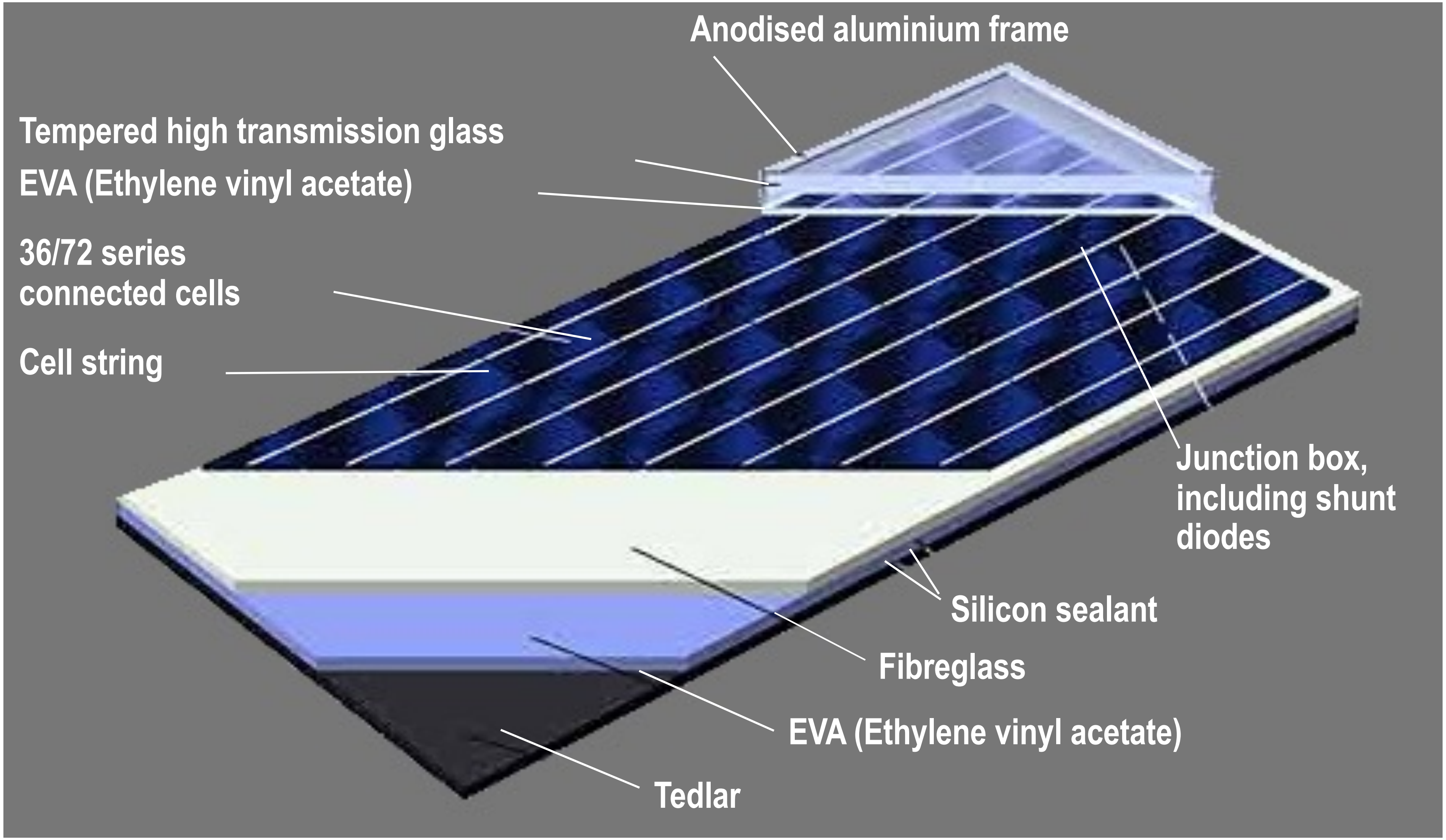


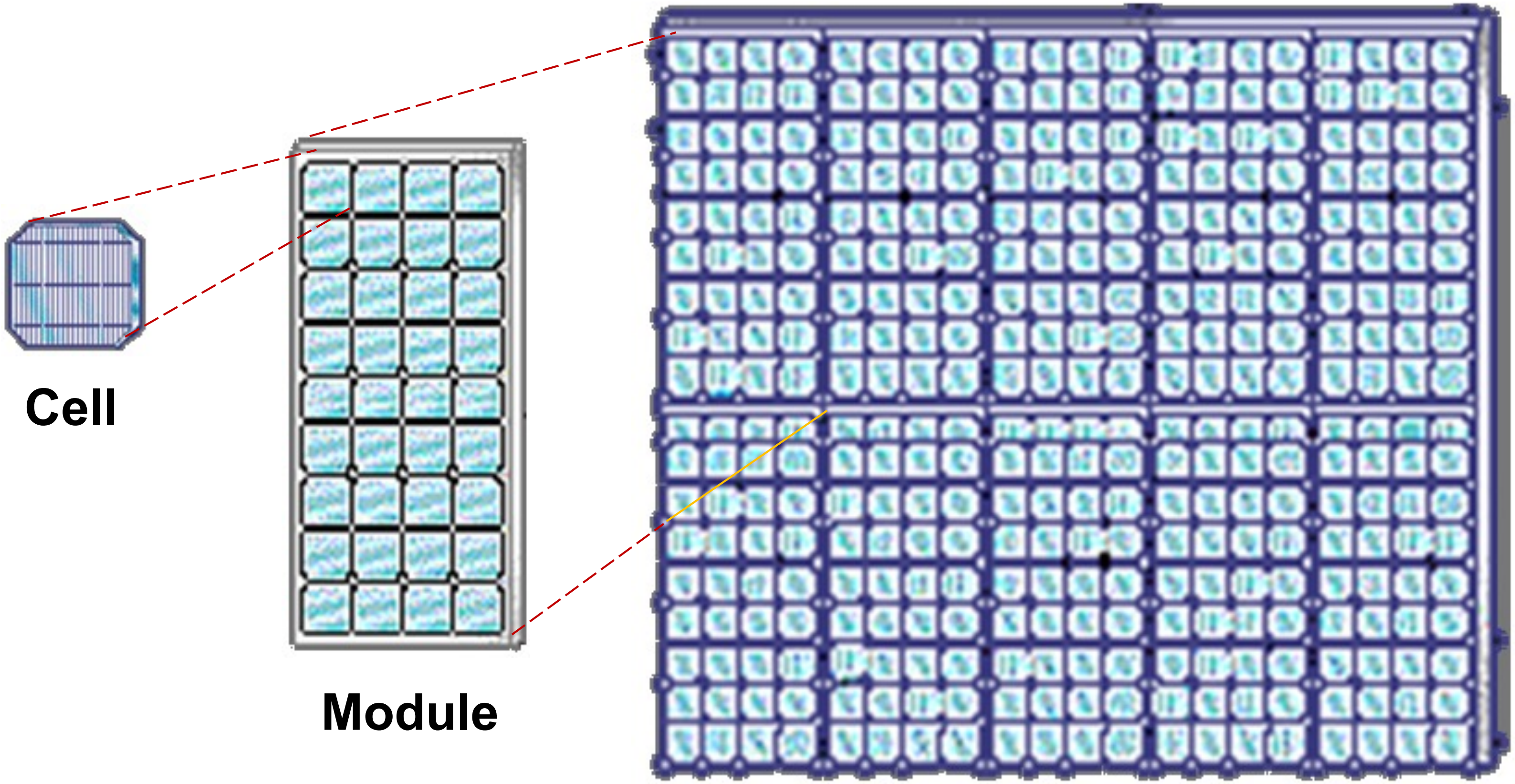
plastic foil (mylar)

Si cells

glas support plate

EVA : EthyleneVinylAcetate polymer
(liquefied to 150° C, then cooled to remove air bubbles)


Anodised aluminium frame
Tempered high transmission glass
EVA (Ethylene vinyl acetate)
36/72 series
connected cells
Cell string
Junction box,
including shunt
diodes
Silicon sealant
Fibreglass
EVA (Ethylene vinyl acetate)
Tedlar



Cell

Module

Panel

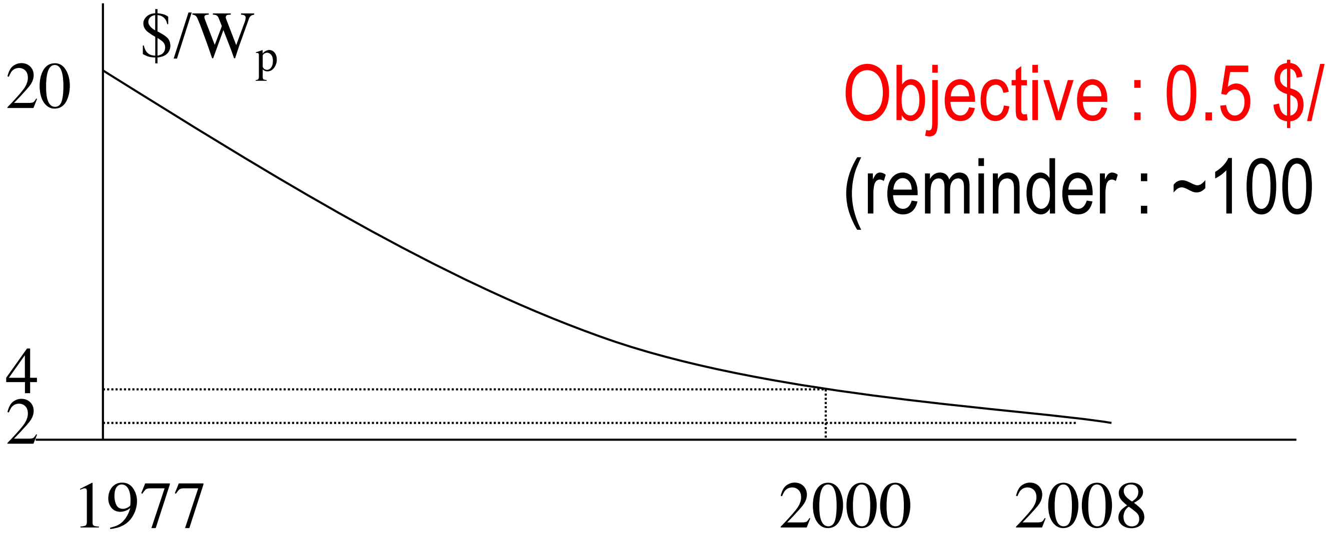
Solar PV ‘power plants’

- should be >100 kW_p, to benefit from an economy of scale and a very efficient **DC/AC inverter**
- connection at 400 V
- with batteries, disjunctors, fuses
- existing installations from 100 kW_p to 10 MW_p

  e.g. 10 MW_p (800 x 800 m), efficiency 15%, load factor 18%, needs IRR of ≥ 1800 $kWh/m^2.yr$

Market

- **1185 GW$_p$** installed late 2022
- **1040 TWh** produced (almost 4% of world electricity)
- consistent growth of >***20% / yr***
- monopolised by silicon technology



Objective : 0.5 $/W$_p$

(reminder : ~100 W$_p$/m^2)

Recombinations

mechanisms of **destruction of charge** carriers (e^-,p^+) (=**losses**)

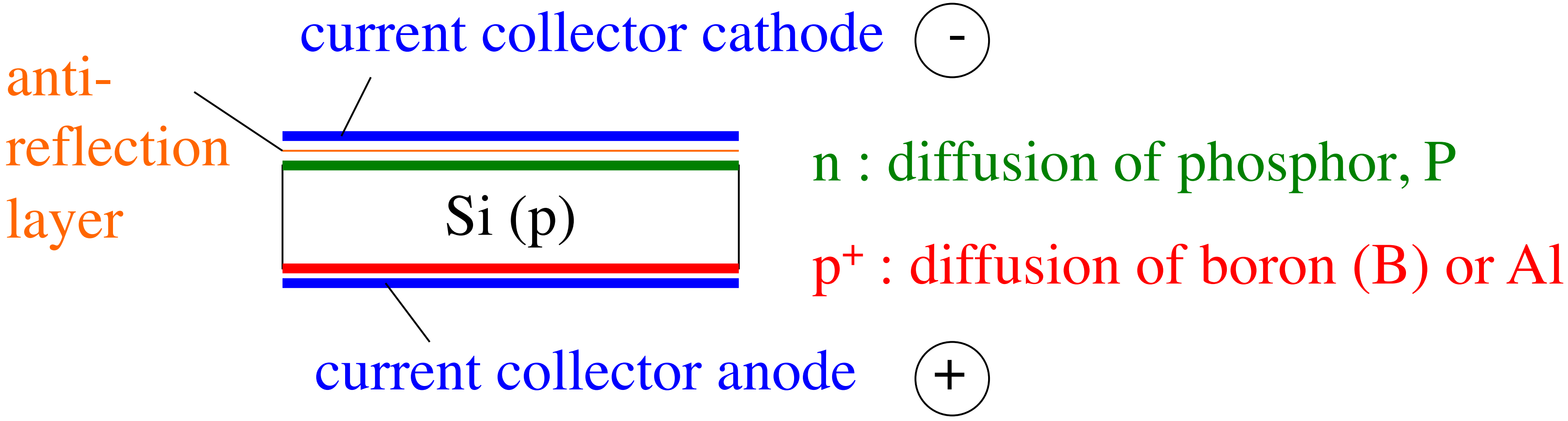
1. return of electrons from bc band to bv band, emitting a photon (luminescense) : this effect is very small in Si
2. SRH (Shockley-Read-Hall) : impurities and structural defects capture e^- and p^+ (= recombination centers, occurring in cascade between the bc and bv energy levels);

   → to reduce this effect : **ultrapure** material is needed (→ up to **monocrystals**)
3. effect Auger (in heavily doped s.c.): the recombination energy is transferred to a third particle (e^- or p^+) as kinetic energy

global recombination rate: $\sim 1/\tau_p$ (n-type) or $\sim 1/\tau_n$ (p-type)

with τ = lifetime of (e- ,p+) : nano- to milliseconds

Solar cell layers, in more detail



current collector cathode -

anti-reflection layer

Si (p)

n : diffusion of phosphor, P

p^+ : diffusion of boron (B) or Al

current collector anode +

Incident photons in Si(p) create the pairs (e^-, p+), with

e^- migrating to n and via the external circuit to the anode

p^+ migrating to p^+ and via the external circuit to the cathode

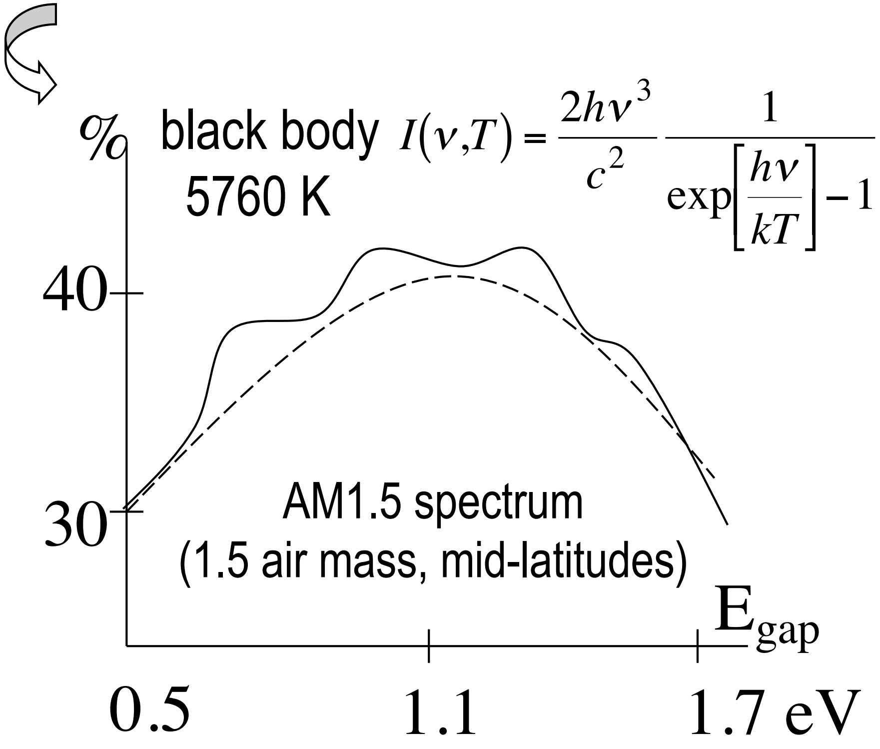
$$e_{out} = i_n = -e_0 \int_{\text{volume V}} (g - r)dV$$

g : pair generation rate (e,p)
r : recombination rate

$$p_{out} = i_p = e_0 \int_{\text{volume V}} (g - r)dV$$

Theoretical efficiency

In theory : photons are generated at 5760 K (sun surface temperature)
→ Carnot efficiency at 293K would then be 95% …
A detailed treatment shows that in practice we find :



$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left[\frac{h\nu}{kT}\right]-1}$$

for a single cell: record for Si = 29%

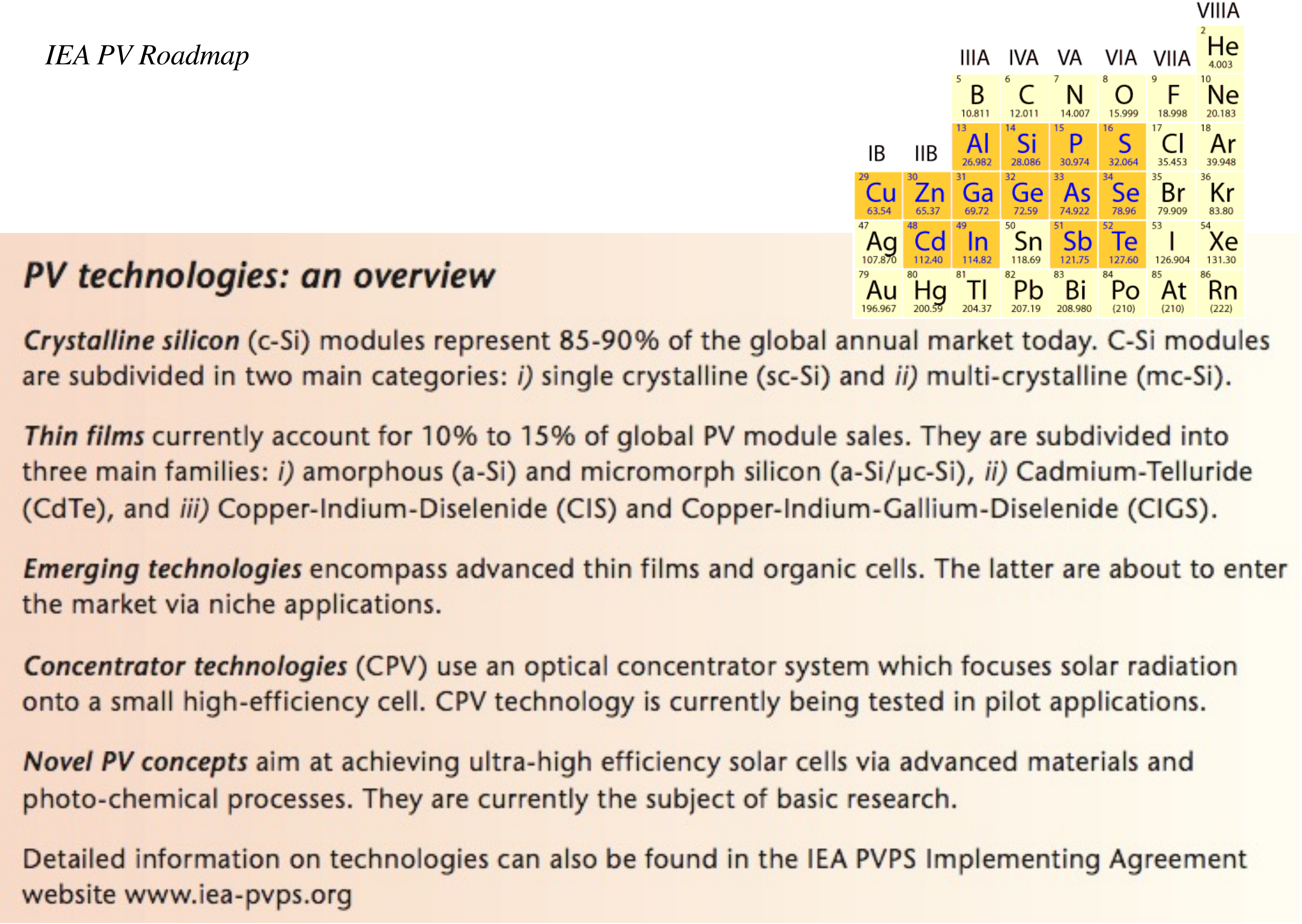
Remark :
a high energy photon can create several pairs (e^-,p^+) !

A stack of cells with decreasing E_{gap} can increase the efficiency (record = 44%).

PV technology

- Fabrication of **high purity Si**
- Fabrication of crystalline Si (3 methods)
- Cutting to wafers and cells
- Costs
- New technologies
  - thin layers (amorphous Si)
  - concentration cells (reflected light multiplication)

IEA PV Roadmap



IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
							2 He 4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
		13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)

PV technologies: an overview

Crystalline silicon (c-Si) modules represent 85-90% of the global annual market today. C-Si modules are subdivided in two main categories: *i)* single crystalline (sc-Si) and *ii)* multi-crystalline (mc-Si).

Thin films currently account for 10% to 15% of global PV module sales. They are subdivided into three main families: *i)* amorphous (a-Si) and micromorph silicon (a-Si/µc-Si), *ii)* Cadmium-Telluride (CdTe), and *iii)* Copper-Indium-Diselenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).

Emerging technologies encompass advanced thin films and organic cells. The latter are about to enter the market via niche applications.

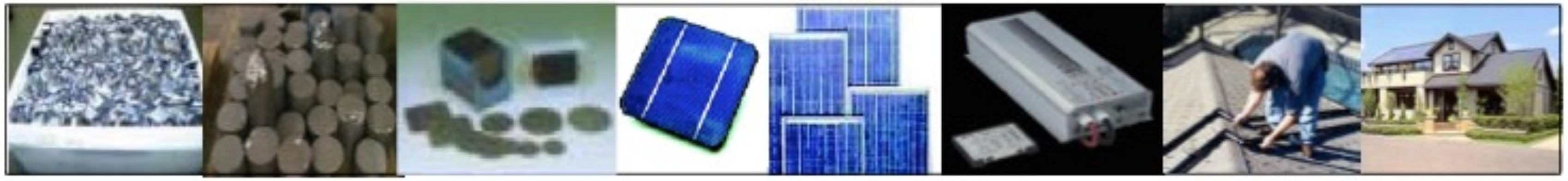
Concentrator technologies (CPV) use an optical concentrator system which focuses solar radiation onto a small high-efficiency cell. CPV technology is currently being tested in pilot applications.

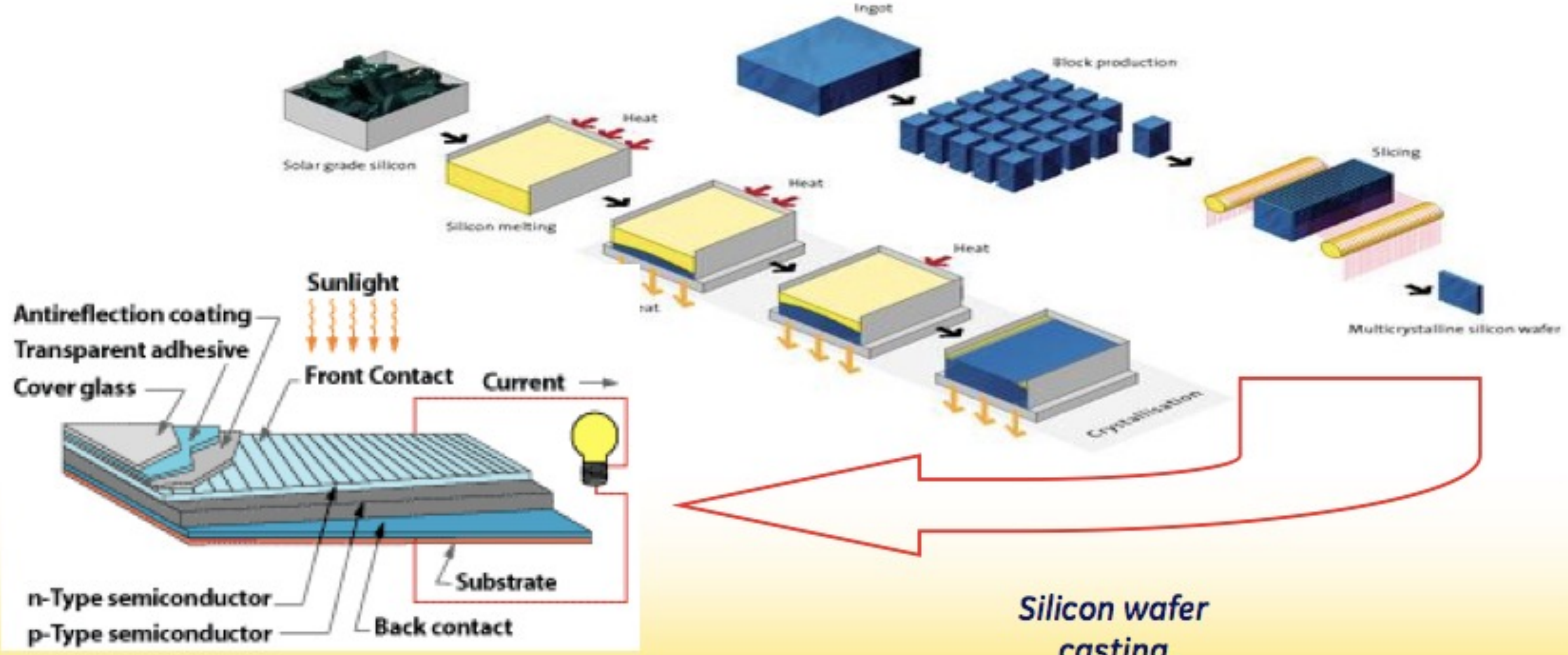
Novel PV concepts aim at achieving ultra-high efficiency solar cells via advanced materials and photo-chemical processes. They are currently the subject of basic research.

Detailed information on technologies can also be found in the IEA PVPS Implementing Agreement website www.iea-pvps.org

Solar PV value chain

Silicon → **Ingots/wafers** → **Cells/modules** → **Components** → **Installation/ Integration**





Silicon wafer casting

Silicon PV technology

- Silicon : > 80% of the market
- for Si only:
  - 40% monocrystalline
  - 25% polycristalline
  - 35% amorphous
- $E_{bandgap}$ = 1.12 eV (= close to the optimum of the solar spectrum)
- bad infrared absorption → wafer must be thick : 0.3 mm

  → disadvantage: long current path for (e^-,p^+)
- must then be ultrapure to avoid recombinations : **costly**

- diamond saw: 0.35 mm thick (14 wafers/cm)

  → 50% per wafer high purity Si is lost by sawing!
- multi-wire saw : 0.15 mm thick (30 wafers/cm)

Ultrapure Si fabrication

1) reduction of sand, SiO_2, by carbon :
   $SiO_2 + \mathbf{C} \rightarrow Si + \mathbf{CO_2}$ 98.7% pure, 1-3 €/kg
   ($\mathbf{CO_2}$ – emissions !)

2) chlorination: $Si + 3\,HCl \rightarrow SiHCl_3$ (liq.) + H_2
   then purification (till 2 ppb) by distillation

3) reduction of $SiHCl_3$ by H_2 (= the reverse of reaction 2) at 1100° C: impurities down to 0.1 ppb, powder of 50 €/kg

Crystalline Si (3 methods)

1) Czochralski method (**costly**) : fusion at **1440° C**, growth of a tube (L=1 m, ϕ=30 cm) for 24 h, Si utilisation of 70%

2) Floating-zone method (**very costly**): polycrystalline Si is remolten against a monocrystal (no contamination, no loss), tubes of ϕ 10 cm

3) Siemens method (cheapest): molten block of 40x40x40 cm^3 is cooled to 1 cm grains (*polycrystalline*)

Cell fabrication, step-by-step

1) chemical surface attack by **hot NaOH or HF** → texturisation (20 μm) to **reduce** the surface light **reflexion** from 40% to 15%
2) diffusion of phosphorous in the surface (+oxidation at **900° C**): n^-
3) screenprinting of aluminium on the back + fusion (**700° C**) : creation of the p^+ layer
4) deposition of silver-glass on the front (cathode collector) by screenprinting
5) deposit of silver on the back (aluminium) by screenprinting (anode)
6) titanium vapor treatment (**400° C**) on the front → TiO_2 layer for **antireflection** (reduced to 1-5%)
7) **plasma attack** to remove n^- edges (phosphorous)

Payback time

- the 'energy' payback time is the duration the device has to operate in order to deliver the energy invested in fabrication:
  - 1.5 to 3.5 yr for crystalline Si
  - 1 to 1.5 yr for amorphous Si

- Remark : for solar thermal absorbers: < 1 yr

Alternative Technologies

- Objectives
  - reduce the cost per module/m^2
  - increase the efficiency

amorphous Si as thin layers

concentration cells

- achieve >20% with cost effective manufacturing

(→ reduction from 3 to 2 €/W$_p$)

Thin film technology

- lower quality and efficiency, but lower cost (6$/kg vs. 53$/kg)
- short current paths : charge carrier lifetime τ can be short
- non-saturated Si (α-Si, Si:H), containing 10% H_2 (1.75 eV) : deposited from SiH_4 plasma at 250° C
- 40 μm thick
- continuous fabrication of the module simultaneously to the cells

Thin film technology

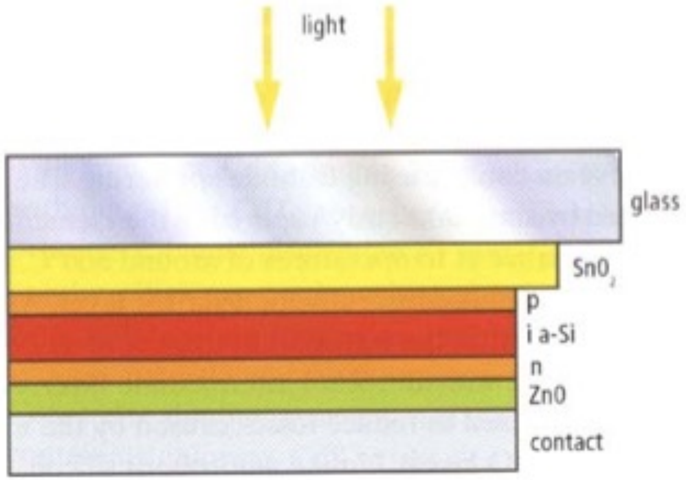
Challenges:

- lower efficiency (10% in research, 5% in modules)
  – improved by tandem concept (successive layers of < 1 μm of SiC:H (2eV), Si:H (1.7 eV), SiGe:H (1.3 eV)) : 10% possible)
- intrinsic instability (rapid impurification)

Other thin layers :

- CIS ($CuInSe_2$, 2 μm, 1.1 eV) : 17% efficiency on module
- CdTe (1.5 eV, low cost by screenprinting, stable) : 17% on module

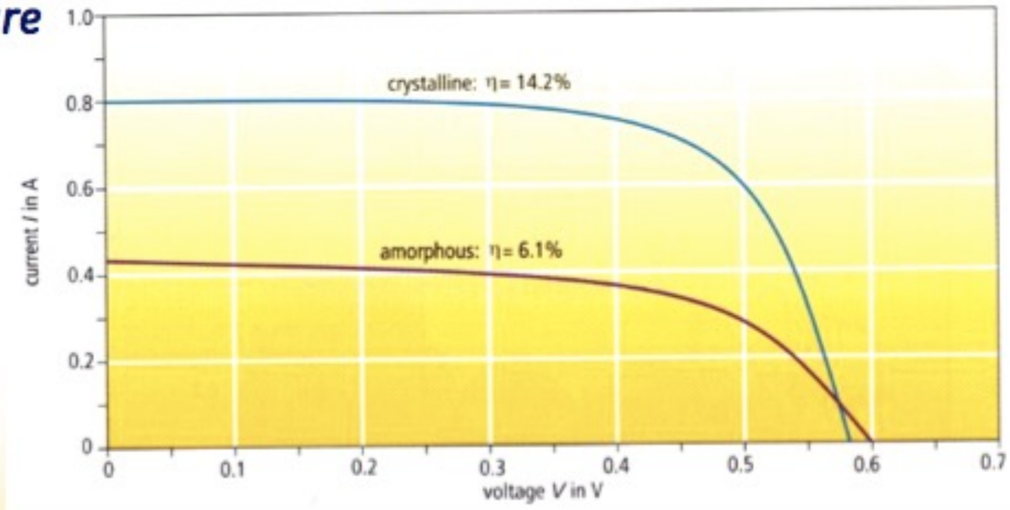
Thin film energy generation



Amorphous Si thin film device structure

- ***pin diode consists of three separate thin a-Si films***
- ***a thin conductive oxide on the glass serves as a window***

Amorphous Si vs. Crystalline Si module



Amorphous Si vs. crystalline Si I-V characteristic

Earthscan

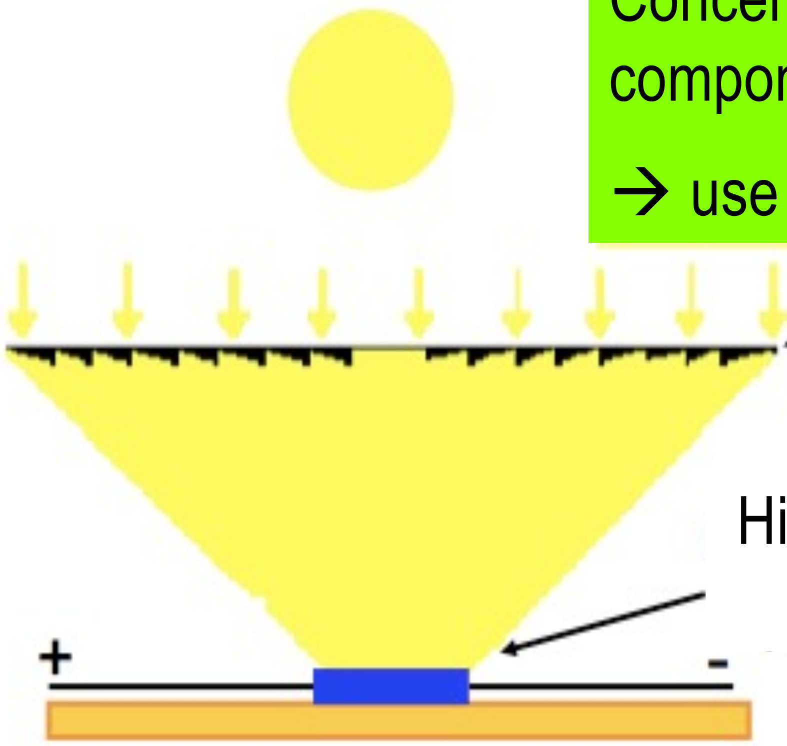
Concentrated PV

- small cells of high efficiency
- only direct solar irradiation is used (30-50 “suns” by focalisation)
- MPP (track the sun trajectory)
- point cell (Stanford, USA) : 26.5% @ 300 suns (1-4 $/cm^2)
- GaAs (OCV 1 V) : 28% @ 1000 suns
- tandem cells GaAs/GaSb : 33% (Boeing)
- triple junction: 44% efficiency
- secure and inexpensive to develop, high potential for low cost PV

Concentrator systems

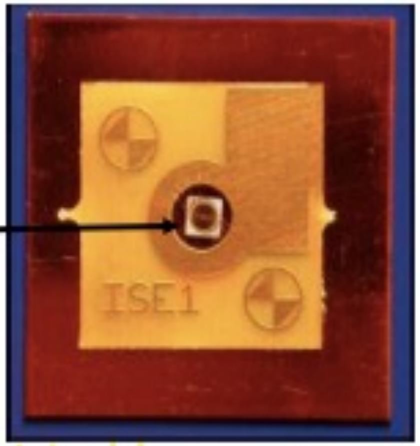
Concentration of 100-1000x with simple optical components (lenses)

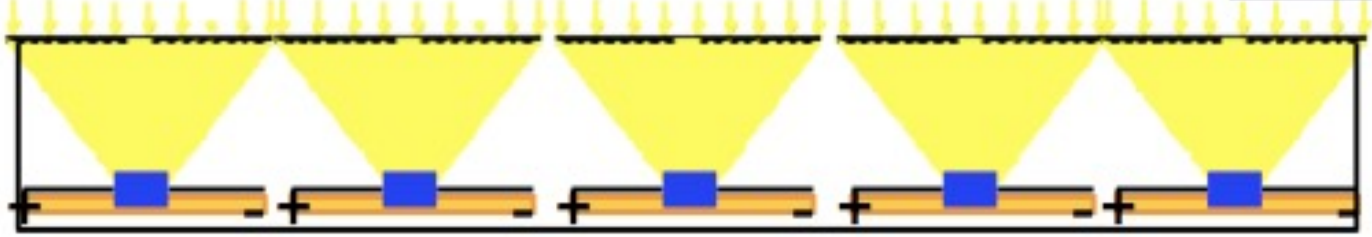
→ use of much lower active cell surface



Fresnel lens

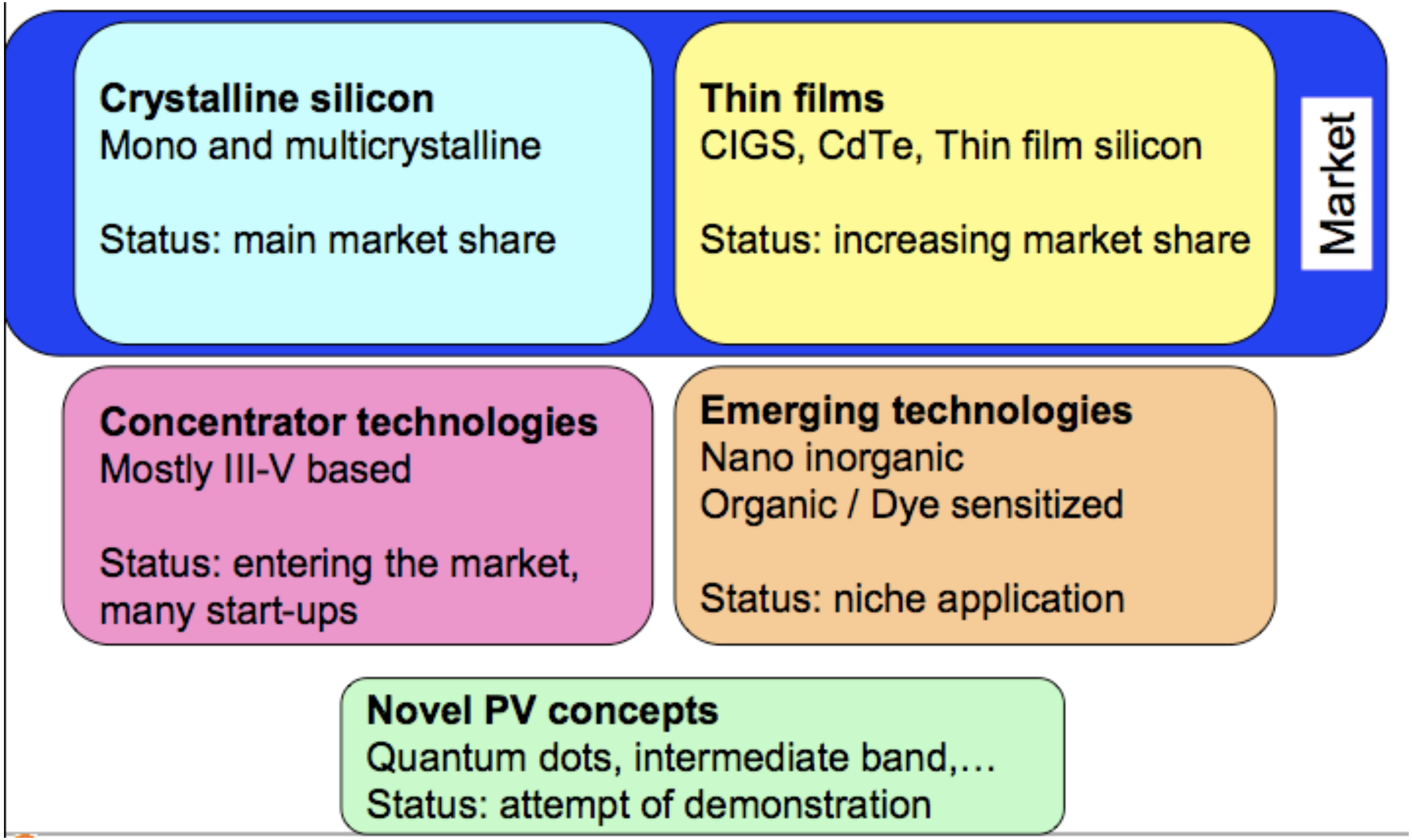
High efficiency cell





Prof. C Ballif, PV-Lab (IMT), EPFL-Neuchâtel

PV technology overview



Crystalline silicon
Mono and multicrystalline

Status: main market share

Thin films
CIGS, CdTe, Thin film silicon

Status: increasing market share

Concentrator technologies
Mostly III-V based

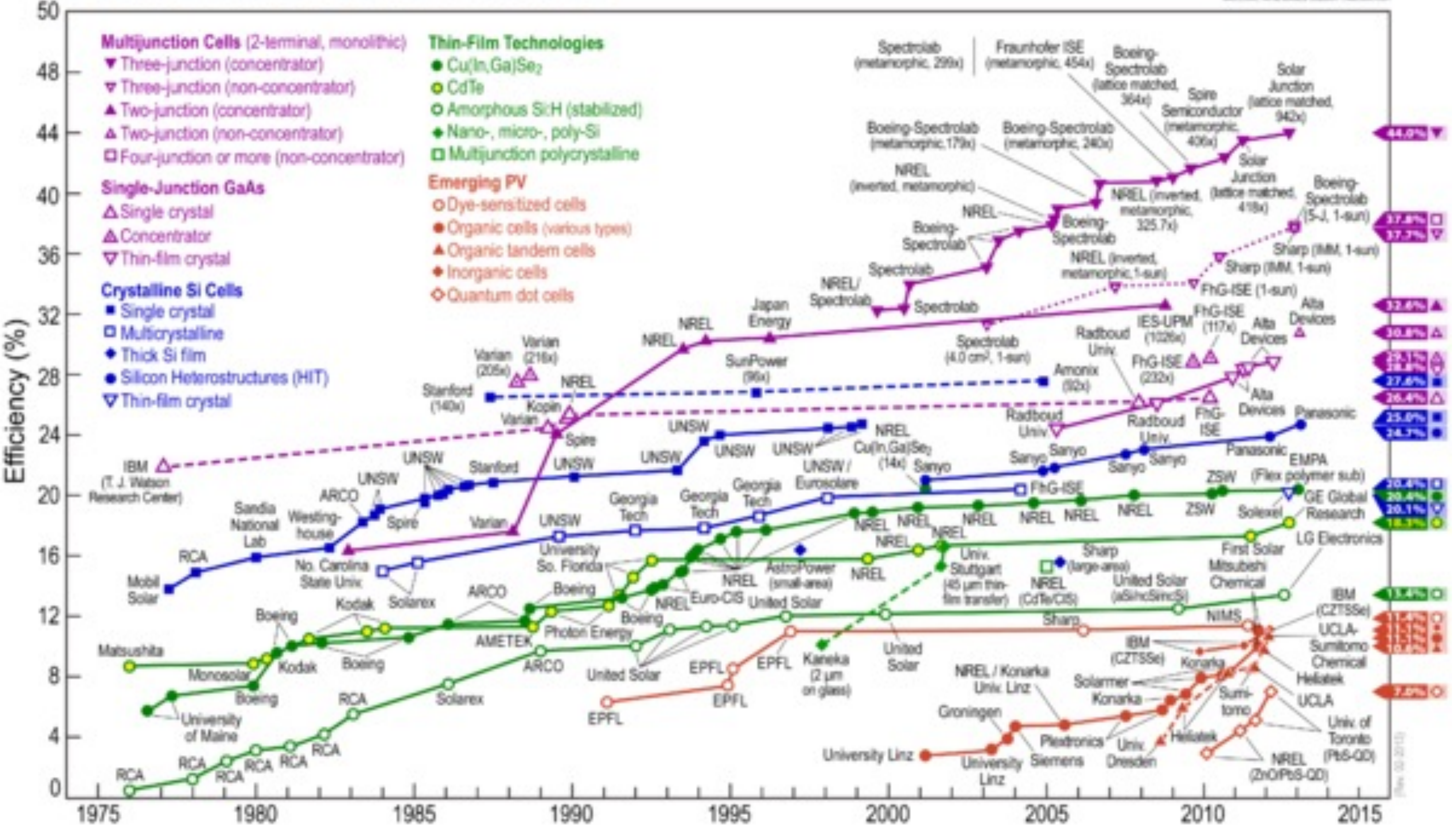
Status: entering the market, many start-ups

Emerging technologies
Nano inorganic
Organic / Dye sensitized

Status: niche application

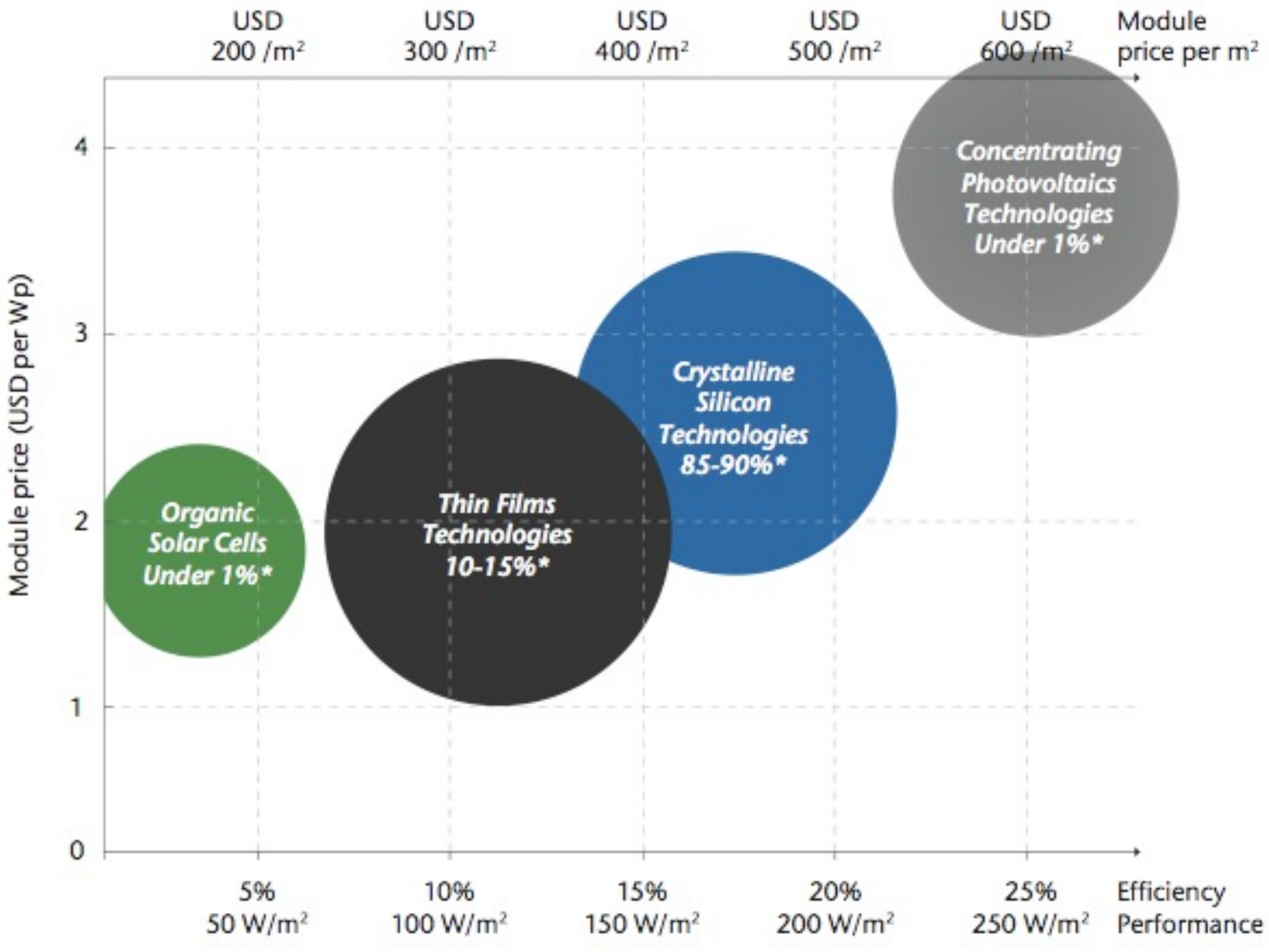
Novel PV concepts
Quantum dots, intermediate band,…
Status: attempt of demonstration

Best Research-Cell Efficiencies



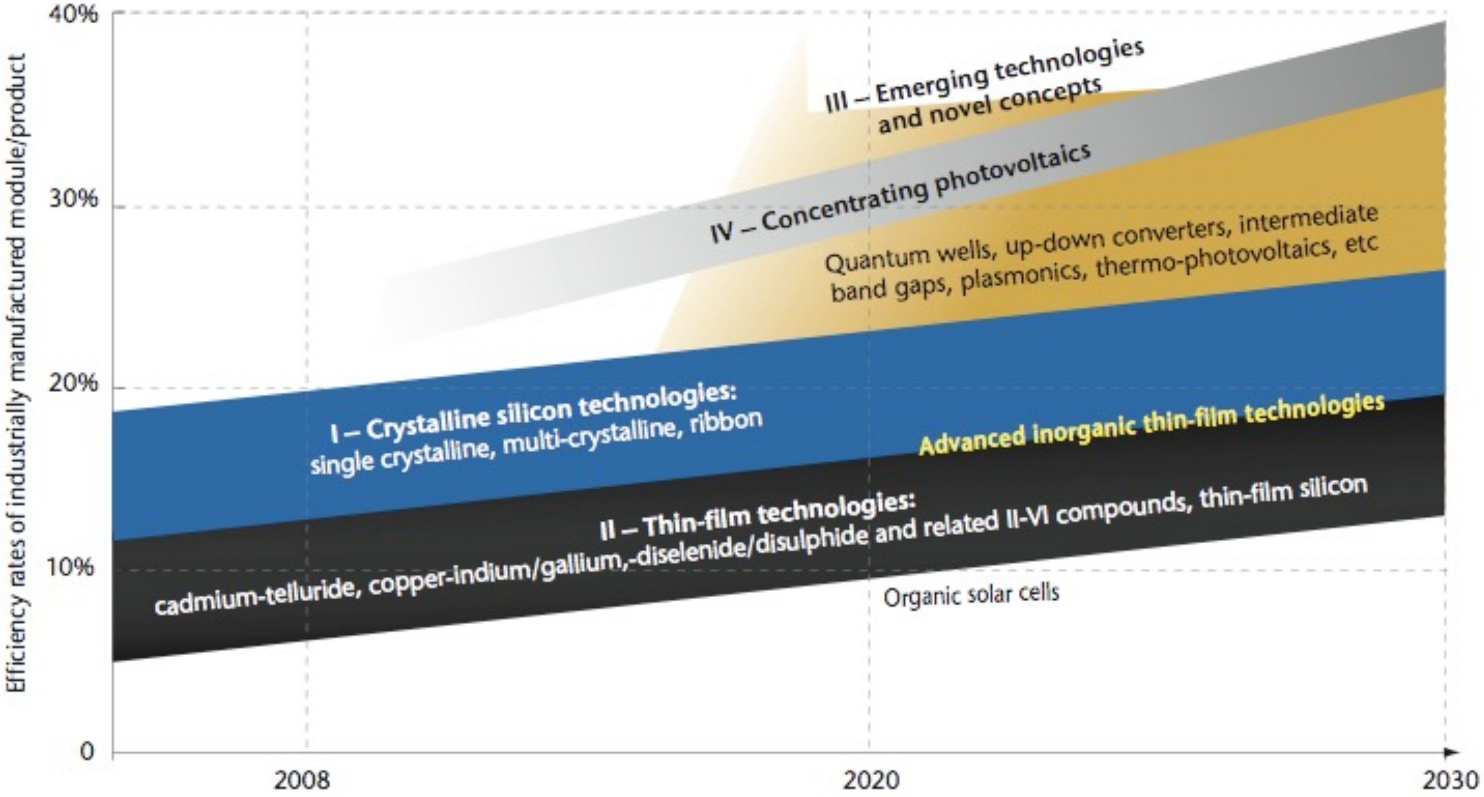
Current performance and price of different PV module technologies*

IEA PV Roadmap



* *percentage share of 2008 market*

Figure 11: Photovoltaic technology status and prospects

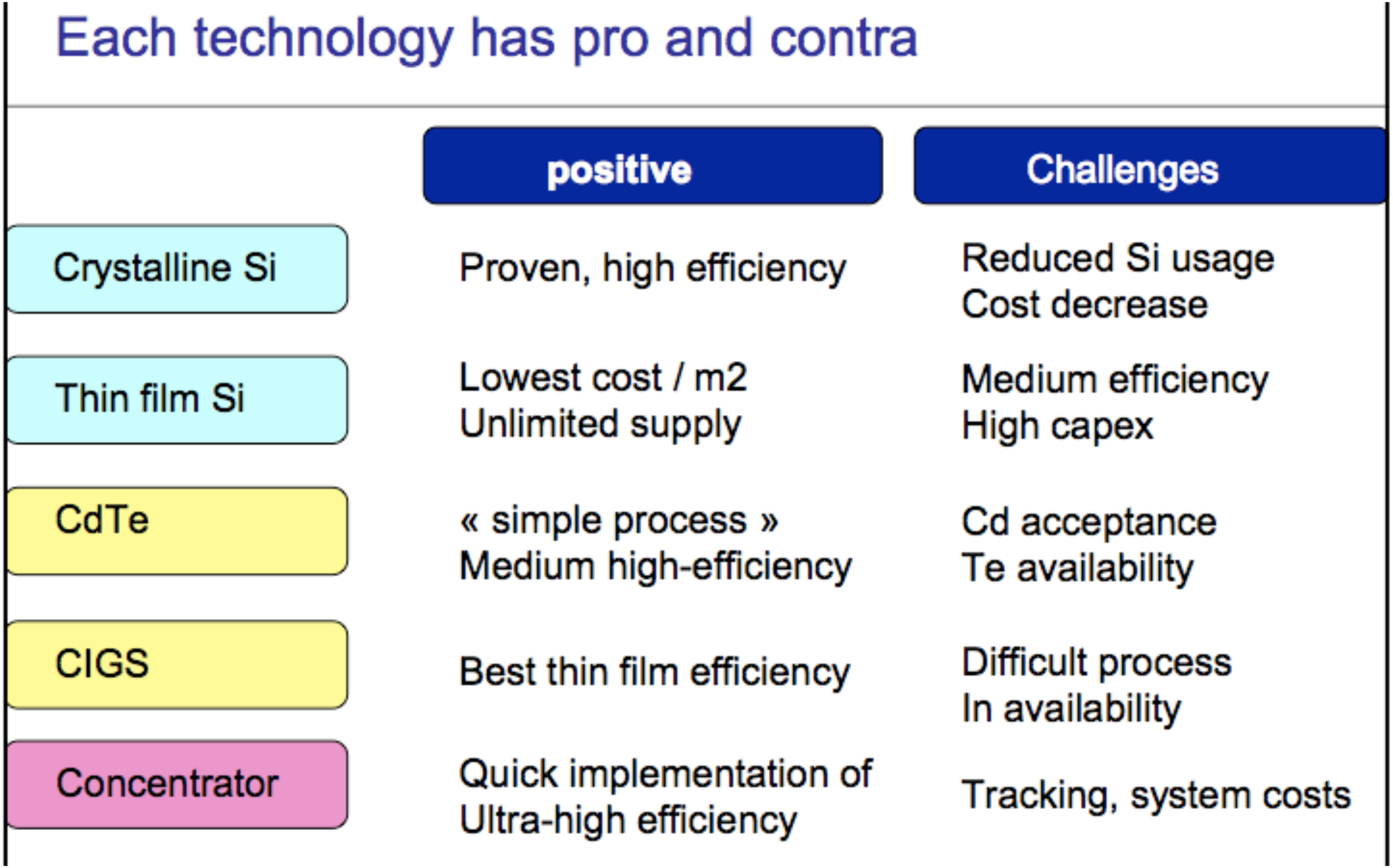


Source: IEA PVPS.

***KEY POINT:** Current technologies will co-exist with emerging technologies and novel concepts.*

Table 1: Current efficiencies of different PV technology commercial modules

Wafer-based c-Si		**Thin films**		
sc-Si	mc-Si	a-Si; a-Si/µc-Si	CdTe	CIS/CIGS
14-20%	13-15%	6-9%	9-11%	10-12%



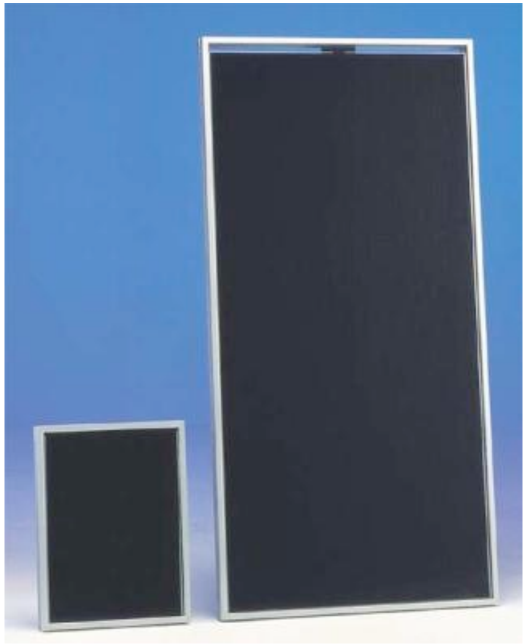
Each technology has pro and contra

	positive	Challenges
Crystalline Si	Proven, high efficiency	Reduced Si usage Cost decrease
Thin film Si	Lowest cost / m2 Unlimited supply	Medium efficiency High capex
CdTe	« simple process » Medium high-efficiency	Cd acceptance Te availability
CIGS	Best thin film efficiency	Difficult process In availability
Concentrator	Quick implementation of Ultra-high efficiency	Tracking, system costs

Technologies

- Efficiencies of various technologies:
  - Crystalline (Si: mono and poly):
    - Efficiency: 14-21%
    - Potential: 20-25%

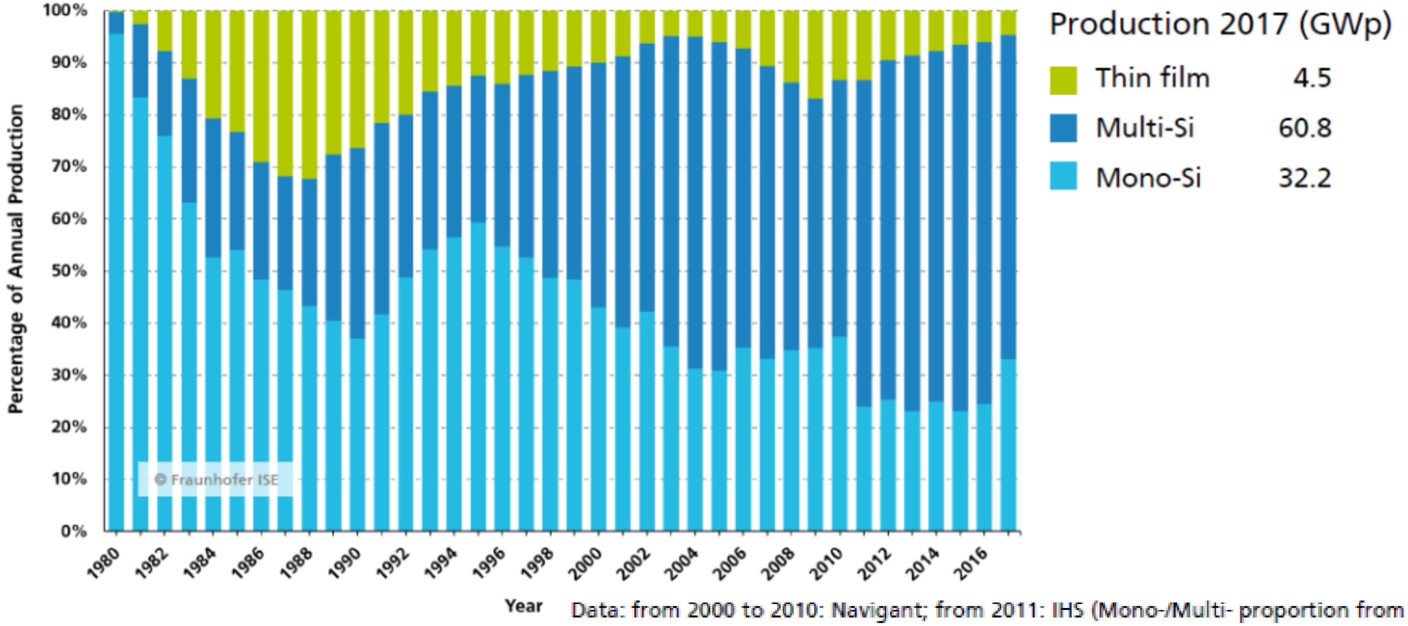
- Thin film (CdTe, CIGS a-Si / µc-Si):
    - Efficiency: 14-16%
    - Potential: 16-20%



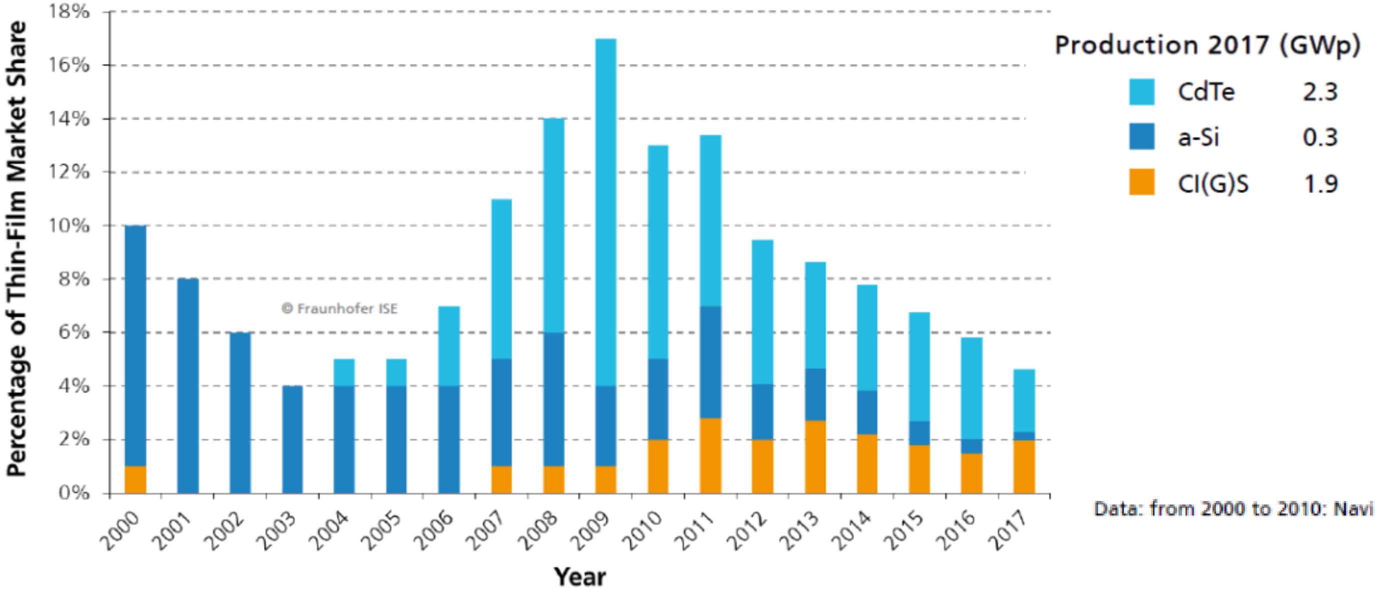
  - Concentrated (III-V-based):
    - Efficiency: 25-30%
    - Potential: 30-50%

Technologies

- Market shares:



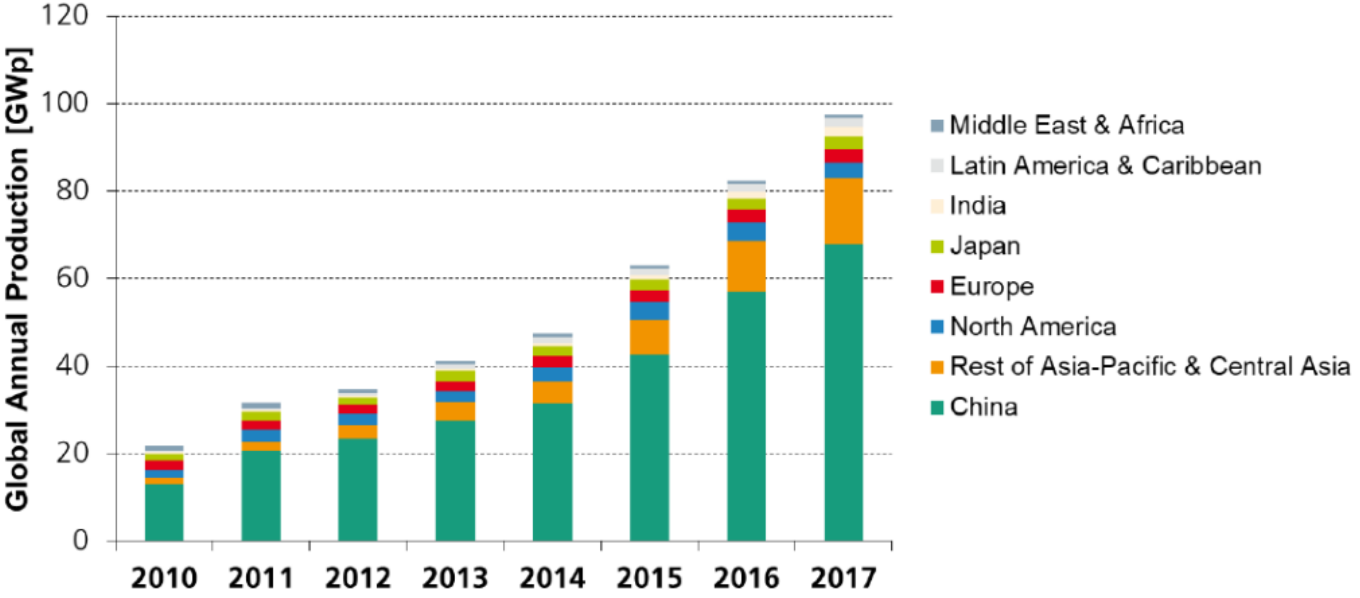
Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion from cell production). Graph: PSE GmbH 2018



Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018

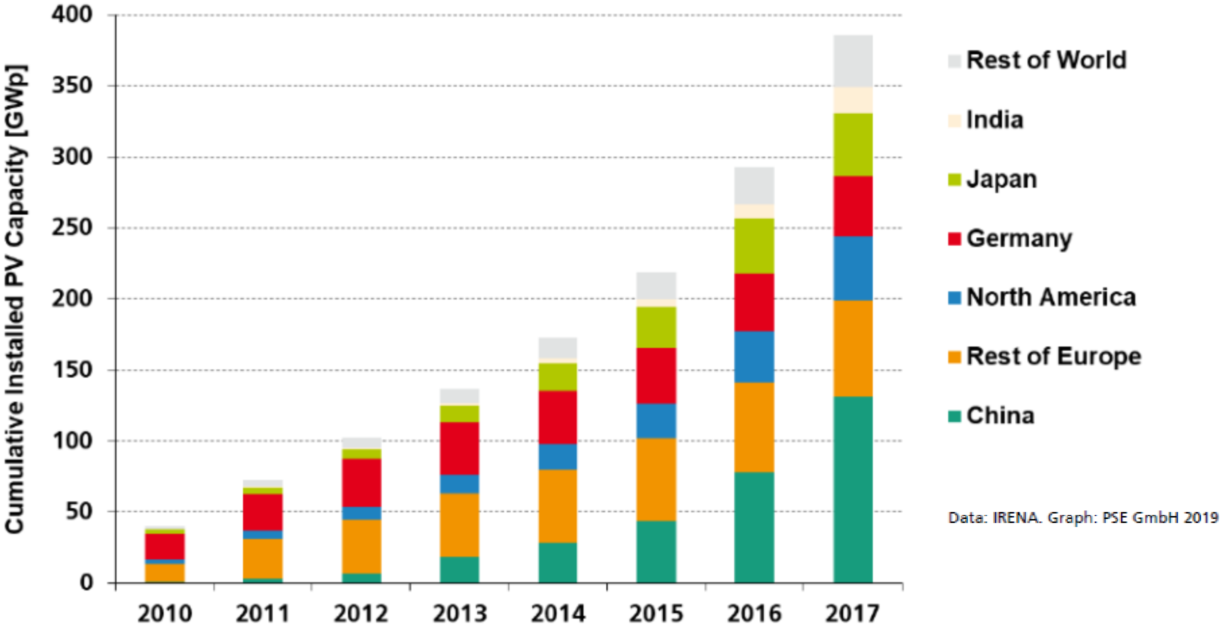
Production and Installation

- Production



Data: Up to 2009: Navigant Consulting; since 2010: IHS. Numbers for 2018 estimated Graph: PSE GmbH 2019

- Installation



Data: IRENA. Graph: PSE GmbH 2019

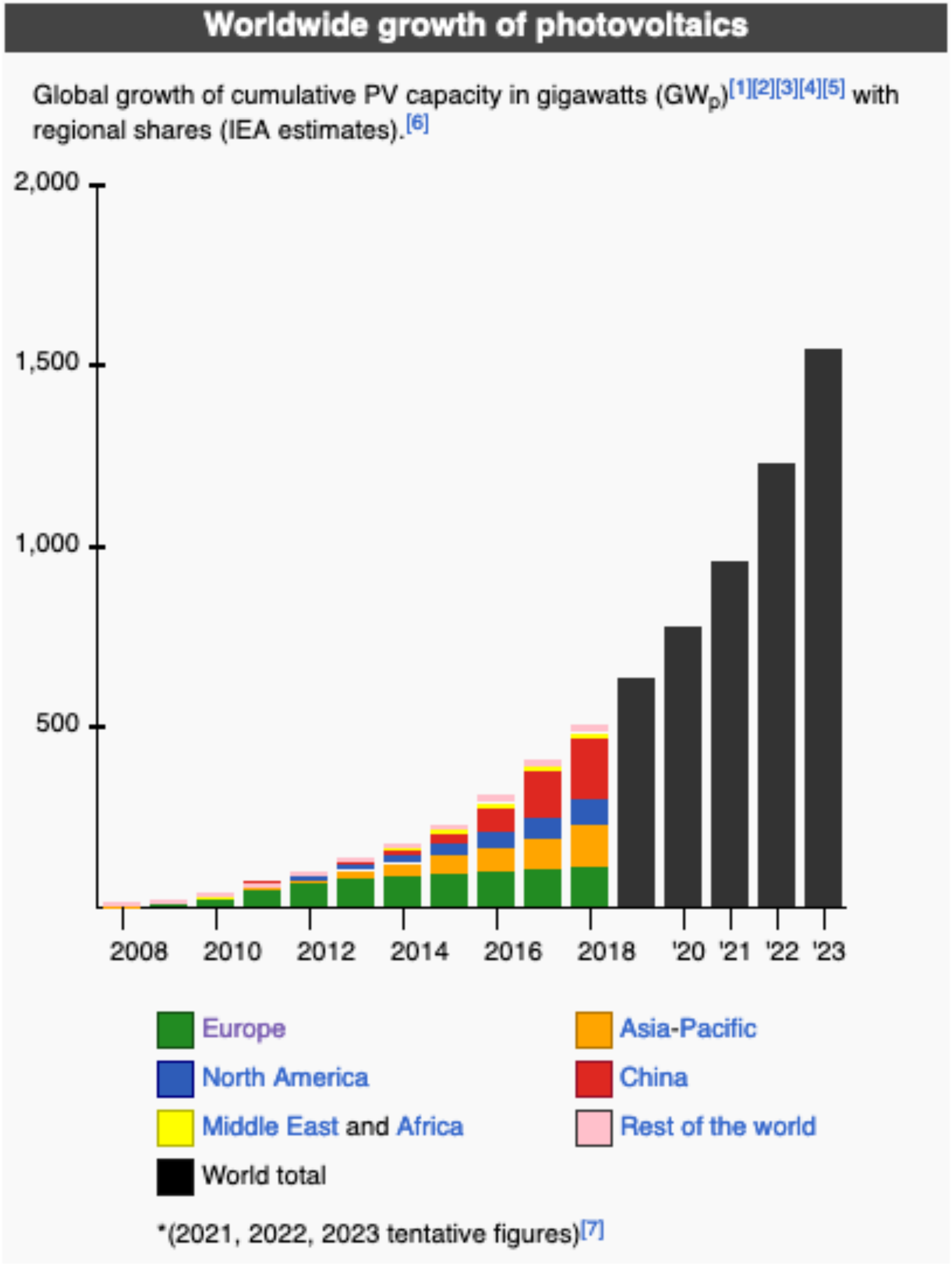
World PV growth

Recent and estimated capacity (GW$_p$)

Year-end	2016[8]	2017[9]	2018[7]	2019[7]	2020[7]	2021E[7]	2022E[10]	2023F[10]
Cumulative	306.5	403.3	512	630	774	957	1225	1541
Annual new	76.8	99	109[11]	118	144[7]	183[7]	268[10]	316[10]
Cumulative growth	32%	32%	27%	23%	23%	24%	28%	26%

China : 393 GW
EU : 200 GW
USA : 113 GW
Japan : 79 GW
Germany : 67 GW
India : 63 GW
AUS : 28 GW
…

https://en.wikipedia.org/wiki/Growth_of_photovoltaics

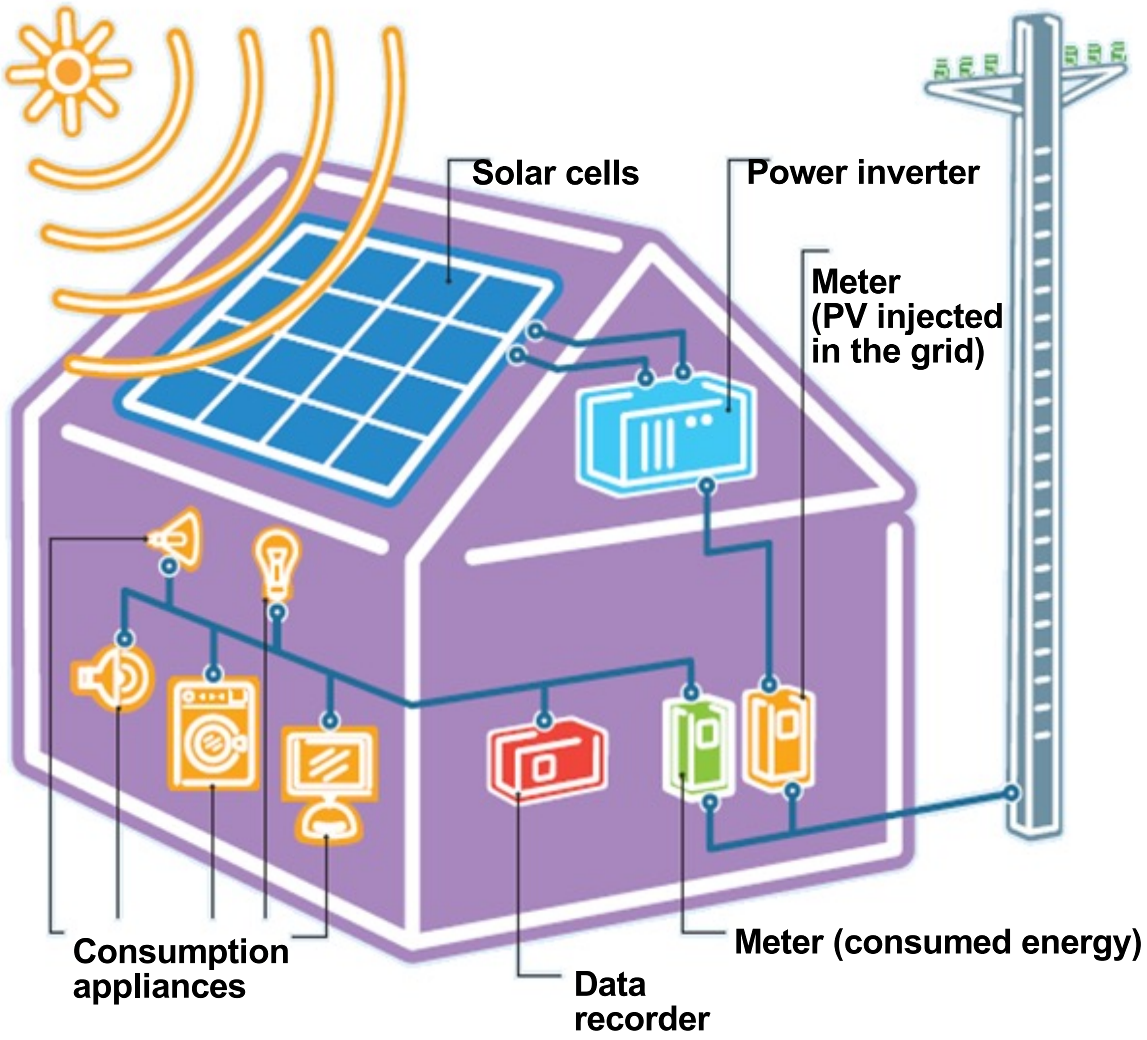


Worldwide growth of photovoltaics

Global growth of cumulative PV capacity in gigawatts (GW$_p$)[1][2][3][4][5] with regional shares (IEA estimates).[6]

*(2021, 2022, 2023 tentative figures)[7]

Residential application

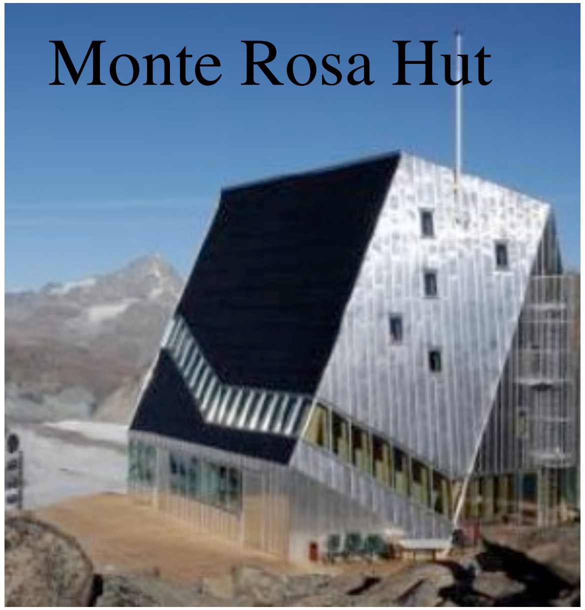


PV building integration

Aesthetics

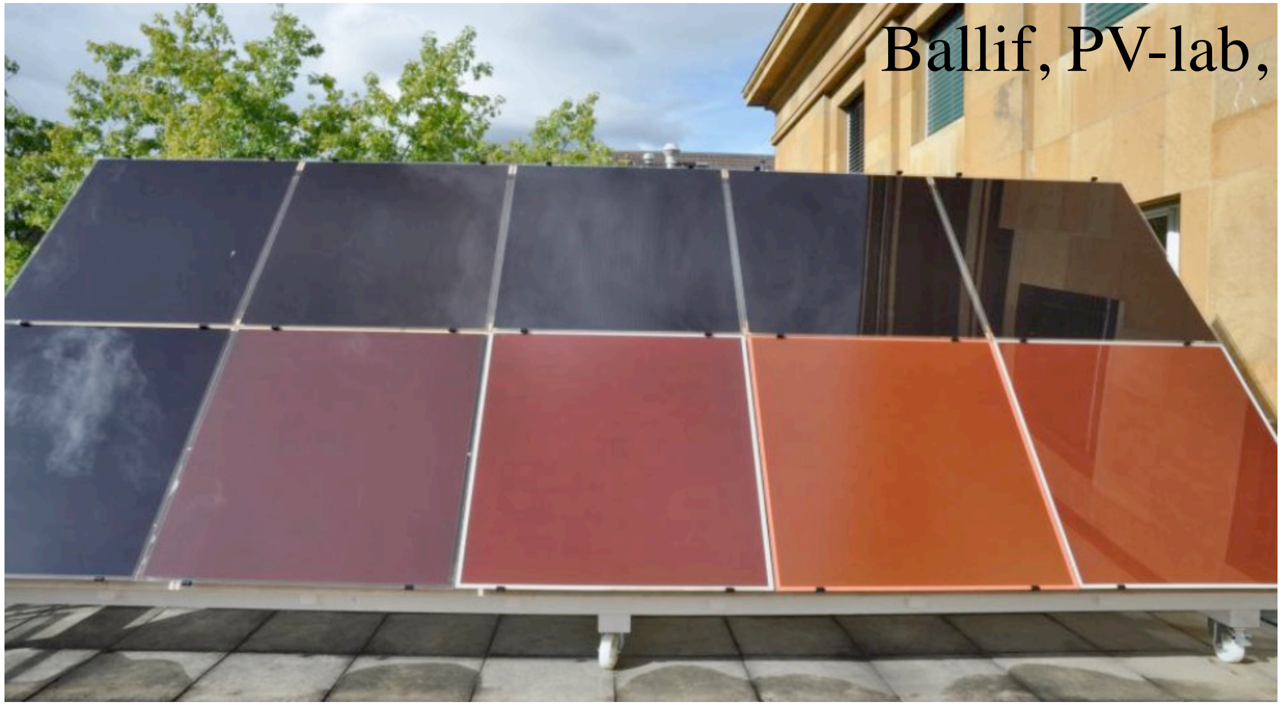
- Photovoltaics: early modules

- Fully integrated today:

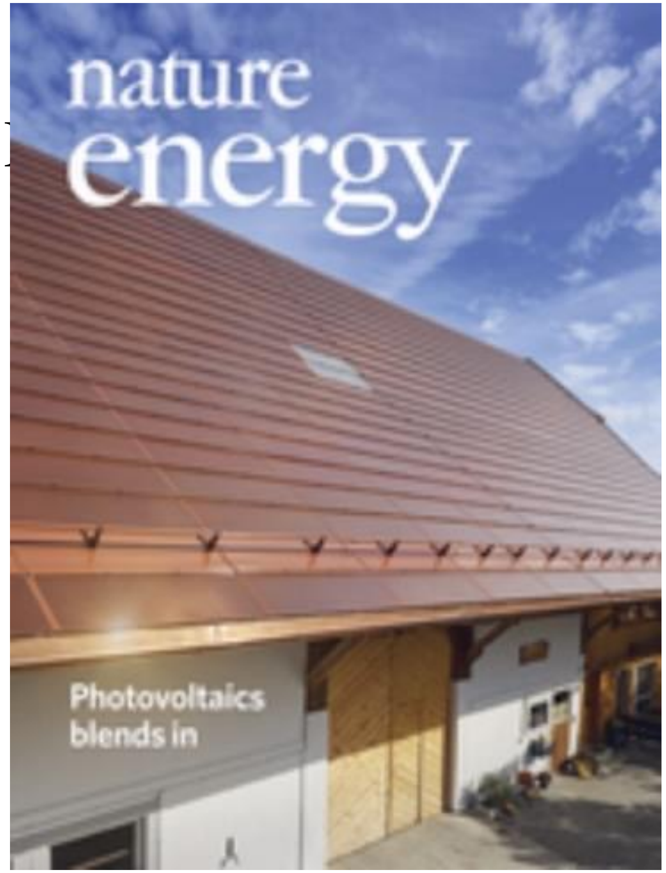


Aesthetics

- Photovoltaics: various colors



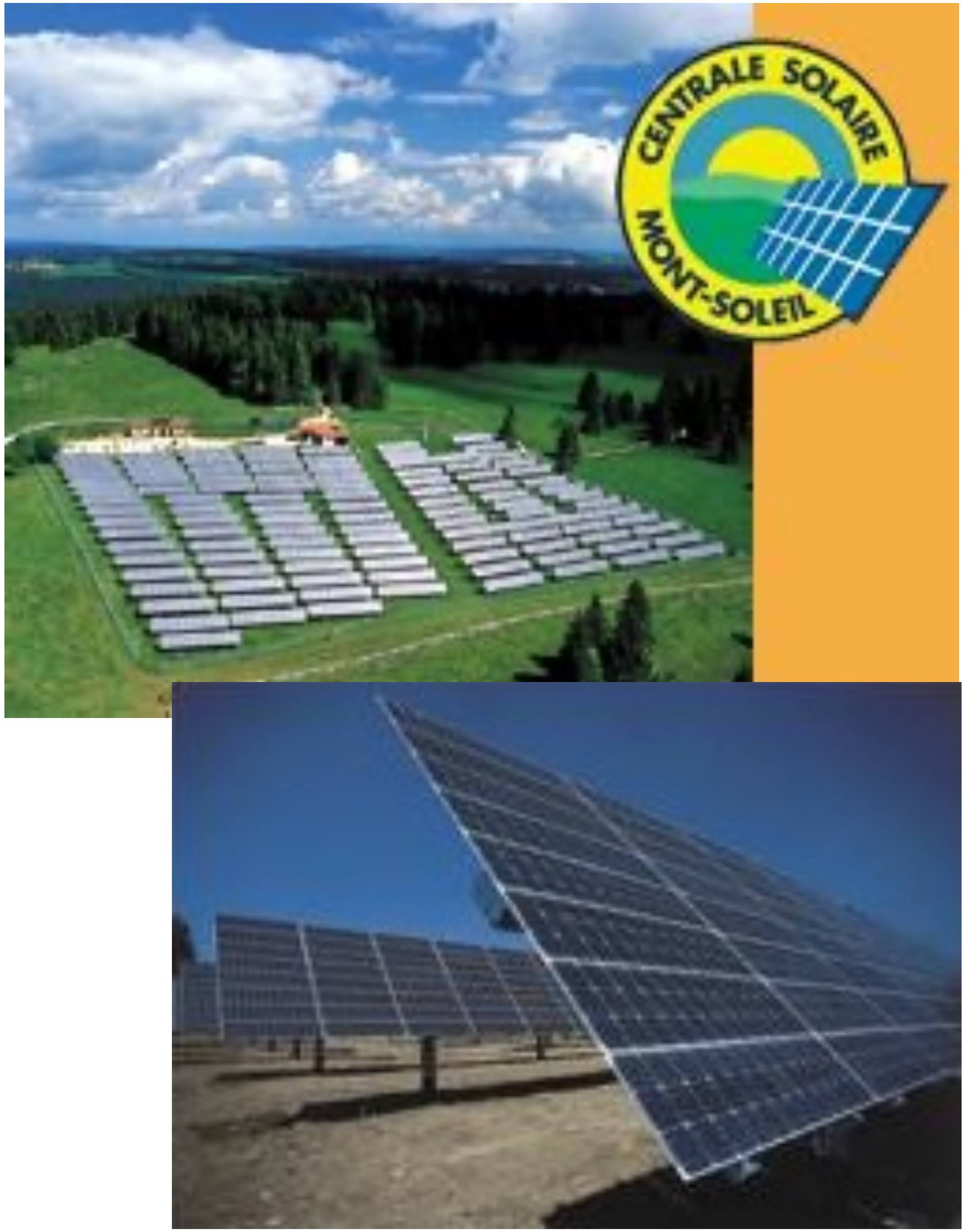
Ballif, PV-lab,



- Covered by prints

KALEO - CSEM

PV power plant



"Mont-Soleil" (in operation since 1992)

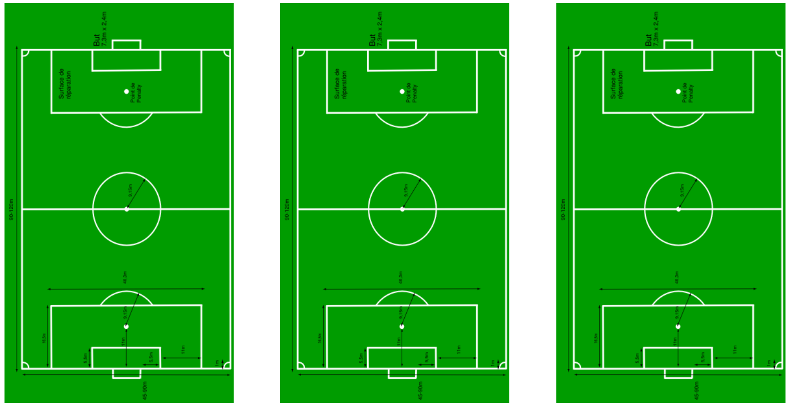
Biggest PV installation in Switzerland till 2005

4500 m^2 Si cells
720'000 kWh/yr
rated power: 500 kW
around 200 households

Cell efficiency: 12-17 %
Efficiency of the inverter: 96 %
Global efficiency: ~ 11.5 %

real land use * 5

Total occupied surface: 20'000 m^2



Equivalent to ~ 3 soccer grounds

‘Swiss stadium’ Power Plant

7’000 panels (12’000 m^2) of polycrystalline Si (efficiency : 15%)
1’200'000 kWh / yr (rated power: 1’300 kW)
around 400 households

Wankdorf, Bern, Switzerland
in operation since 2005/2007

Romande Energie – EPFL Solar Power Plant

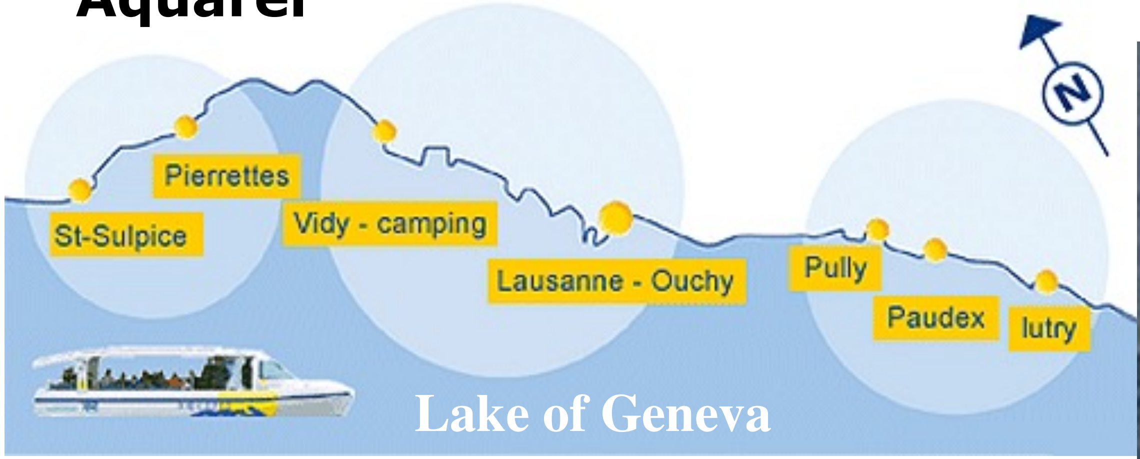
(in operation since August 2010)

2 MWe
15 MCHF

In 2012 biggest PV installation in Switzerland, with 20’000 m^2 of PV and annual production of 2 GWh (~ 3% of EPFL consumption)

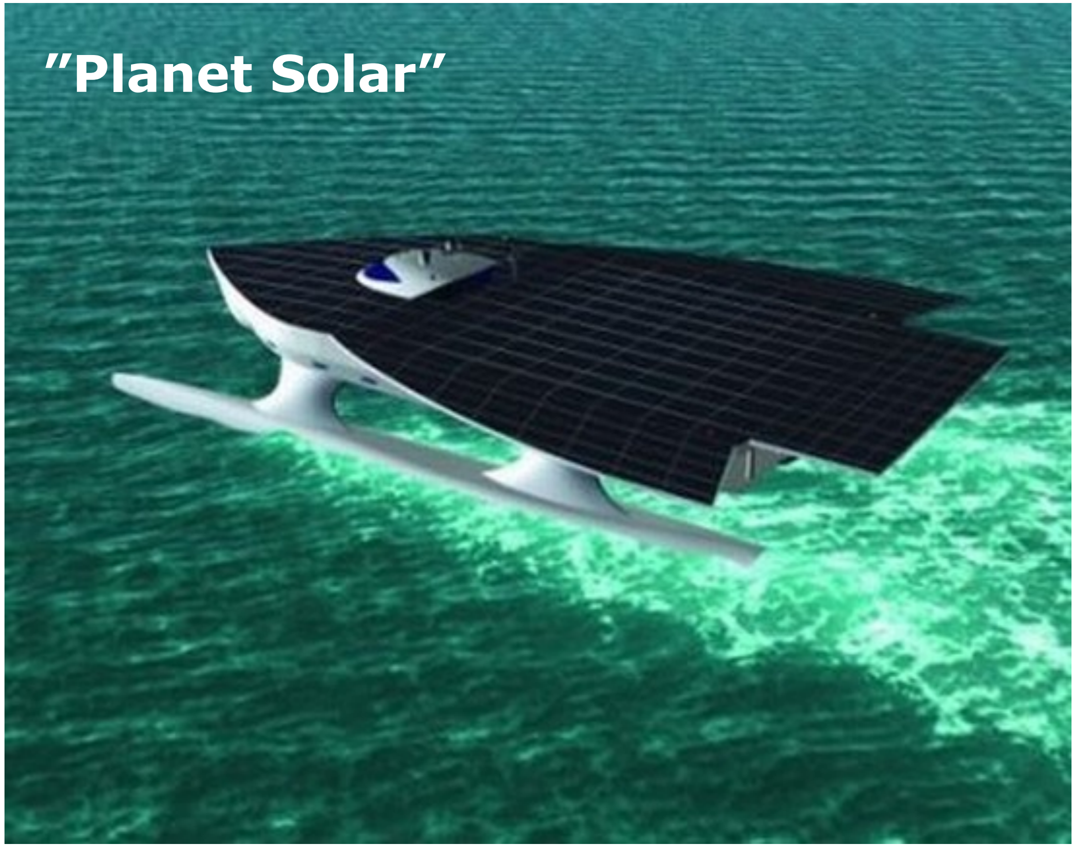
Solar shuttle boat

"Aquarel"



First regular shuttle service of electro-solar tourist boat in Europe; the autonomy of the boat is ensured by batteries that can receive or deliver electricity from/to the grid

Solar ship



World's largest solar-powered catamaran

102 feet long, 50 feet wide multi-hull vessel

500 m^2 black PV panels, containing 38'000 SunPower next generation cells

top speed 27 km/h, seating capacity 50 passengers

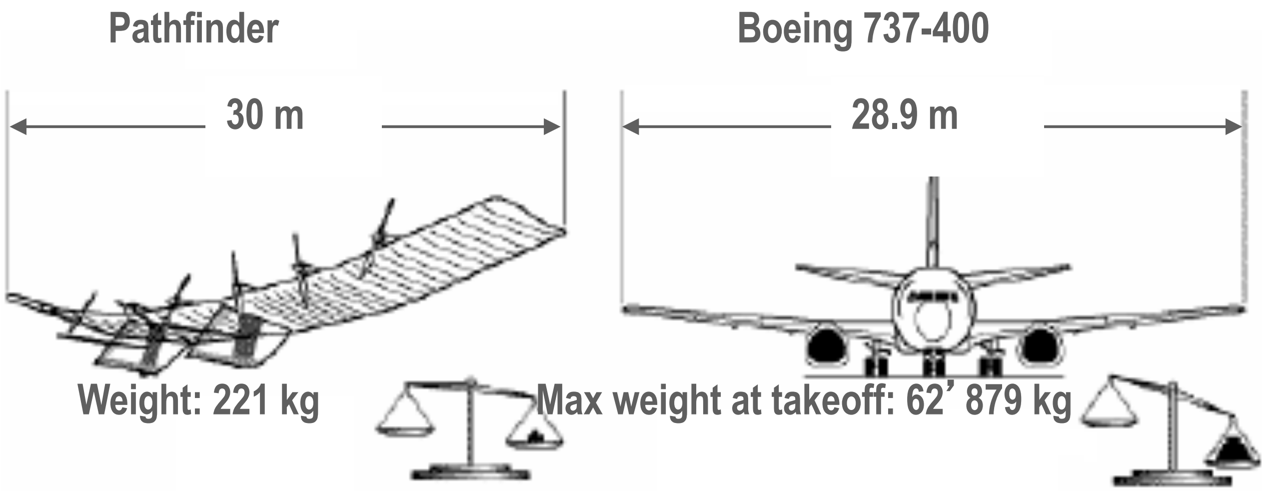
Cost: 18 million €

Solar flight?

Solar-powered, remotely piloted aircraft (USA, 1988)

7'200 W
6 electric engines
(2 h autonomy on battery)

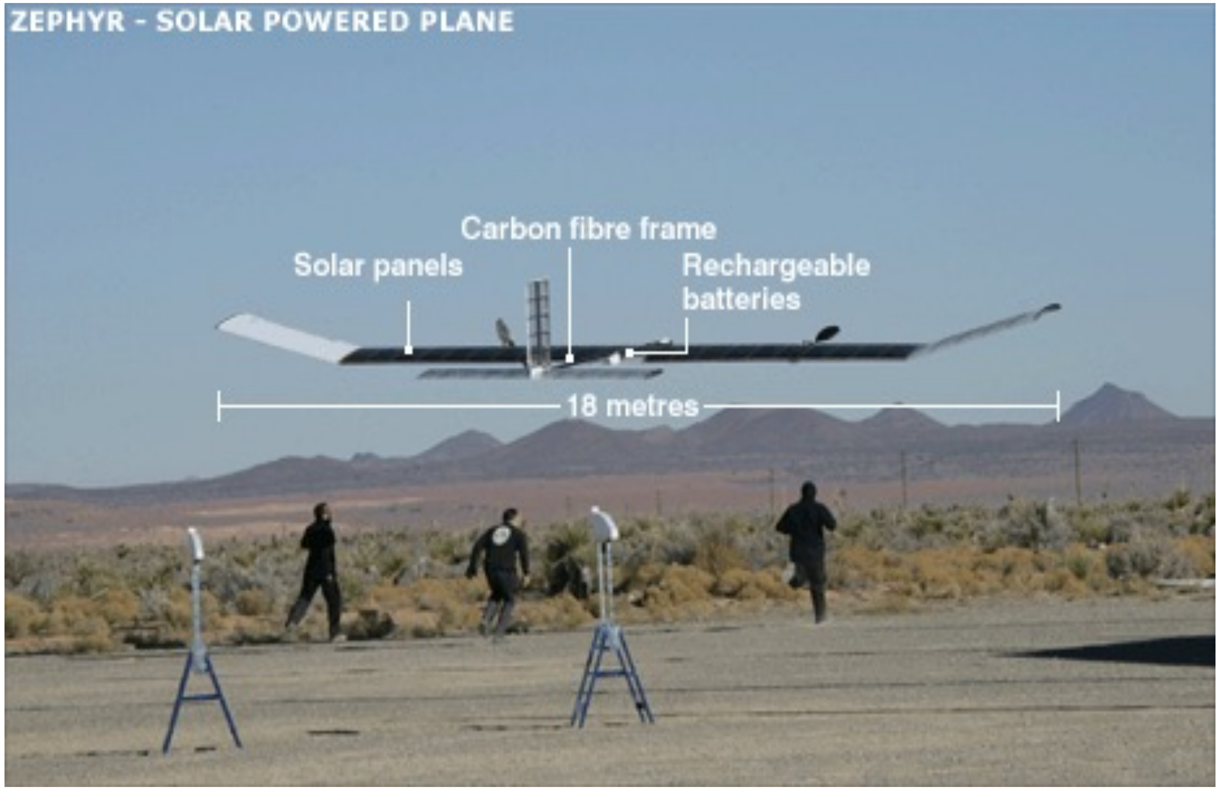
Successful record flight - 80'000 feet, in 1998 - a significant milestone on the way to commercial solar-powered aircraft acting as low-cost complements to satellites (operational flying altitude: more than 20 km)



“Zephyr-6” Solar-Powered Plane, the “eternal flight” plane

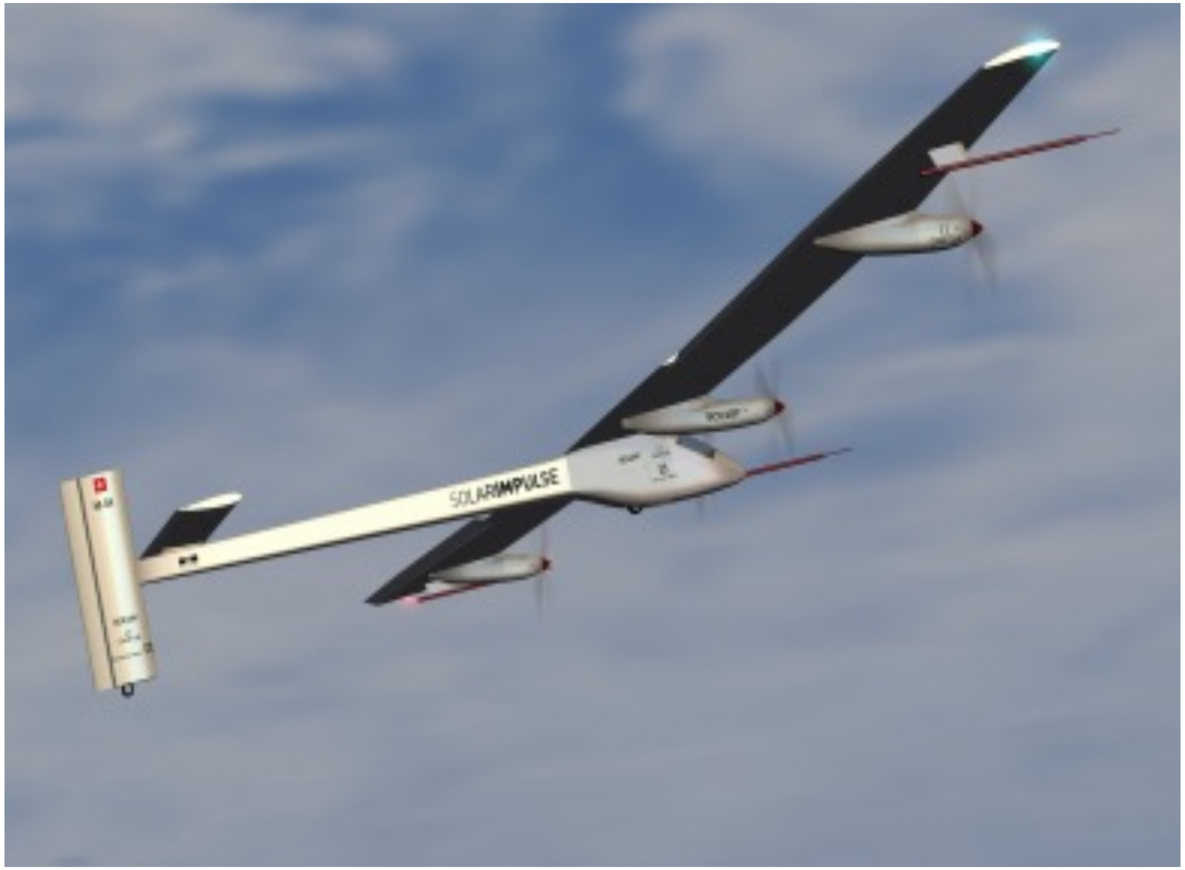
UK-built solar-powered plane that has set an unofficial world endurance record for a flight by an unmanned aircraft (14 days and 24 minutes, mid-July 2010)

Extremely thin and light solar panels cover its wings; Zephyr has a lot of surface for solar panels and a lot of lift relative to its 50 kg weight (thanks to a carbon-fiber body)



“Solar Impulse”

Proposed by Bertrand Piccard, this aircraft should achieve the first round-the-world manned solar airplane flight



With 200 m^2 of PV and 12 % total efficiency of the propulsion chain, the plane’s motors achieve just 8 horsepower or 6 kW

= the amount of power of the Wright brothers plane in 1903

Solar Impulse's wings (nearly the wingspan of an Airbus 340) are multifunctional:
they carry load, produce energy, and house an electrical network; they are to be ultra-strong, efficient and light structures

© Solar Impulse / Claudio Leonardi

PV installed in Switzerland

M^2	Type	Production	Remark
30 mio m^2 estimate (assumption: 100 W_p/ m^2)	Silicon modules	2.6 TWhe (9.36 PJ) 2.97 GW installed peak power	
Potential	138 mio m^2 on roofs	7 TWh (50% roof use)	calculated assuming 200 kWh/m^2.yr (20% efficiency)
	52 mio m^2 on façades	2.6 TWh (cosϕ factor)	
	island installations	several TWh	

>15% of electricity

Other estimates go from 30 TWhe to 60 TWhe / yr for Swiss PV potential

Compared to solar thermal installations (CH)

m^2	Type	Thermal prod. in PJ	Remark
1’544’500	glazed collectors on house roofs	2.5	space + hot water heating
175’ 000	unglazed collectors not always on roofs	0.2	private/public pool heating
876’ 000	agricultural collectors on roofs	0.4	for hay drying
Total : 2.6 mio		1.63	
Potential:	138 mio m^2 roofs	100 PJ if 50% roof space used	Assumption : 30% eff. 400 $kWh/m^2.yr$

= 30% of space + HW heat

PV in Europe

- 2022: 209 GWe installed; 203 TWhe produced
  - 80% crystalline Si
  - 19% thin film cells (a-Si, CdTe, CuInSe, $GaSe_2$, tandem cells)
  - 1% concentration cells and organic cells
- combined with storage, hybridisation; smart grids

Target	2007	2020	2030	2050
GWp	5	150	397	962
TWh	5.4	180	556	1347

→ 1100-1400 h / yr load factor at peak

Potential of PV electricity generation

With 10% efficiency PV panels

🟩 Total US electricity

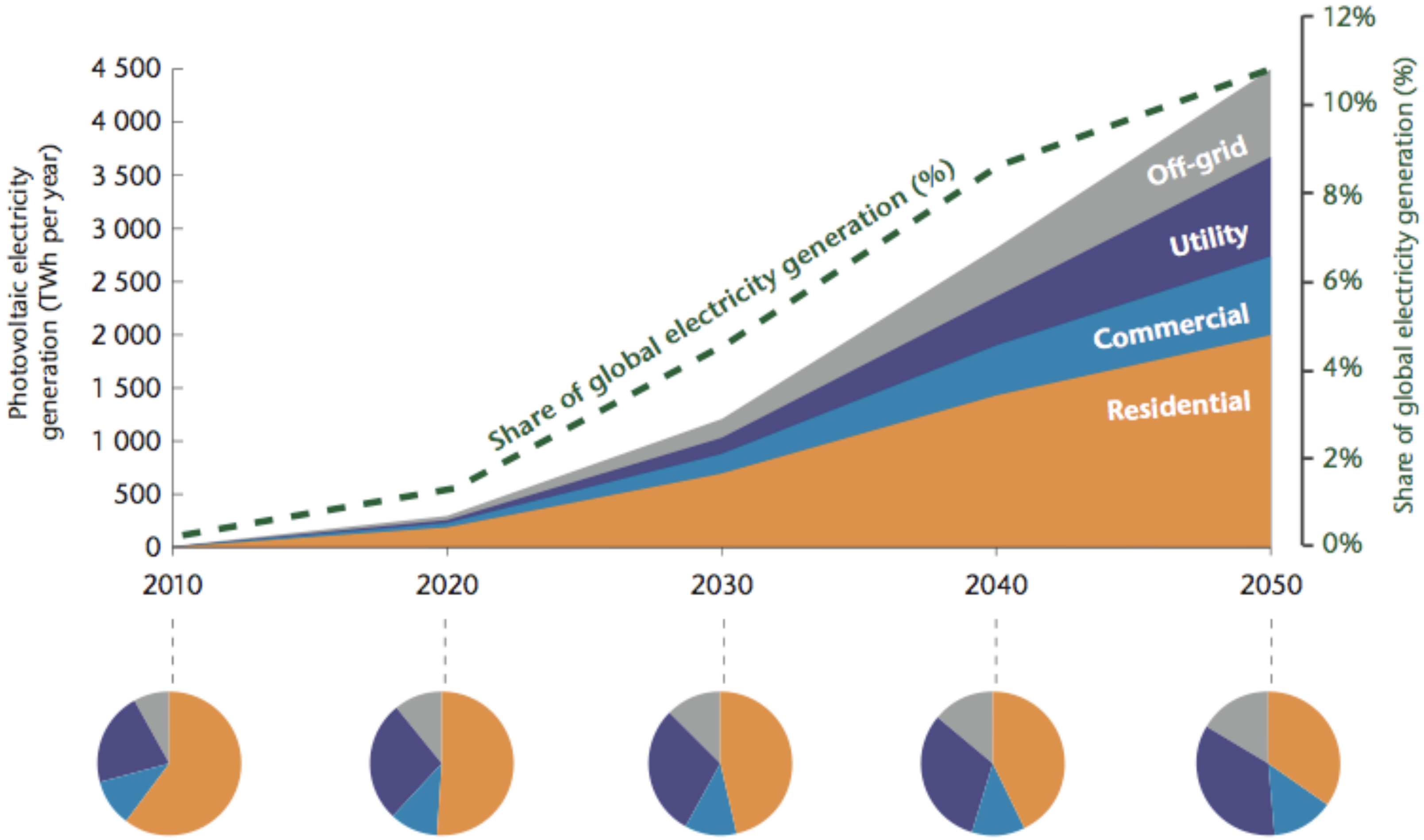
□ Total US energy

Market end-use sectors:

- **Residential** (typically <**20 kW** on individual homes)
- **Commercial** (typically <**1 MW** for commercial office buildings, schools, hospitals, and retail)
- **Utility** scale (starting **>1 MW,** mounted on buildings or directly on the ground)
- **Off-grid** applications (varying sizes)

These different applications have different system costs and compete at different price levels.

Evolution of photovoltaic electricity generation by end-use sector



Summary

- Solar PV power is a commercially available and reliable technology with a **significant potential** for long-term growth in nearly all world regions.
- It is estimated that by **2050**, PV will provide **≈11%** of global electricity production (by 2030: 5%) and avoid 2.3 Gt/yr of CO_2 emissions (3 TW installed).
- PV will achieve competitive parity with the power grid by 2020 in many regions.