EPFL

SOLAR ENERGY

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Outline

- Introduction
  - The sun: spectrum, black body and airmass approximations
- Solar to Electricity
  - Semiconductor technology (conversion)
  - Solar cells, solar modules and solar systems
- Solar to heat
  - Principles
  - Solar collector
  - Solar concentrator
- Solar to Fuel
  - Principles
  - Solar collector
  - Solar concentrator

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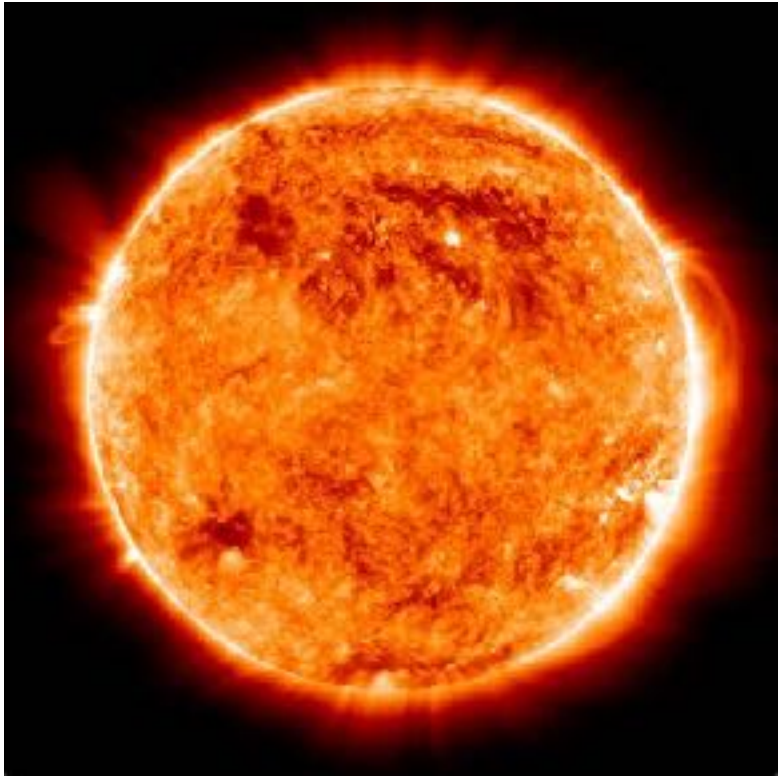

Introduction

The Sun

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The energy from the sun

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Key figures :

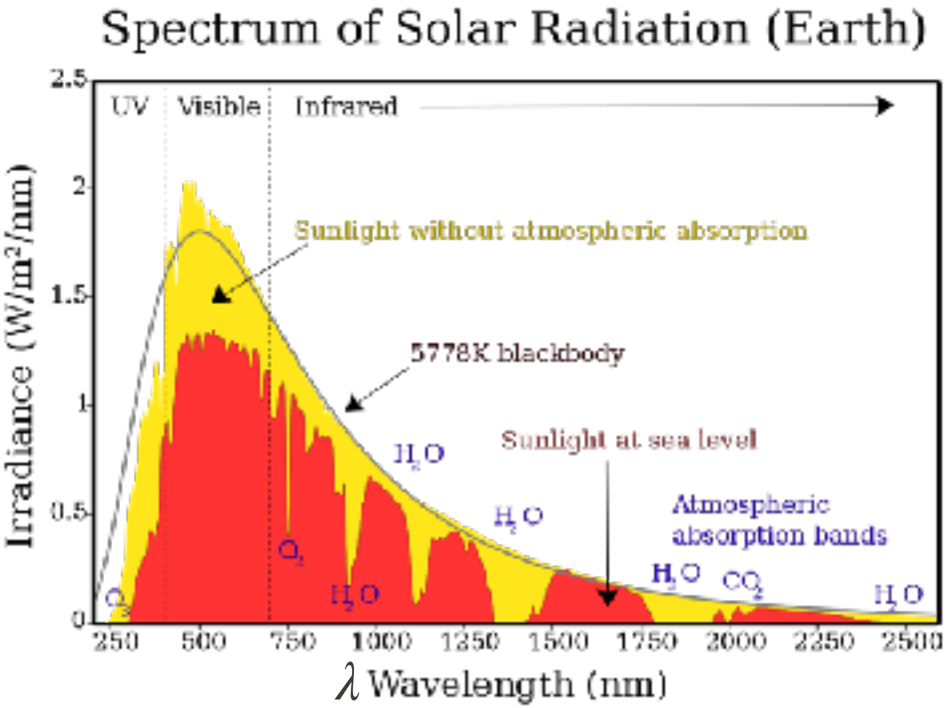
- Irradiance: $I = \int_0^\infty E(\lambda, 5780K)\, d\lambda$
- In space (~black body) = 1360 W/m2
- At Earth's surface **1000 W/m2**

World primary energy needs: 160'000 TWh/year.

➢1 year of solar irradiation = 6500 years of world energy needs

➢1.5 hours/year is enough

➢Covering 0.1% of earth surface with 20% efficiency solar panels is enough to cover this need.



Irradiance and location : Air Mass

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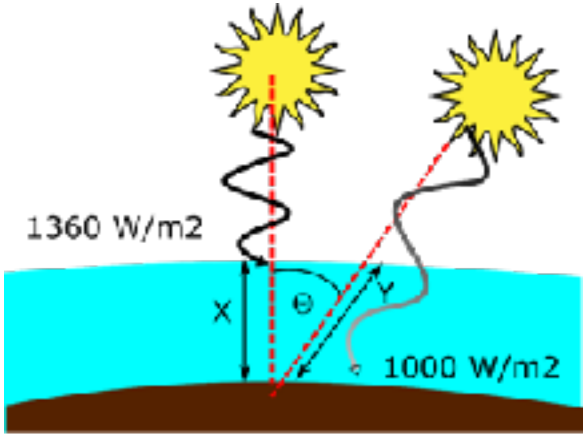
Air mass: path length the light has to travel through the atmosphere

- AM_0: solar spectrum outside atmosphere 1360 W/m2
- $AM_{1.5D}$: solar spectrum in our latitude at noon, only direct radiation, normalized at 900 W/m2
- $AM_{1.5G}$: include diffuse radiation, normalized at 1000W/m2
- AM_x: defines both a spectrum and power density

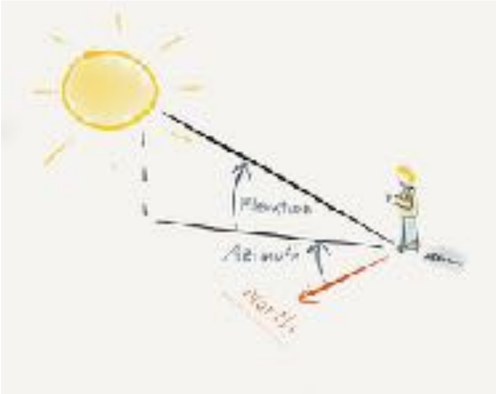
$$AM = \frac{1}{\cos\theta} = \frac{Y}{X}$$



Irradiance and location : Air Mass

OBVIOUS WARNING (not to remember) : Position of the sun is location and time dependent!

- φ : azimuth angle => $\sin\varphi = \cos\delta\sin\omega/\cos\alpha$
- α : elevation angle => $\sin\alpha = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$
- δ: solar declination => rising/setting slope
- ϕ: location latitude (47° for Switzerland)
- ω: hour angle => 15°*(Solar time -12h)



The solar intensity with respect to the AirMass is given by :

$$I = 1.1\ I_0 \bullet 0.7^{AM^{0.678}}$$

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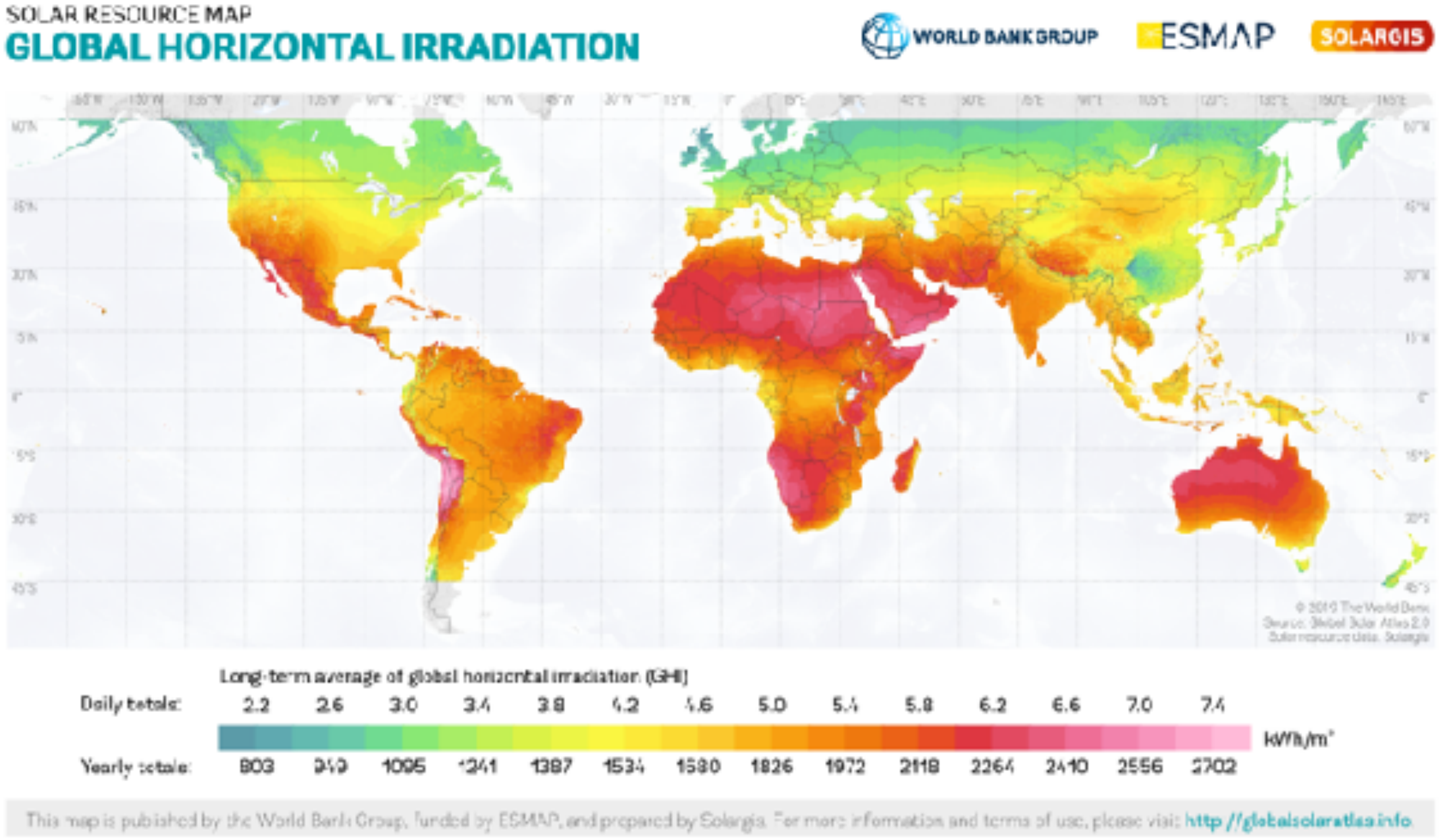
Availability (location dependant)



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Types of solar radiation

Global Horizontal Irradiance (GHI)

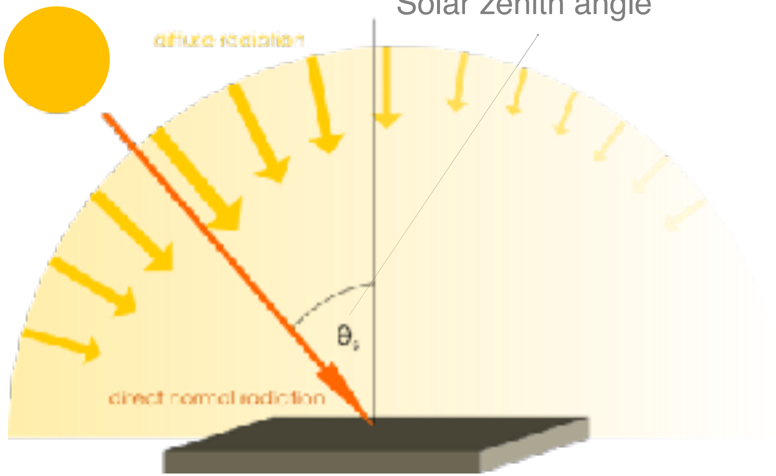
Total radiation measured on a horizontal surface

Direct normal/ beam radiation
- Direct solar beam (at clear sky)

$$GHI = DHI + DNI \cdot \cos(\theta_s)$$

Solar zenith angle

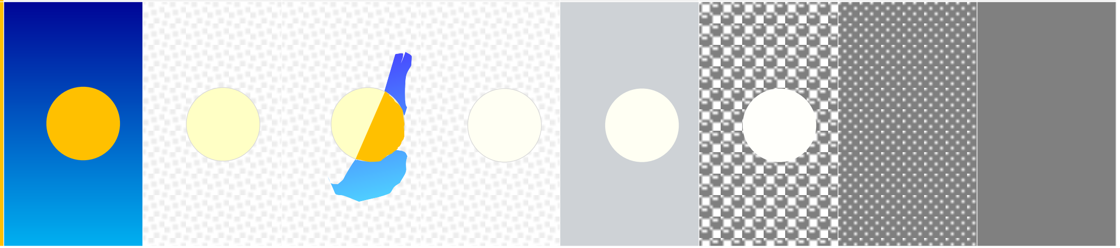
Diffuse Horizontal Radiation
- Scattered radiation from the solar beam by particles in the atmosphere (clouds, ground reflection, smog, etc.)



Source: NREL, http://rredc.nrel.gov/solar/glossary/gloss_g.html

Diffuse & global radiation

Solar radiation: **Typical values dependent on the weather conditions**

Weather	**Chilly, clear, blue sky**	**Thick smog**	**Sun is coming out**	**Sun = yellow disc**	**Sun = white disc**	**Sun just discernab le**	**High smog**	**Overcast weather**
GHI [W/m²]	*1000*	*600*	*500*	*400*	*300*	*200*	*100*	*50*
DHI [%]	*10%*	*50%*	*30%*	*50%*	*60%*	*100%*	*100%*	*100%*
Sky view								

Availability (location dependant)

In Switzerland:

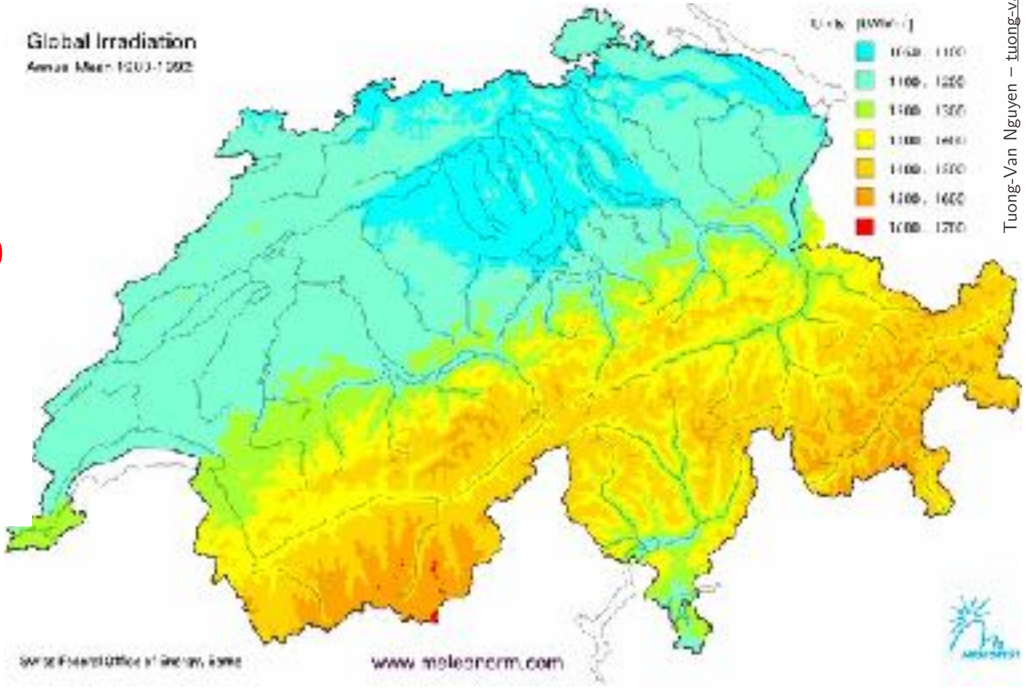
Annual irradiance: ~**1000-1300 kWh/m2**

=> 1000h equivalent solar hour (1000W/m2)

As comparison :

LHV_Diesel : 10 kWh/l

=> Switzerland can produce 100 L of diesel /m2 over the year!



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Energy on an inclined surface

Total radiation on inclined surface [W/m²]

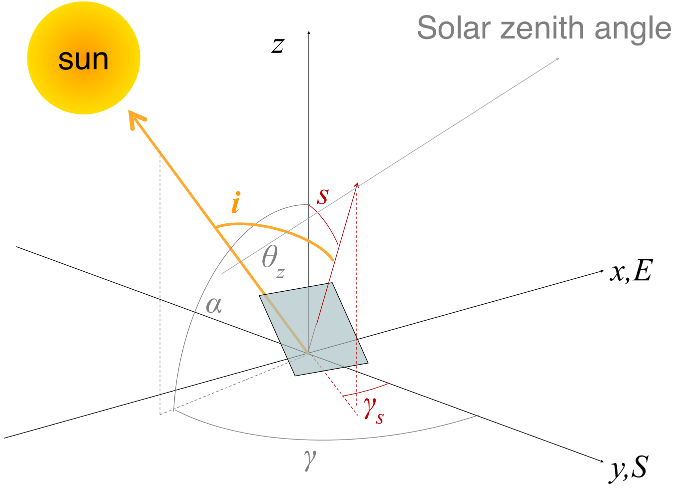
$$g_i = (d_i + b_i)$$

Beam component [W/m²]

$$b_i = DNI \cdot \cos(i)$$

Diffuse component [W/m²] (isotropy assumption)

$$d_i = \underbrace{d_h}_{GHI - DNI \cdot \cos(\theta_s)} \cdot 0.5 \cdot (1 + \cos(i))$$

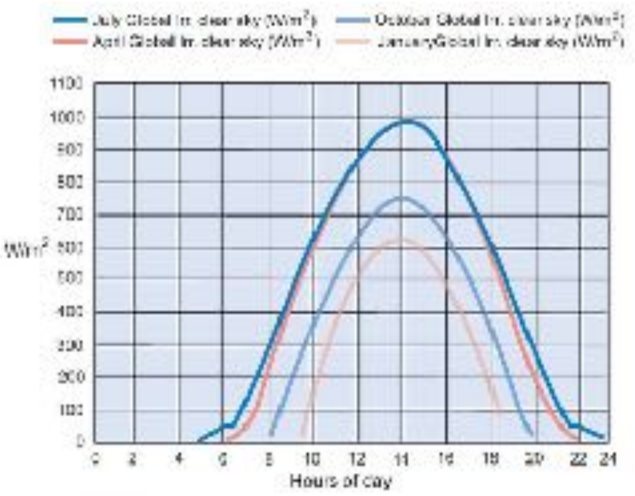


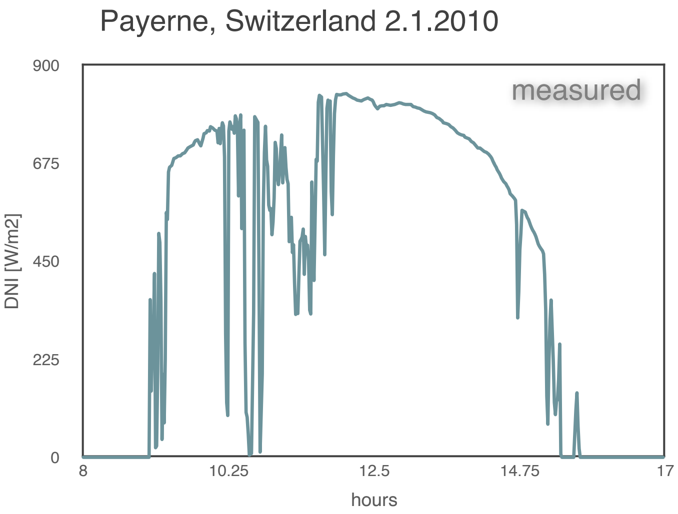
Source: J.E. Hay & D.C. McKay, "Estimating Solar Irradiance on Inclined Surfaces: A Review and Assessment of Methodologies", Int. J. of Sol. Eng., 1985

Transience in solar radiation

Daily

- Intermittance in between hours/minutes → buffer storage
- Variation between day and night → intra-day day storage



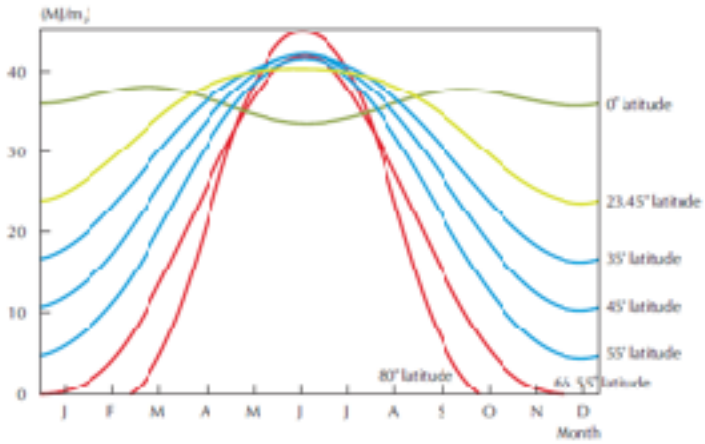


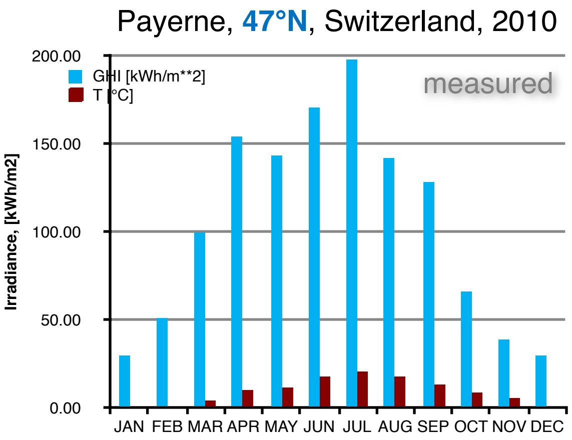
Source: „Solar Energy Perspectives“, IEA 2011, Baseline Surface Radiation Network (BSRN), http://www.pangaea.de/advanced/index.php

Transience in solar radiation

Seasonal

- At the **equator (0° latitude)** → lowest seasonal dependence
- The more extreme north (+°)/or south (-°), the higher the seasonal dependence

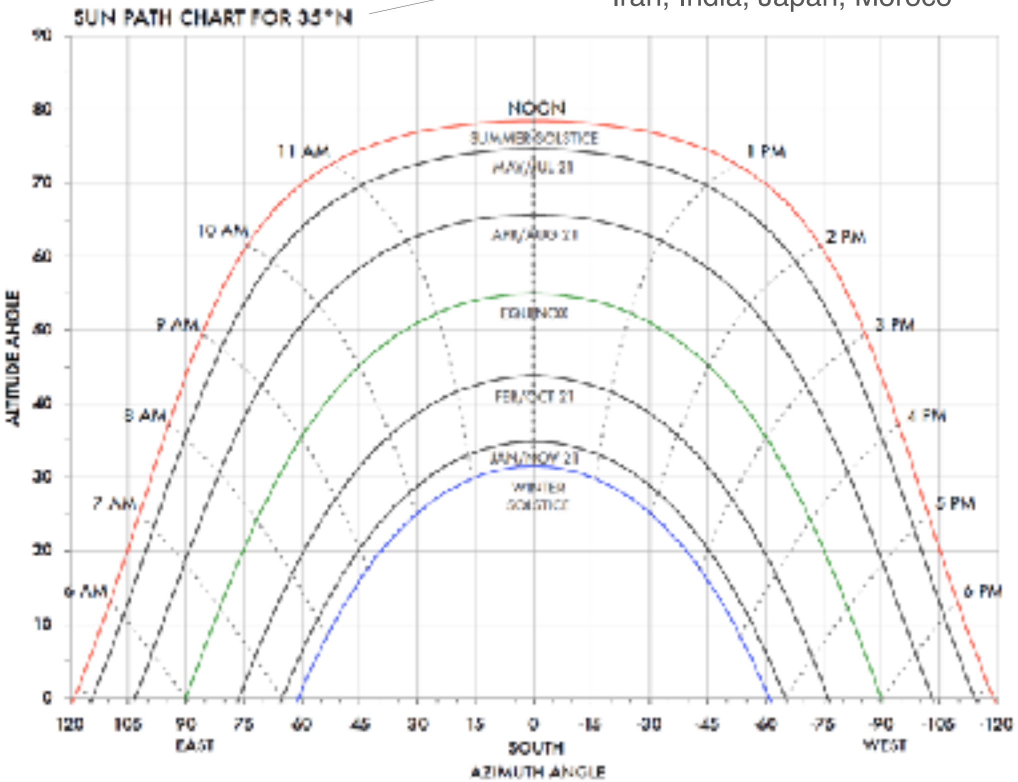




Source: „Solar Energy Perspectives“, IEA 2011, Baseline Surface Radiation Network (BSRN), http://www.pangaea.de/advanced/index.php

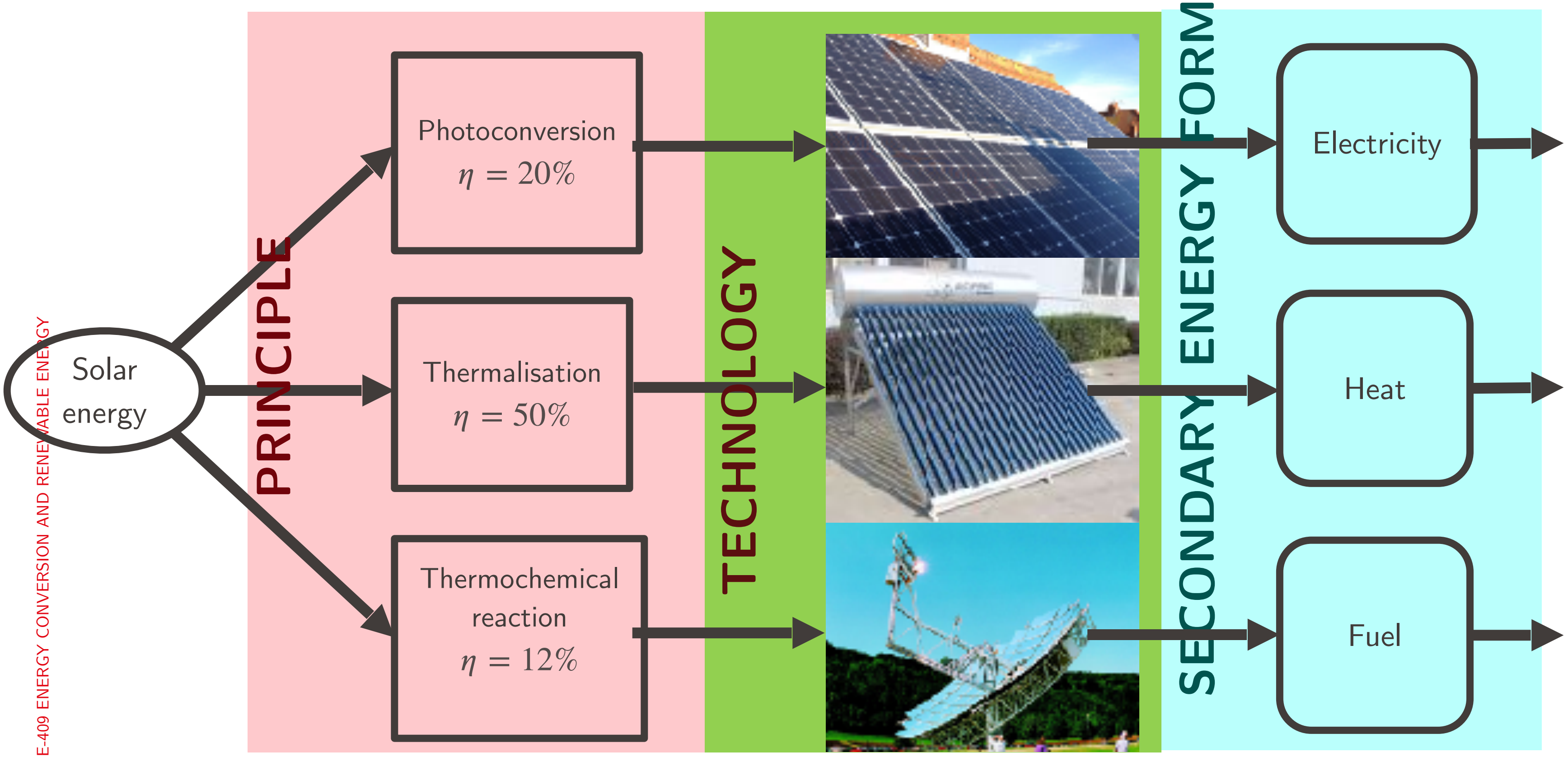
Solar path throughout the year

35° Northern parallel, countries: Algeria,Tunisia, Greece, Cyprus, Syria, Iraq, Iran, India, Japan, Moroco



Source: http://www.reevadiy.org/renewable_energy_tech.html

How to harvest solar energy



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Solar to Electricity

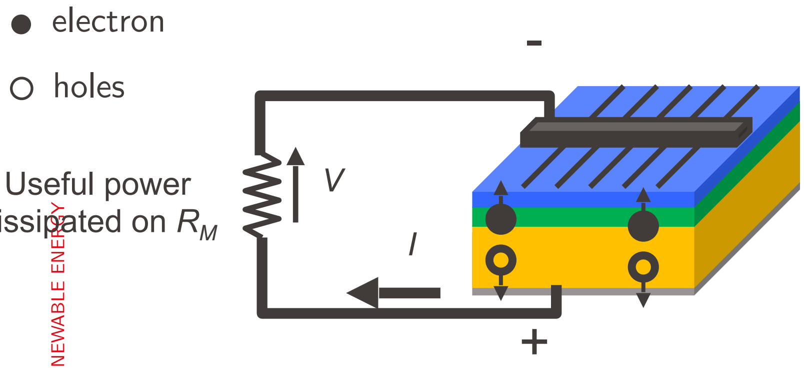
Semiconductor technology : Conversion

Solar cell modeling

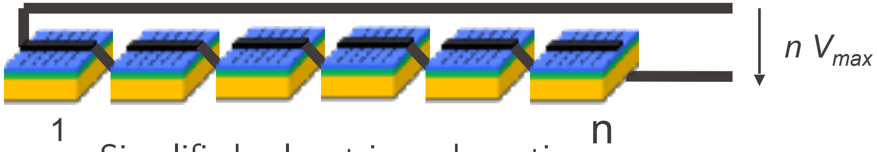
Solar modules manufacturing

Solar systems components

Basic principle



Simplified solar cell cross-section



Simplified solar string schematic

- Standard test condition:
- Ir = 1000W/m2
- T = 25°C
- E :measured power in this condition

efficiency : $\eta = \frac{E_{Peack} = VI}{Ir * S_{cell}}$

Increase voltage by connecting cells in series. The industrial standard is 60 or 72 cells in series.

=> V = 40-50V & I = 7

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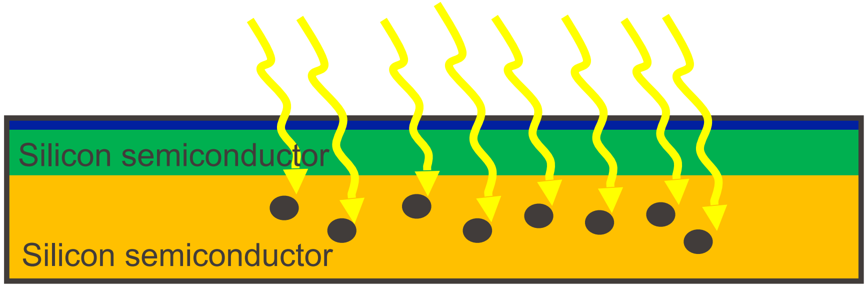
Semiconductors : the conversion key

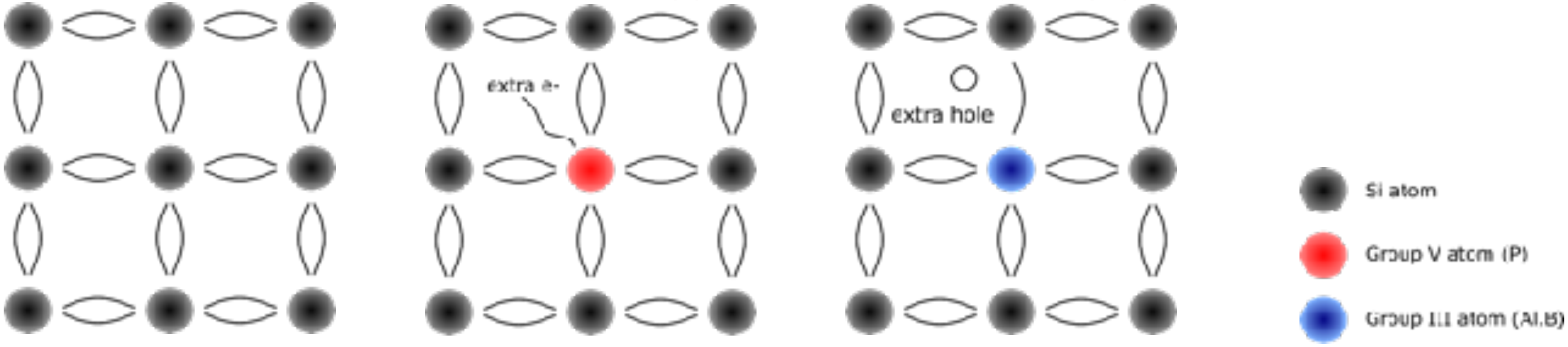
n−Type (-)

p−Type (+)



This is called a P-N junction!

Undoped Si | n−Type (-) | *p*−Type (+)



overall neutral | overall neutral with free electrons | overall neutral, with free holes

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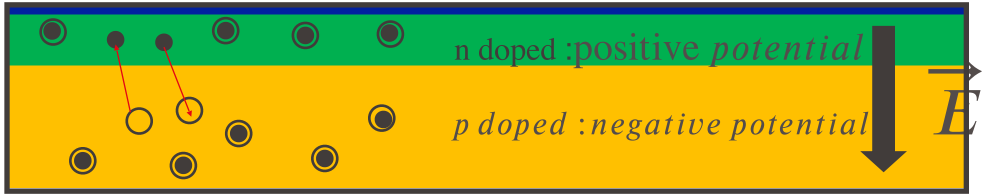
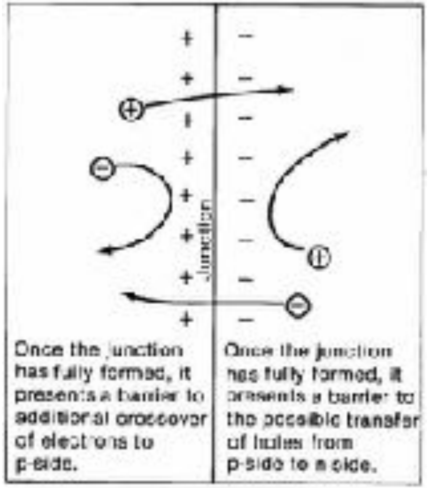
Semiconductors : the conversion key

n–Type (-)

p–Type (+)





n–Type (-) p–Type (+)

- Light can generate electron-hole pairs, if $h\nu > E_g$ (E_g: semiconductor bandgap)
- Electrons (Negative charges) have to travel to the n-side
- Holes (Positive charges) to the p-side
- The junction act as a barrier and filter out electron from holes

In a range at the n-p interface the charges will cancel out.
But overall an electric field is generated ACROSS the juntion

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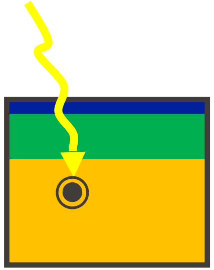
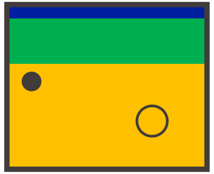
Semiconductors : the conversion key

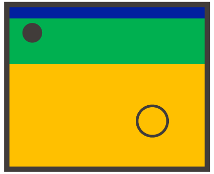
Step 1:
a photon hits an electron-hole pair



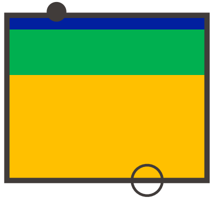
Step 2:
The electron and the hole split and move around



Step 3:
The electron gets dragged by the electic field of the P-N juntion



Step 4:
The electron and the hole are collected at the contacts



Note : this can happened in the p and n regions, it does not matter

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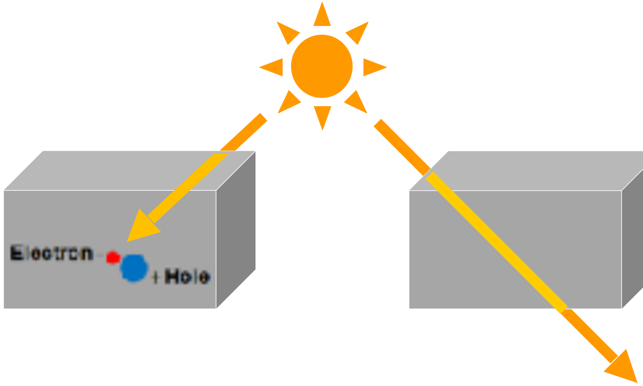
PV materials

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

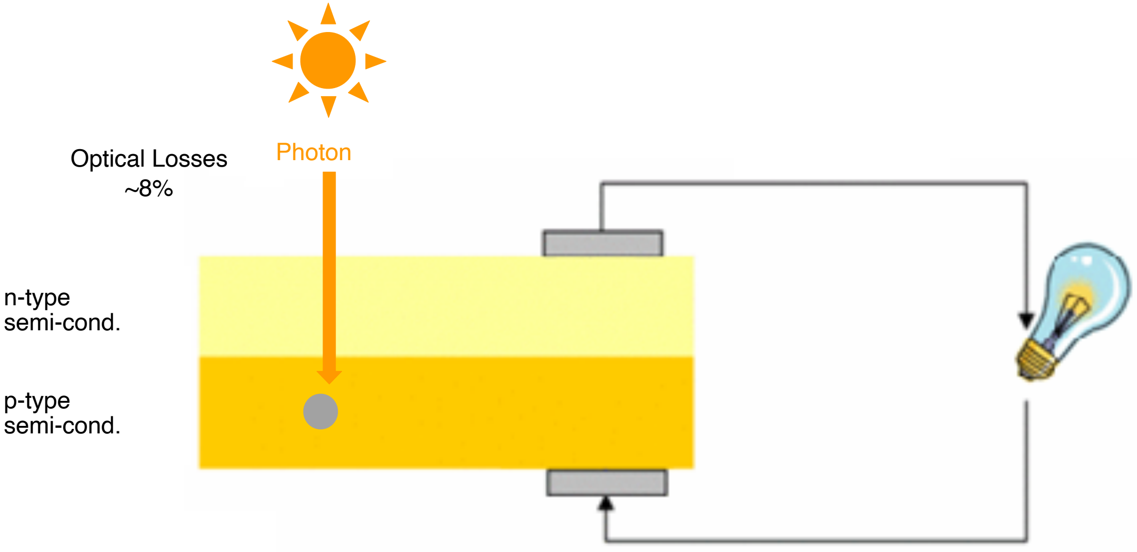
Material	E_{gap} [eV]
Silicon	1.11
Gallium arsenide	1.43
Aluminium-Gallium arsenide	1.70

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

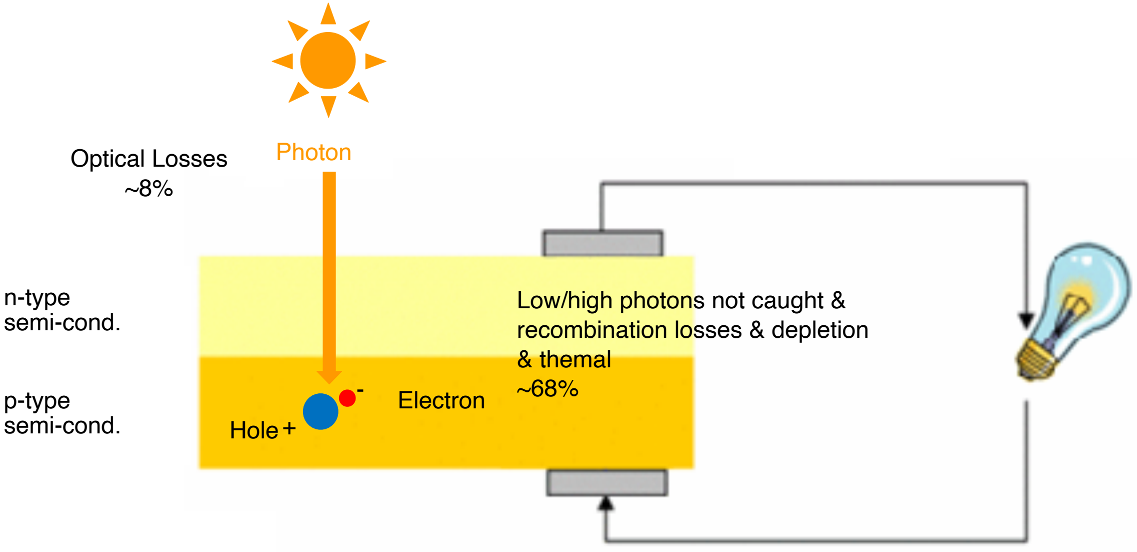
Photons with less energy pass through the material without PV effect



Working principle of a photovoltaic cell



Working principle of a photovoltaic cell



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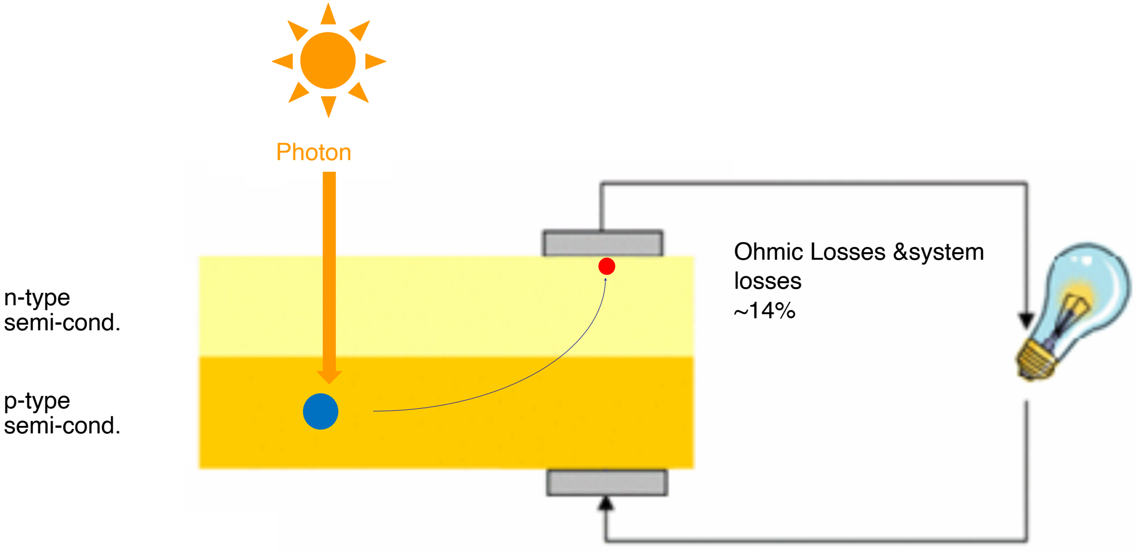
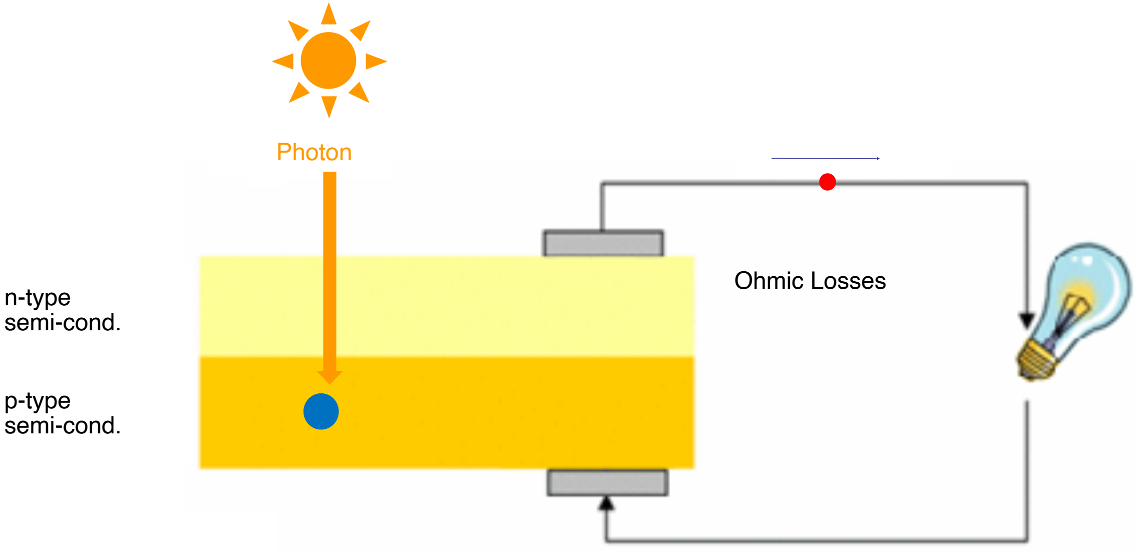
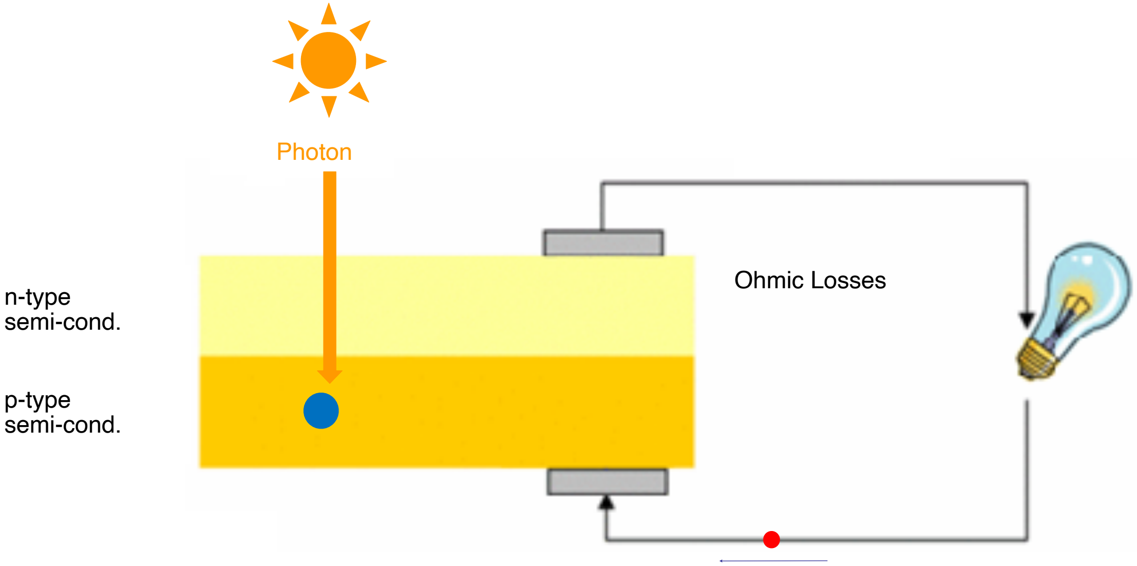


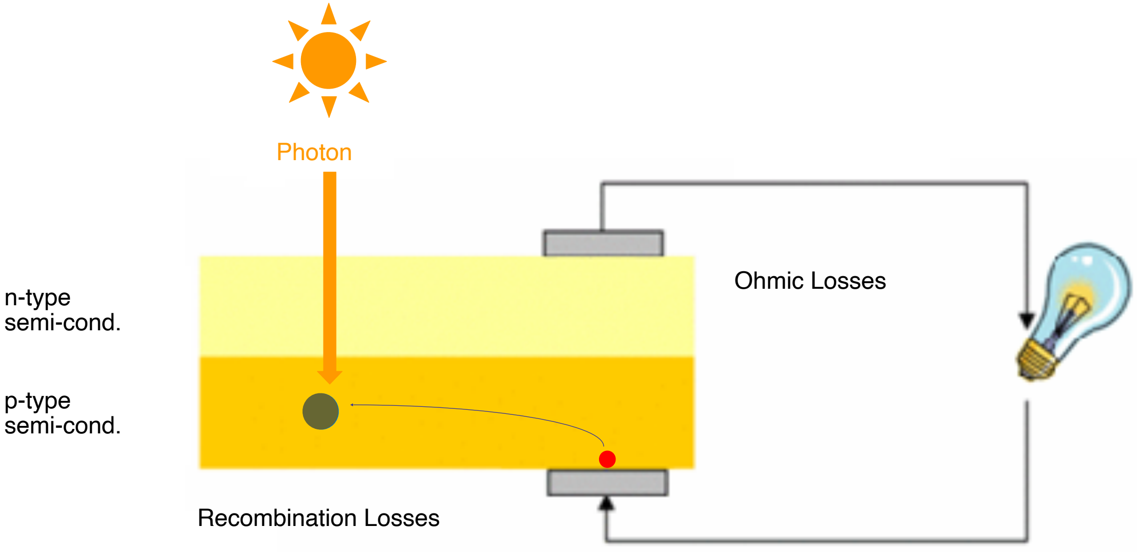
Working principle of a photovoltaic cell



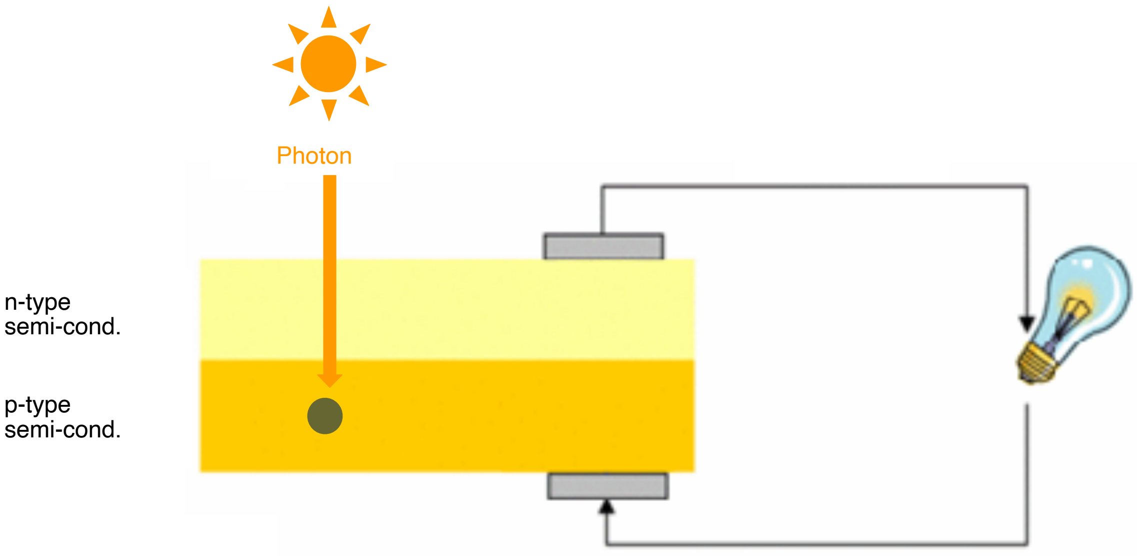
Working principle of a photovoltaic cell



Working principle of a photovoltaic cell

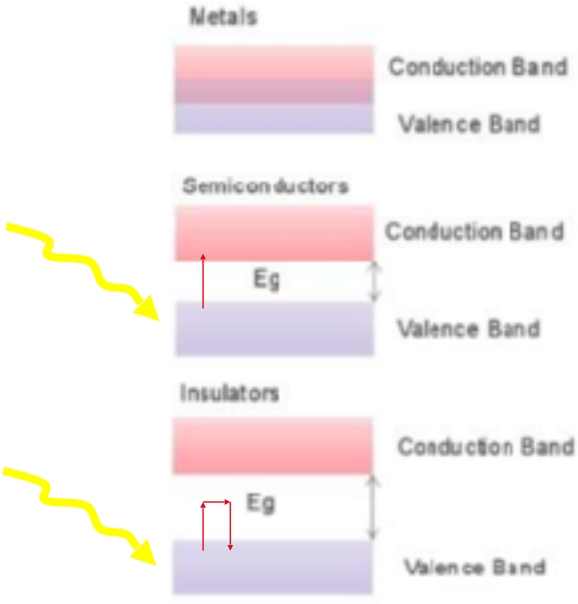


Working principle of a photovoltaic cell

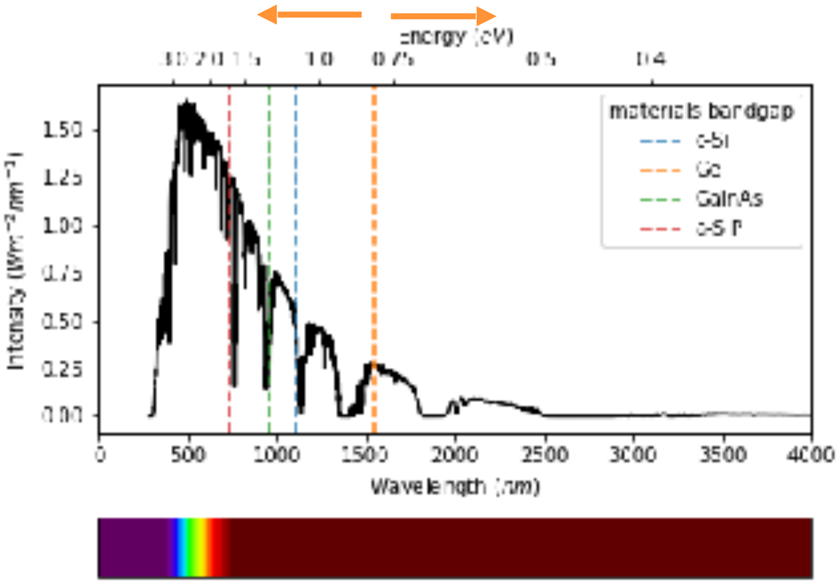


Semiconductors : the conversion key

- The trick is : not every photon can split an electron hole pair
  - The photon needs to have an energy superior to the band-gap (Eg) of the semiconductor
  - For an insulator, the gap is so large, no «earth» photons can provide enough kick to split an e-h pair



absorbed
not-absorbed



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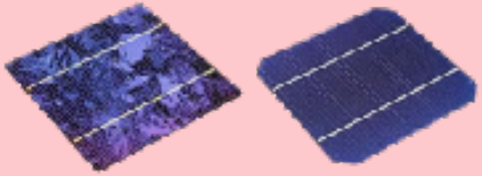
Solar photovoltaic technologies

All based on the same semiconductor principles : Some with different materials, different manufacturing methods…

Crystalline Silicon



Polycrystalline

Monocrystalline

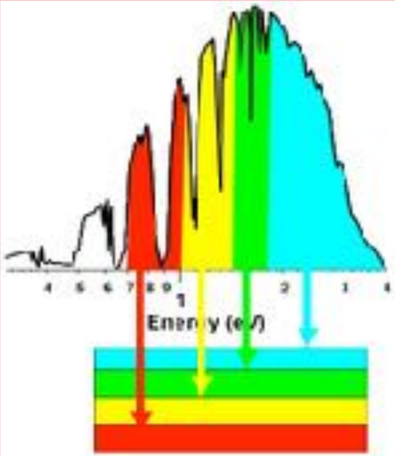
- IBC
- PERC/L/T
- Tilting ribbons…

Thin films

Thin-films

- CIGS
- CaTe

Multi-junctions



- III-V cells
- Stacks of cells

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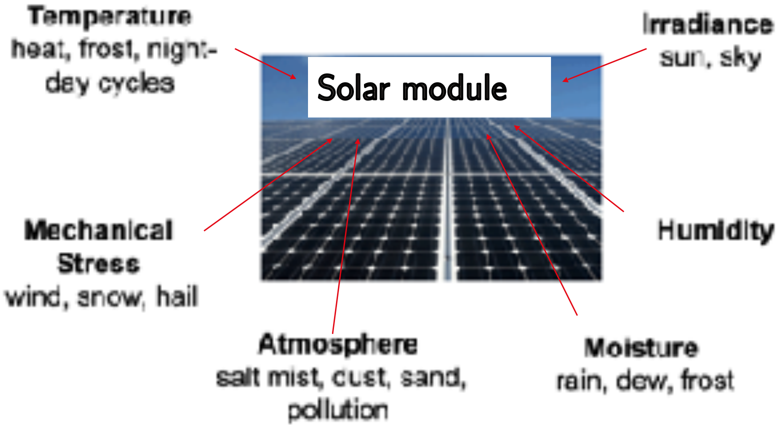
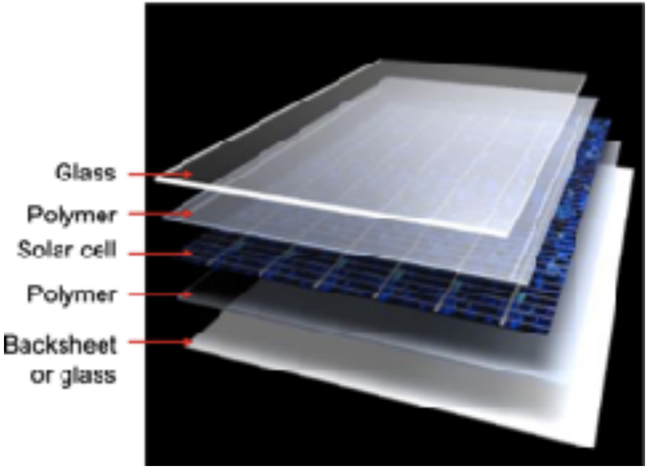
From cells to modules

- A solar cell in its own is very thin (250um) and very brittle. To protect it, ensure long term usage and sa we encapsulate them in modules



Crystalline PV lay-up : the active component is sandwiched between two polymeric encapsulants.



The stack is then laminated up to 200°C to seal the module.

- WARNING: Poor encapsulation and lamination is a MAJOR cause of failure (yellowing, humidity protection, delamination....)

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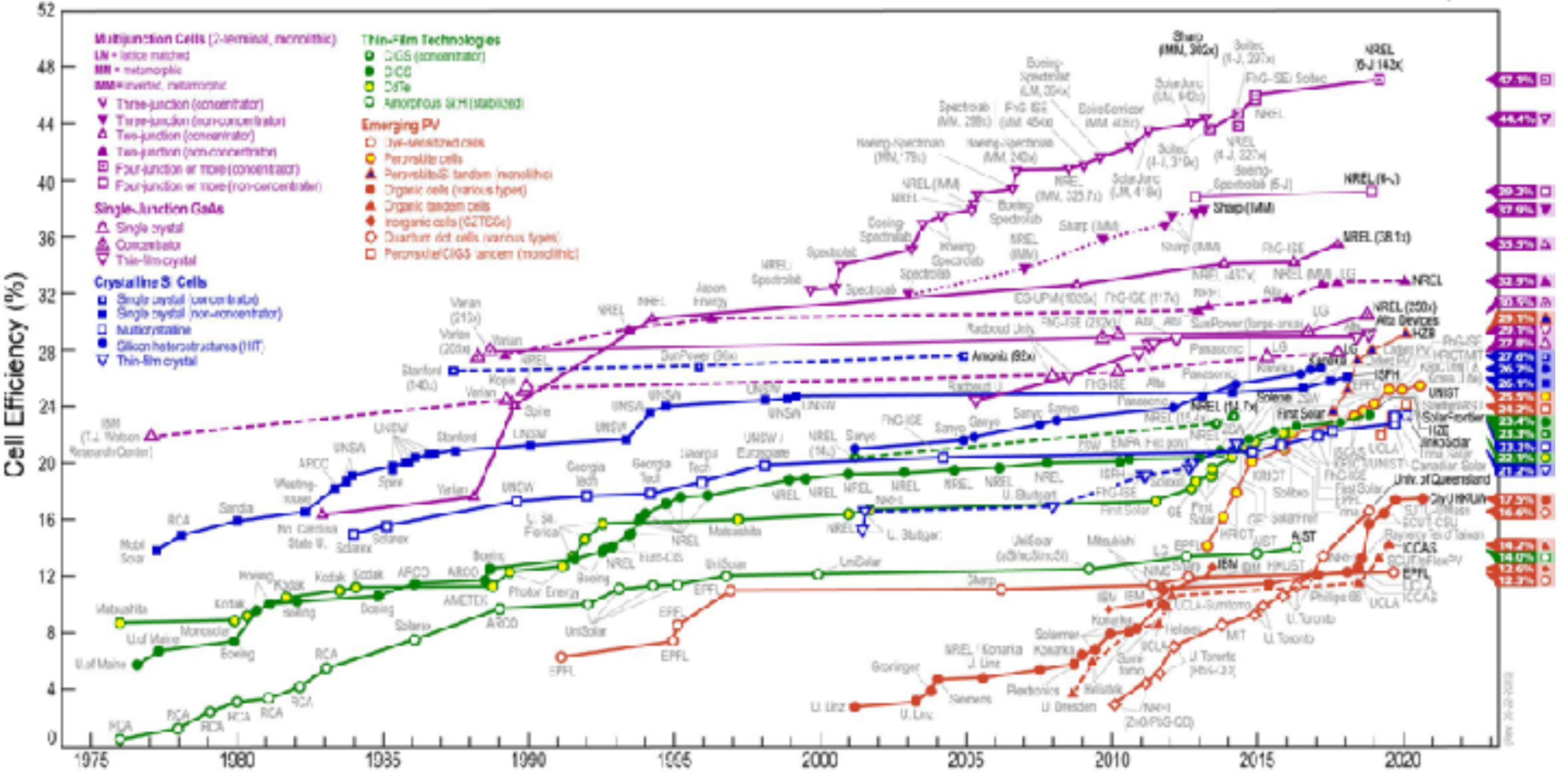
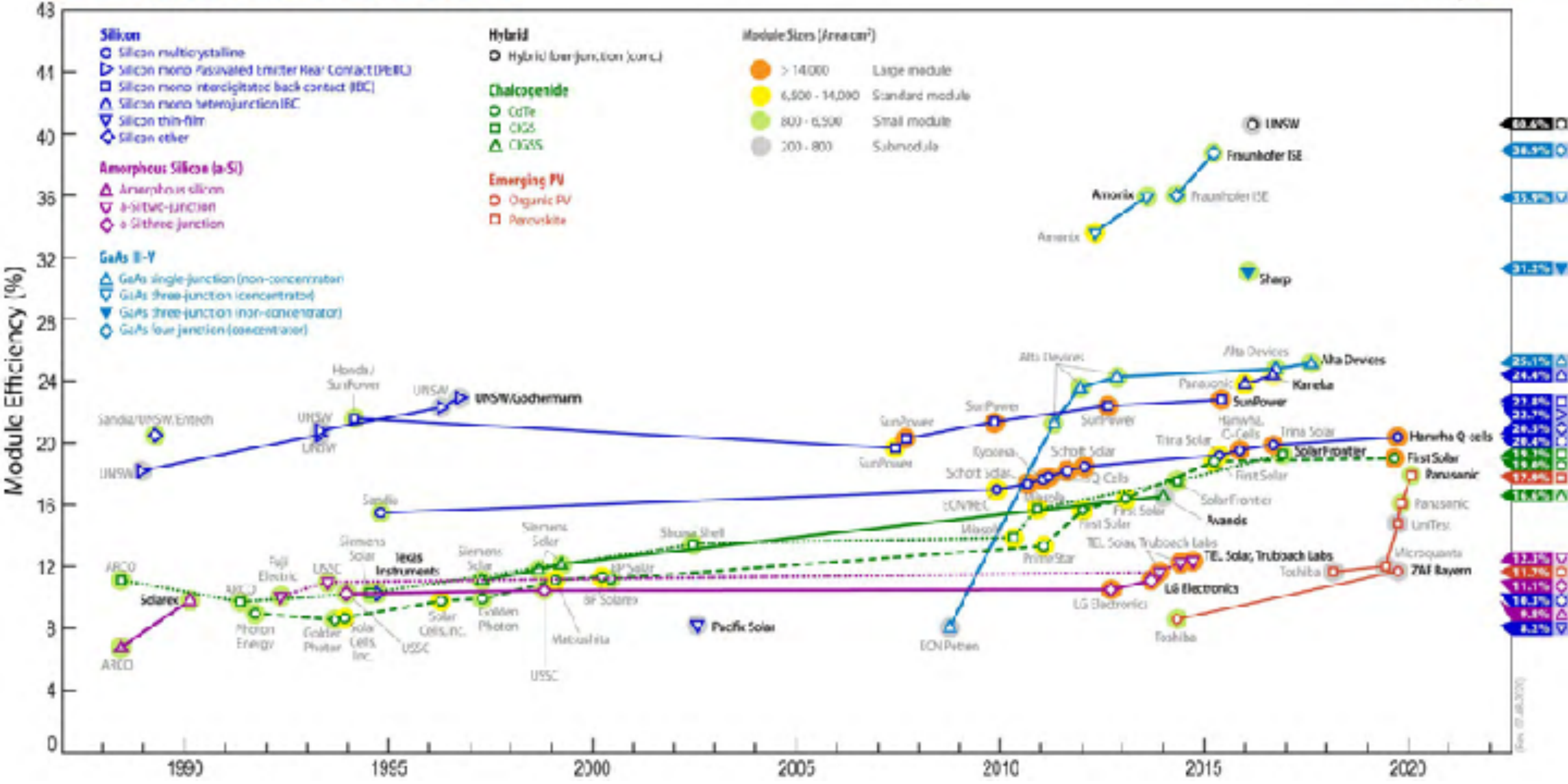
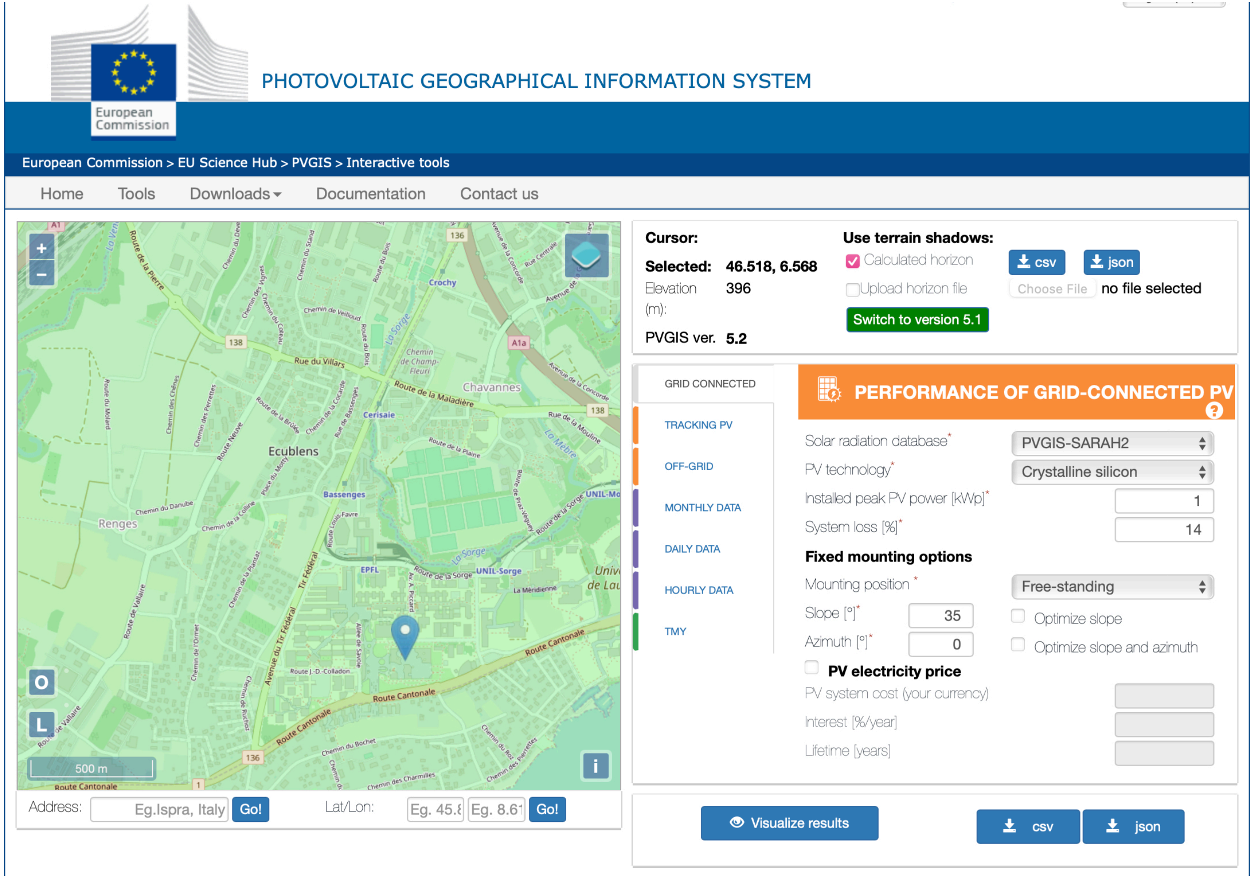
Best Research-Cell Efficiencies



Champion Module Efficiencies



PVGIS : https://re.jrc.ec.europa.eu/pvg_tools/en/



PVGIS : https://re.jrc.ec.europa.eu/pvg_tools/en/

PERFORMANCE OF GRID-CONNECTED PV: RESULTS

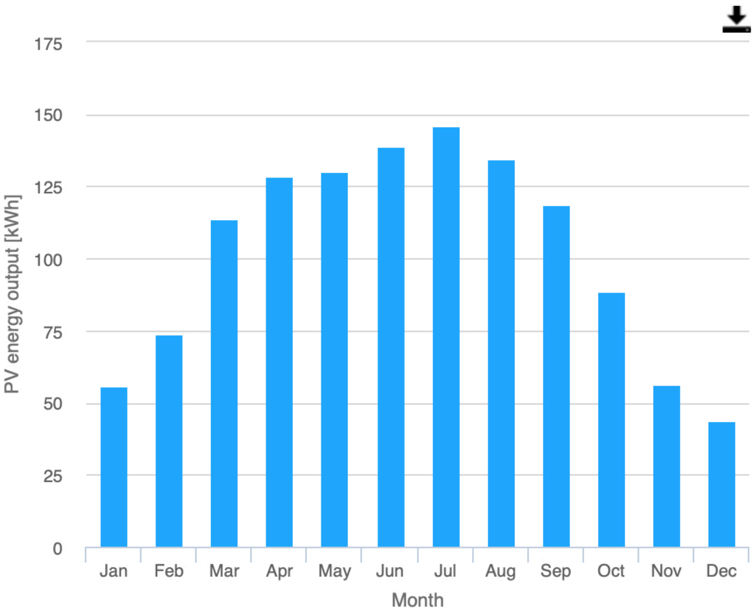
PV output | Radiation | Info | PDF

Summary

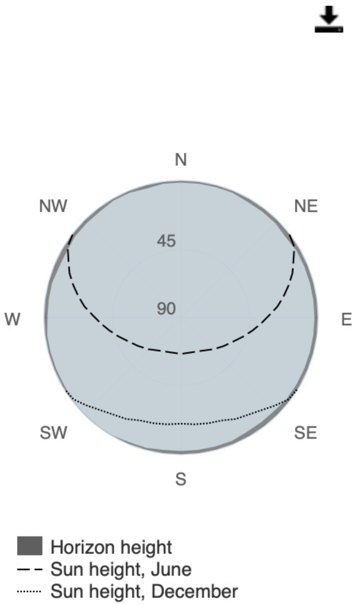
Provided inputs:	
Location [Lat/Lon]:	46.518,6.568
Horizon:	Calculated
Database used:	PVGIS-SARAH2
PV technology:	Crystalline silicon
PV installed [kWp]:	1
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	35
Azimuth angle [°]:	0
Yearly PV energy production [kWh]:	1228.61
Yearly in-plane irradiation [kWh/m^2]:	1560.63
Year-to-year variability [kWh]:	56.46
Changes in output due to:	
Angle of incidence [%]:	-2.76
Spectral effects [%]:	1.27
Temperature and low irradiance [%]:	-7.04
Total loss [%]:	-21.27

Monthly energy output from fix-angle PV system



Outline of horizon



Solar photovoltaic systems efficiency

Characteristics

Efficiency decreases with increasing cell temperature (thermal losses) & radiation

Electrical power output

$$\dot{E}[W] = \underbrace{\eta_{el}(T_{cell})}_{\text{thermal efficiency}} \cdot \underbrace{g_i\left[\frac{W}{m^2}\right]}_{\text{Radiation on inclined surface}} \cdot \underbrace{A_{coll}\left[m^2\right]}_{\text{Surface area of collector}}$$

Average electrical power ouput

$$\bar{\dot{E}}[W] = \bar{\eta}_{el} \cdot GHI\left[\frac{W}{m^2}\right] \cdot A_{coll}\left[m^2\right]$$

Efficiency

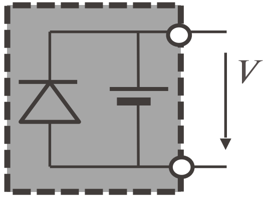
$$\eta_{el}(T_{cell}) = \eta_{25°C} \cdot \underbrace{\left(100\% - f_{200W/m^2} \cdot \left[1 - \frac{GHI - 200W/m^2}{800W/m^2}\right]\right)}_{\text{Correction factor for GHI < 1000W/m}^2} \cdot \underbrace{\left(1.0 + c_{x°C}^{PV} \cdot \left(T_{x,cell}^{PV} - T_{NOCT}\right)\right)}_{\text{Correction factor for cell temperature above norm}}$$

Manufacturer		Suntech [1]	Yingli Solar [2]	
Country		*China*	*China*	
Base material (coating)		*Polycrystalline Si*	*Multicrystalline Si*	*Monocrystalline Si*
Product specification		*STP305 – 24/Ve*	*YL210-P-23b / YL310-P-23*	*YL280C-30b*
Module size [mm x mm]	$A_{module} = H_{module} \times W_{module}$	*1956 x 992 (x 40)*	*1310 x 990 (x 40) / 1970 x 990 (x40)*	*1650 x 990 (x 40)*
NOCT [°C] [3]	T_{NOCT}	*45 +/- 2*	*46 +/- 2*	*46 +/- 2*
Rated power [W_{mpp}] [4]	P_{mpp}	*305*	*210 / 310*	*280*
Cell efficiency [%]	$\eta_{25°C}$	*15.7*	*16.2 / 15.9*	*17.1*
Efficiency depreciation at GHI = 200 W/m² [$\%_{rel}$]	$f_{200W/m2}$	*4.5*	*5.0*	*3.5*
Temperature dependency [- / °C]	$c_{x°C}$	*-0.0043*	*-0.0045*	*-0.0042*

[1] http://www.suntech-power.com/images/stories/pdf/brochures_2013/EN/STP%20285-305%20Ve(poly)_EN_web.pdf
[2] http://www.yinglisolar.com/assets/uploads/products/downloads/DS_PANDA60Cell-30b_DE_DE_B&B_201212_v02.20-new.pdf
[3] Nominal Operating Cell Temperature (NOCT). 20°C $T_{ambient}$, 800 W/m2, DIN EN 60904-3
[4] Standard Conditions (STC): 25°C T_{cell}, AM 1.5 Spectra, 1000 W/m2, DIN EN 60904-1

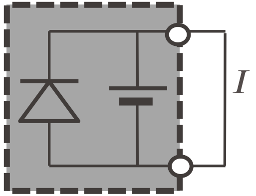
Solar cell & module characterization

- In first approximation, a solar cell behaves as a diode:
  1. It shows a highest potential but no current
     - no electrons cross the junction, but they really want to
  2. It shows a highest current but no potential
     - All electrons cross freely the junction
  3. It shows some potential and some current but not at max values



Open-circuit conditions

$I = 0 \Rightarrow V = V_{oc}$

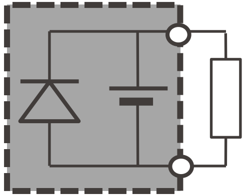


Short-circuit conditions

$V = 0 \Rightarrow \; I_{sc} \equiv -I_{ph} \approx 35\frac{mA}{cm^2}$

For a standard a=156mm cell:

$I_{sc} \approx 8A$



R_{MPP} Ideal power dissipation on R_{MPP}

$R_{MPP} = V_{MPP}/I_{MPP}$

This directly comes from the P-N junctions

- Electrons can go to the n-side but not back to the p-side (max potential, but no current)
- In other words, the current can only go in one direction

- https://www.youtube.com/watch?

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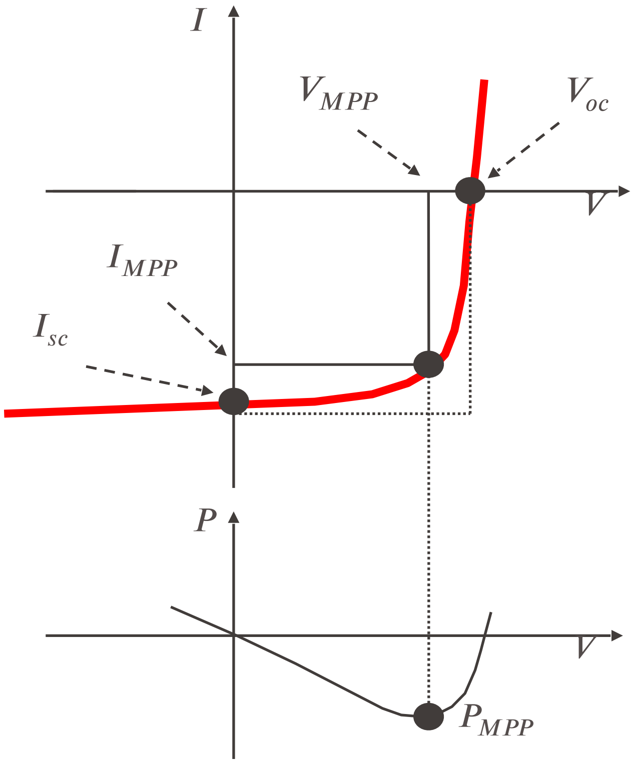
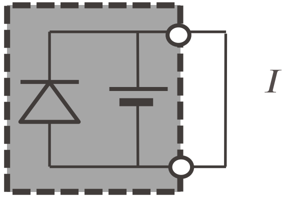
Solar cell & module characterization

$$I_{Load} = I_D - I_{ph} = I_0\left[\exp\left\{\frac{qV}{kT}\right\} - 1\right] - I_{ph}$$





Short-circuit conditions

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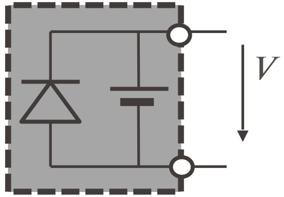
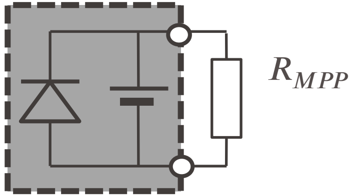
For a standard 156mm cell: $I_{sc} \approx 8A$



Open-circuit conditions

$I = 0$ => $V = V_{oc}$



Ideal power dissipation on R_{MPP}

$R_{MPP} = V_{MPP}/I_{MPP}$

Fill factor (FF) : $FF = \dfrac{P_{MPP}}{I_{sc}V_{oc}} = \dfrac{I_{MPP}V_{MPP}}{I_{sc}V_{oc}}$

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System component : Maximum Power Point Tracker (MPPT)

For the moment, we did not consider how to extract power from solar cell (ie. what happens after the charges are collected at the contacts)

- In order to extract a maximum of power, we need an MPPT : Maximum Power Point Tracker

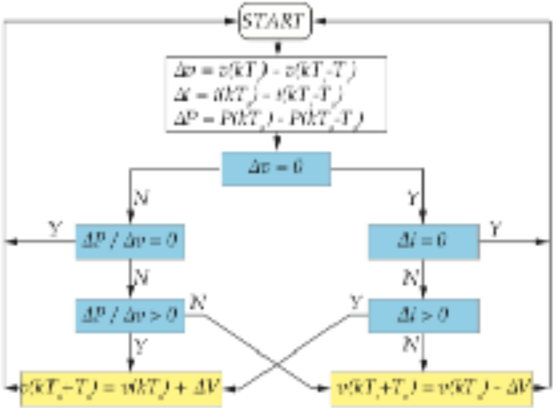
The MPPT will ensure max power output, for whatever outdoor conditions.

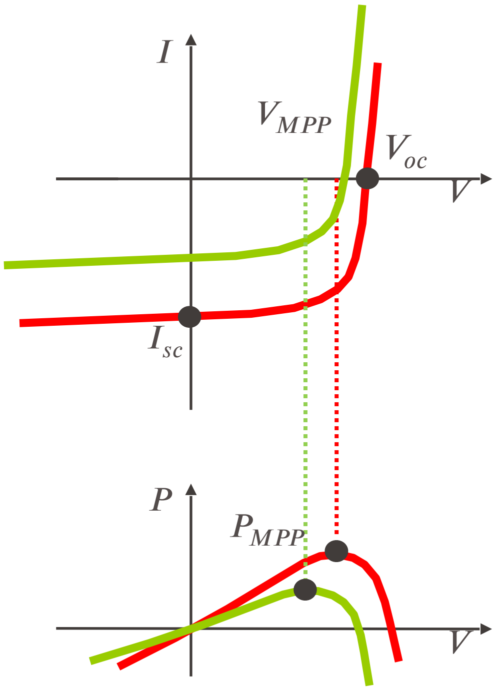
- Irradiance effect

$$\text{Irr} \nearrow \;\Rightarrow \text{I}_{\text{sc}} \nearrow,\; V_{oc} \approx \nearrow \;\Rightarrow P_{MPP} \nearrow$$

- Temperature effect:

$$T \nearrow \;\Rightarrow I_{sc} \nearrow, V_{oc} \swarrow \;\Rightarrow P_{MPP} \searrow \;\text{(for c-Si)}$$





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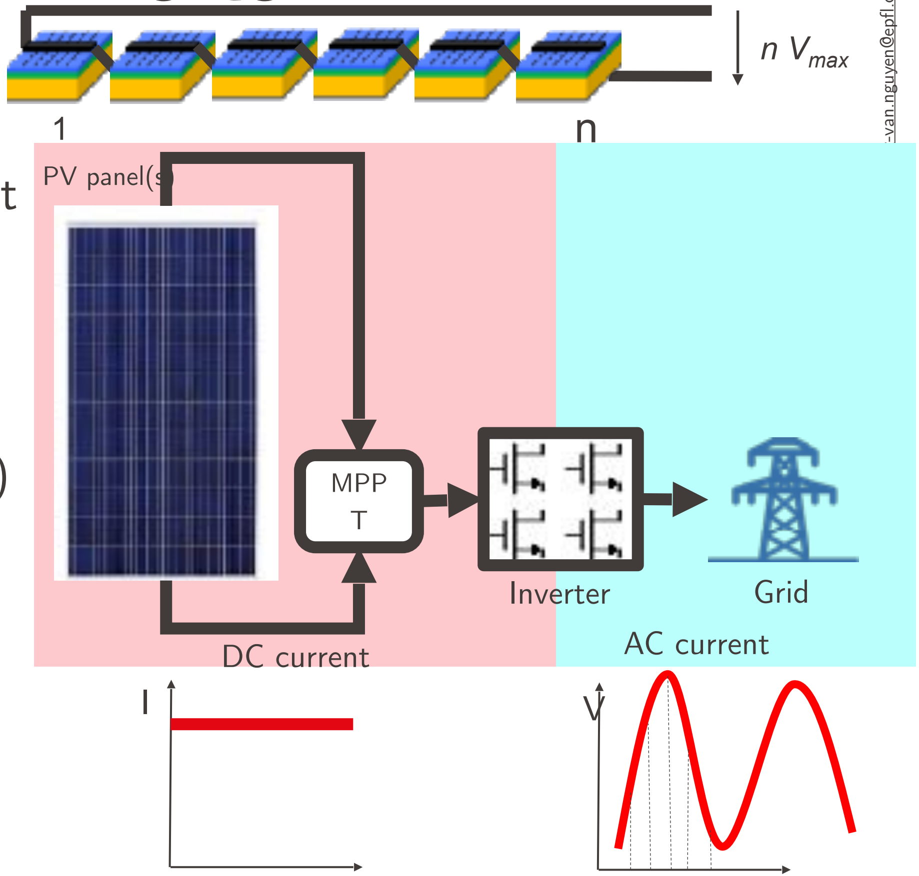
System component : Inverter

Coupling PV panels to the grid with converter

- Converts DC current from PV to AC current of the grid
- Usually attached and coupled with the MPPT
- Measure the voltage on the grid (high freq.) then inject current synchronously
- Have shorter lifetime than PV array
  - 15 years vs 25-30 years



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Solar photovoltaic systems

Flat plate PV

Cristalline silicon

Share of 2008 market

85-90%

- **Materials:** single-cristalline (sc-Si), multi-cristalline (mc-Si)
- **Efficiency** : 14-40% (sc-Si), 13-15 (mc-Si)
- **Cost** : 400-500$/m²
- **Advantages** : proven, high efficiency
- **Challenges** : Capex decrease

Thin film

10-15%

- Thin film silicon, CIGS ($Cu(In,Ga)_2Se$), CdTe
- 6-9% (a-Si), 9-11% (CdTe), 10-21% CIGS
- 250-400$/m²
- (Si) Lower cost, unlimited supply; (CdTe) «simple manifacture», medium efficiency; (CIGS) highest thin film eff
- (Si) medium eff; (CdTe) Te availability; (CIGS) difficult processing

Organic

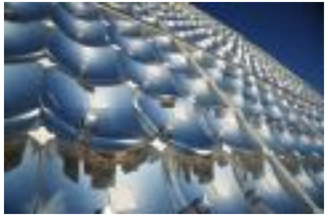
<1%

- Dye sensitized solar cells (DSSC) *@ EPFL from Prof. Grätzel in 1990*
- 3-5% (DSSC)
- 50-200$/m²
- Low-cost, abundant material (TiO_2) porous nano-layer, colorful (esthetic)
- Not yet large scale production, lifetime

- LCOE : 18-36 ct$/kWh$_{el}$

Concentrating

CPV



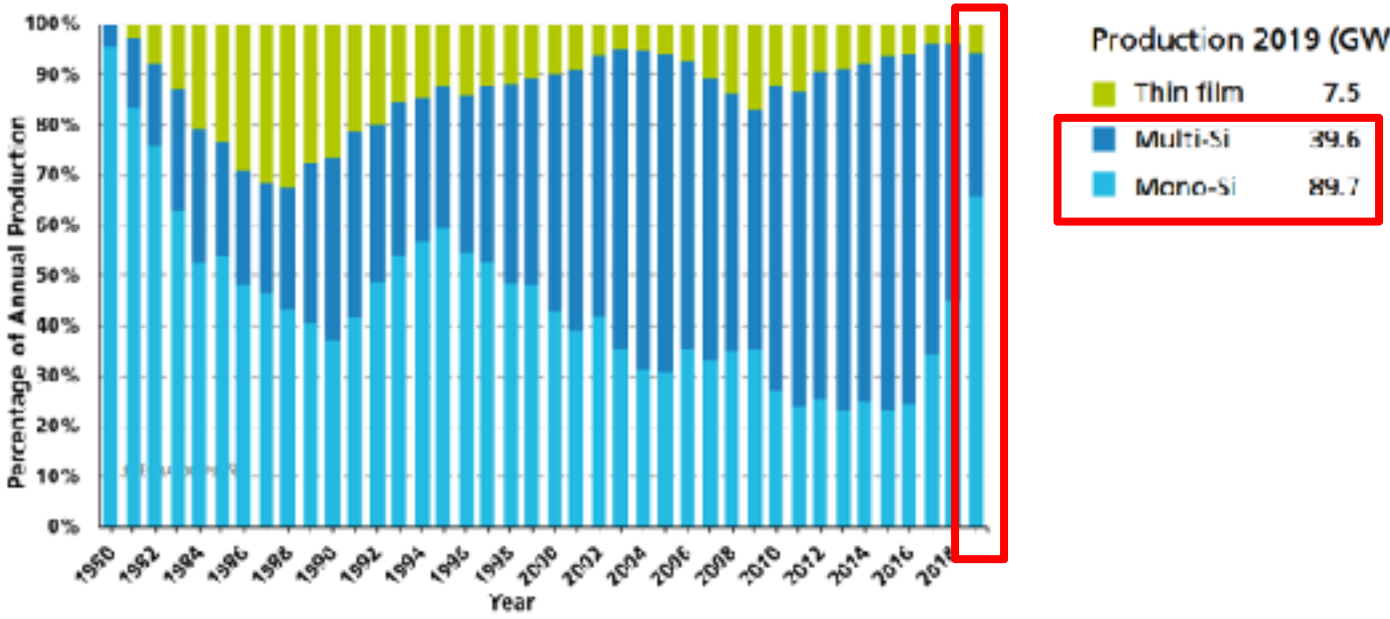
<1%

- Usually triple junction high-efficiency cells (based on c-Si, Ge, InGaP, Ga,As, InGaAs)
- 30-40%
- 550-700$/m²
- Highly efficient, can be combined with thermal energy harvesting
- Costly, Regions with high DNI

- LCOE : >18 ct$/kWh$_{el}$

Source: "Technology Roadmap: Solar Photovoltaic Energy - 2014 edition", IEA, 2014,

PV production and Market



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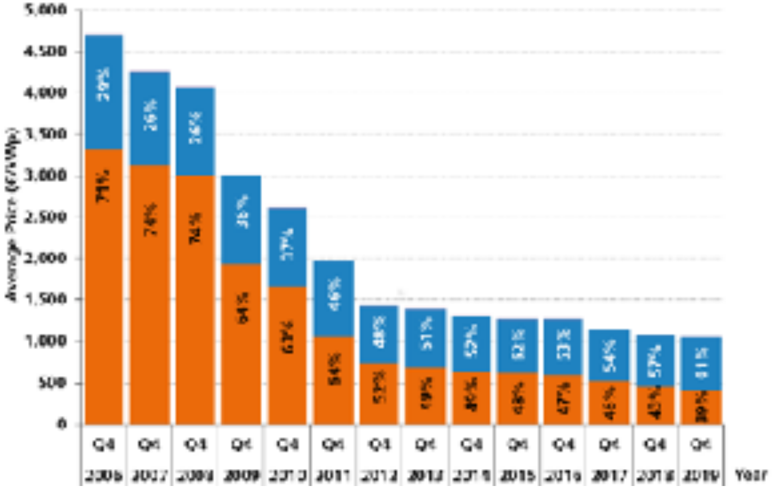
PV production and Market

	Lab eff	Industrial eff (Module eff)	Cost (CHF/W) (module level)
Mono c-SI	27%	24% (20%)	0.3
Multi c-Si	23%	20% (16%)	0.3
Thin films	23%	19 % (12%)	0.3
Multi-junctions	47%	41%	0.77

+ cost of inverter (0.3 CHF/W) (almost as much!)
+ installation cost

Still, the cost of solar decreases every year. !



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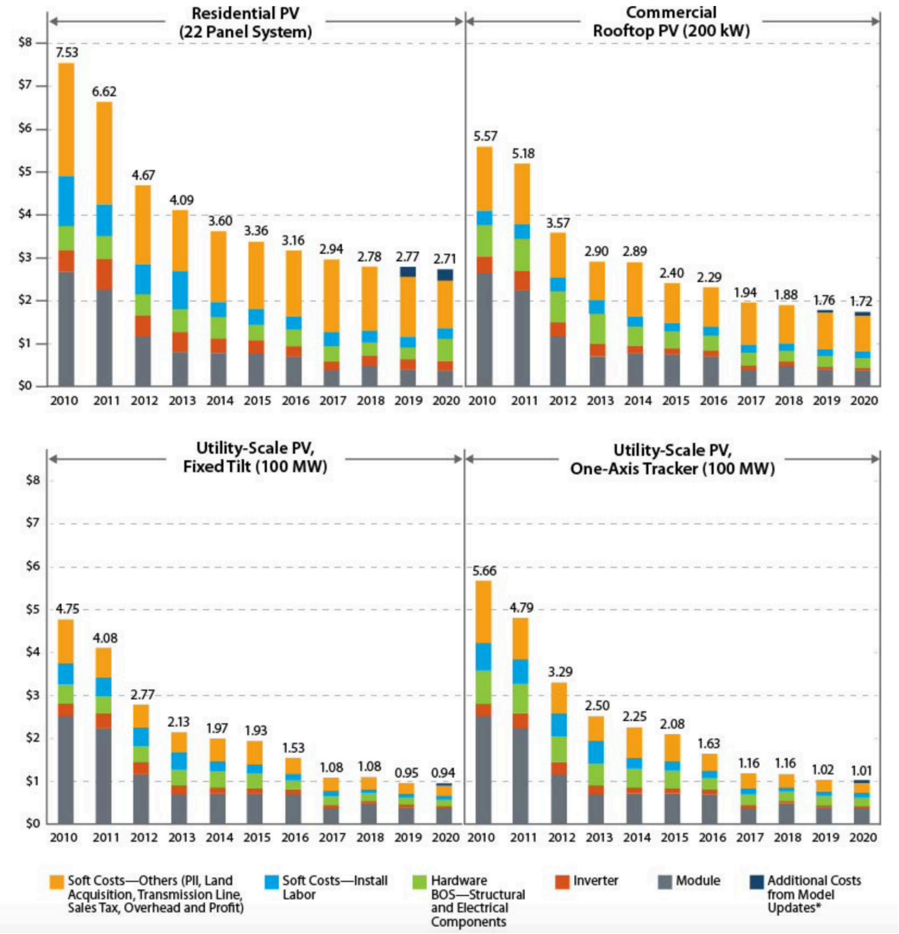
Cost of PV systems in USD/Wp



- Watt peak = area*efficiency*100
- calculated under standard conditions
  - light intensity is 1000 W/m2, with a spectrum similar to sunlight hitting the earth's surface at latitude 35°N in the summer (airmass 1.5), the temperature of the cells being 25 °C
- USD/DC Wp system cost

Feldman, David, Vignesh Ramasamy, Ran Fu, Ashwin Ramdas, Jal Desai, and Robert Margolis. 2021. U.S. Solar Photovoltaic System Cost Benchmark: Q1 2020. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77324. https://www.nrel.gov/docs/fy21osti/77324.pdf.

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Solar Systems

Self-consumption

System integration

Classifications

- There are mainly 3 classes of PV systems

Installed power

- Residential scale

[1-50 kWp]

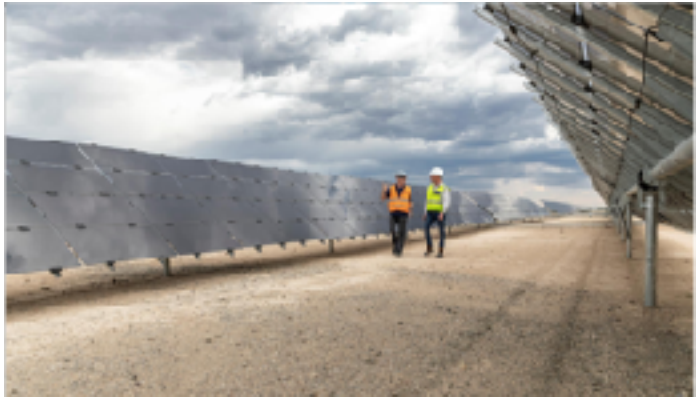
- Commercial/industrial scale

[1-10 MWp]

The EPFL Lausanne campus is the largest integrated solar park in Switzerland

- Utility scale

[0.1-10 GWp]



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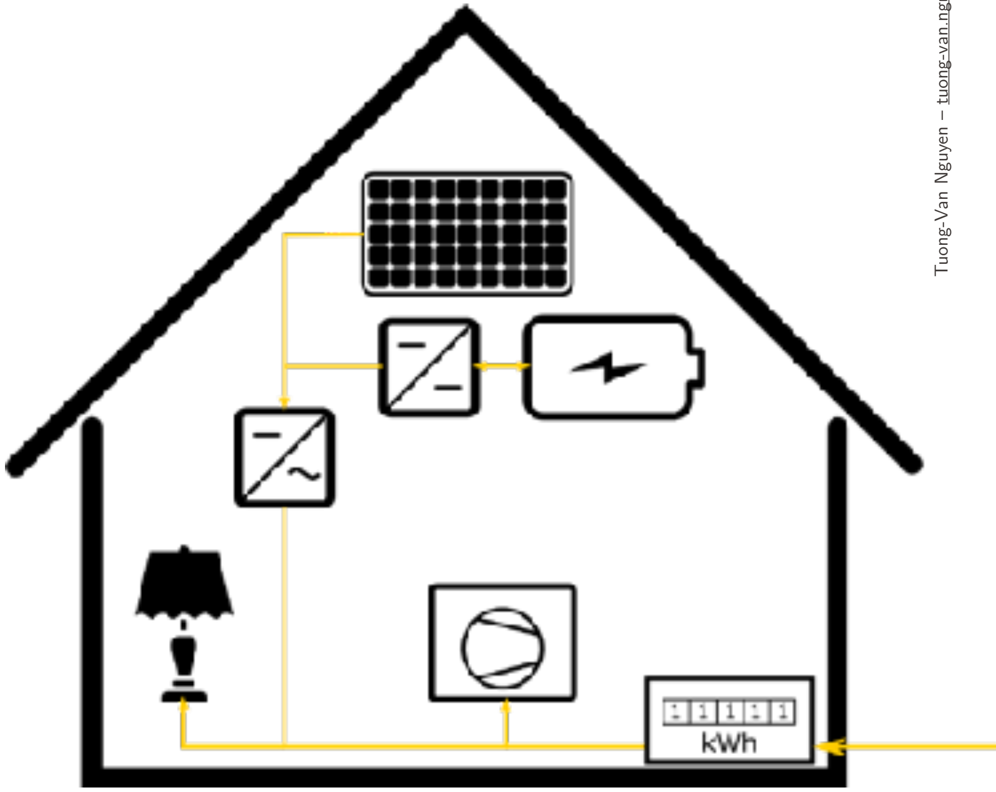
Behind the meter PV

- For residential and industrial scale only
- Best economic interest: use solar energy to cover own consumption
- A LOT harder than it seems !



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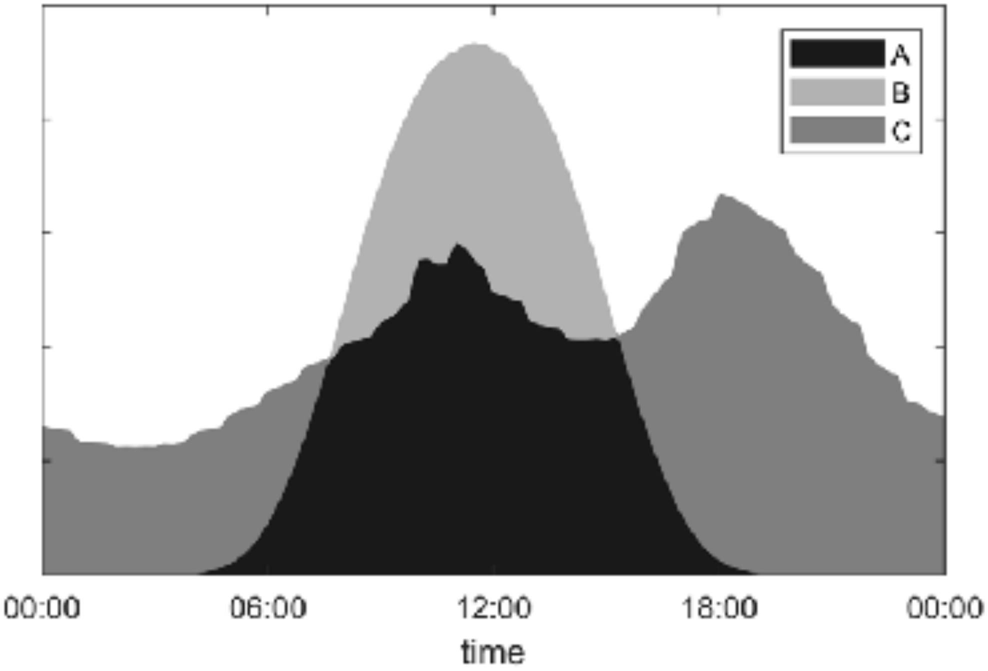
Behind the meter PV

Different concept

- *Self consumption*: you consume part of what you produce
- *Self sufficiency:* your produce part of what you consume
- *Autonomy* : you produce all you need, without need of the grid to buy of sell.
- *Neutrality* : over a year, you've produced what you have consumed



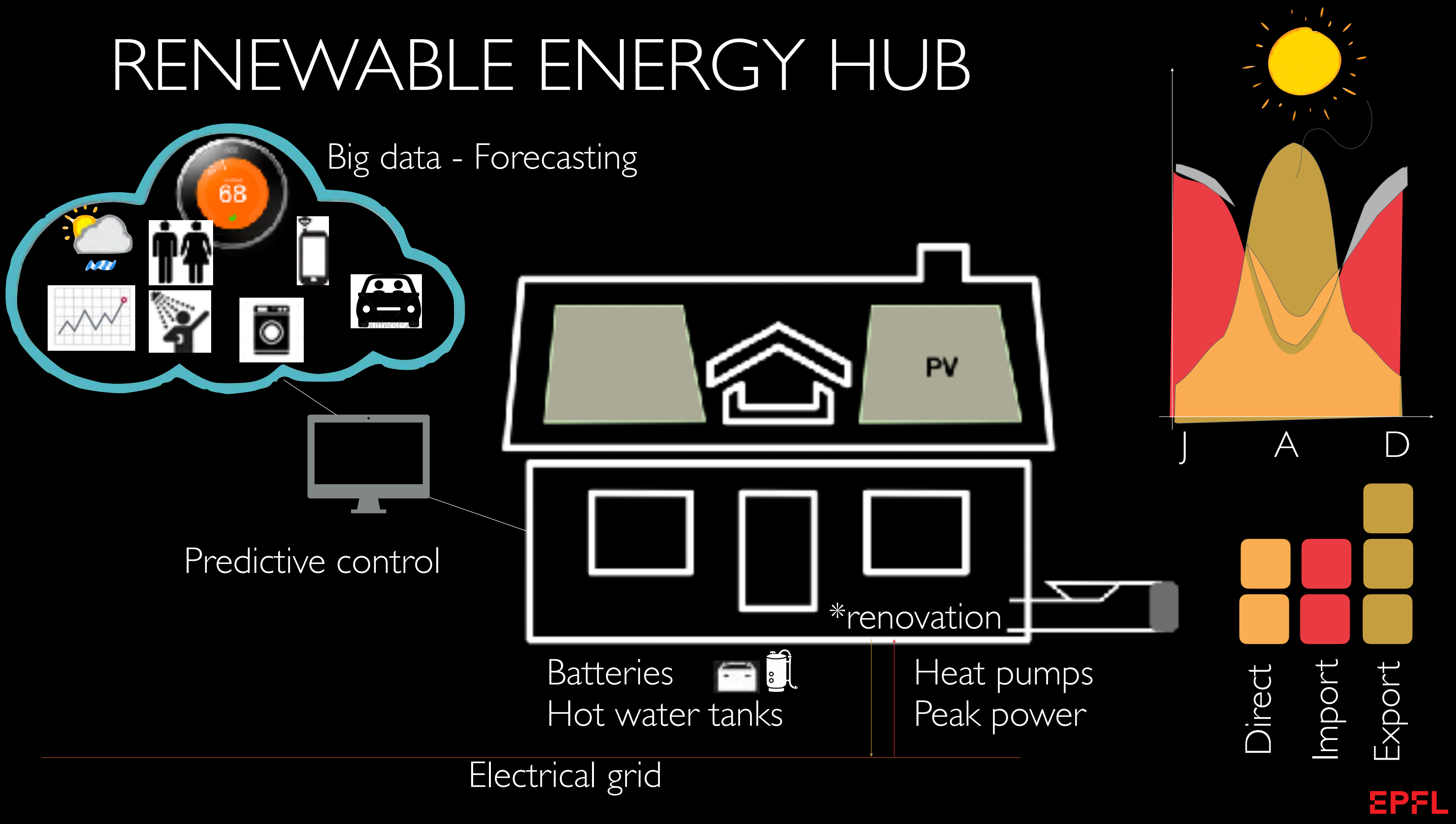
Self consumption: $\dfrac{A}{A+B}$

Self sufficiency: $\dfrac{A}{A+C}$

Autonomy: $C = \varnothing \Rightarrow$ no grid

Neutrality: $A + B = A + C$

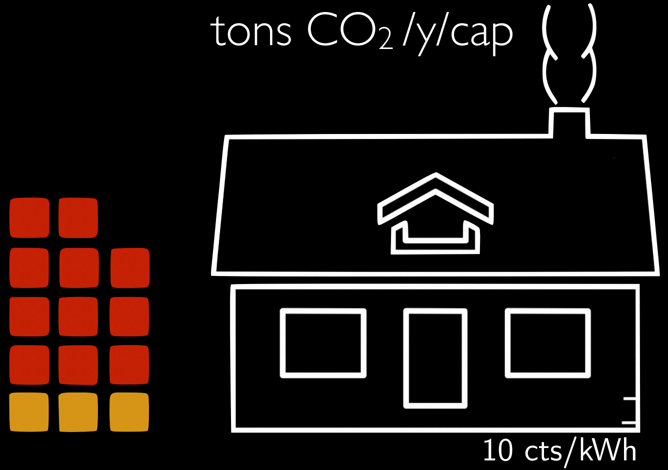
RENEWABLE ENERGY HUB



RENEWABLE ENERGY HUBS
75+ % CO2 EMISSIONS REDUCTION

1.10

tons CO_2 /y/cap

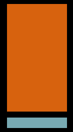


592

CHF/y/cap

Energy : **542** CHF/y/cap

Investment : **50** CHF/y/cap

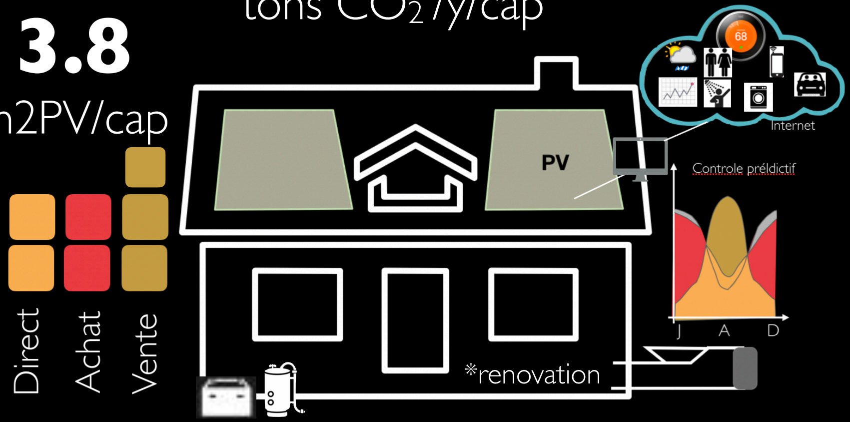


0.25 - 0.04

tons CO_2 /y/cap

3.8

m2PV/cap

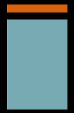


493

CHF/y/cap

Energy : **43** CHF/y/cap

Investment : **450** CHF/y/cap



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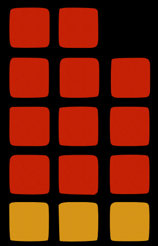
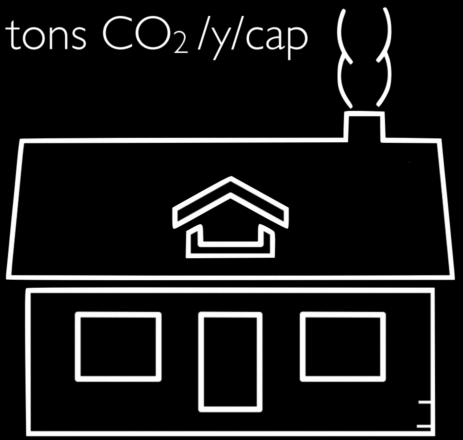
RENEWABLE ENERGY HUBS
75+ % CO_2 EMISSIONS REDUCTION

1.10

tons CO_2 /y/cap





10 cts/kWh

2022

1018

CHF/y/cap

Energy : **968** CHF/y/cap

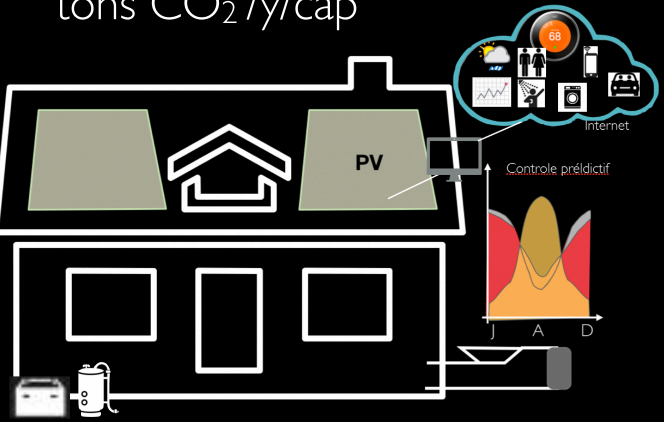
Investment : **50** CHF/y/cap

0.25 - 0.04

tons CO_2 /y/cap

3.8

m2PV/cap

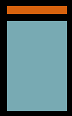


493

CHF/y/cap

Energy : **43** CHF/y/cap

Investment : **450** CHF/y/cap



EPFL

Implementation constraints on solar systems

- A set of examples from industrial applications

- In snowy countries, a frameless module will not retain snow in winter!

Here is the inverter, attached using the PV racks

- In windy countries, fixation is key. The « highest power » orientation of the modules is not chosen because of resulting drag from the wind (heavier frames, more concrete foots...).

The case would lead to higher investment costs and higher ROI!

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Solar to Heat

Principles

Solar collector

Solar concentrator

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Principles

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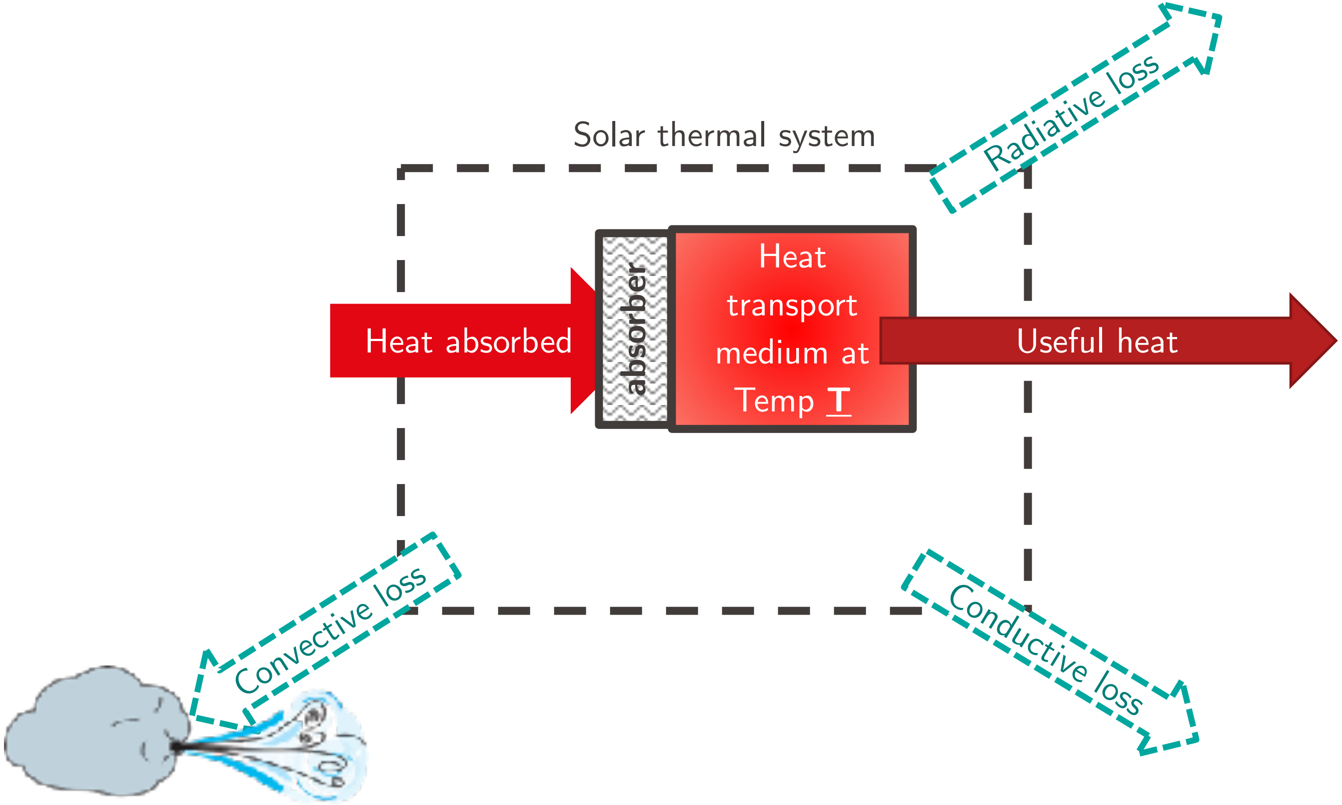

Principles

2 main approches :

Non or low concentrating

- Low temperature 30°C<T < 240°C
- Working fluid (heat transport medium): air, water, oil (methanol)
- Technologies:
  - Flat plate collectors
  - Evacuated tubular collector
  - 2D compound parabolic collector

Concentrating

- High to very high temperature range (300°C< T < 1000°C)
- Working fluid : water, molten salt
- Technologies:
  - Parabolic through
  - Linear Fresnel
  - Towers
  - dishes

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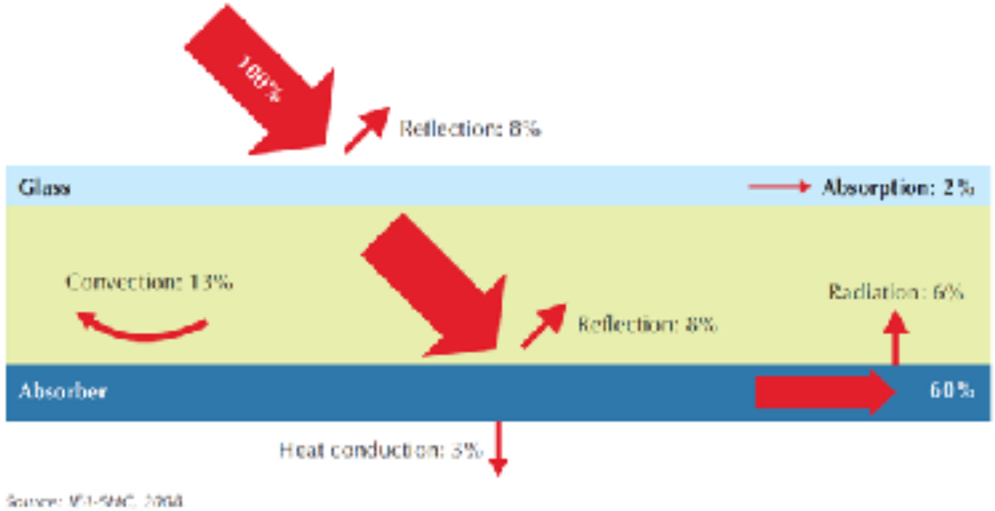
Working principle of a (flat plate) thermal collector

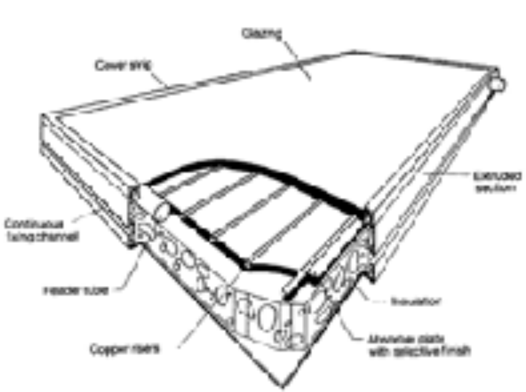


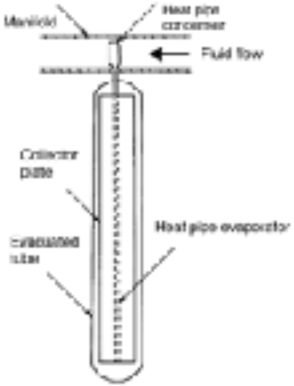
- Standard flat-plate collectors can provide heat at temperatures up to 80°C
- **Optical losses** grow with increasing angles of the incident sunlight,
- **Thermal losses** increase rapidly with the working temperature levels
- The **efficiency** of flat-plate collectors is as high as 60%

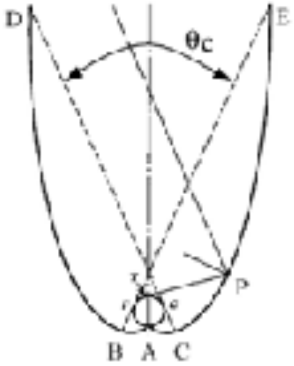
Source: „Solar Energy Perspectives“, IEA 2011

Non-concentrating / stationary collectors

Flate plate | **Evacuated tube** | **Compound parabolic**







Source: Kalogirou, S.A., Solar thermal collectors and applications. Progress in Energy and Combustion Science, 2004. 30(3): p. 231-295.; http://uk.solarcontact.com/solar-heating/solar-collector/plate-collector; http://www.see-change.org.au/solar-hot-water-systems-2/; http://www.ics.ele.tue.nl/~akash/maartje/searchSystemsBySystem.php?ID=1020&page=2

Non-concentrating / stationary collectors

Efficiency decreases with increasing receiver temperature (thermal losses) & radiation

Characteristics

Thermal power output

$$\dot{Q}[W] = \underbrace{\eta_{th}(T_{inlet})}_{\text{thermal efficiency}} \cdot \underbrace{g_i\left[\frac{W}{m^2}\right]}_{\text{Radiation on inclined surface}} \cdot \underbrace{A_{coll}\left[m^2\right]}_{\text{Surface area of collector}}$$

Average thermal power ouput

$$\bar{\dot{Q}}[W] = \bar{\eta}_{th} \cdot GHI\left[\frac{W}{m^2}\right] \cdot A_{coll}\left[m^2\right]$$

Efficiency

$$\eta_{th}(T_{inlet}) = \eta_0 - a_1 \cdot \frac{(T_{inlet} - T_a)}{g_i} - a_2 \cdot \frac{(T_{inlet} - T_a)^2}{g_i}$$

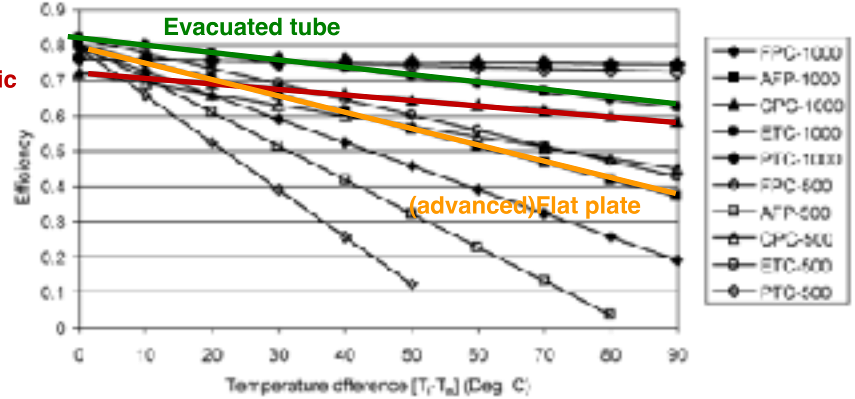


Fig. 20. Comparison of the efficiency of various collectors at two irradiation levels, 500 and 1000 W/m².

Source: Kalogirou, S.A., Solar thermal collectors and applications. Progress in Energy and Combustion Science, 2004. 30(3): p. 231-295.

Non or low concentrating

- Flat Plate solar collector

Examples

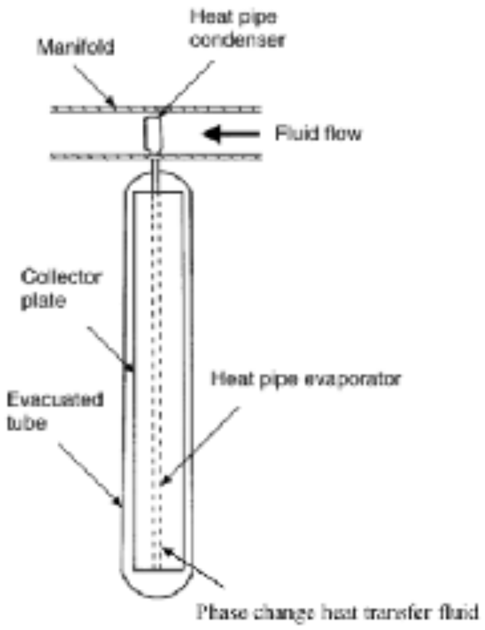
Source: wksolar

Non or low concentrating

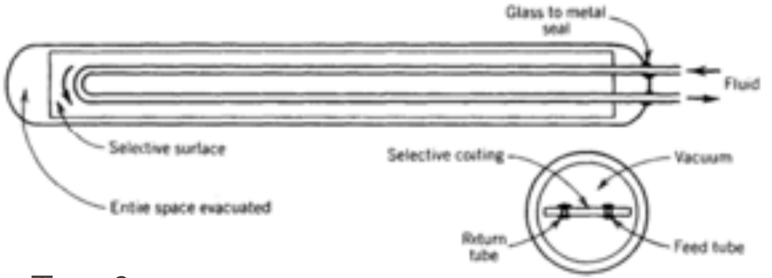
- Evacuated tubes solar collector

- Use direct and some diffuse radiation
- Concentration: 1
- Temperature range : 50-200° C
- Use liquid-vapor phase change fluids
- Conductive heat loss reduce through vacuum
- Radiative heat loss reduced with selective surface

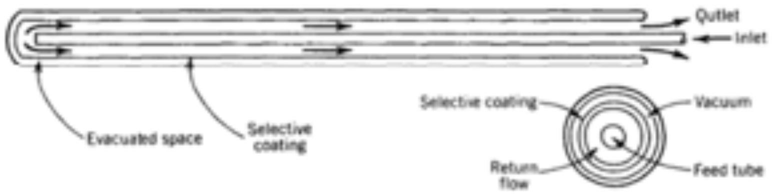
Type 1



Type 2



Type 3



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Non or low concentrating

- Evacuated tubes solar collector

Examples

Source: solarstart

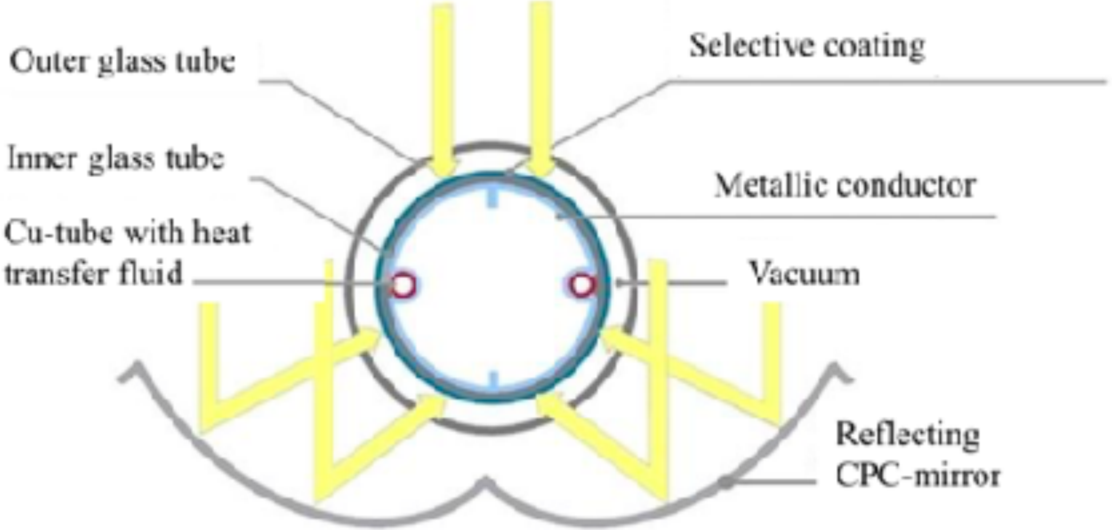
Source : SunBest

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Non or low concentrating

- 2D parabolic solar collector

- Direct and some diffuse radiation
- Temperature range: 60-240°C
- Concentration 1-5
- Takes advantages of selective coating and vacuum tubes to reduce heat losses
- Concentrator naturally reduce reflection



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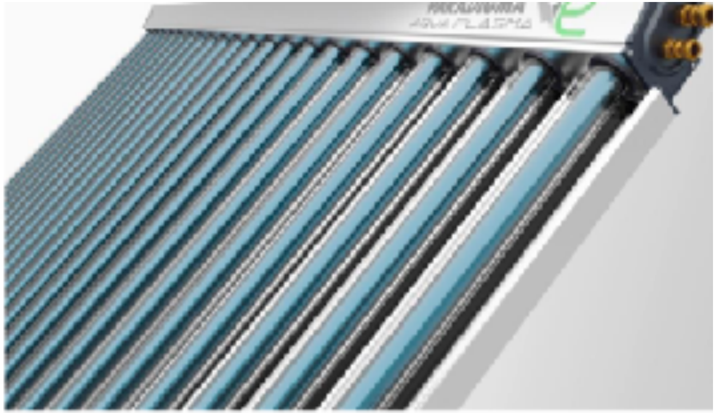
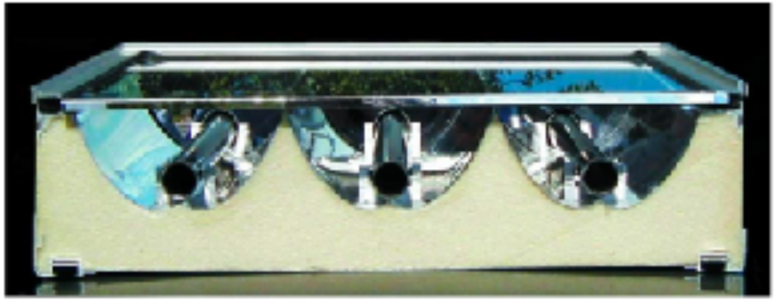
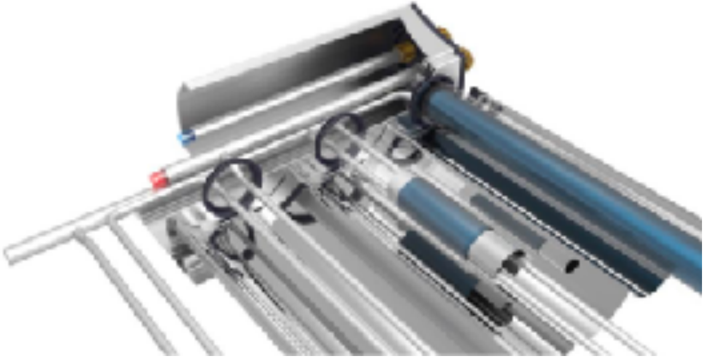
Non or low concentrating

- 2D parabolic solar collector

Examples







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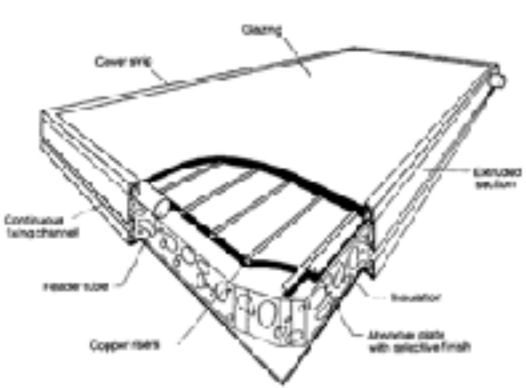
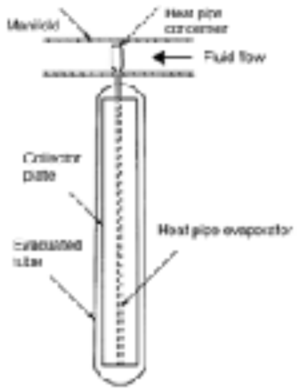
Non-concentrating / stationary collectors

Flate plate



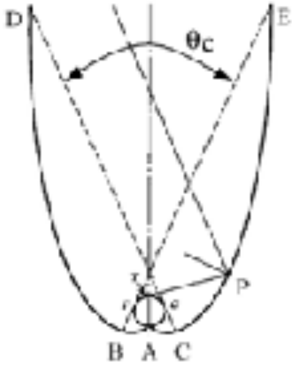
- **Outlet T** : 30-80°C
- **Efficiency (**1000W/m²**)** : 60%$_{@30°C}$ -40%$_{@80°C}$
- **Concentration factor** : 1
- **Applications** : hot water, heating
- **Cost** : 206 US$$_{2003}$/m²

Evacuated tube



- 50-200°C
- 75%$_{@30°C}$ -65%$_{@80°C}$
- 1
- hot water, heating, absorption cooling, low temperature process heat
- 430 US$$_{2003}$/m²

Compound parabolic



- 60-240°C
- 70%$_{@30°C}$ -60%$_{@80°C}$
- 5
- hot water, heating, absorption cooling, low temperature process heat
- 310 US$$_{2003}$/m²

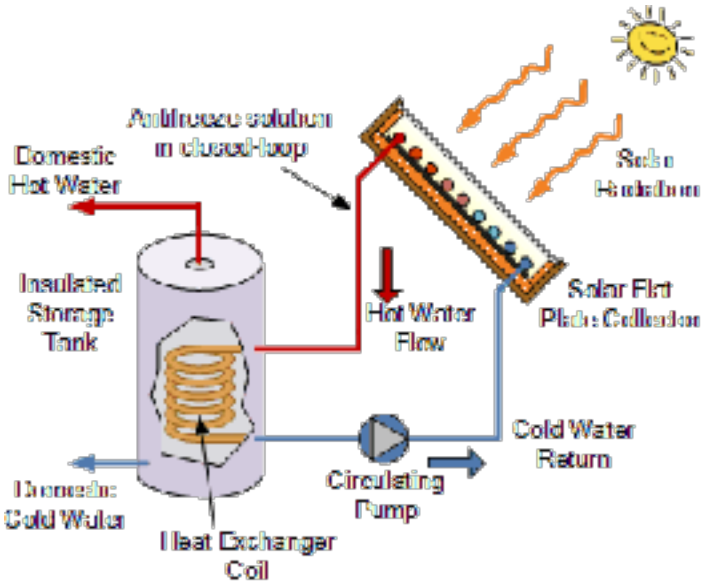
- **Heat transfer fluid** : hot water (usually)

Source: Kalogirou, S.A., Solar thermal collectors and applications. Progress in Energy and Combustion Science, 2004. 30(3): p. 231-295.; Kalogirou, S.A., *The potential of solar industrial process heat applications.* Applied Energy, 2003. **76**(4): p. 337-361.

Non or low concentrating

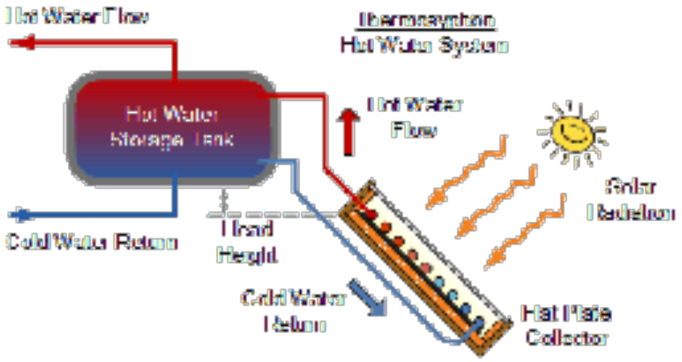
- System integration

1. Indirect hot water:
<u>Forced convection</u>



Source: https://www.alternative-energy-tutorials.com/

2. Thermosyphon:
<u>natural convection</u>



<u>Sizing and price:</u>
For domestic hot water: 1m2 /person
Price of thermal energy : 8-15 cts/kWh
(Nat Gas: 6-7 cts/kWh)

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Concentrating Solar

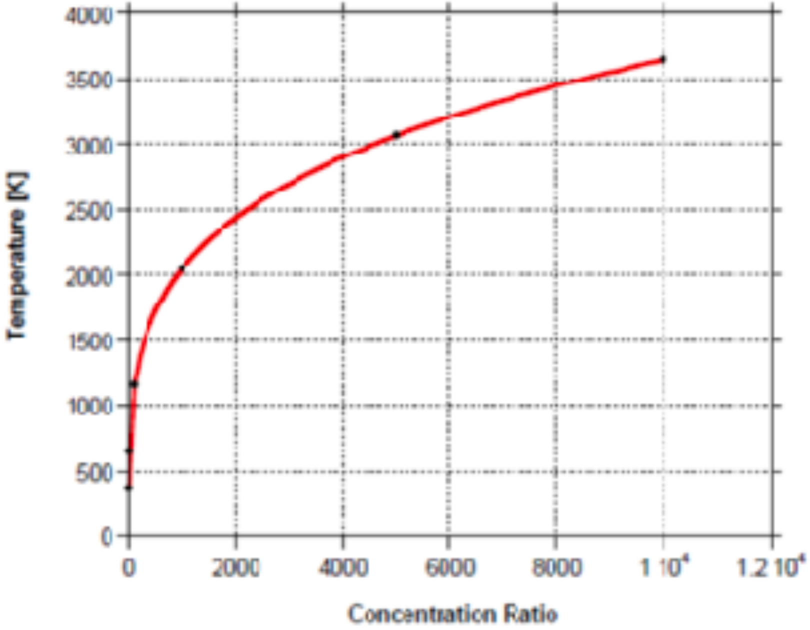
- Mostly used for electricity generation (using a heat engine : e.g. Rankine cycle)

Advantages:

- Higher temperature/efficiencies achievable
- Reflecting surface requires less material, simpler structure

Disadvantages:

- No diffuse radiation collected
- May require tracking (more mechanical complexity)
- Reflecting surface degrades with time (soiling)



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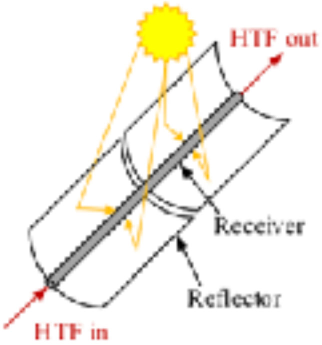
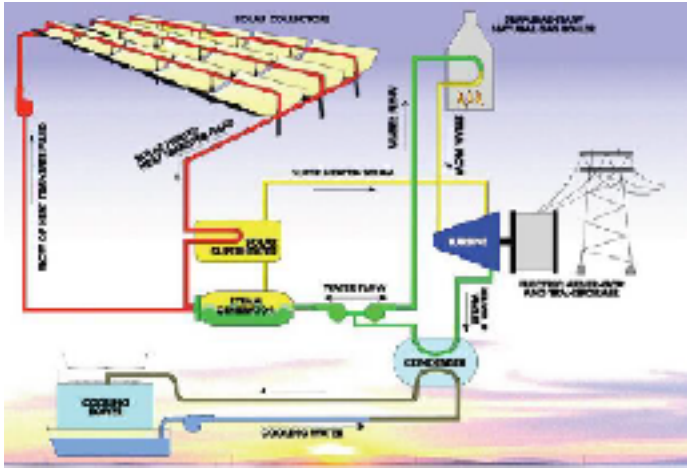
Concentrating Solar

- Parabolic through

Line focusing
C = 30-80
Temp: 60-300 °
1 axis tracking North-South



System example: SEGS in California:
360 MW, hybrid solar and gas
Synthetic oil at 400°C



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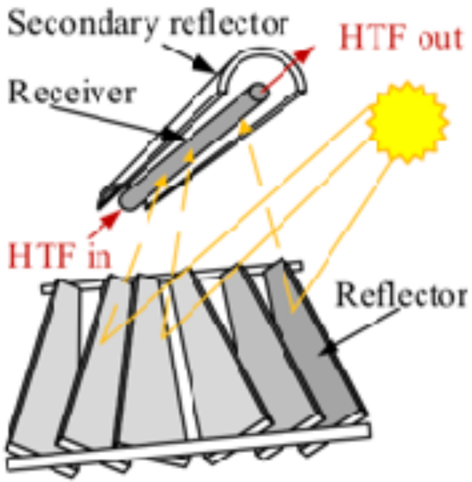
Concentrating Solar

- Linear Fresnel

- Line focusing
- C: 30-80
- Temp: 60-250°C
- Unidirectional
- 1-axis tracking N-S



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Concentrating Solar

- Linear Fresnel example

- Lanzhou Dacheng Dunhuang (China) 50MW Molten Salt Fresnel CSP Project
- 15h thermal capacity storage
- Largest Fresnel CPS plant in the world (they say).

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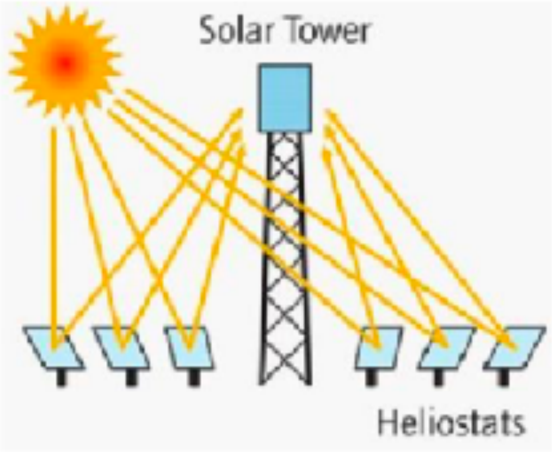
Concentrating Solar

- Concentrating tower

- Point focusing
- C: 200-1000
- Temperatures 300- 1000°C
- 2-axis tracking heliostats



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Concentrating Solar

- Concentrating tower example

- **Crescent Dunes Solar Energy Project (US, near Las Vegas)**
- 110 MW
- 1.1GWh storage
- LCOE : 138 $/MWh (vs 30 $/MWh for a large PV plant nearby)

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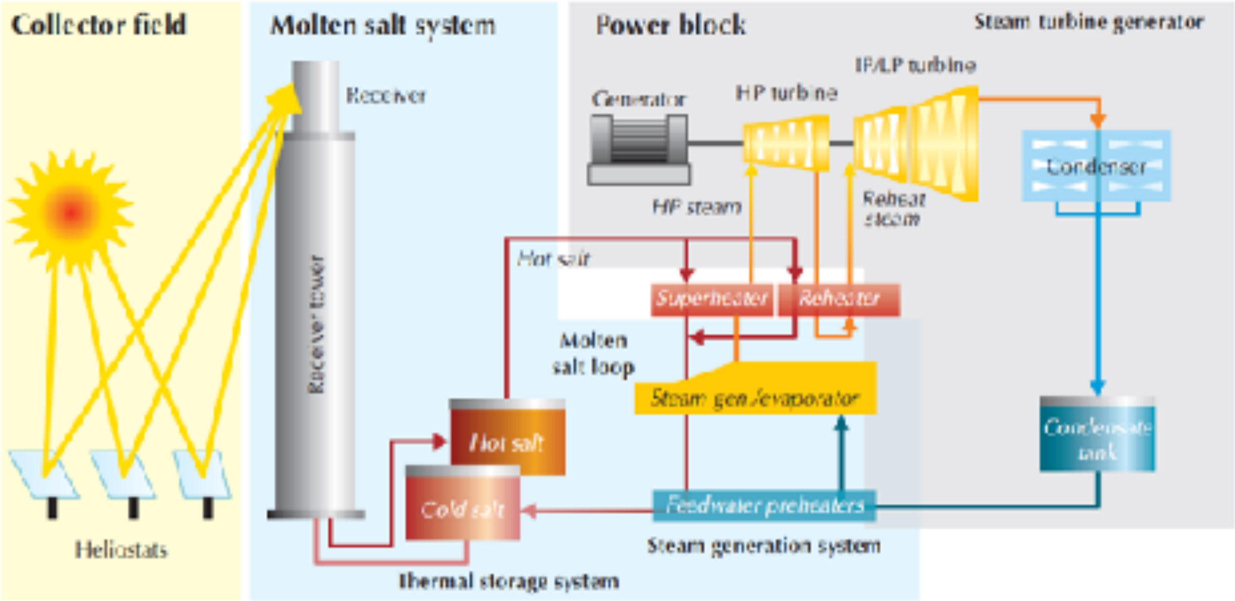
Concentrating / tracking collectors

Applications

- **Electricity production**

«Solar Electricity Generation System (SEGS)»

- Rankine cycle (steam based)
- HTF: Molten salt
- T < 600°C
- Solar only



Source: „Solar Energy Perspectives“, IEA 2011

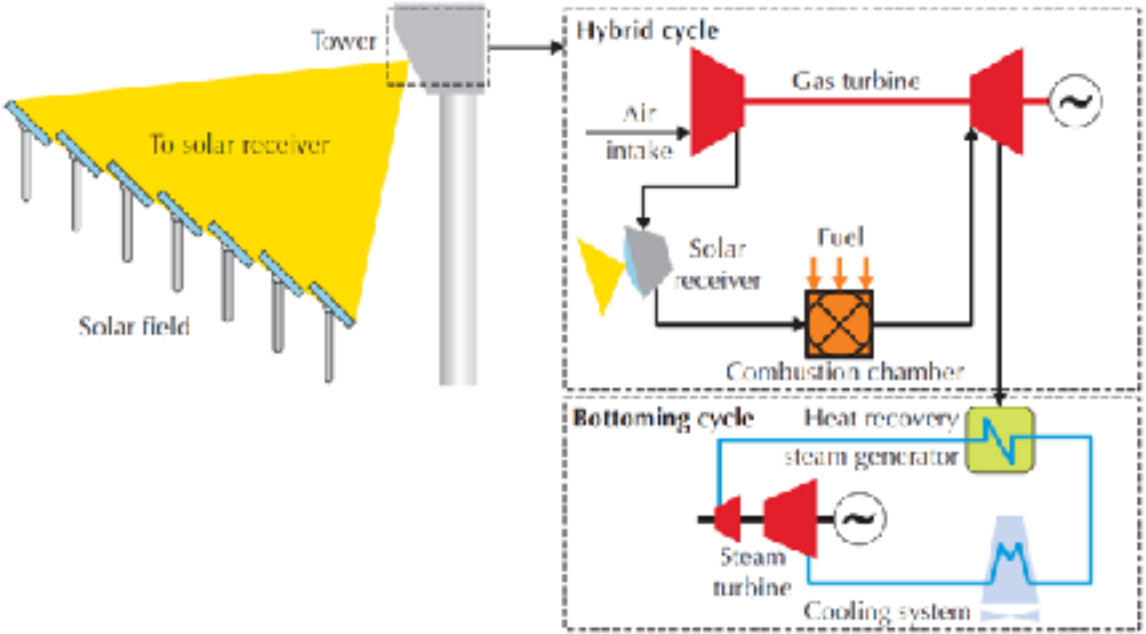
Concentrating / tracking collectors

Applications

- **Electricity production**

«Integrated solar combined cycle system (ISCC)»

- Brayton cycle (gas based)&Rankine
- HTF: Pressureized air
- T ~ 850°C
- Hybrid solar - fuel



Source: „Solar Energy Perspectives", IEA 2011

Concentrating Solar

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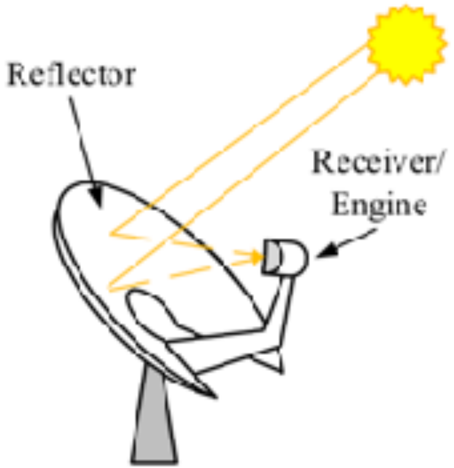
- Concentrating dishes

- Point focusing
- C = 1000-4000
- 2 axis parabolic tracking

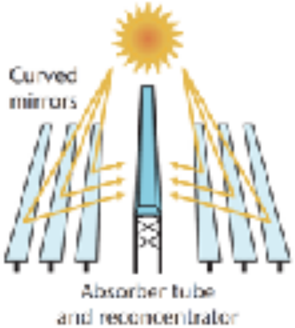


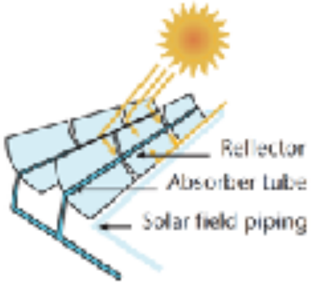
- Autonomous power generation via

Concentrating / tracking collectors

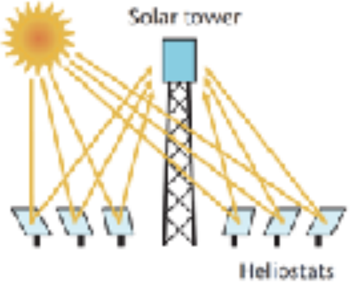
Work only with direct solar radiation, best deployed in regions with high DNI

One-axis tracking





Two-axis tracking



Linear fresnel

- **Outlet T** : 60-250°C
- **Efficiency** (1000W/m²) : 85%$_{@30°C}$ -70%$_{@250°C}$
- **Concentration factor** : 10-40
- **Cost** : N/A
- **LCOE** : N/A

Parabolic trough

- 60-250°C
- 85%$_{@30°C}$ -75%$_{@250°C}$
- 15-45
- 250 US$_{2015}$/m² , 17ct$_{2015}$/ kWh$_e$

Heliostat field

- 100-1500°C
- 90%$_{@30°C}$ -88%$_{@250°C}$
- 100-1500
- 200 US$_{2015}$/m², 14ct$_{2015}$/ kWh$_{ec}$

Parabolic dish

- 100-500°C
- 90%$_{@30°C}$ -88%$_{@250°C}$
- 100-1000
- N/A$_l$

- **Applications** : process heat, electricity production
- **Heat transfer fluids** : air, thermal oil, steam, molten salt

Source: Kalogirou, S.A., Solar thermal collectors and applications. Progress in Energy and Combustion Science, 2004. 30(3): p. 231-295.; „Solar Energy Perspectives", IEA 2011; R. Pitz-Paal et al. „Development Steps for Parabolic Trough Solar Power Technologies With Maximum Impact on Cost Reduction ", Journal of Solar Energy Engineering, 2007, Vol. 129 / 371; Truchli "Current and Future Costs for Parabolic Trough and Power Tower Systems in the US Market ", 2010, SolarPaces, NREL

source :ETHZ solar mini-refinery

Solar to Fuel

Conversion pathways

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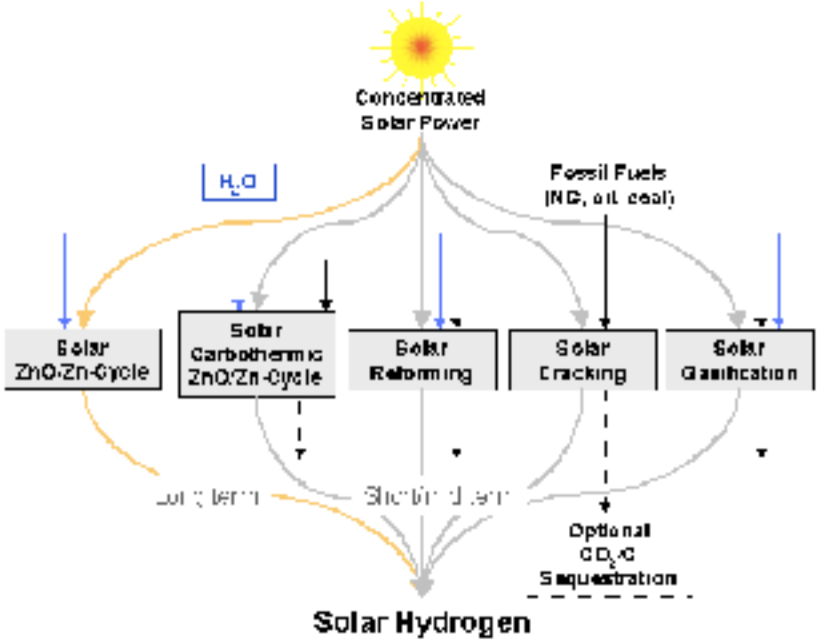
Concentrating / tracking collectors

Applications

- Fuel production (H_2)

- -
- HTF: H_2O/ nat gas
- T ~ 1000°K



40 kW
120 m²
HT
eff =14-25 %

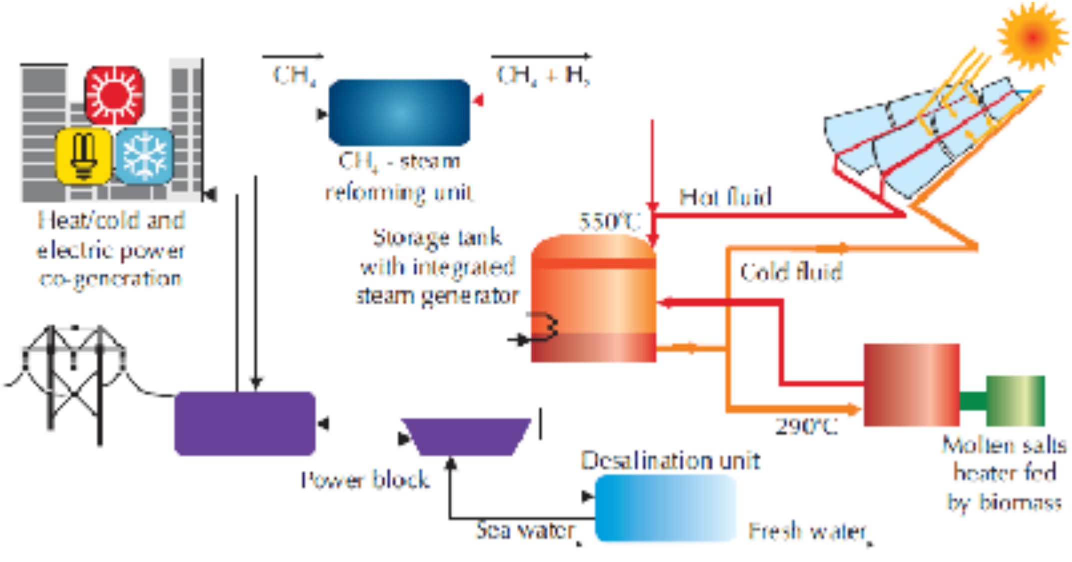
Source: „Solar Energy Perspectives“, IEA 2011, Solar Technology Laboratory (PSI)

Concentrating / tracking collectors

Applications

- Fuel production (CH_4,H_2)
- Electricity
- Heat

- Rankine cycle
- HTF: Molten salt
- T < 600°C



Source: ENEA-UTRINN-STD.

Source: „Solar Energy Perspectives“, IEA 2011

Exercise : find the PV panels ☺

source : Solaxess SA

Summary

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Solar energy

- Irradiance at earth surface: 1000 W/m2
- AM1.5G definition
- Annual irradiance :1000 kWh/m2

Solar to electricity : PV

- Main technology: (mono) c-Si
- Temperature effect
- Efficiency 20%
- Energy payback time 1.5 years
- Cost : 1300 $/kW

Solar to heat

- Solar collector
  - T = 30-240°
  - Working fluid: Water with additive
  - Used for domestic hot water
- Concentrated solar
  - Working fluid : Molten Salt for heat storage
  - High T (>400 °C) => thermal cyle to produce electricity
  - Concentration = 30-4000

System integration

- What technological synergies
- Storage
- Which demand to cover
- to what expenses ?

Solar to fuel:

- From fossil fuel: $CH_4(+H_2O) \rightarrow H_2 + byproduct$
- From water : $H_2O\,(+metal?) \rightarrow H_2 + byproduct$
- Typical temperature and efficiency

The PV rule of thumb to shine in society

definition

Rule of 1000 for PV :

X =

1000W of PV at 1000CHF/kW,
exposed for 1000h/year under 1000W/m2 irradiance,
1000 kWh/year
And cost 1000 CHF.

X =

1000 kWH/YEAR for a 1000 CHF !

(assuming 1000h of equ.sun/year at 1000W/m^2) -> slight over-estimation

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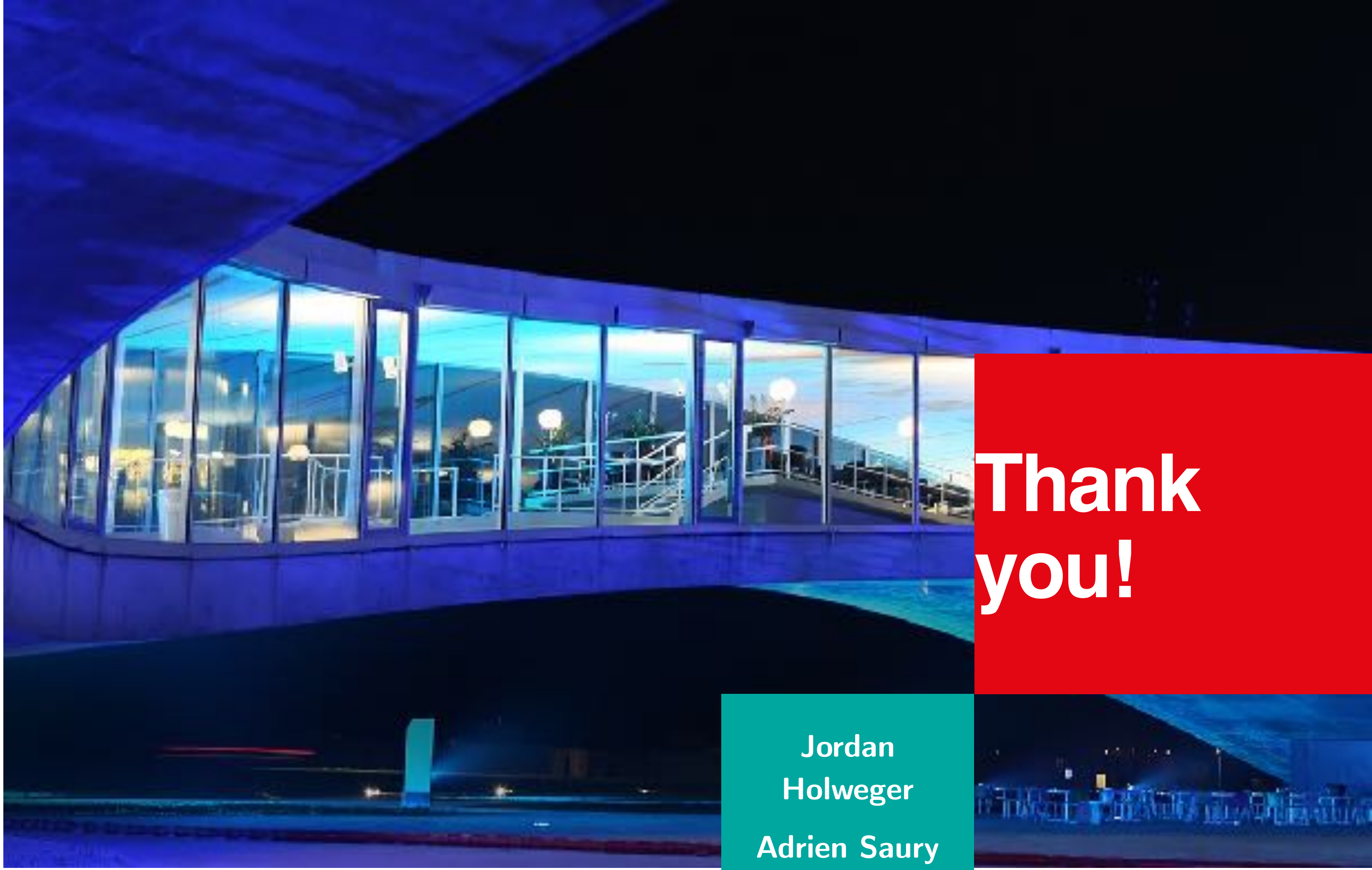

Thank you!

Jordan Holweger

Adrien Saury