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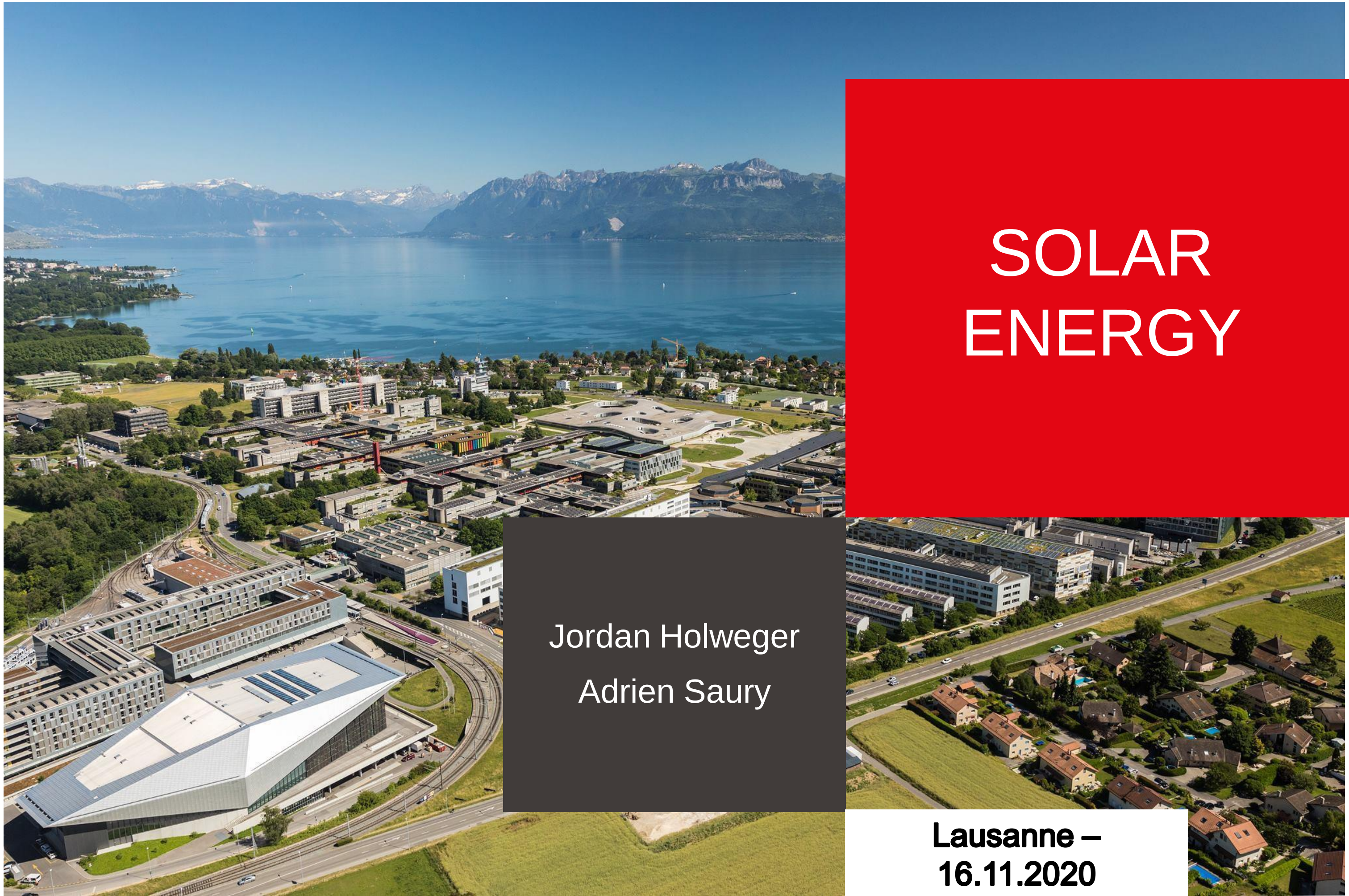

SOLAR ENERGY

Jordan Holweger

Adrien Saury

Lausanne – 16.11.2020

École polytechnique fédérale de Lausanne

Goals

- ***Master*** the various solar energy conversion pathways
- ***Identify*** pros and cons of each conversion technologies
- ***Apply*** a basic knowledge to real case scenarios

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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
  - Conversion pathways
- Solar systems
  - Self consumption
  - System integration

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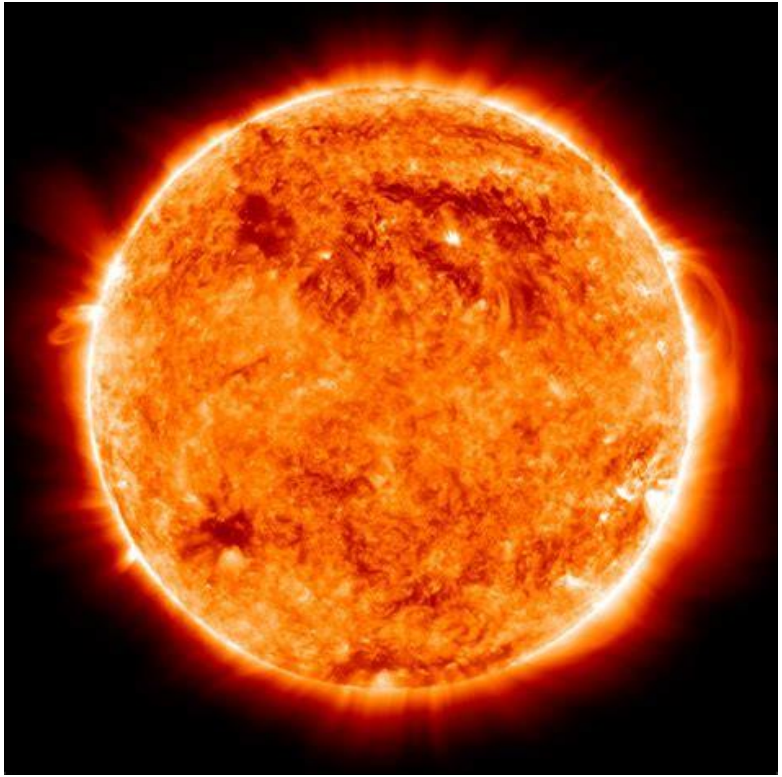

Introduction

The Sun

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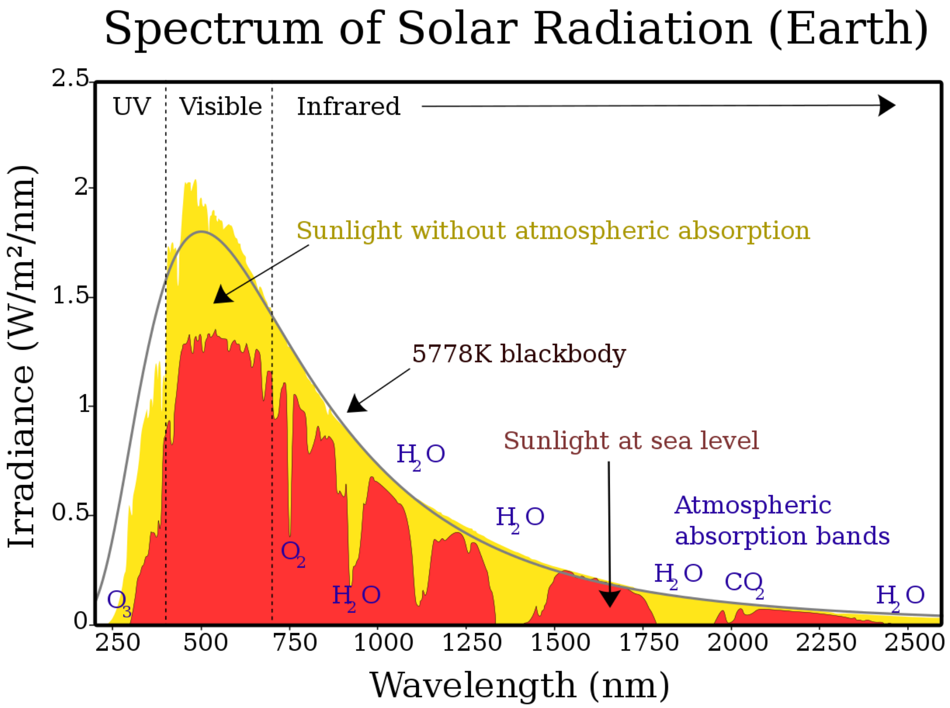
The energy from the sun

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

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

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**



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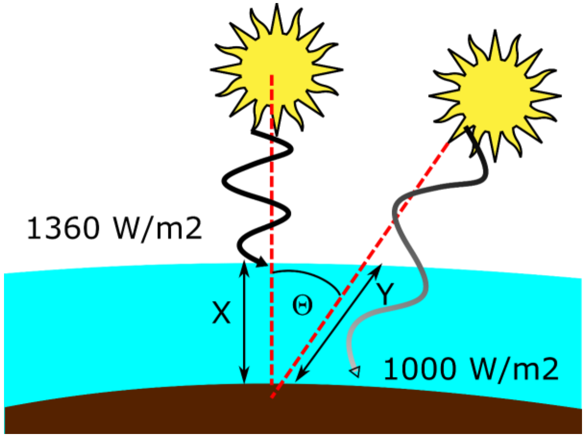
Irradiance and location : Air Mass

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

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



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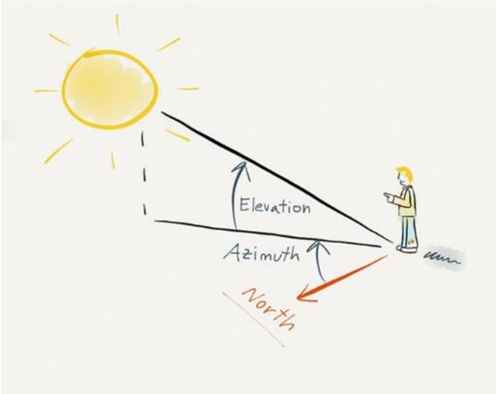
Irradiance and location : Air Mass

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 :

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

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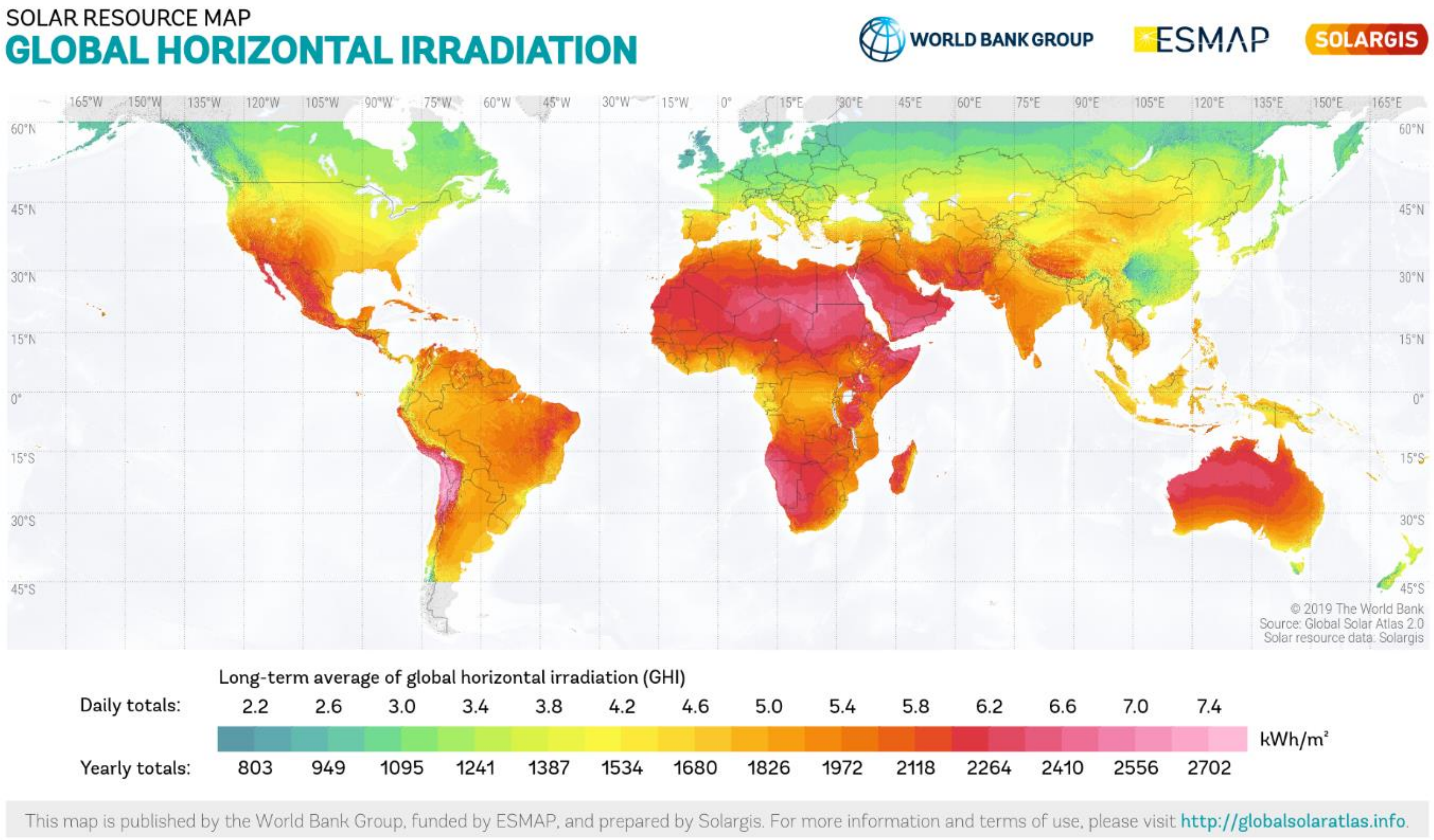
Availability (location dependant)



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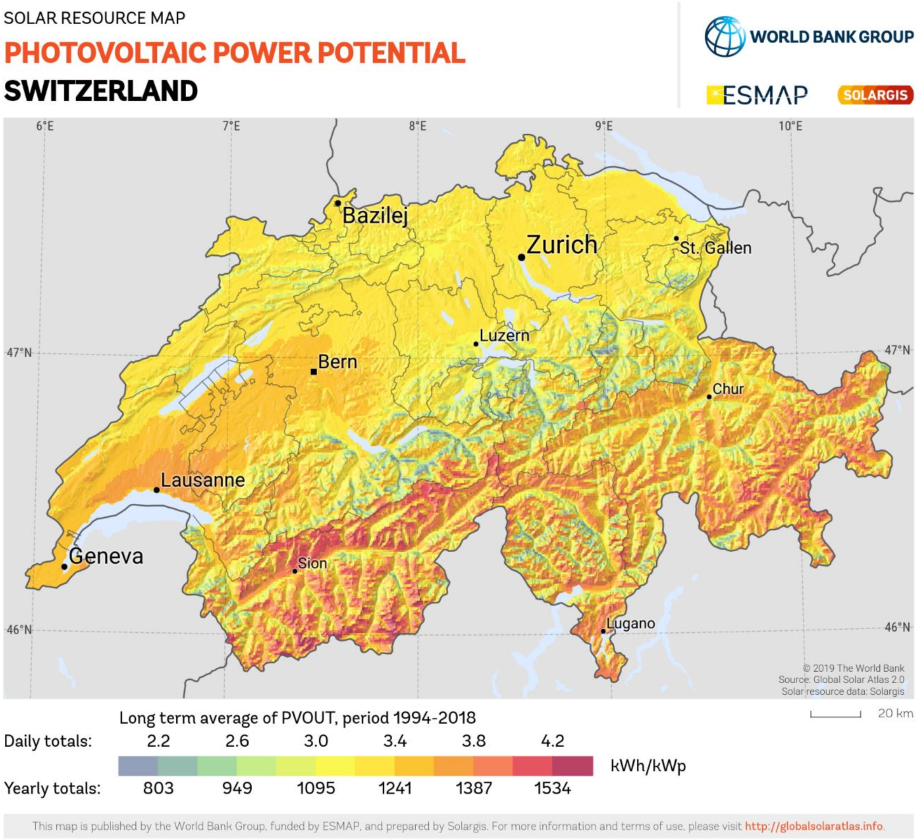
Availability (location dependant)

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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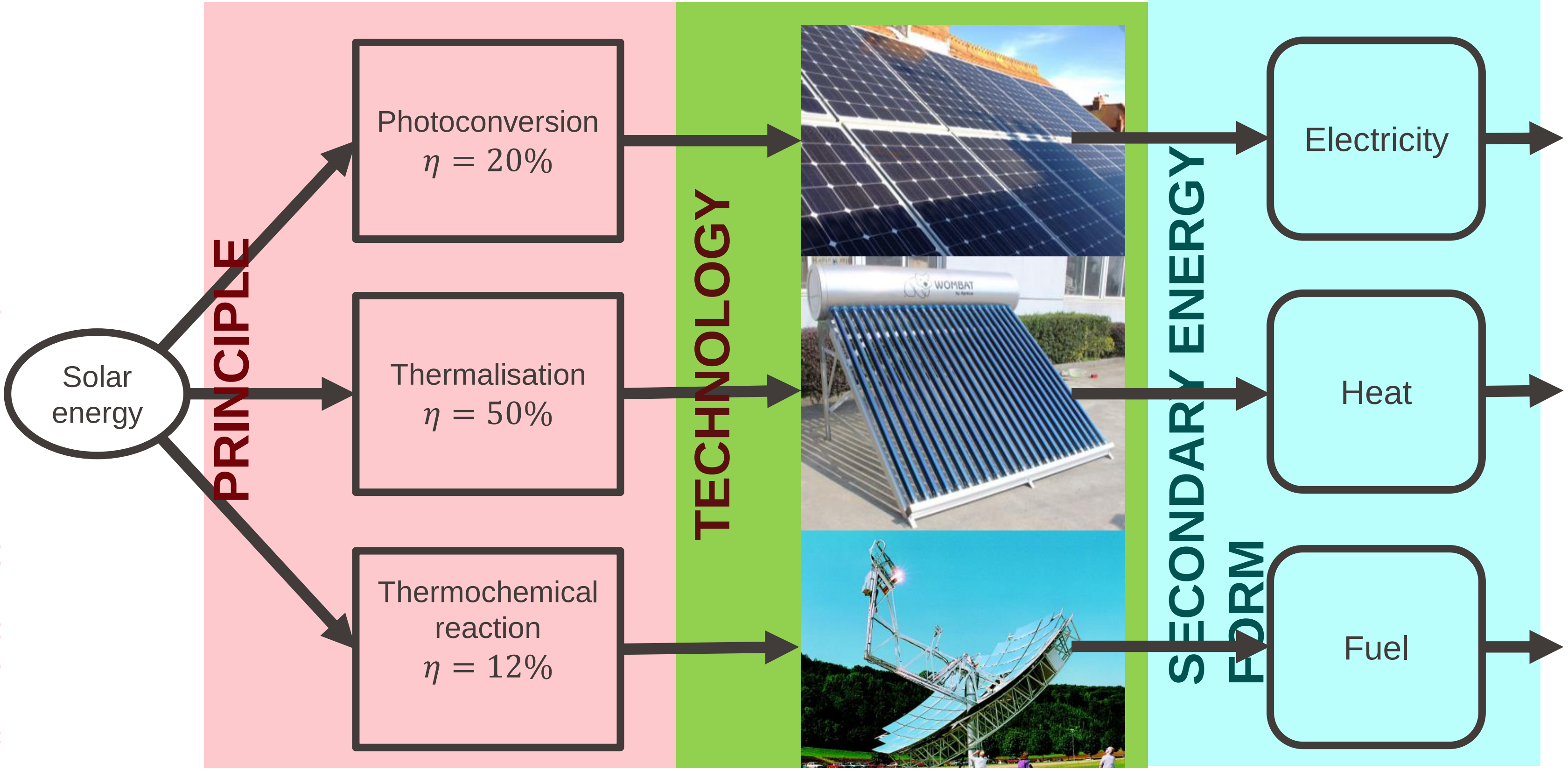
How to harvest solar energy



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Solar to Electricity

Semiconductor technology : Conversion

Solar cell modeling

Solar modules manufacturing

Solar systems components

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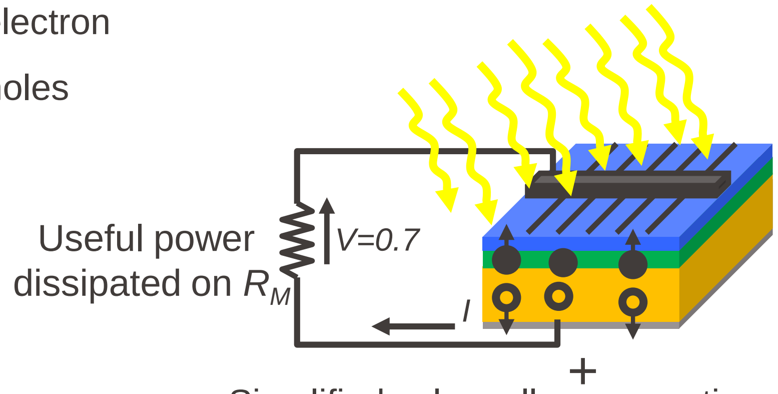
Basic principle

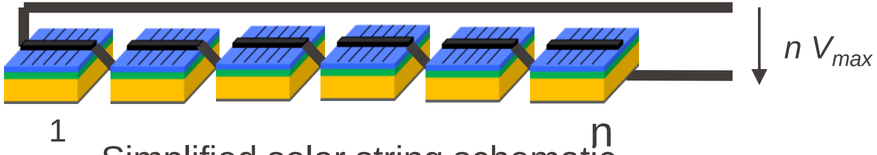
- ● electron
- ○ holes



Simplified solar cell cross-section

- Standard test condition:
- I = 1000W/m2, AM1.5G
- T = 25°C
- P is always measured in this condition

efficiency : $\eta = \frac{P_{MPP} = VI}{I * S_{cell}}$



Simplified solar string schematic

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

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

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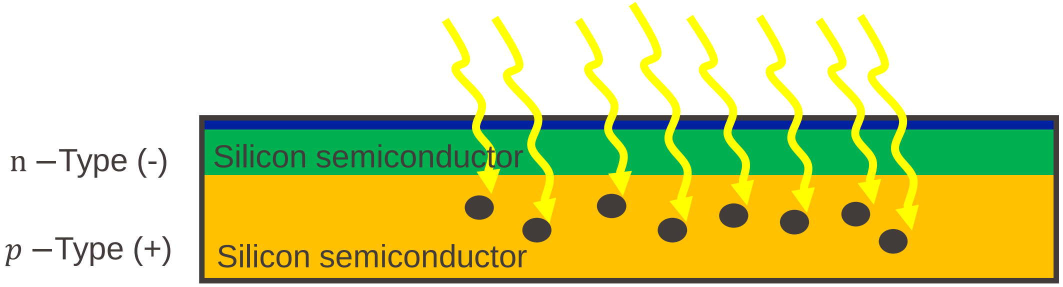
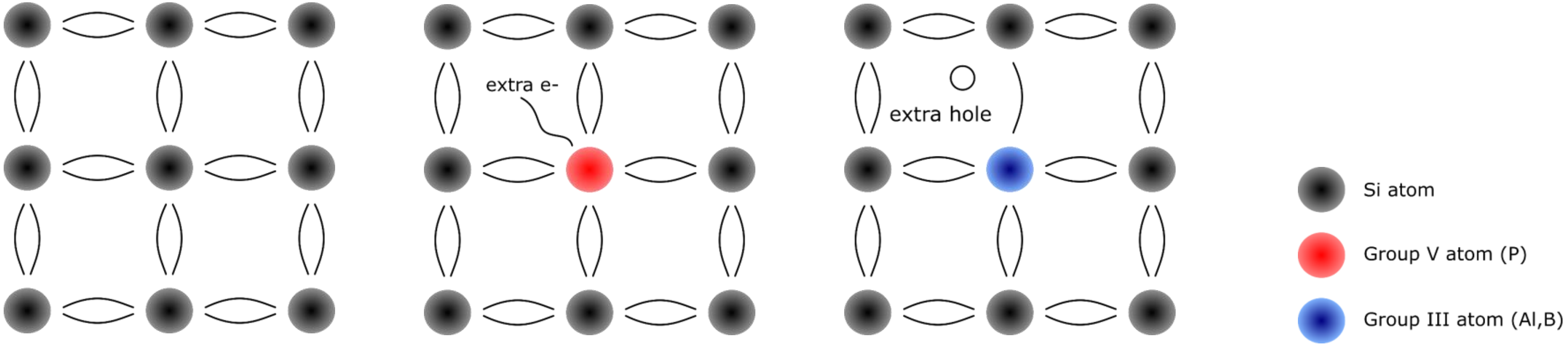
Semiconductors : the conversion key



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

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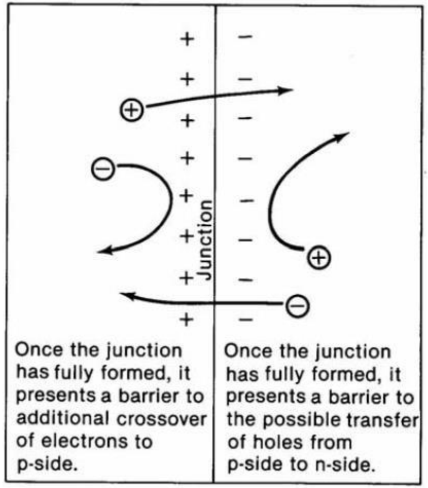
n –Type (-)

p –Type (+)



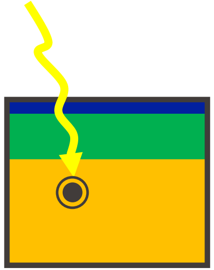
n –Type (-) p –Type (+)

- Light can generate and 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

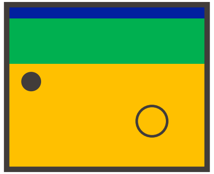
In a range at the n-p interface the charges will cancel out.
But overall an electric field is generated ACROSS the juntion

Semiconductors : the conversion key

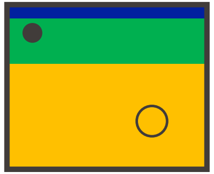
Step 1:
a photon hits an electron-hole pair



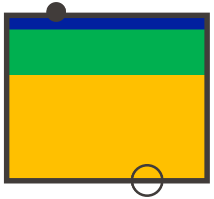
Step 2:
The electron and the hole split and move around



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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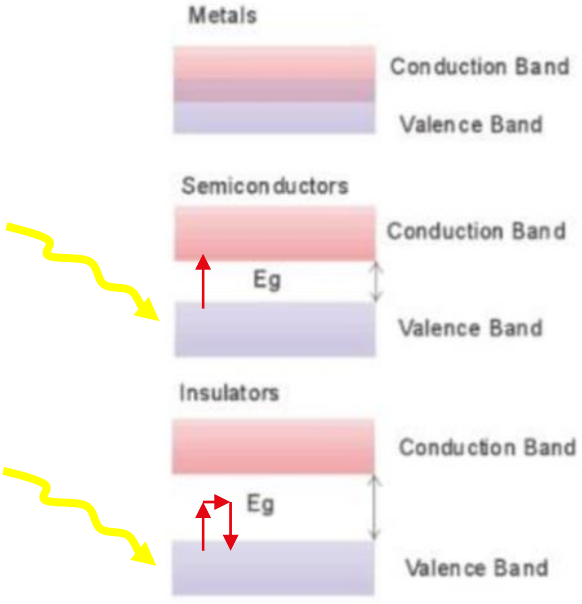
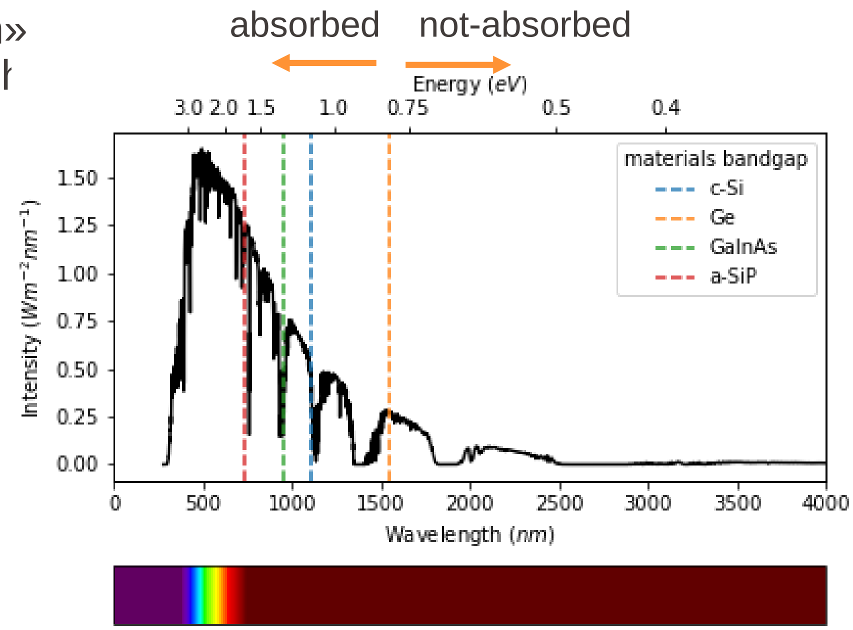
Semiconductors : the conversion key

- 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





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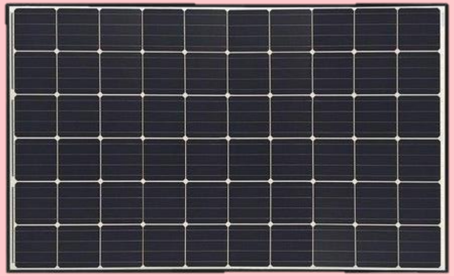
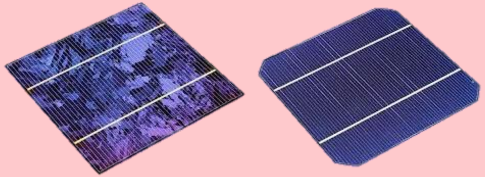
Solar photovoltaic technologies

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

Crystalline Silicon

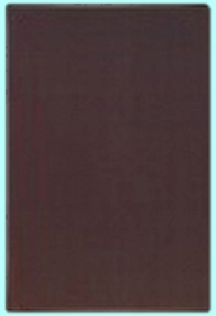




Polycrystalline

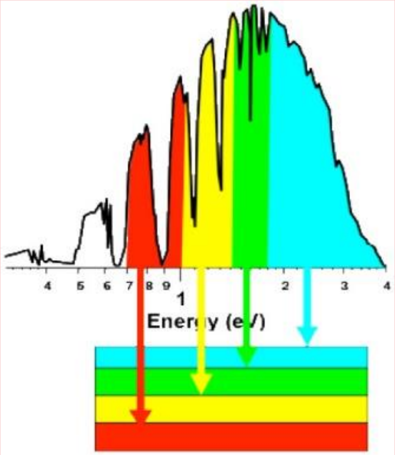
Monocrystalline
- IBC
- PERC/L/T
- Tilting ribbons…

Thin films



Thin-films
- CIGS
- CaTe

Multi-junctions



- III-V cells
- Stacks of cells

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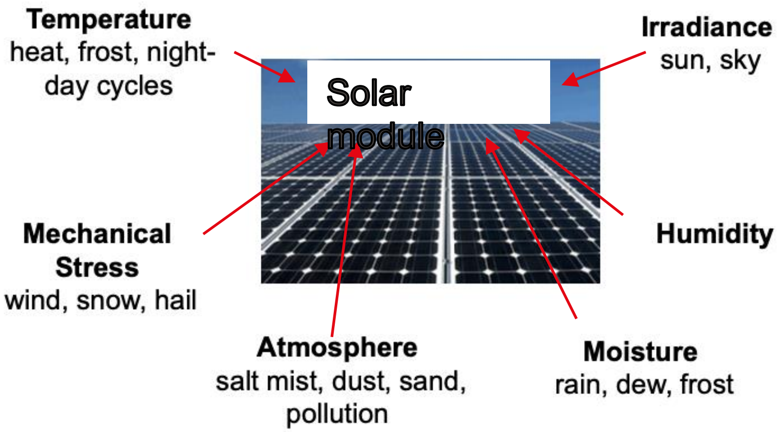
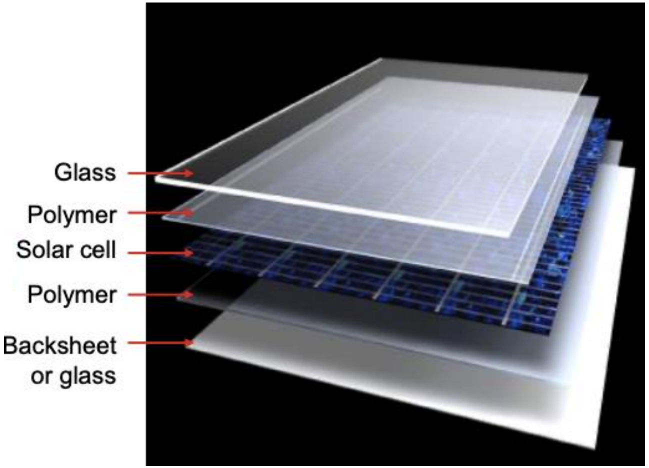
From cells to modules

- A solar cell in its own is very thin (250um) and very brittle. To protect it, ensure long term usage and safety, 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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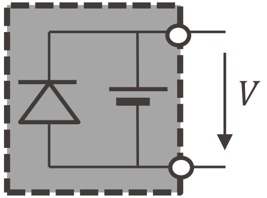
Solar cell & module characterization

- 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

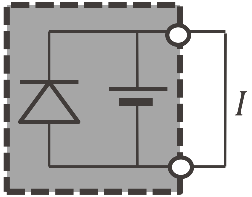
This directly comes from the P-N junctions

- 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?v=BHA4teZmwT0



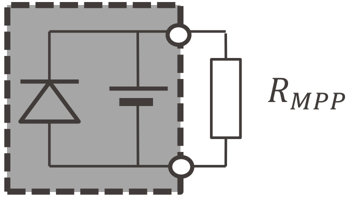
Open-circuit conditions
$I = 0 \Rightarrow V = V_{oc}$



Short-circuit conditions

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

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



Ideal power dissipation on R_{MPP}
$R_{MPP} = V_{MPP}/I_{MPP}$

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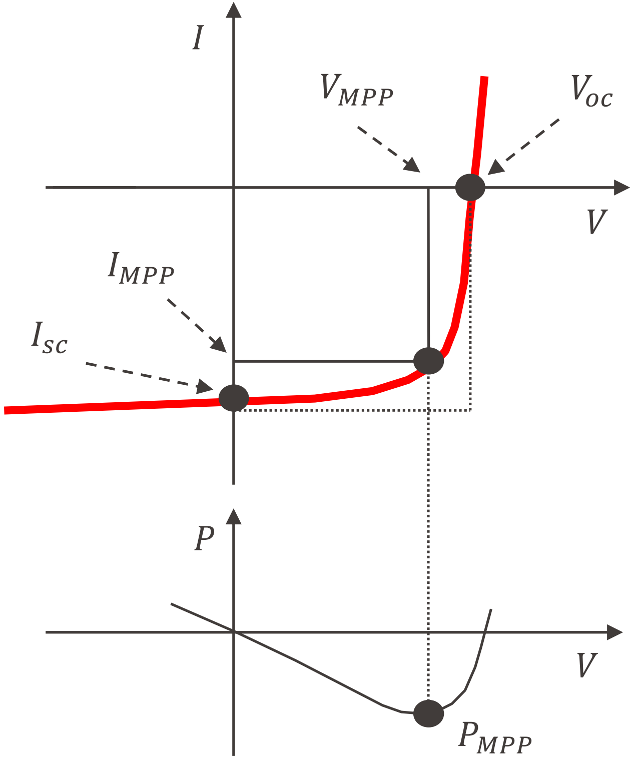
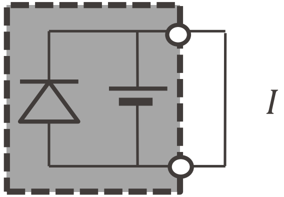
Solar cell & module characterization

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





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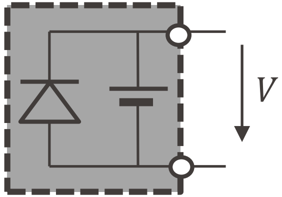
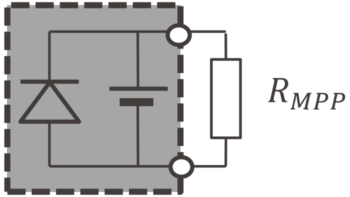


Open-circuit conditions

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



Ideal power dissipation on R_{MPP}

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

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

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System component : 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

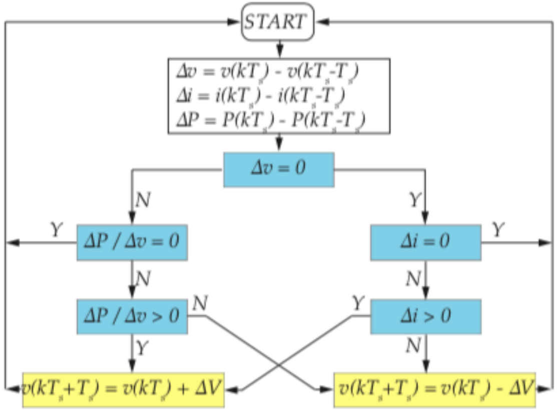
The MPPT will ensure max power output, for whatever outdoor conditions.

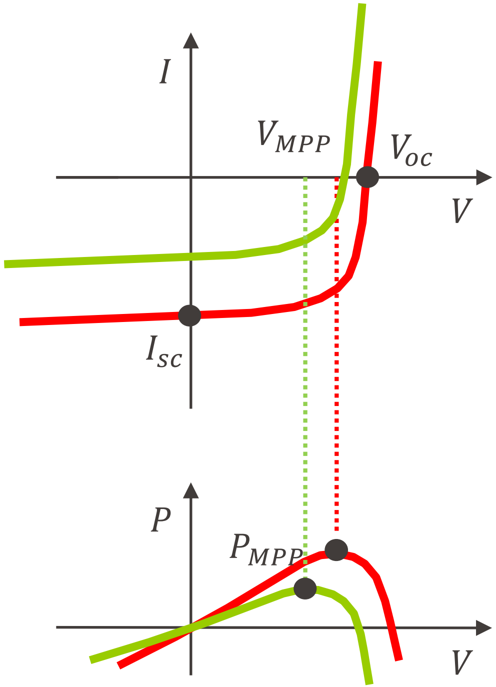
- Irradiance effect

$$\mathrm{Irr} \nearrow \Rightarrow \mathrm{I_{sc}} \nearrow, V_{oc} \approx\nearrow \Rightarrow P_{MPP} \nearrow$$

- Temperature effect:

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





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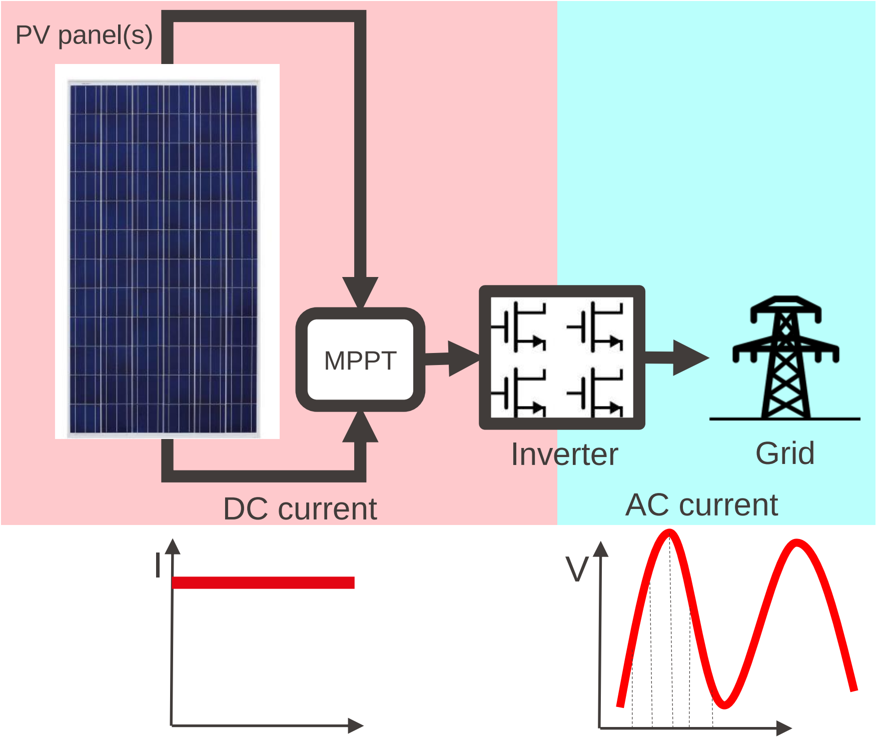
System component : Inverter

Grid tie inverter : (fully grid coupled PV utility)

- 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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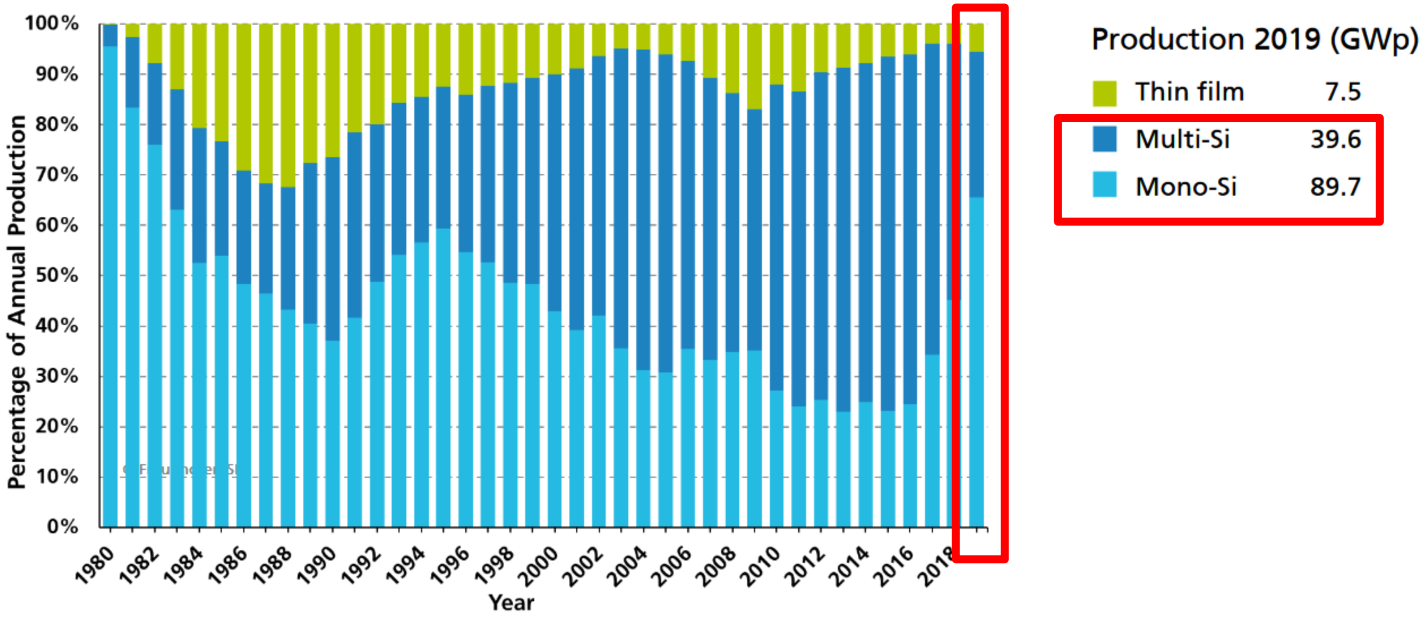
PV production and Market



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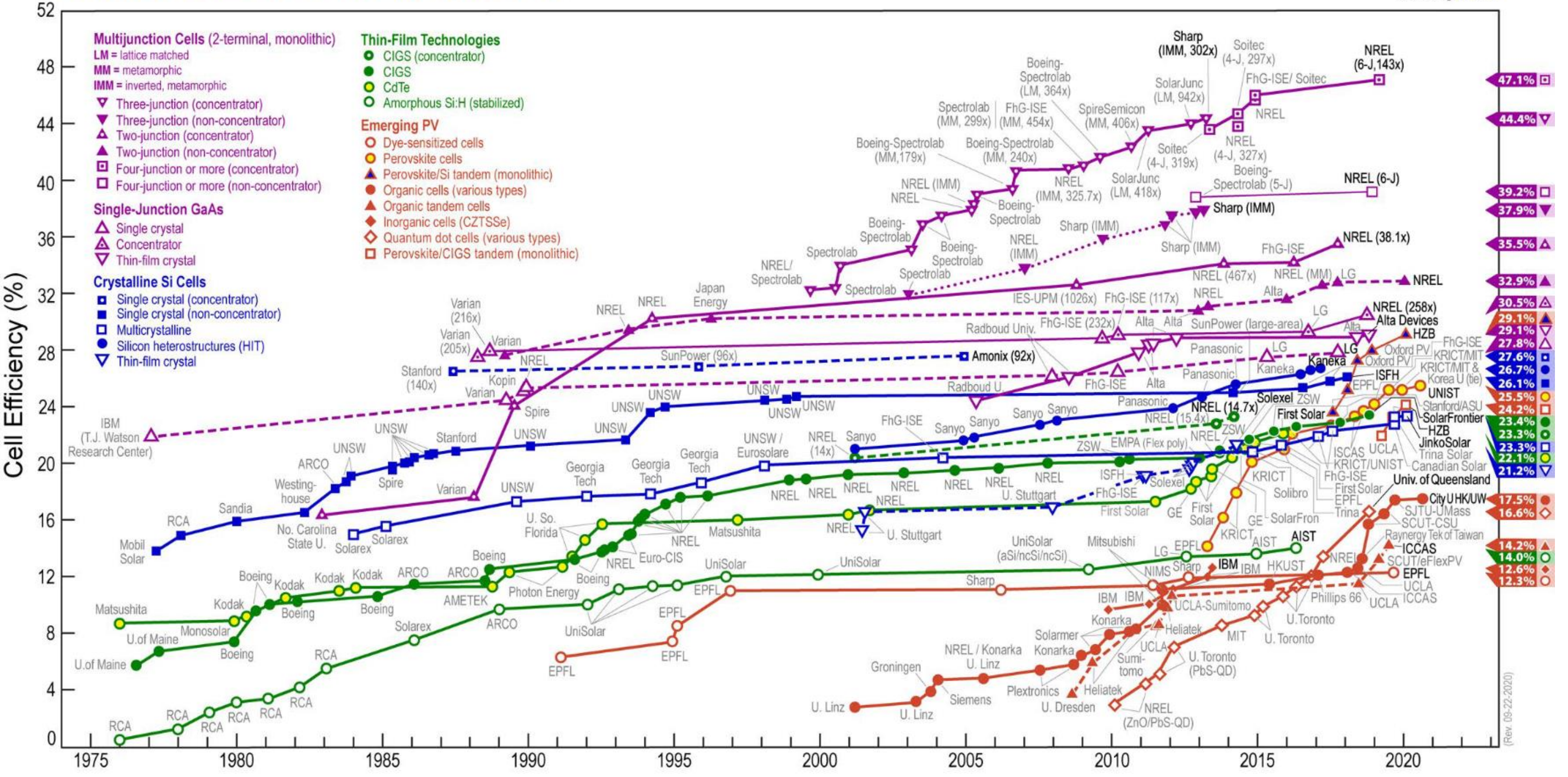
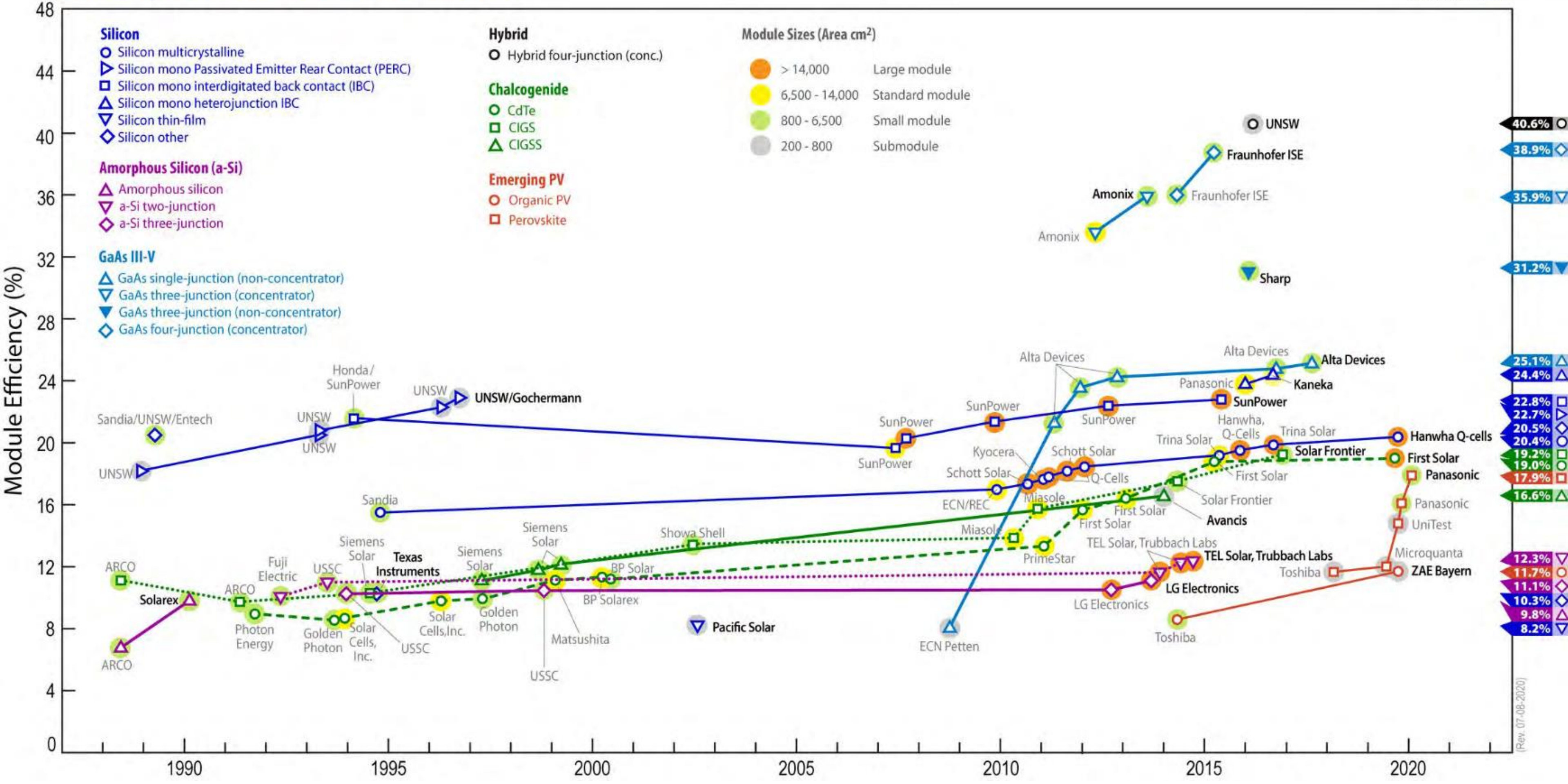
Best Research-Cell Efficiencies

NREL
Transforming ENERGY



Champion Module Efficiencies

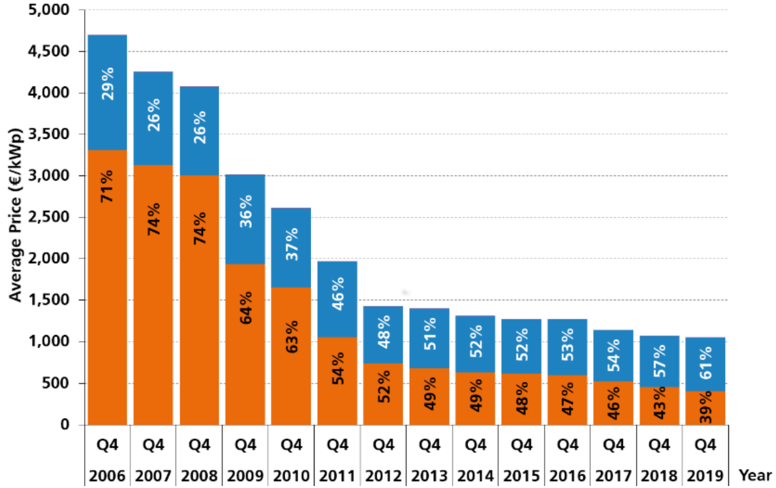


PV production and Market

	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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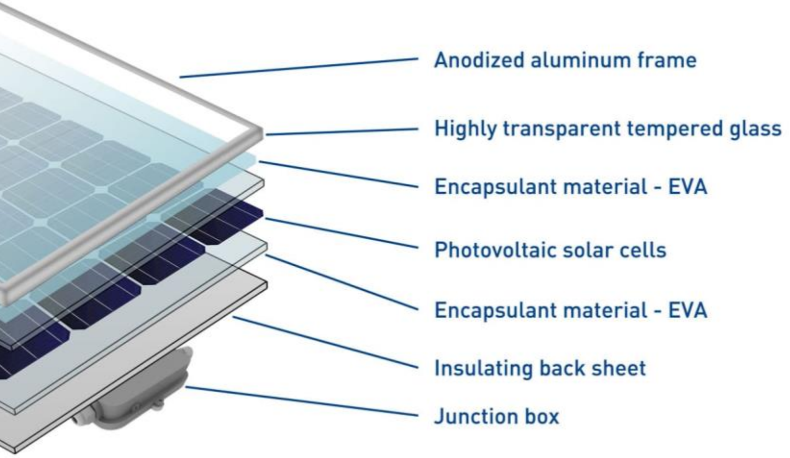
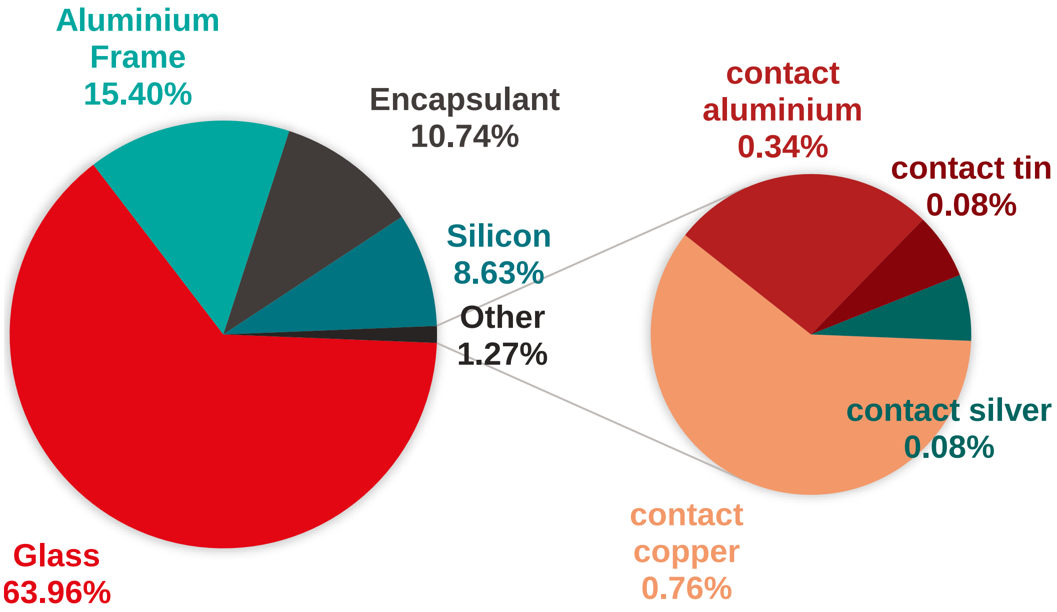
PV modules material breakdown





Energy payback time: 0.4 to 1.5 years

EU,PEFCR, Photovoltaic Modules Used In Photovoltaic Power Systems For Electricity Generation,2019

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Solar to Heat

Principles

Solar collector

Solar concentrator

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Principles

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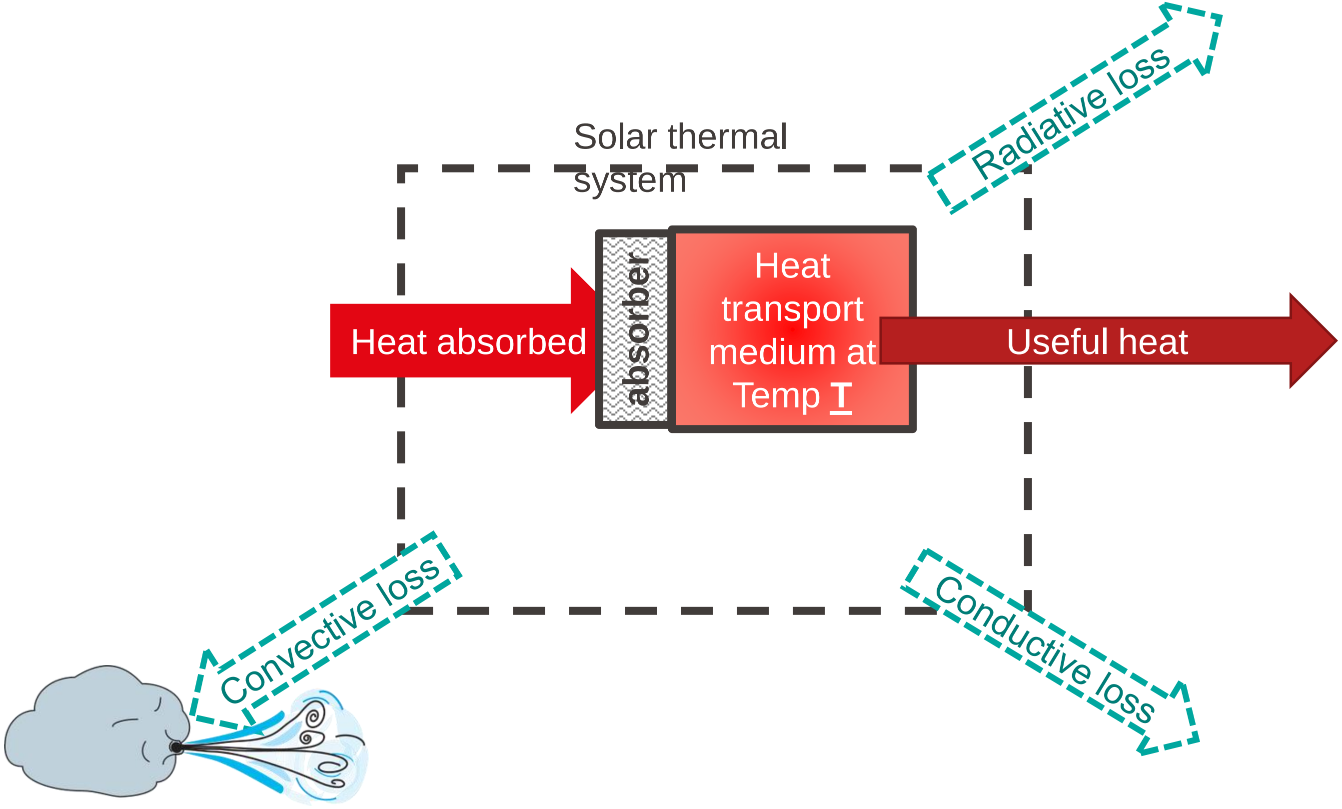

Principles

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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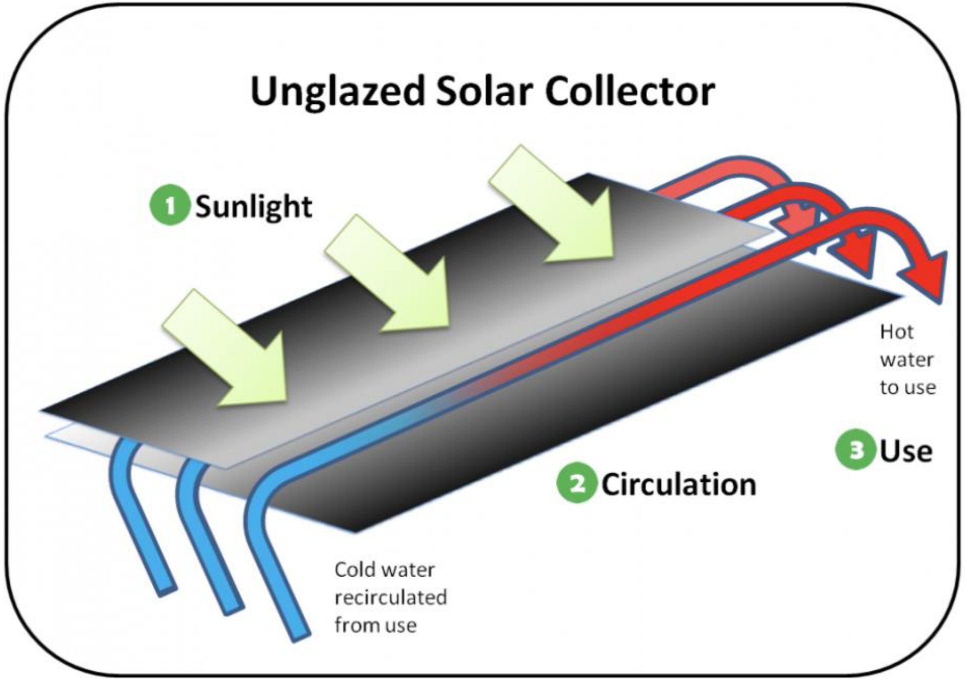
Non or low concentrating

- The most simple solar collector



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Non or low concentrating

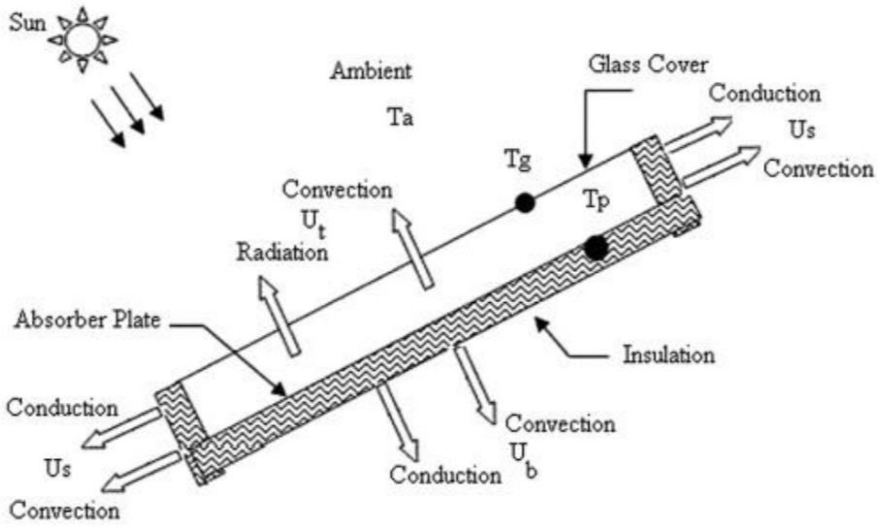
- Flat Plate solar collector

Characteristics:

- Operating temp range: 30-80°C
- Concentration ratio : 1
- Use only direct radiation
- Working fluid, air or water (topology adaptation, see next slide)

Heat loss source:

- Reflection (flat plate)
- Radiative (use vacuum to reduce emissivity)
- Conduction (mitigated by good insulation)
- Convection (use better insulation)



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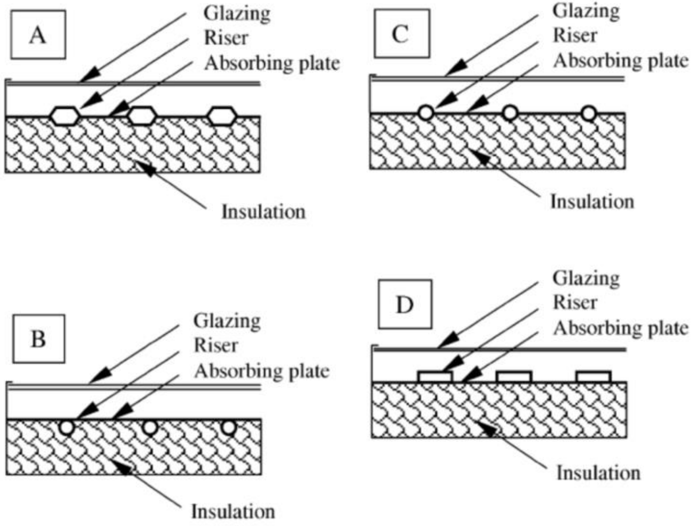
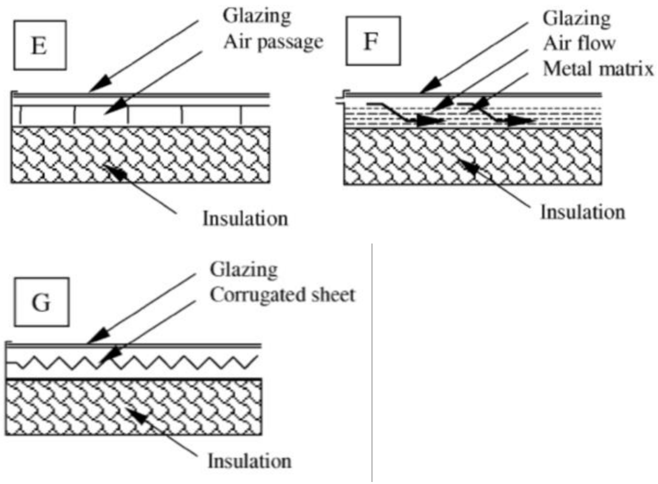
Non or low concentrating

- Flat Plate solar collector topology

Water as working fluid



Air as working fluid



Air VS water:

- Lower heat capacity and lower heat transfer coeff => **higher volumetric flow and pumping power**

+ open or closed loop**: direct convective heating**

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Non or low concentrating

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- Flat Plate solar collector

Examples

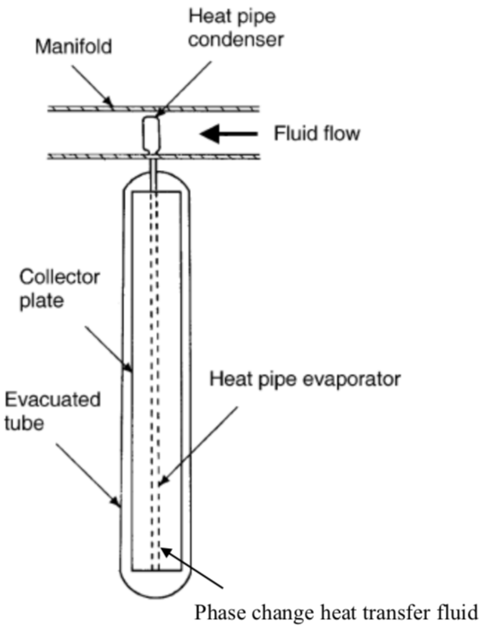
Source: wksolar

Non or low concentrating

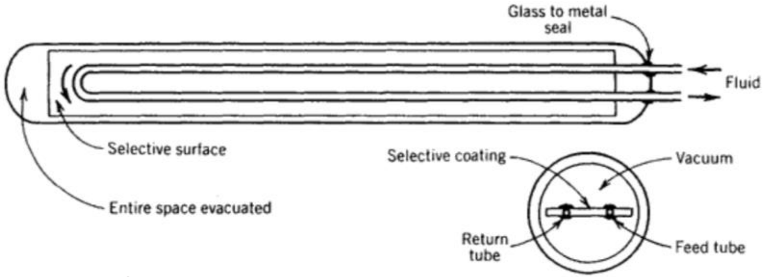
▪ Evacuated tubes solar collector

- 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

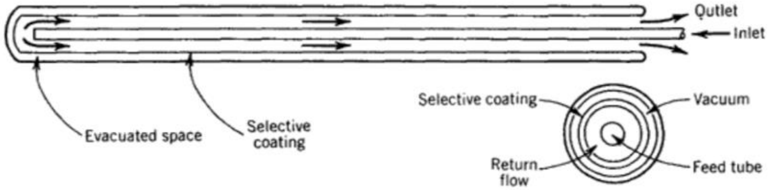
Type 1



Type 2



Type 3



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Non or low concentrating

- Evacuated tubes solar collector

Examples

Source: SunBest

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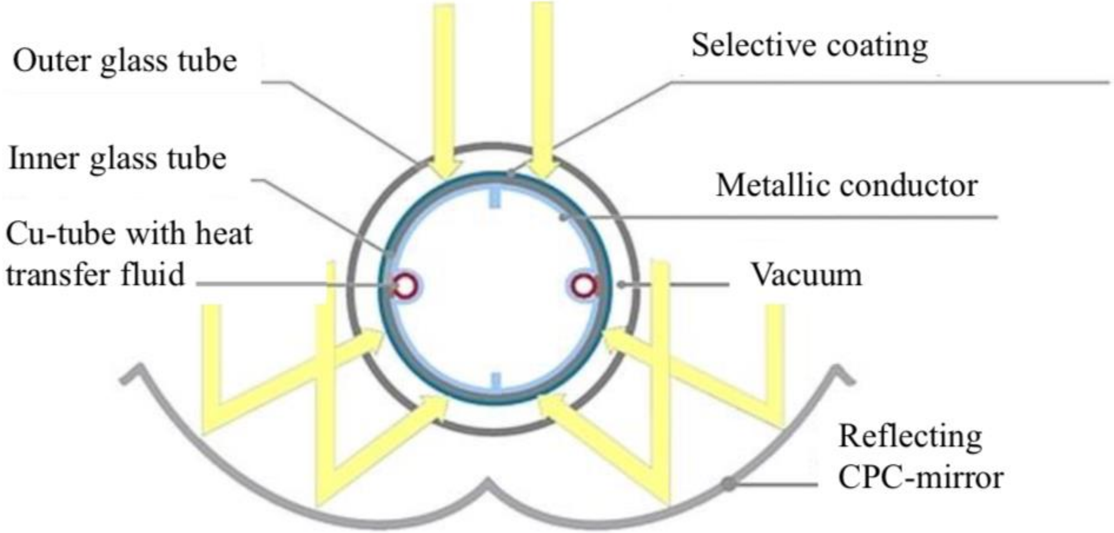
Non or low concentrating

- 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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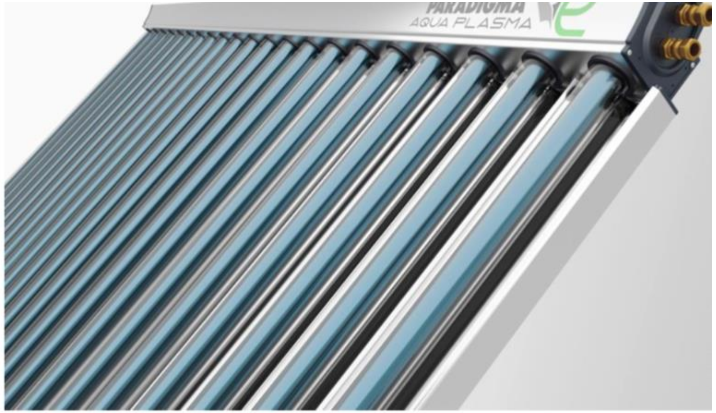
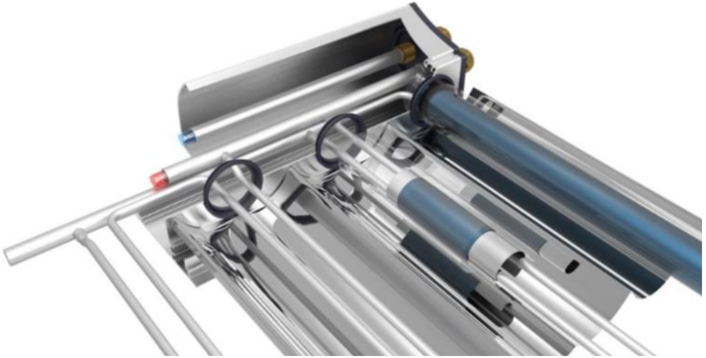
Non or low concentrating

- 2D parabolic solar collector

Examples





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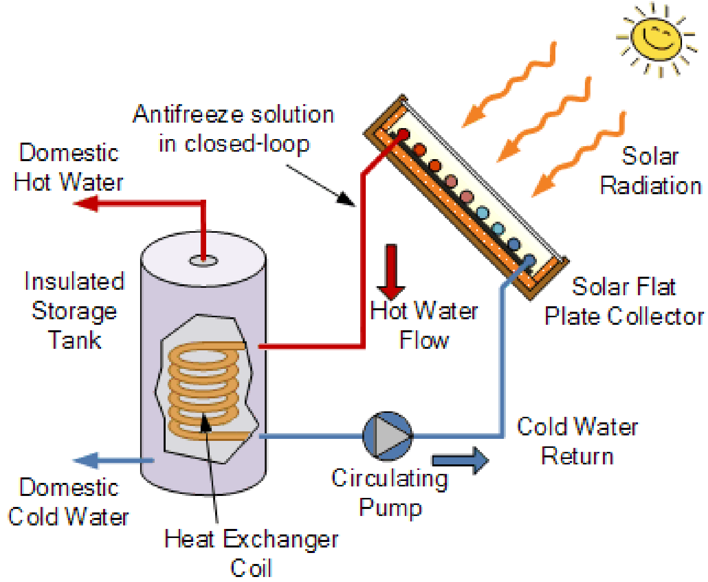
Non or low concentrating

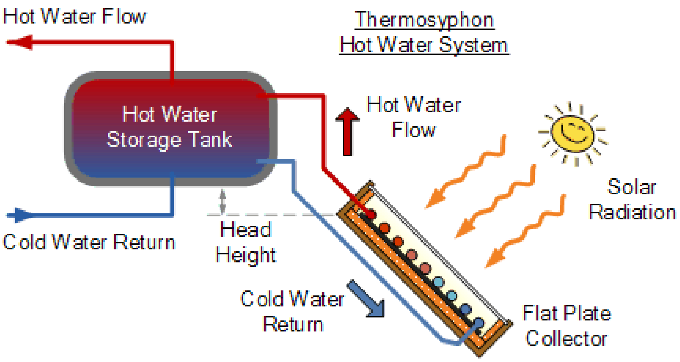
- System considerations

1. Indirect hot water:
Forced convection



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

2. Thermosyphon:
natural convection



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

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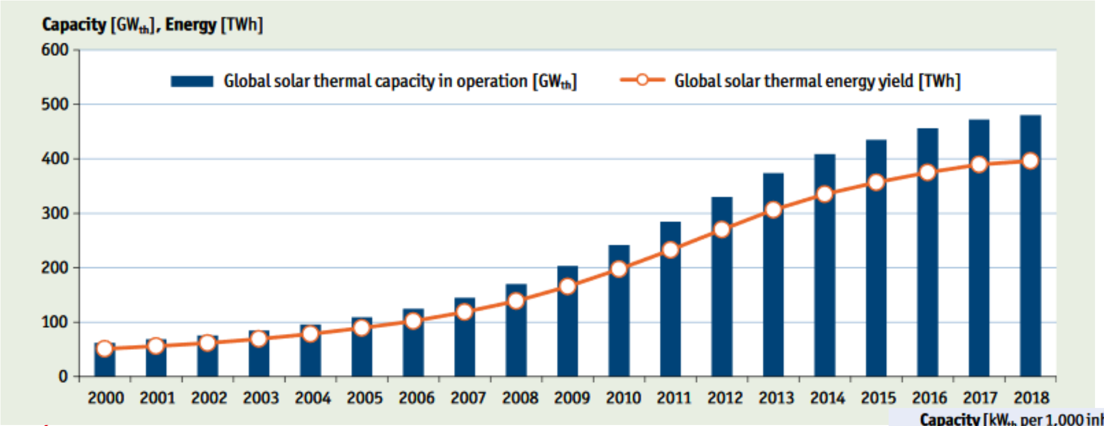
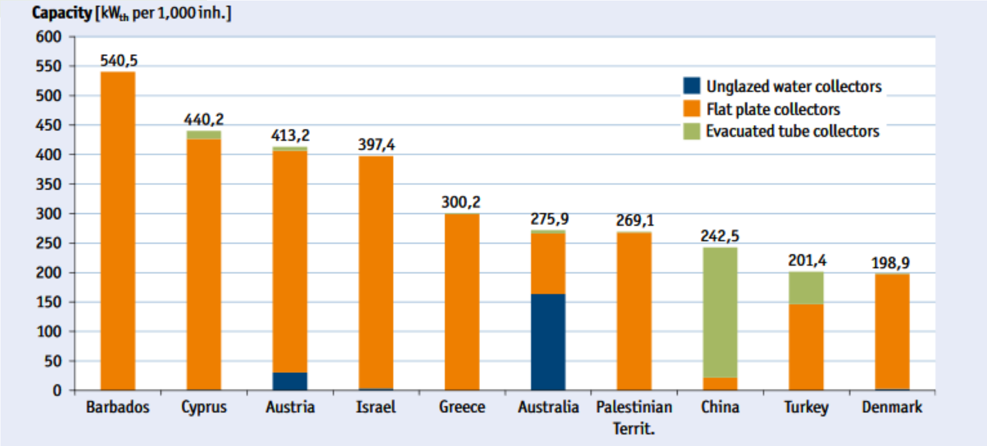
Non or low concentrating

- Capacity and cost



480 GW in 2018

Source: IEA,SHC, *Solar heat worldwide 2019*



Source: IEA,SHC, *Solar heat worldwide 2019*

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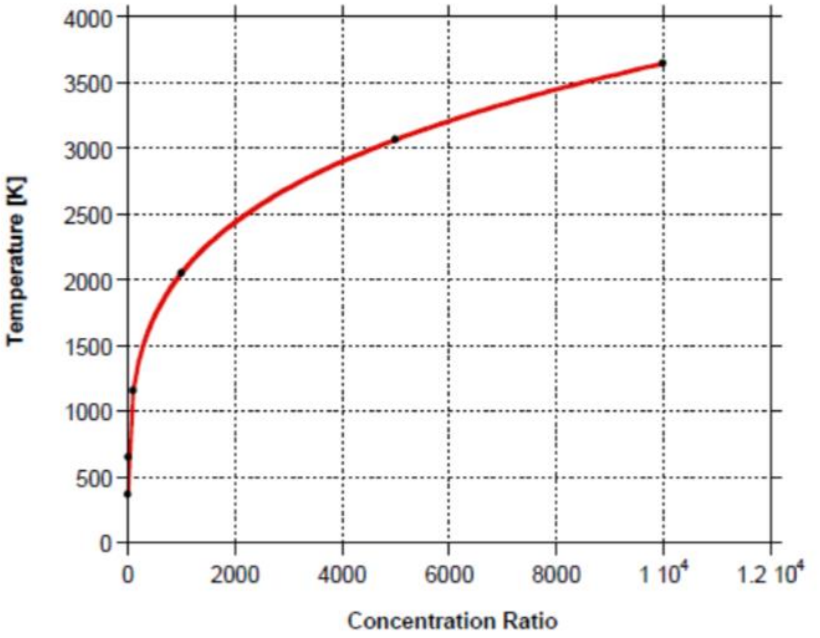
Concentrating Solar

- 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

- Solar to heat … to electricity ?

Process efficiency

$$\eta = \eta_{optics}\,\eta_{receiver}\eta_{engine}$$

Ideal case:

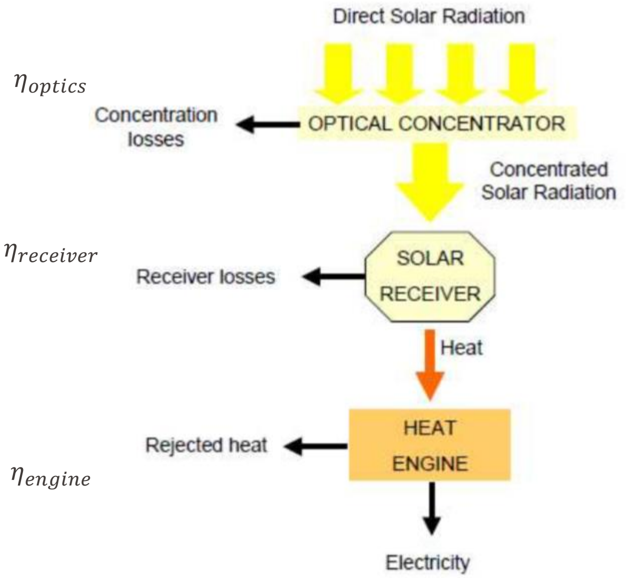
$$\eta_{optics} = 1,$$

$$\eta_{receiver} = \frac{Q_{abs} - Q_{loss}}{Q_{solar}} = \alpha - \frac{\epsilon\sigma T_H^4}{CI}$$

$$\eta_{engine} = \eta_{carnot} = 1 - \frac{T_{amb}}{T_H}$$

$$\eta = \left(\alpha - \frac{\epsilon\sigma T_H^4}{CI}\right)\left(1 - \frac{T_{amb}}{T_H}\right)$$

↘ with T_H ↗ with T_H



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Concentrating Solar

- Solar to heat … to electricity ?

Solve for $\frac{d\eta}{dT_H} = 0$

$$\frac{d\eta}{dT_H} = \left(-\frac{4\epsilon\sigma T_h^3}{CI}\right)\left(1-\frac{T_{amb}}{T_H}\right) + \left(\alpha - \frac{\epsilon\sigma T_H^4}{CI}\right)\left(\frac{T_{amb}}{T_H^2}\right)$$

$$= \frac{\alpha T_{amb}}{T_H^2} - \frac{4\epsilon\sigma T_H^3}{CI} = 0$$

$$\Leftrightarrow \alpha C I T_{amb} - 4\epsilon\sigma T_H^5 = 0$$

$$\Rightarrow \boxed{T_H = \left(\frac{\alpha C I T_{amb}}{4\epsilon\sigma}\right)^{\frac{1}{5}}}$$

Nomenclature:

C: concentration ratio

I: solar irradiance

A: absorber surface

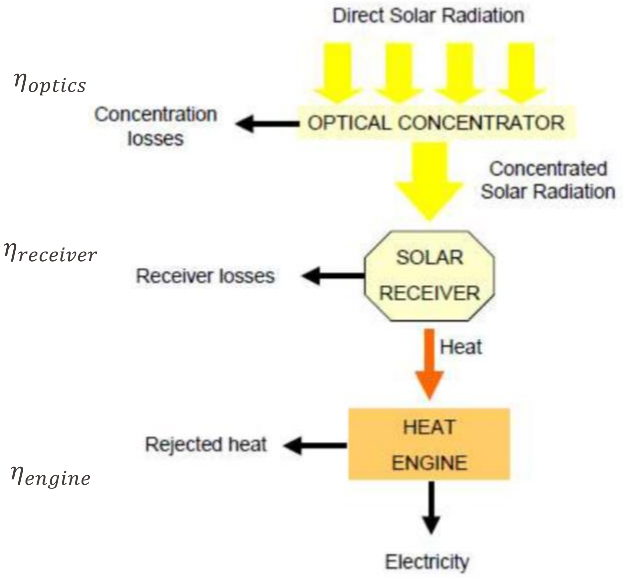
T_H: temp of the absorber

T_{amb}: ambient temperature

α: absorptivity

ϵ: emissivity

σ: Stefan- Boltzmann constant



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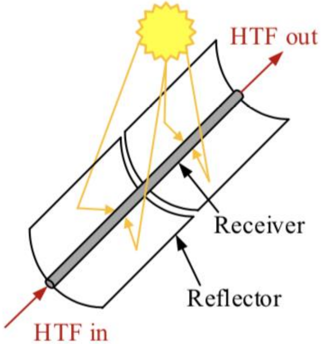
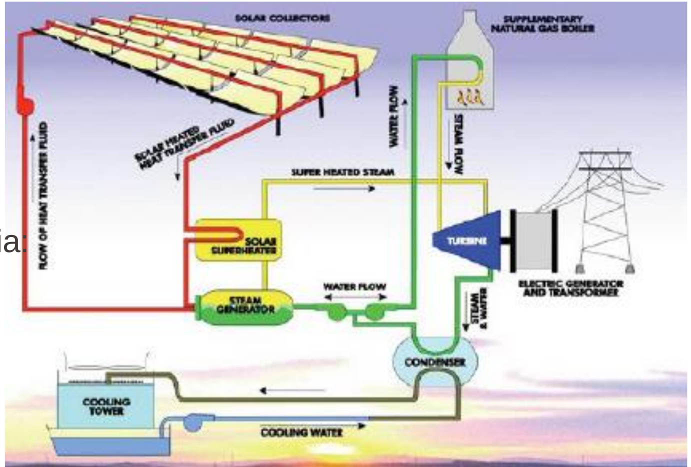
Concentrating Solar

- 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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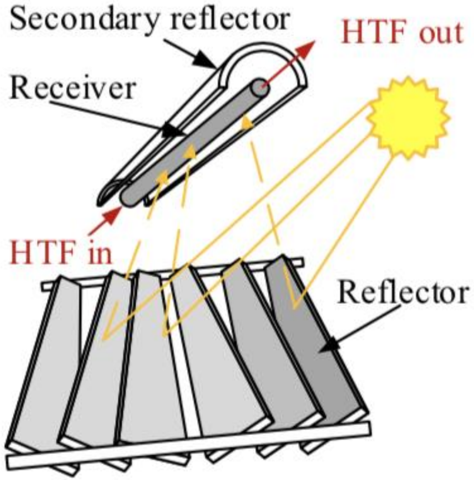
Concentrating Solar

- Linear Fresnel

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



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Concentrating Solar

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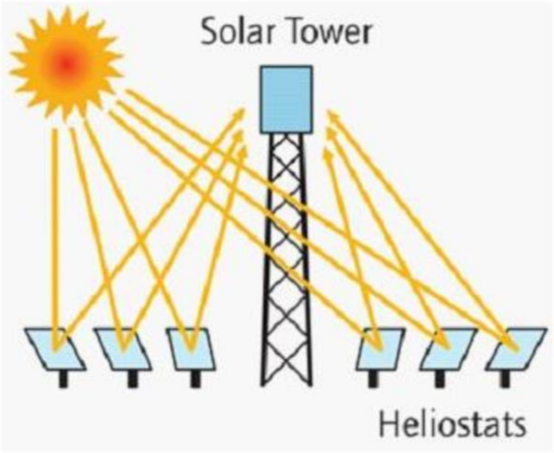
- Linear Fresnel example

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

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 Solar

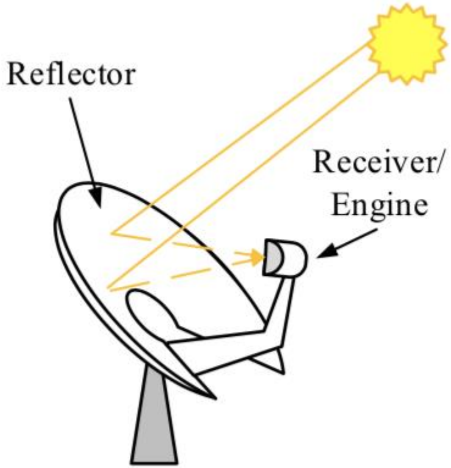
- Concentrating dishes

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

via Stirling or Brayton mini turbines

- Remote application

- Au



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source :ETHZ solar mini-refinery

Solar to Fuel

Conversion pathways

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Solar to fuel : road map

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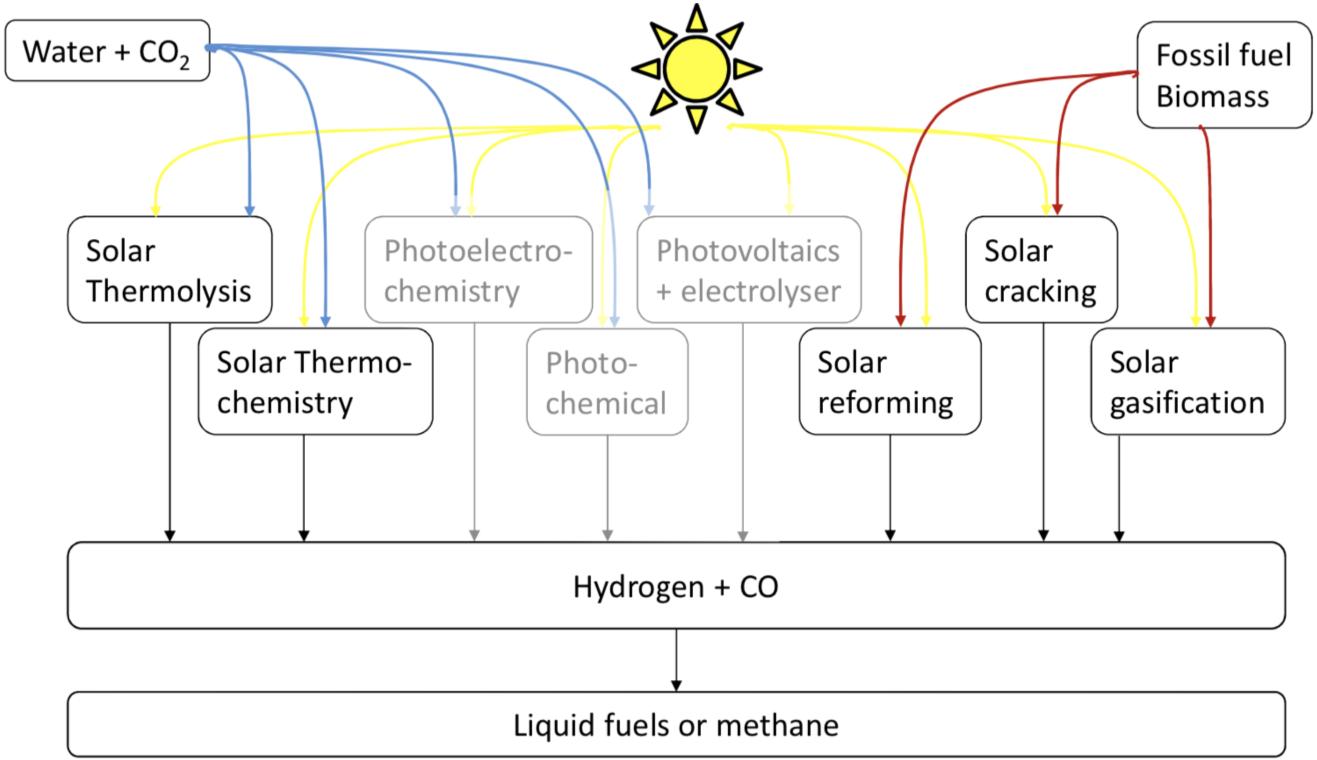
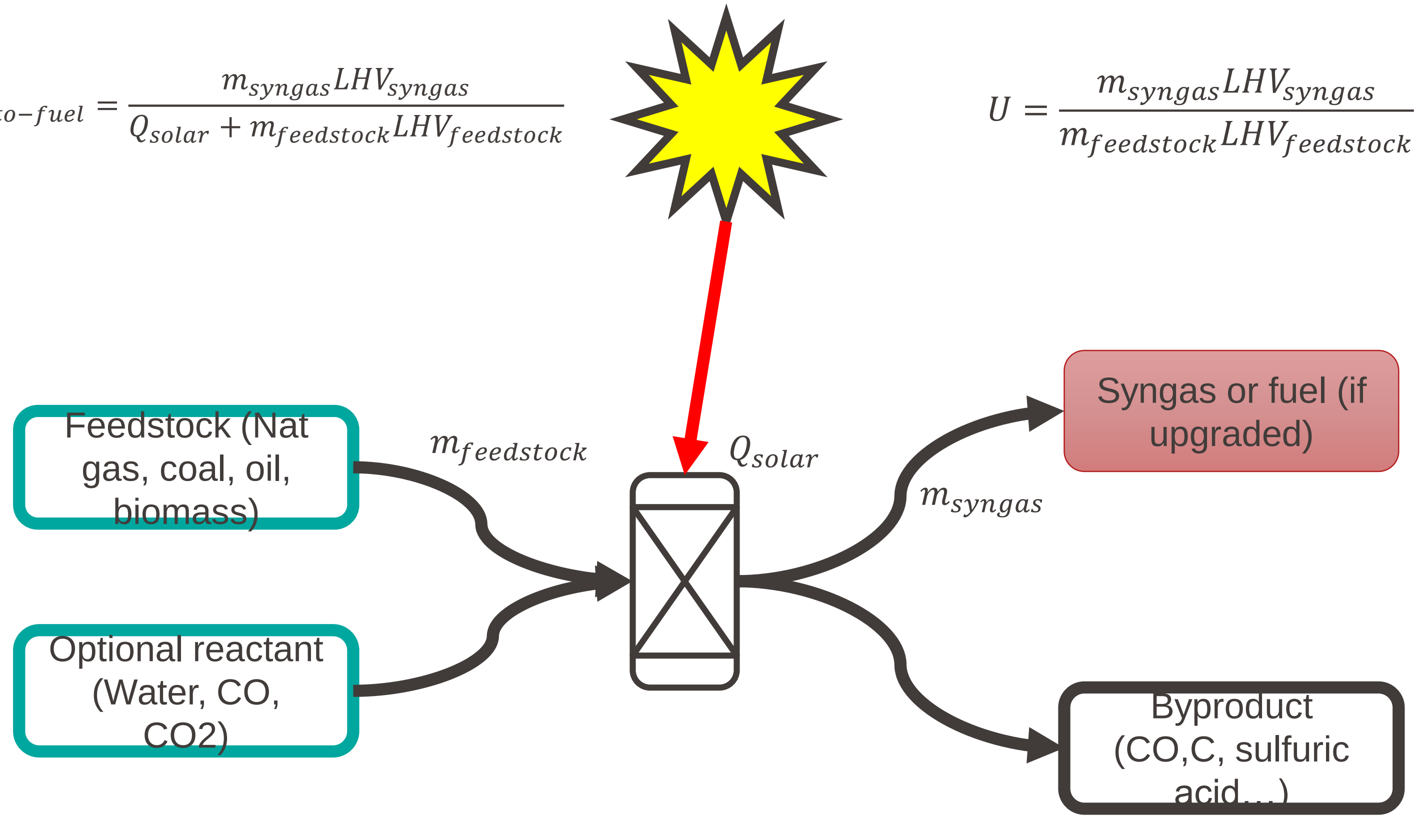


Solar to fuel : main principle

$$\eta_{solar-to-fuel} = \frac{m_{syngas} LHV_{syngas}}{Q_{solar} + m_{feedstock} LHV_{feedstock}}$$

$$U = \frac{m_{syngas} LHV_{syngas}}{m_{feedstock} LHV_{feedstock}}$$



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Solar to fuel : main principle

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Using Gibbs equation we know : $\Delta G = \Delta H - T\Delta S$

ΔG : *Gibbs free energy variation*
ΔH : *Enthalpy variation*
ΔS : *Entropy variation*

For a reaction to be thermodynamically spontaneous, we need : $\Delta G < 0$

Therefore, we may play with ΔH and ΔS, that is intrinsic to the reaction. Or, we may play with T ! → Use of solar heat to drive a reaction !

For an endothermic reaction $\Delta H < 0$, we may provide heat to compensate for the one absorbed during the reaction

For an exothermic reaction $\Delta H > 0$, we may recover the excess heat released by the reaction

Solar cracking

General chemical reaction:

$$C_nH_m \rightarrow nC + \frac{m}{2}H_2$$

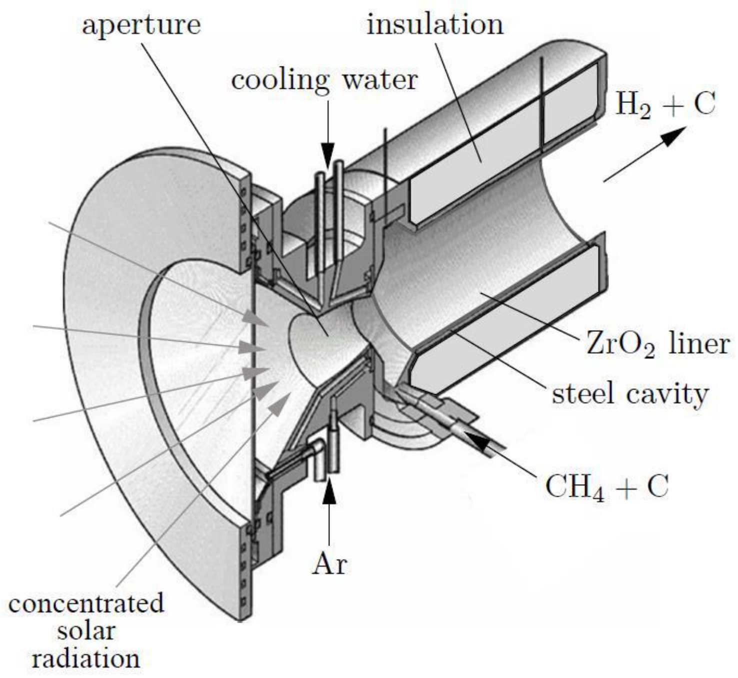
For natural gas:

$$CH_4 \rightarrow C + 2H_2 \left(\Delta H = 74.85\frac{kJ}{kmol}\right)$$

Using a catalyst and high temperature (>1200°C) !

Efficiency (LHV basis) :

16% average, up to 30 %



ETHZ and PSI, Maag et al. 2010

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Solar steam reforming

- 2 fold reaction for Hydrogen production (from carbon oxides) :

<u>Steam methane reforming:</u>

$$CH_4 + H_2O \rightarrow CO + 3H_2 \left(\Delta H = 206 \frac{kJ}{kmol}\right)$$

<u>Water gas shifting:</u>

$$CO + H_2O \rightarrow CO_2 + H_2 \left(\Delta H = -41 \frac{kJ}{kmol}\right)$$

Temperature: 700-925°C

Efficiency (LHV Basis): 65-75 %

Most widely used reaction to produce H_2 (49%),

however the energy source is often not solar ☹

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Solar gasification

- For Hydrogen production (from pure carbon source) :

Eg. from coal or biomass :

$$C + H_2O \rightarrow CO + H_2 \left(\Delta H = 131 \frac{kJ}{kmol} \right)$$

High temperature (>700°C), avoiding combustion

Efficiency (LHV Basis) around 30%, temperature around 1500°C

Advantage : produces CO, which can be again refined by solar steam reforming.

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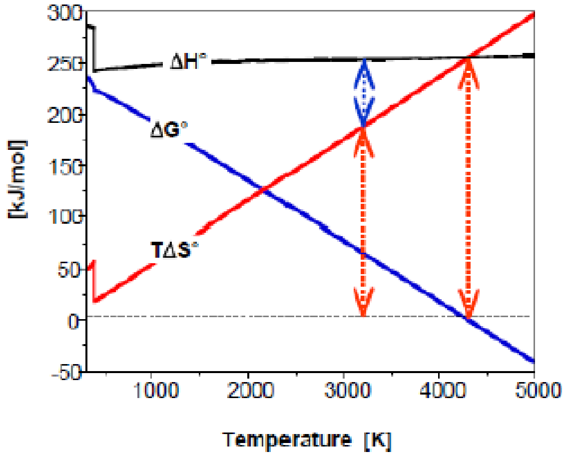
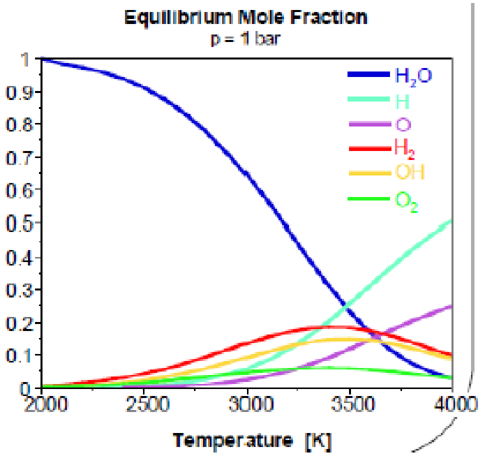
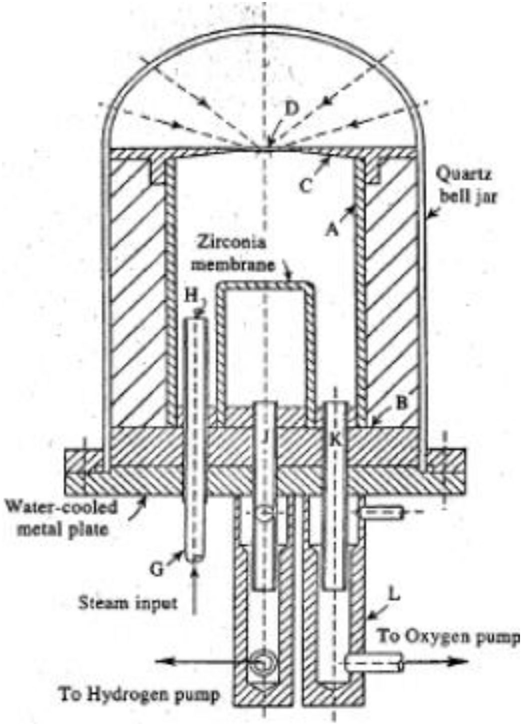
Solar thermolysis

- For Hydrogen production (from water) :

Solar energy used as heat source, for direct thermolysis of water : $H_2O \rightarrow \frac{1}{2}O_2 + H_2$







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Solar thermo-Chemistry

- Multi-step water splitting for Hydrogen production

$$ZnO \leftrightarrow Zn + 1/2\ O_2 \longrightarrow O_2$$

$$H_2 \longleftarrow ZnO + H_2 \leftrightarrow \mathrm{Zn} + \mathrm{H_2O}$$

Advantages:

- Clean separation of oxygen and hydrogen
- Lower temperature
- Other metals also possible as catalysts

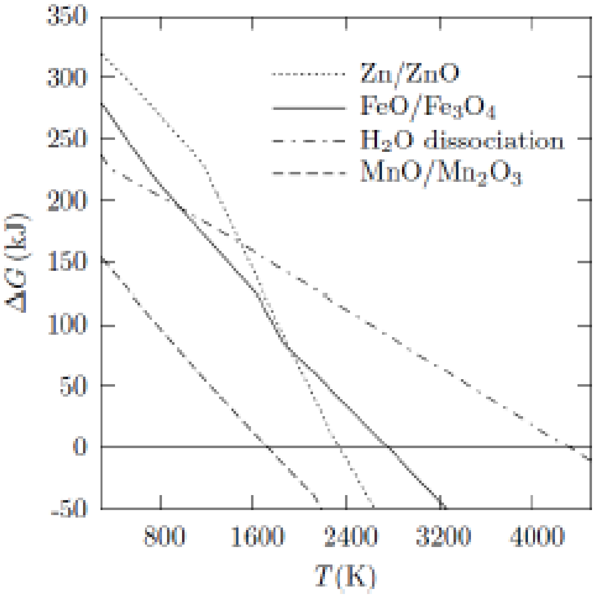

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Photo-Chemistry

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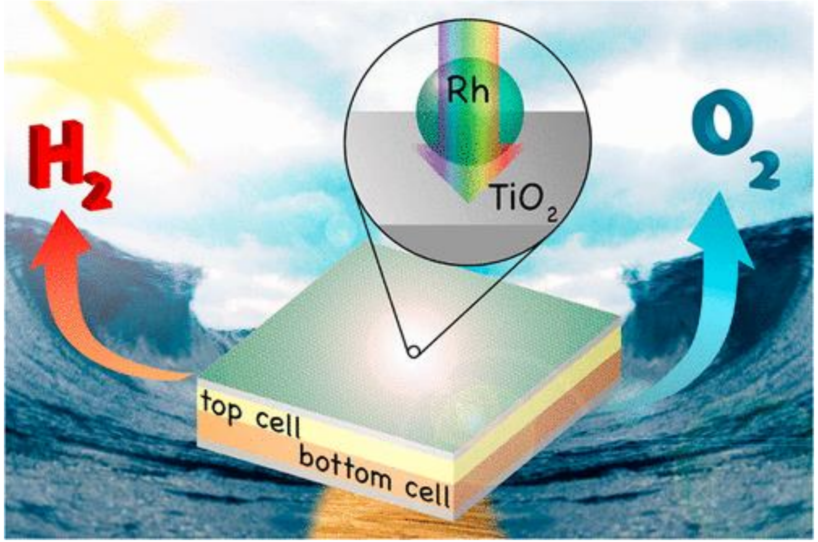
- Powering chemical reactions

World record efficiency (LHV Basis): 19%

- Is it worth it compared to a good PV array and appropriate electronic devices ?

$$E > 1.23eV$$

$$H_2O \leftrightharpoons \frac{1}{2}O_2 + H_2$$



ACS Energy Lett. 2018, 3, 8, 1795–1800
Publication Date:June 25, 2018
https://doi.org/10.1021/acsenergylett.8b00920

Solar Systems

Self-consumption

System integration

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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

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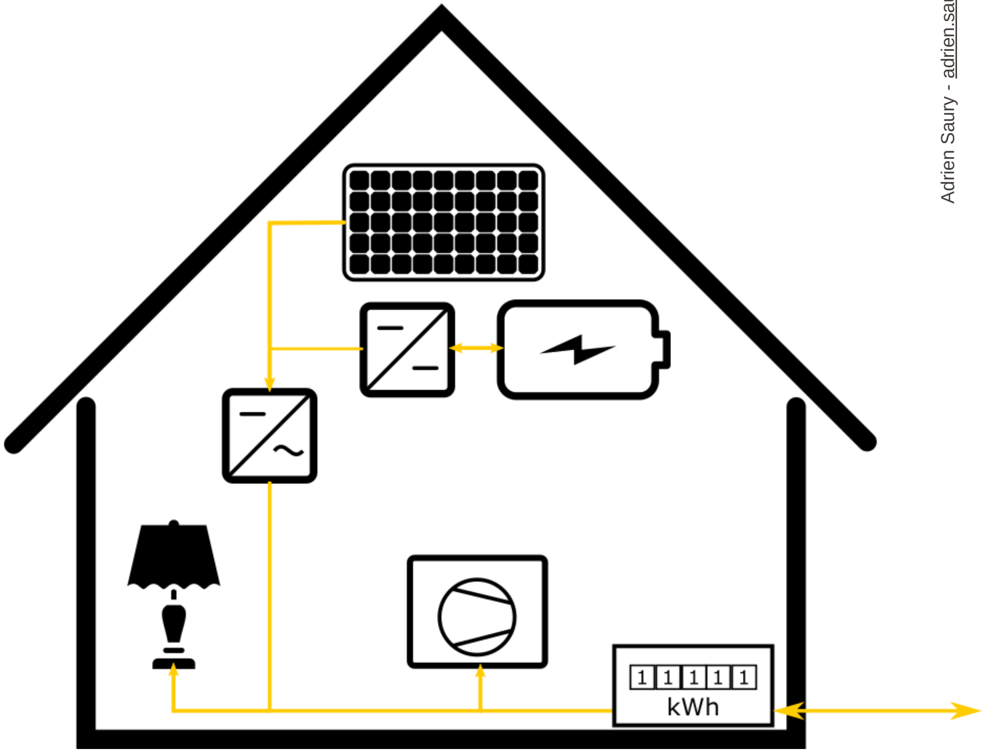
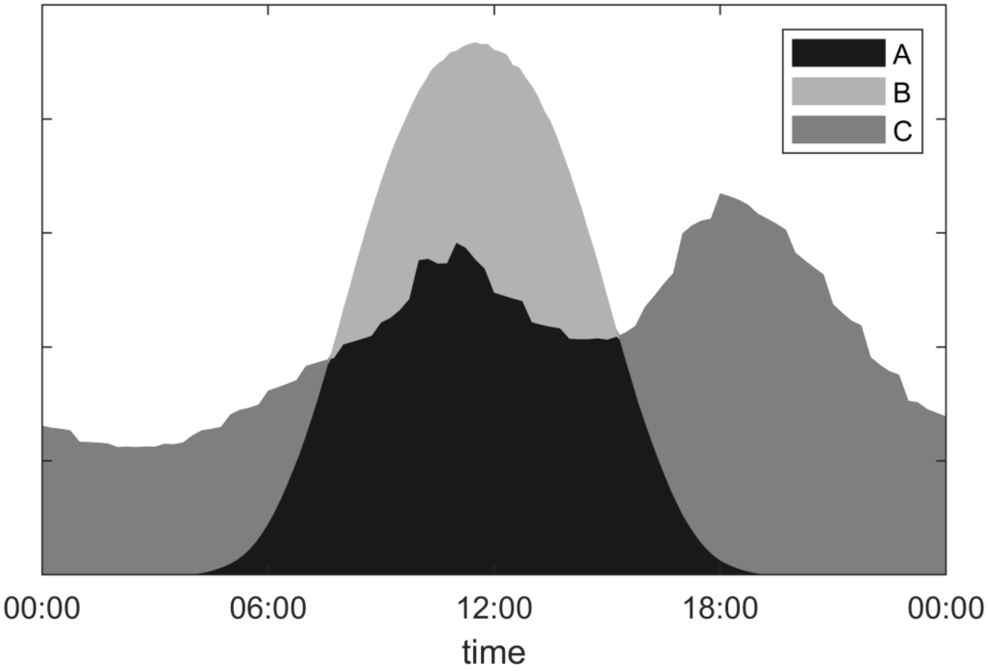
- For residential and industrial scale only
- Best economic interest: use solar energy to cover own consumption
- A LOT harder than it seems !



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: $\frac{A}{A+B}$

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

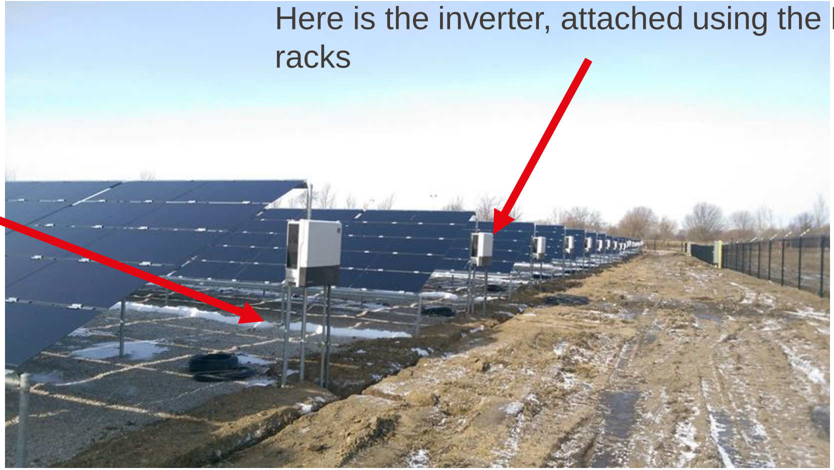
Autonomy: $C = \emptyset \Rightarrow$ no grid

Neutrality: $A + B = A + C$

Considerations on solar systems

- A set of examples from industry

- In snowy countries, a framless 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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Self consumption

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- What to do then ? That's the big question!

It all depends on :

1. What demand do you have
   - Individually, in cooperative, by buildings…
   - Hot water, mobility, electricity, heating, cooling… and WHEN you MIGHT need it

2. What other technologies you may use in synergy
   - Battery storage to cover night demand
     - Use your new Tesla as the battery?, use a larger collective battery ?
   - Thermal storage (daily, seasonal…)
   - Cooperation between buildings ?
     - A heat pump cooling a shopping mall but heating your house ?
   - …. There are SO many options ☺

3. At which investment and operation costs ?

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Summary

Exercise : find the PV panels ☺
source : Solaxess SA

Solar energy

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

Solar to heat

- Solar collector
  - T = 30-240°
  - Working fluid: Water with additive
  - Used for domestic hot water
- Concentrated solar
  - Working fluid : Molten Salt can be stored
  - High T => heat engine to produce electricity
  - C = 30-4000

Solar to electricity : PV

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

Considerations on System integration

- What technological synergies
- 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,
X =
1000 kWh/year
And cost 1000 CHF.

1000 KWH/YEAR for a 1000 CHF !
(assuming 1000h of equ.sun/year at 1000W/m^2) -> slight over-estimation

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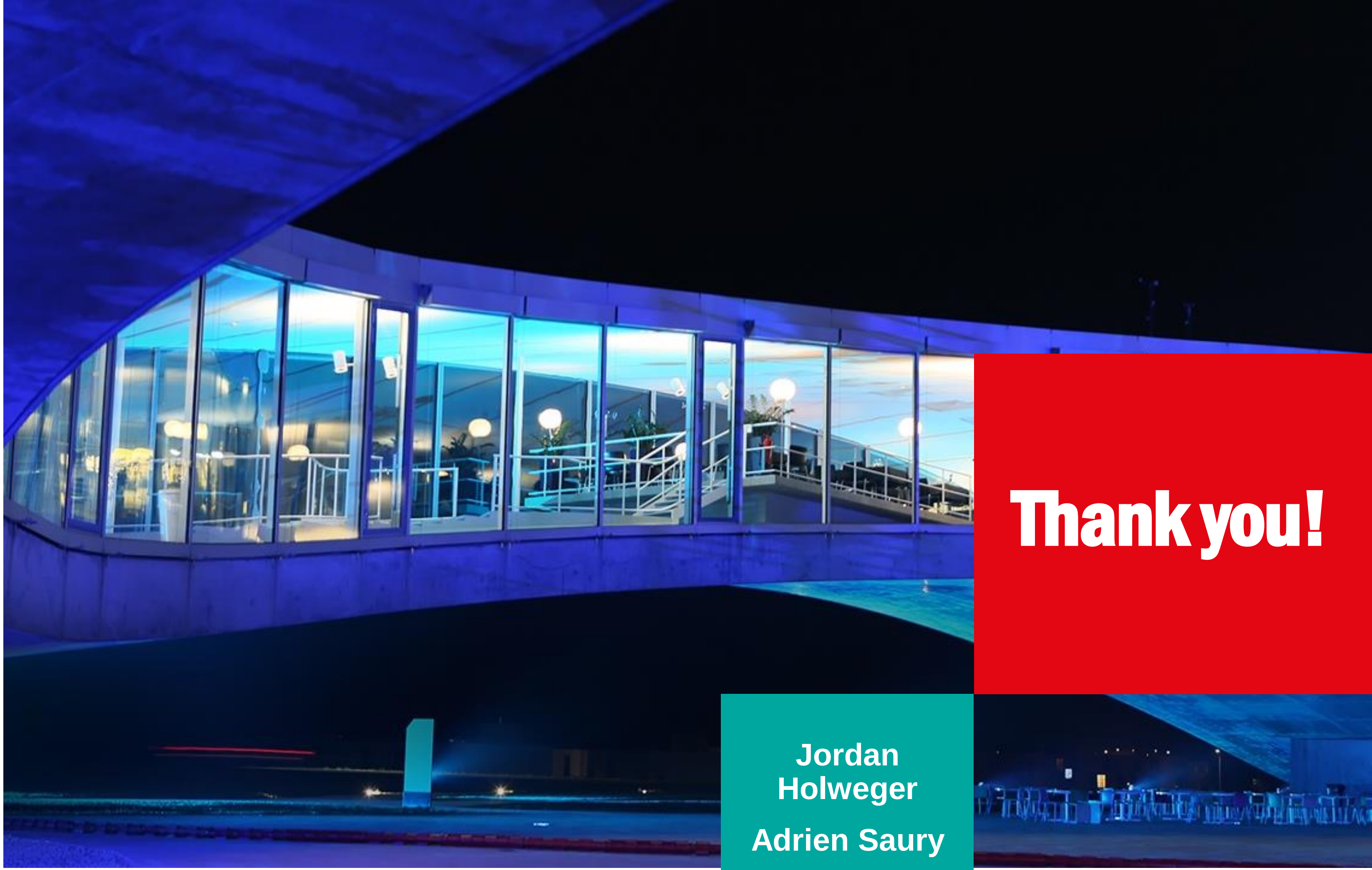

Thank you!

Jordan Holweger

Adrien Saury