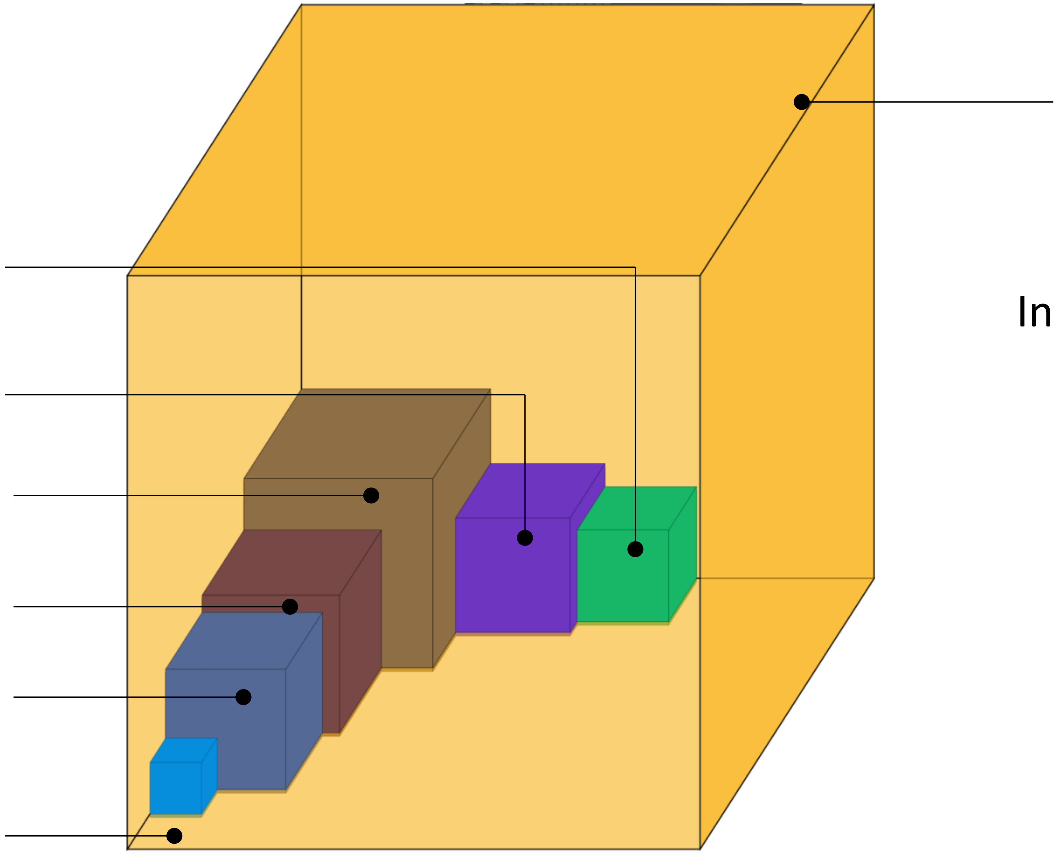
Lecture 8
Solar energy

PHY 555 – Energy & Environment

Erik Johnson, Mathieu de Naurois, Daniel Suchet

Omanobserver

Why solar?



Wind in 2018

Uranium reserve
(excluding sea-water & breeder)

Coal reserve

Oil reserve

Gas reserve

Total Primary Energy Supply
in 2018
18 TWy

Solar power in 2018
(land only, including weather)
23 000 TWy

Adapted from M. Perez et al.,
IEA-Solar Heating and cooling program, 2015

In France, $1000\,\mathrm{W/m^2}$ direct

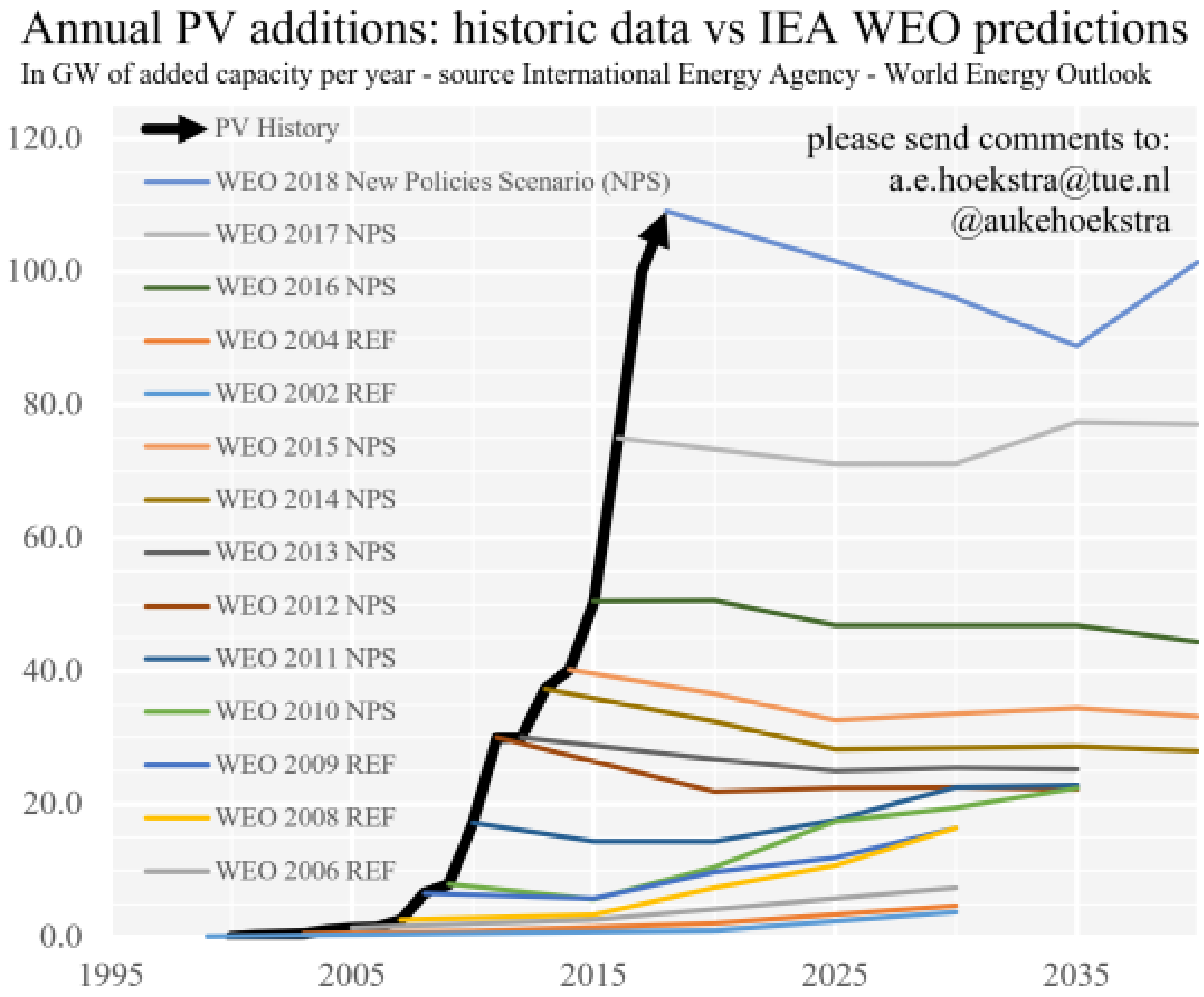
$150\,\mathrm{W/m^2}$ on average
(day/night, clouds & rain…)

French electricity production in 2018
⇔
15% of road surfaces
(including weather & efficiency)

Diffuse, intermittent… certainly !

But still an energetic manna !

The sky is the limit!



Annual PV additions: historic data vs IEA WEO predictions

In GW of added capacity per year - source International Energy Agency - World Energy Outlook

please send comments to:
a.e.hoekstra@tue.nl
@aukehoekstra

2020 : 140 GWp installed !

IEA PVPS Global Market Snapshot 2021

Installed / nominal / nameplate / rated capacity
=
Maximal power when everything's ok

Actual production=
Installed capacity
x
Load factor
(PV 15%, wind 20%, thermal 80%)

Always check the units (power? energy?) and the definitions of a quantity under scrutiny !

I. Solar energy resource

II. Thermodynamics of solar energy conversion
  A. Solar heating
  B. Concentrated solar power
  C. Photovoltaics

III. Overview of the silicon PV technology

IV. PV today and tomorrow

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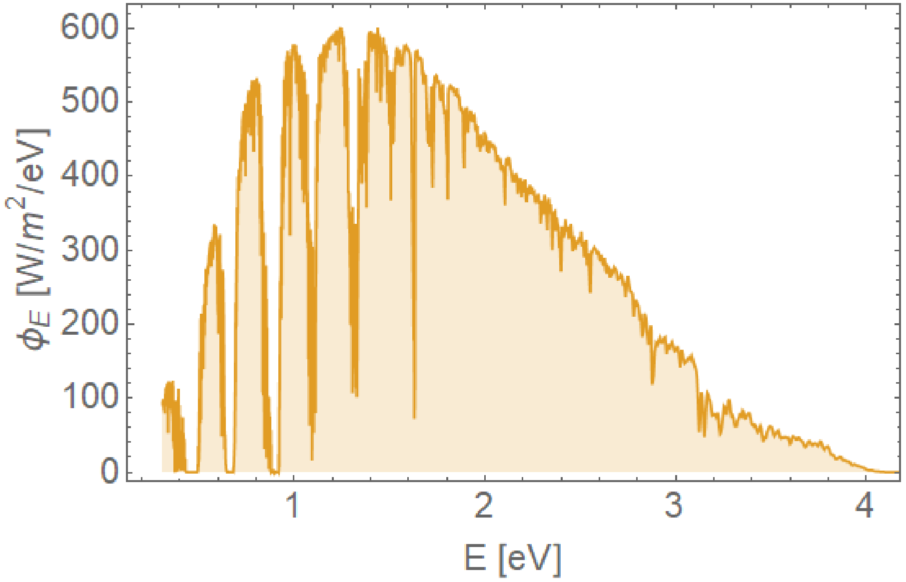
Solar flux – the usual approach

Surface temperature : 6000 K Emitted power: *Stefan law* $P_\odot = 4\pi R_\odot^2\, \sigma T^4$

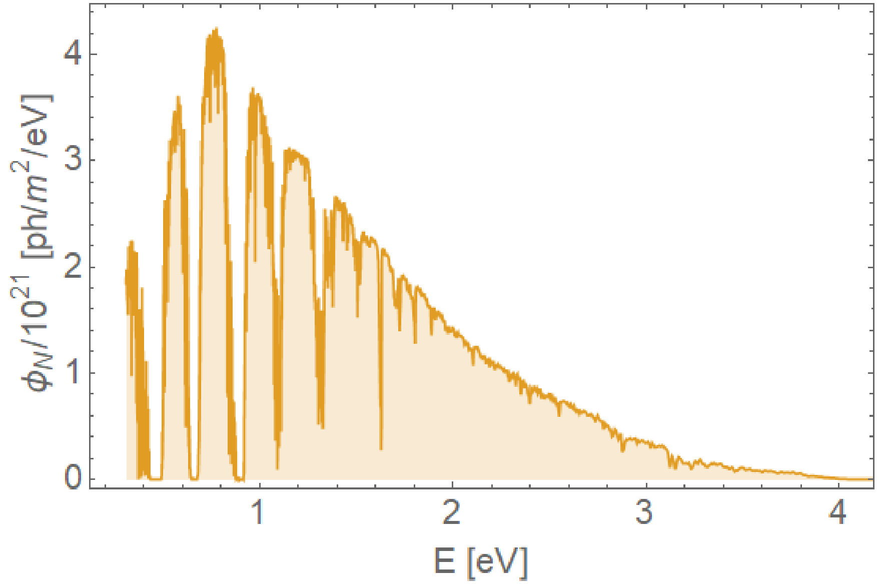
Intensity reaching the Earth :

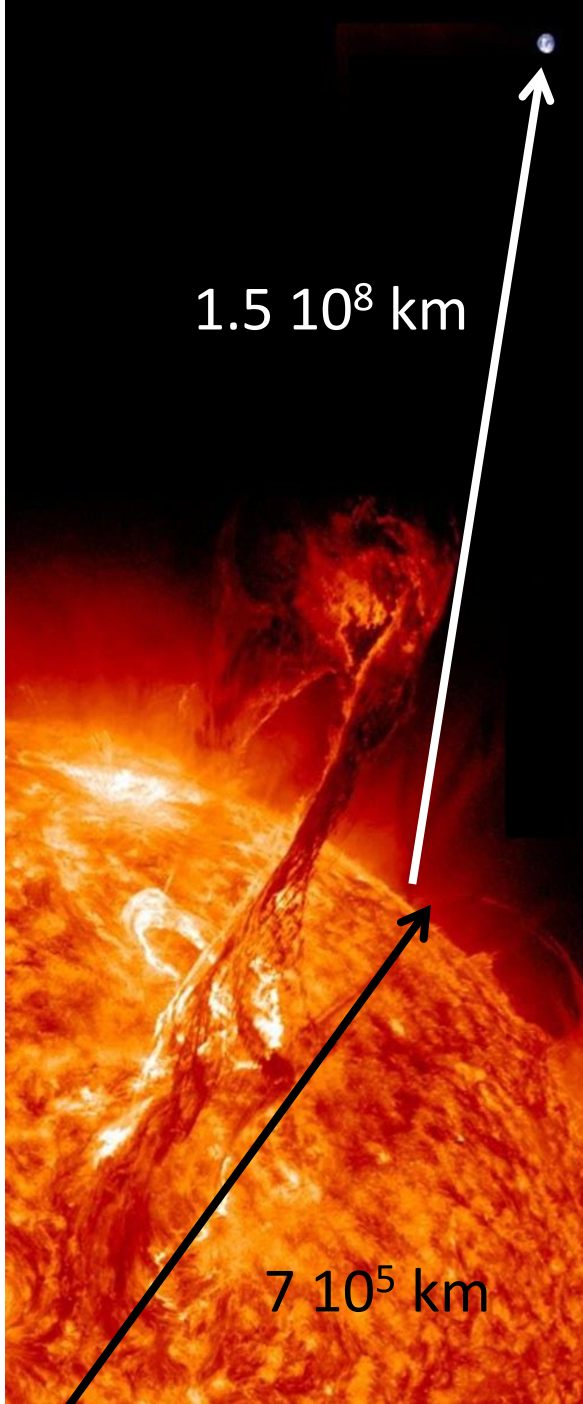
$$G_{\mathrm{SC}} = \frac{P_\odot}{4\pi D^2} = \frac{\Omega_\odot}{\pi}\sigma T^4 = 1360 \mathrm{W/m^2}$$



Photon flux reaching the Earth :

$$J_N = 4 \times 10^{21}\ \mathrm{m^{-2}.s^{-1}} = 700\ \mathrm{A/q/m^2}$$





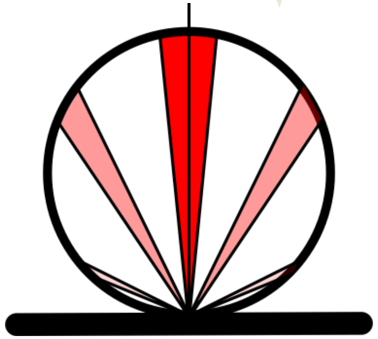
Solar flux – a different approach

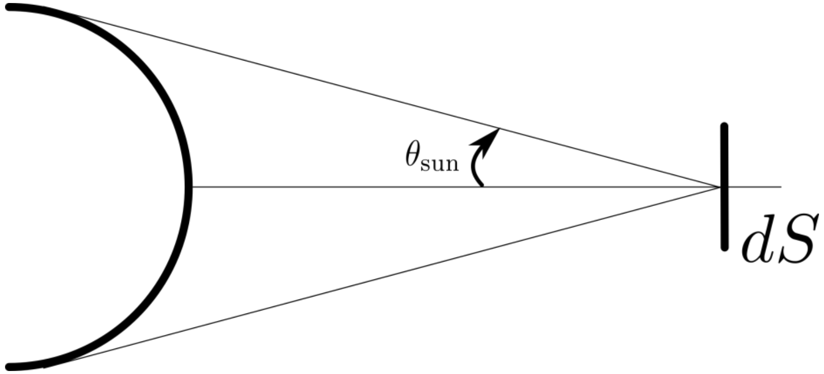
Emitted spectrum : *Planck law*

$$\phi_E(E,\,\Omega) = \frac{\cos\theta}{4\pi^3\hbar^3c^2}\frac{E^3}{\exp\left(\frac{E}{k_BT}\right)-1}$$

Black body has a **Lambertian** emission

$$\phi_E(\Omega) = \int dE\phi_E(E,\,\Omega) = \frac{\cos\theta}{\pi}\sigma T^4$$





$$P = \frac{1}{\pi}\underbrace{dS\int\cos\theta d\Omega}_{\text{etendue}}\times\sigma T_{\text{sun}}^4 = \sin^2\theta_{\text{sun}}dS\times\sigma T_{\text{sun}}^4$$

Low concentration

$$\simeq\theta_{\text{sun}}^2\times\sigma T_{\text{sun}}^4dS$$

$$\simeq\frac{\Omega_{\text{sun}}}{\pi}\times\sigma T_{\text{sun}}^4dS$$

High concentration

$$\simeq\sigma T_{\text{sun}}^4dS$$

The power received by a surface depends
on the **optical étendue** of the system

Solar flux – back on tracks

Surface temperature : 6000 K $$P = \frac{1}{\pi}\underbrace{dS\int \cos\theta\, d\Omega}_{\text{etendue}} \times \sigma T_{\text{sun}}^4 = \sin^2\theta_{\text{sun}}\, dS \times \sigma T_{\text{sun}}^4$$

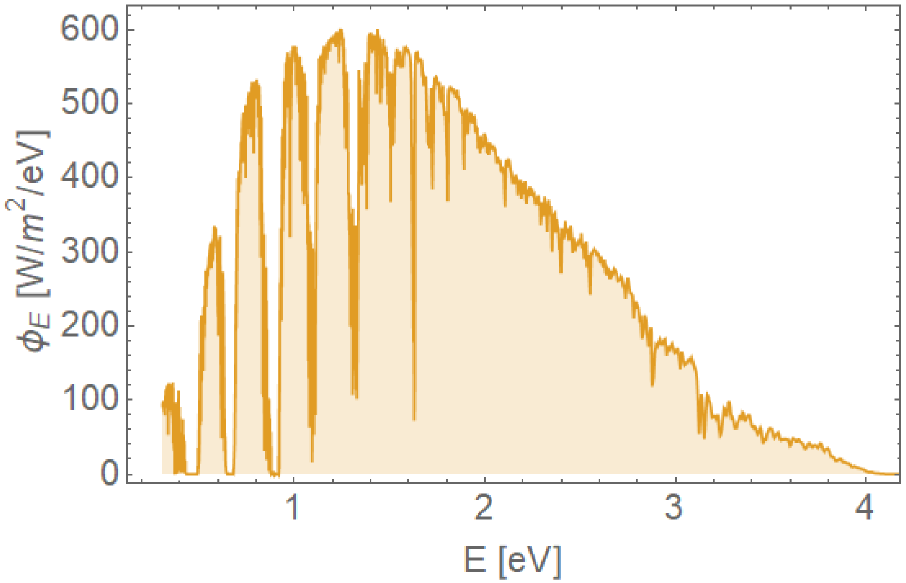
Angular diameter: $$2\theta_{\text{sun}} \simeq 2\left(\frac{R_{\text{sun}}}{1\,\text{a.u.}}\right) = 0.52^\circ$$

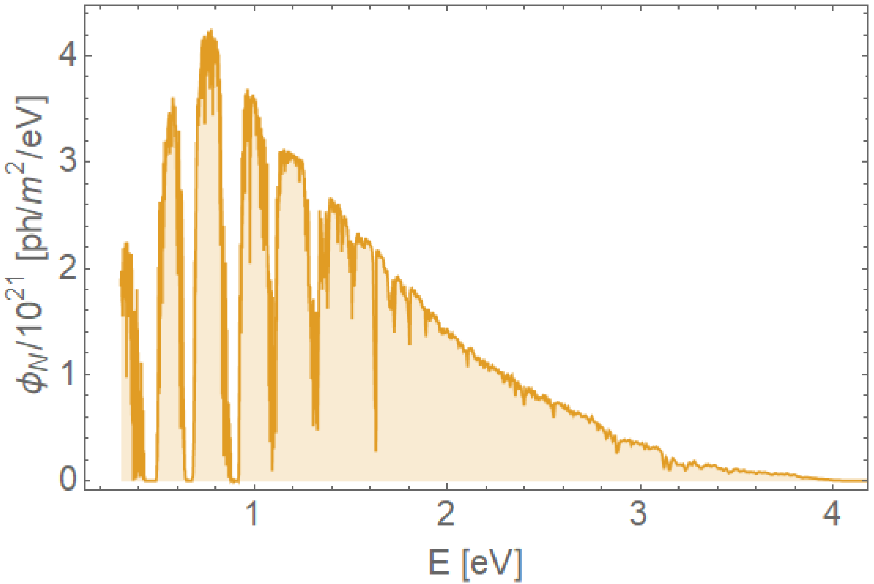
Intensity reaching the Earth :

$$G_{\text{SC}} = \sin^2\theta_{\text{sun}} \times \sigma T^4 = 1360\,\text{W/m}^2$$

Photon flux reaching the Earth :

$$J_N = 4\times 10^{21}\,\text{m}^{-2}.\text{s}^{-1} = 700\,\text{A/q/m}^2$$





A little bit of Sci-Fi

Niklai’s Kardashev scale (1964)

Type I

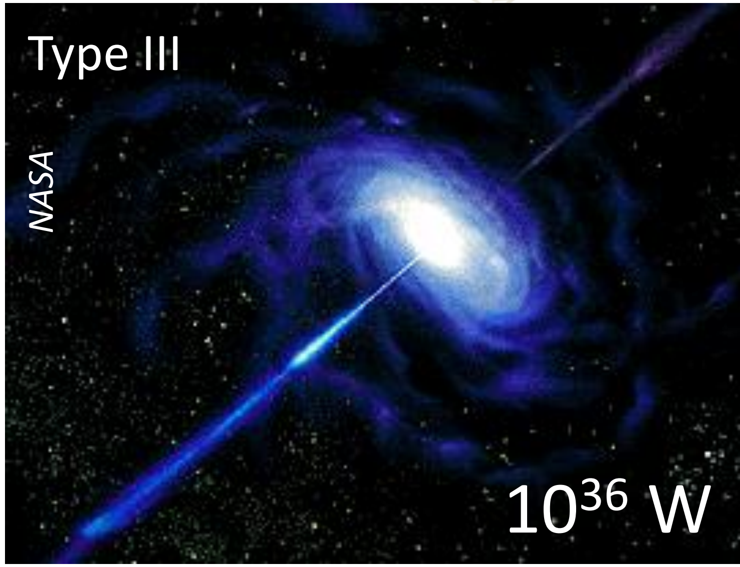
10^{16} W

streetwisereports

Type II

10^{26} W

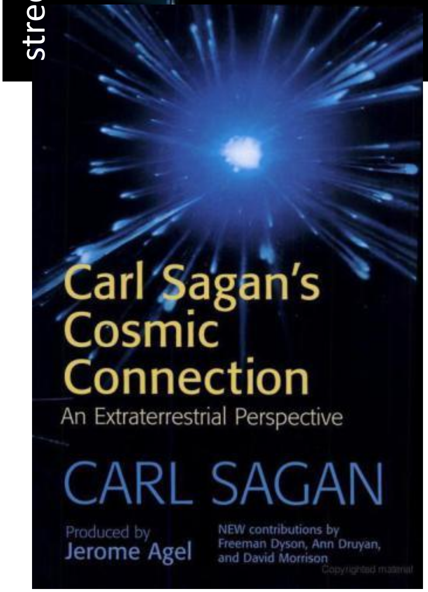
Danielle Futselaar
SETI International



Type III

10^{36} W

NASA



Carl Sagan’s
Cosmic
Connection
An Extraterrestrial Perspective

CARL SAGAN

Produced by
Jerome Agel

NEW contributions by
Freeman Dyson, Ann Druyan,
and David Morrison

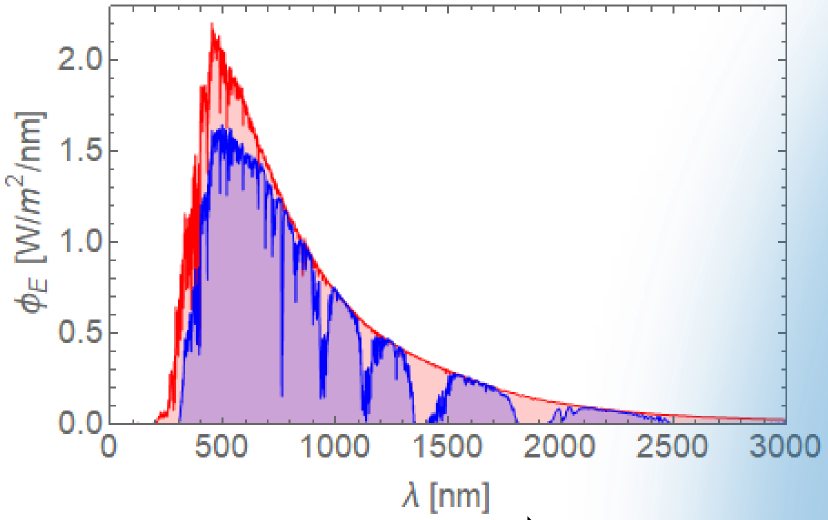
In 2015, world consumption
10^{13} W

Type 0.7…

Solar radiation on Earth

Intensity reaching the atmosphere :

$$G_{\mathrm{SC}} = 1360\,\mathrm{W/m^2}$$



Intensity transmitted through the atmosphere:

$$\boxed{G_{\mathrm{AM\,1.5}} = 1000\,\mathrm{W/m^2}}$$

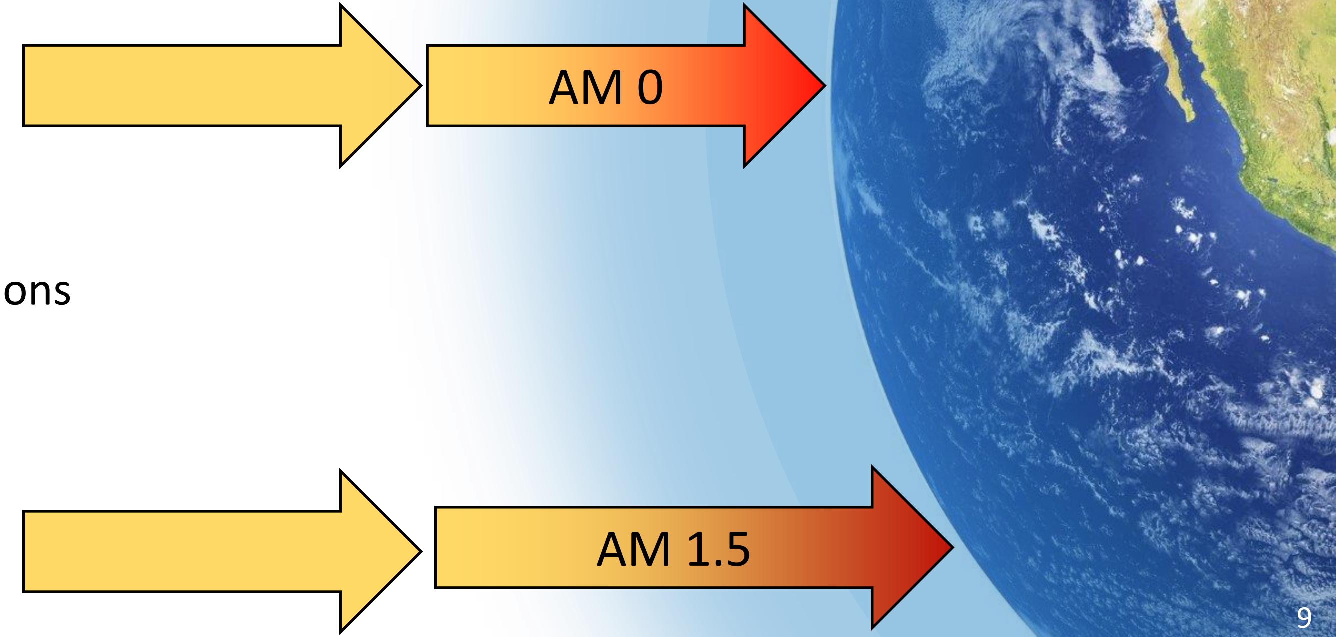
Influence of latitude,

Influence of seasons,

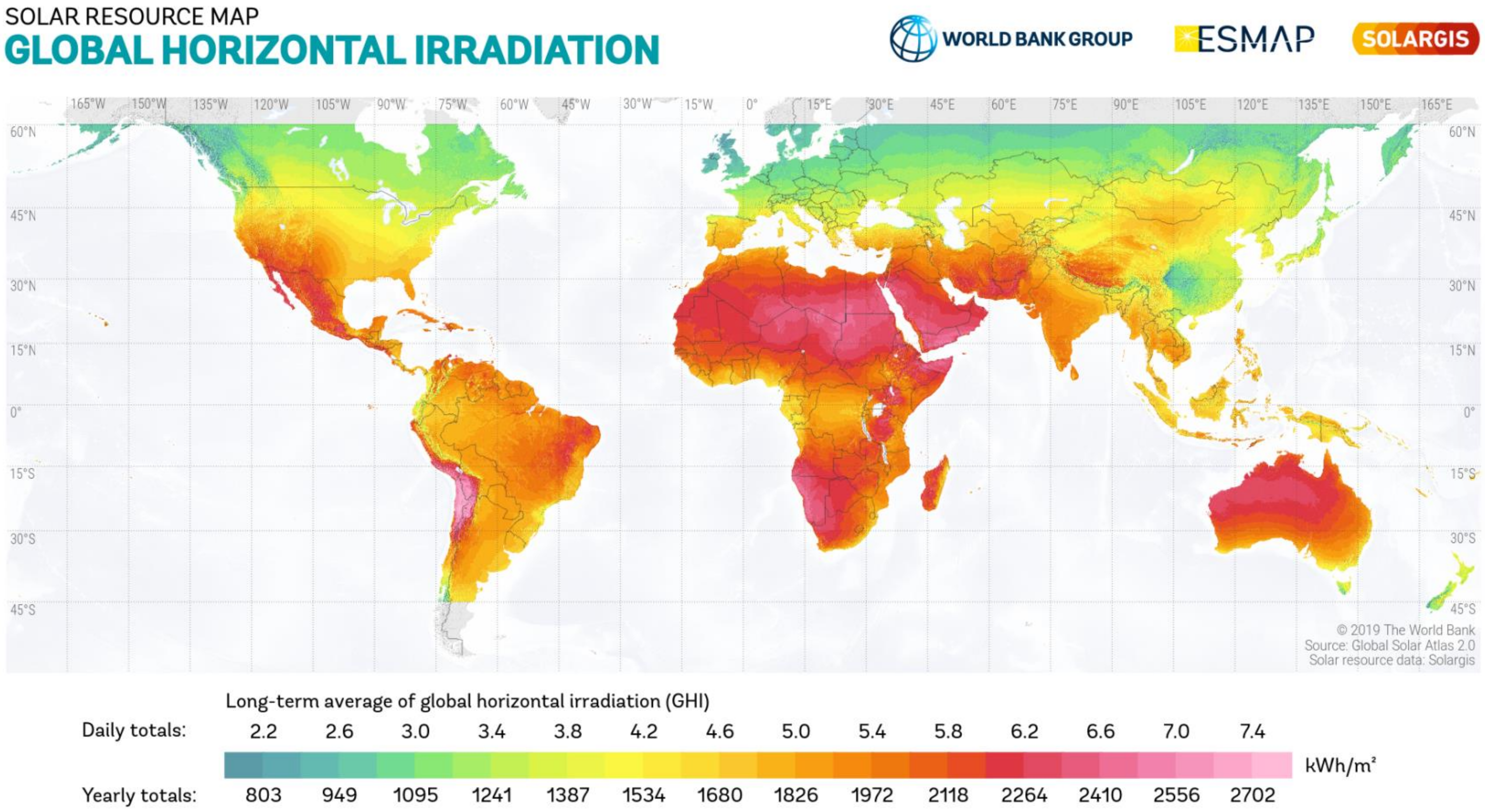
Influence of day-night cycles,

Influence of weather conditions

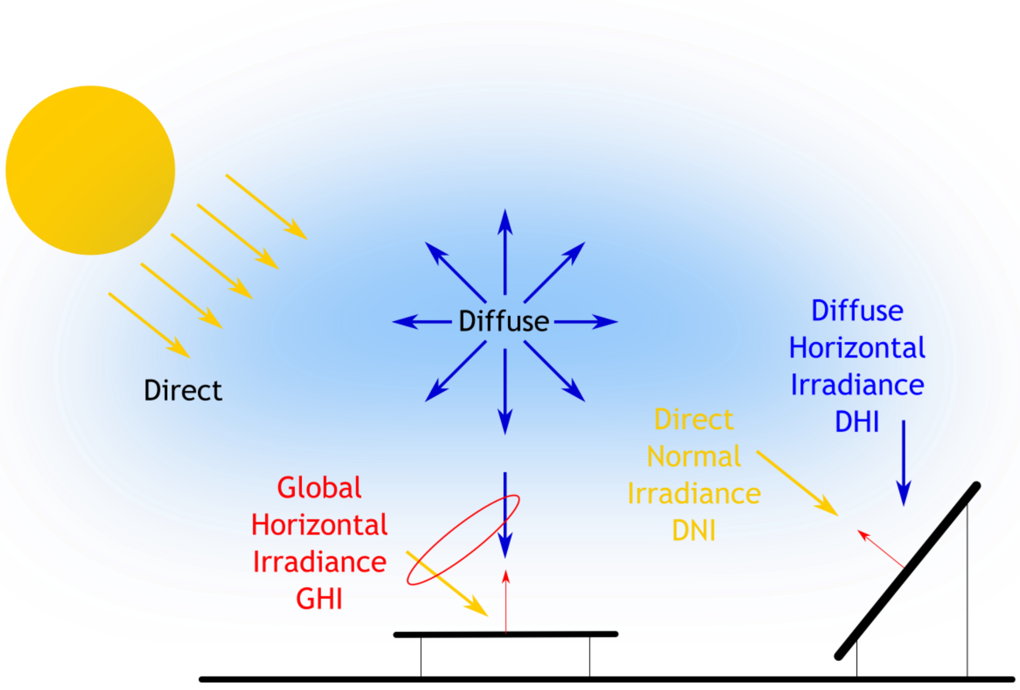
$$\boxed{\bar{G}_{\mathrm{France}} = 150\,\mathrm{W/m^2}}$$



Spatial distribution of the solar resource



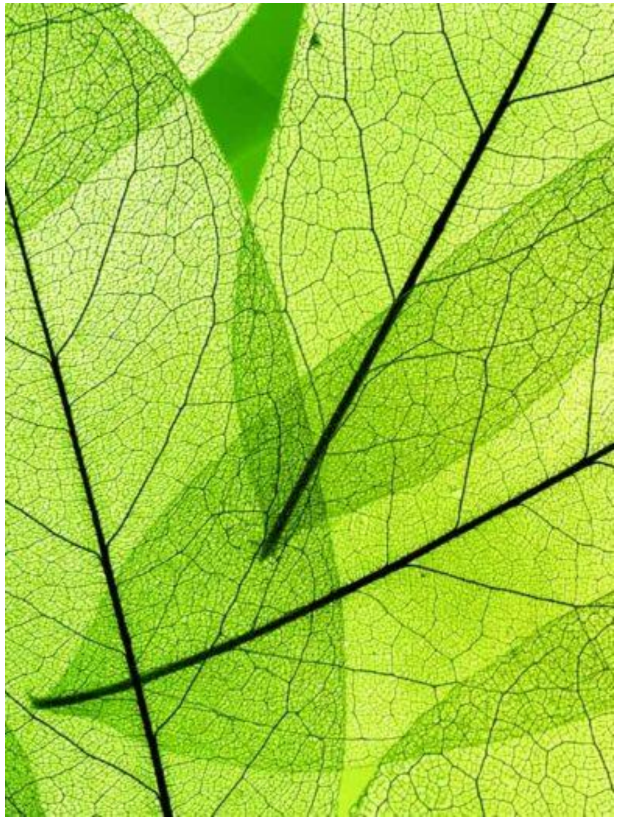
© 2019 The World Bank
Source: Global Solar Atlas 2.0
Solar resource data: Solargis



Energy transformation

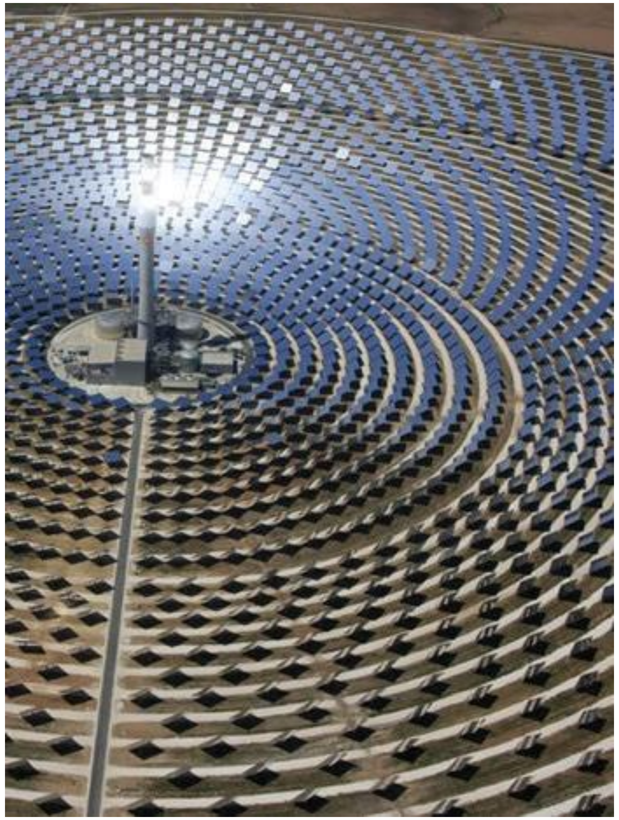
$$\bar{G}_{\text{mean}} = 150\,\mathrm{W/m^2}$$

$$G_{\text{max}} = 1000\,\mathrm{W/m^2}$$



To biomass
Photo-synthesis
1% efficiency

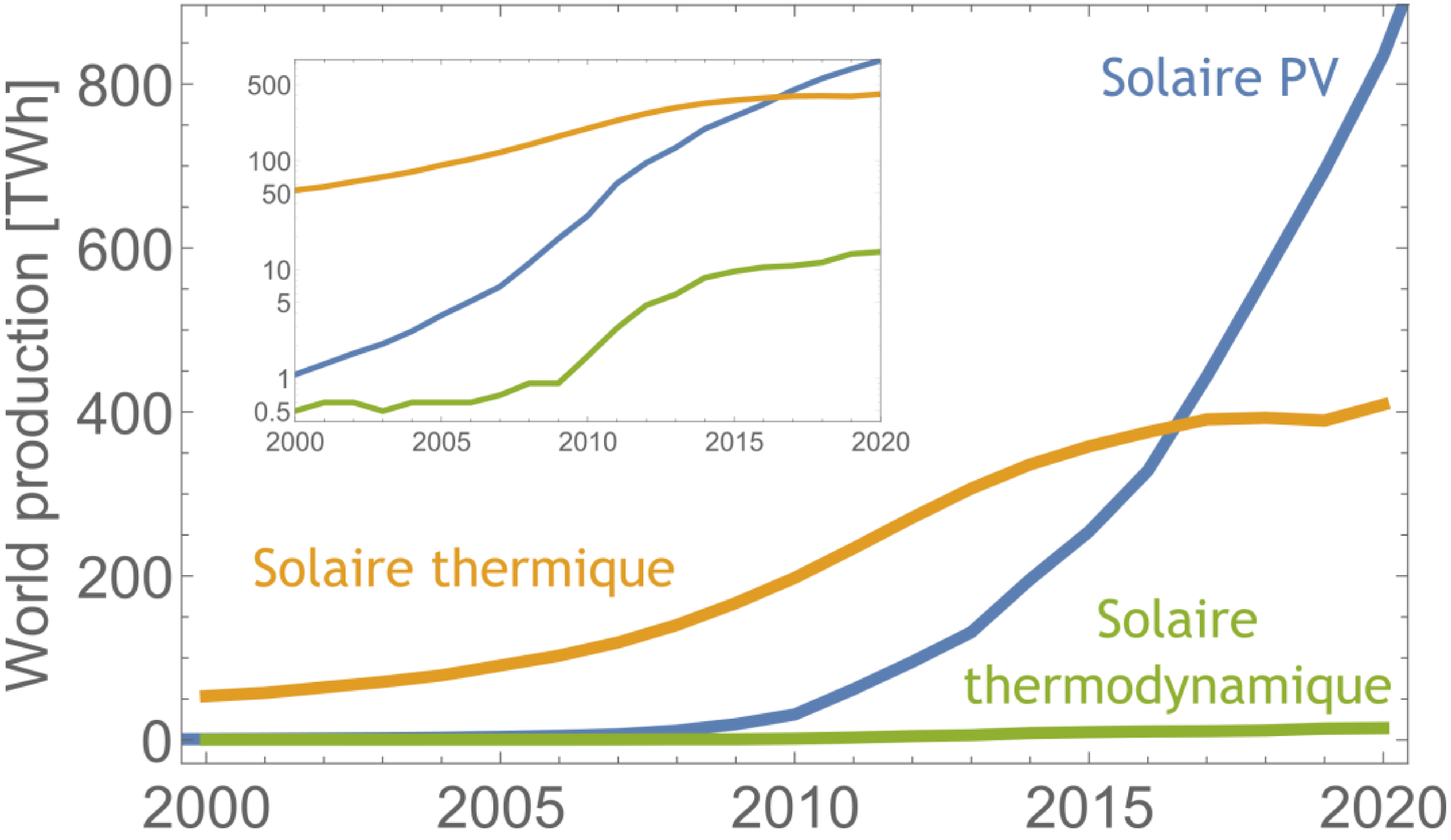
To heat
Solar heating (and cooling)
80% efficiency



To heat then electricity
Concentrated Solar Power(CSP)
20% efficiency

To electricity directly
Solar Photovoltaics (PV)
20% efficiency

Spoiler alert



Data : IEA, BP statistics

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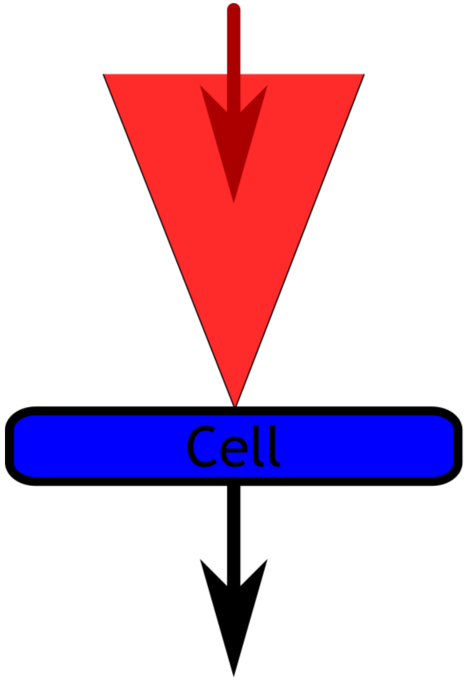
Solar heating


Evacuated Tubes


Flat Panel



$$\dot{Q}_{\text{sun}} = \frac{\Omega_{\text{sun}}}{\pi} \times \sigma T_{\text{sun}}^4 dS$$

Power absorbed from the Sun

$$\dot{Q}_{\text{rad}} = \sigma T_{\text{cell}}^4 dS$$

Power radiated by the absorber

Steady state temperature

$$T_{\text{cell}} \leq \left(\frac{\Omega_{\text{sun}}}{\pi}\right)^{1/4} T_{\text{sun}}$$

$$\dot{Q}_{\text{in}} = \dot{Q}_{\text{sun}} - \dot{Q}_{\text{rad}}$$

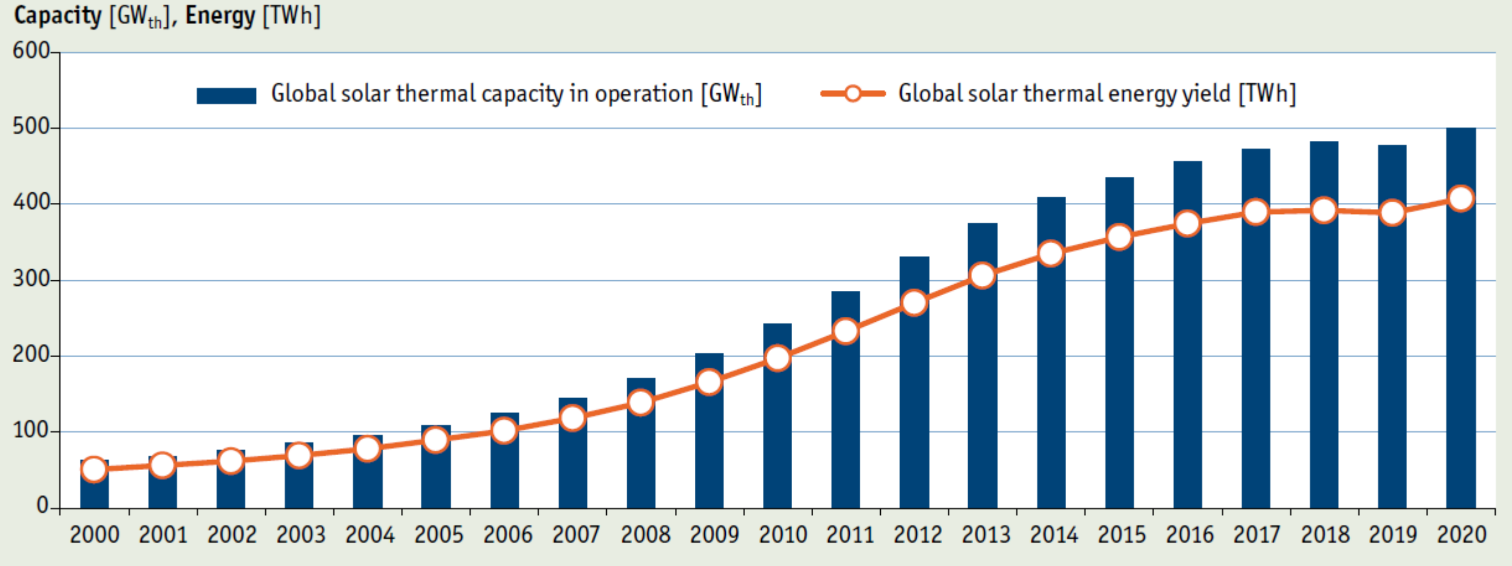
The remaining power is used for heating

See PC 8

Solar heating

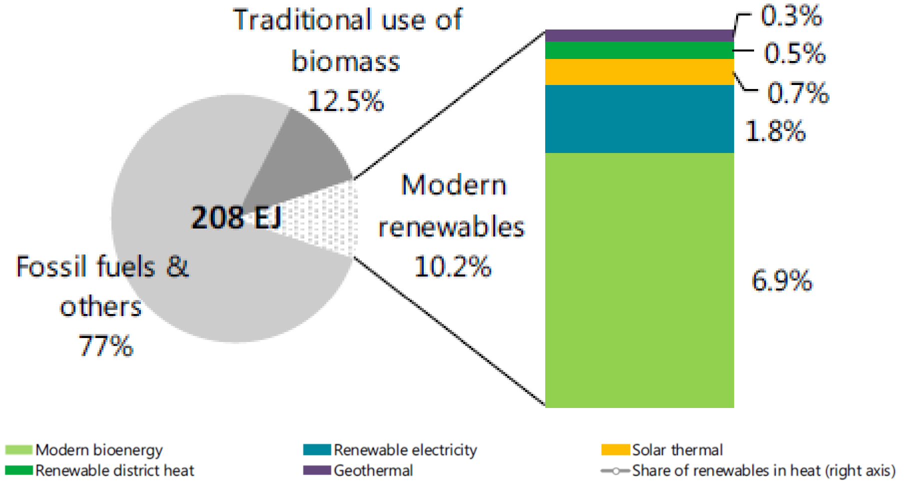
Evacuated Tubes

Flat Panel



Global solar thermal capacity in operation and annual energy 2000 – 2020

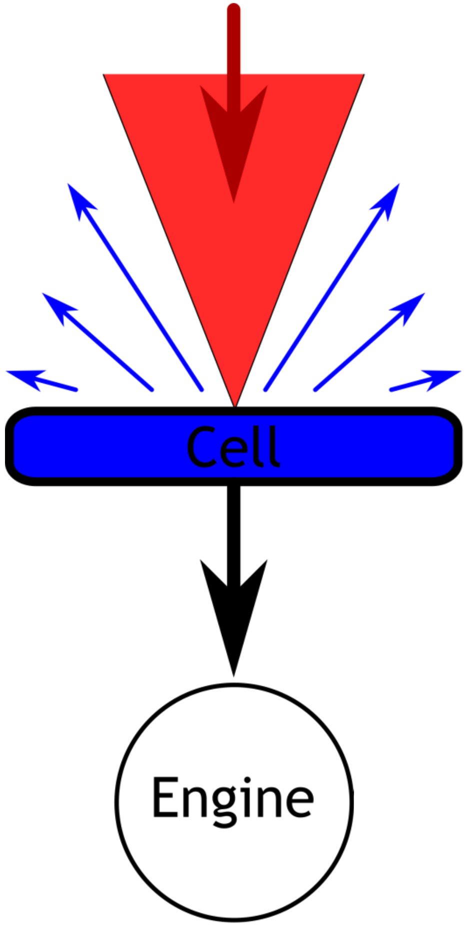
Energy source shares in global heat consumption, 2018



IEA (2019). All rights reserved.

90% used for Domestic Hot Water

From light to work: the Müzer engine



$$\dot{Q}_{\mathrm{sun}} = \frac{\Omega_{\mathrm{sun}}}{\pi} \times \sigma T_{\mathrm{sun}}^4 dS$$

Power absorbed from the Sun

$$\dot{Q}_{\mathrm{rad}} = \sigma T_{\mathrm{cell}}^4 dS$$

Power radiated by the absorber

$$\dot{Q}_{\mathrm{in}} = \dot{Q}_{\mathrm{sun}} - \dot{Q}_{\mathrm{rad}}$$

The remaining power is provided to a Carnot Engine

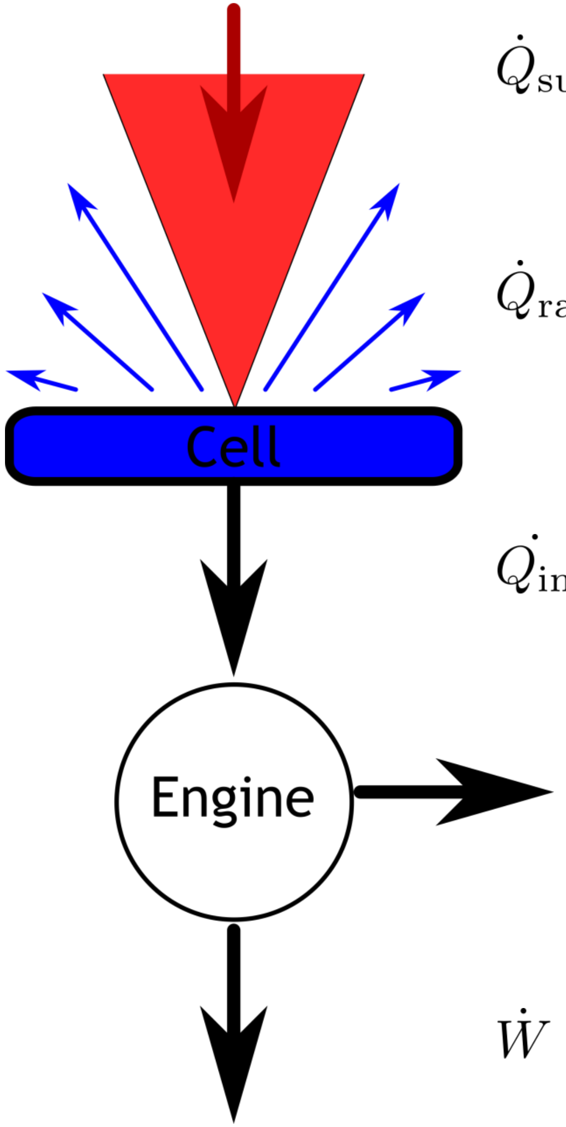
$$\dot{Q}_{\mathrm{out}} = \frac{T_{\mathrm{atmo}}}{T_{\mathrm{cell}}} \dot{Q}_{\mathrm{in}}$$

Heat must be expelled such that $S_{in} = S_{out}$

$$\dot{W} = \dot{Q}_{\mathrm{in}} - \dot{Q}_{\mathrm{out}}$$

The remaining power can be converted into work

From light to work: the Müzer engine



$$\dot{Q}_{\rm sun} = \frac{\Omega_{\rm sun}}{\pi} \times \sigma T_{\rm sun}^4 dS$$

$$\dot{Q}_{\rm rad} = \sigma T_{\rm cell}^4 dS$$

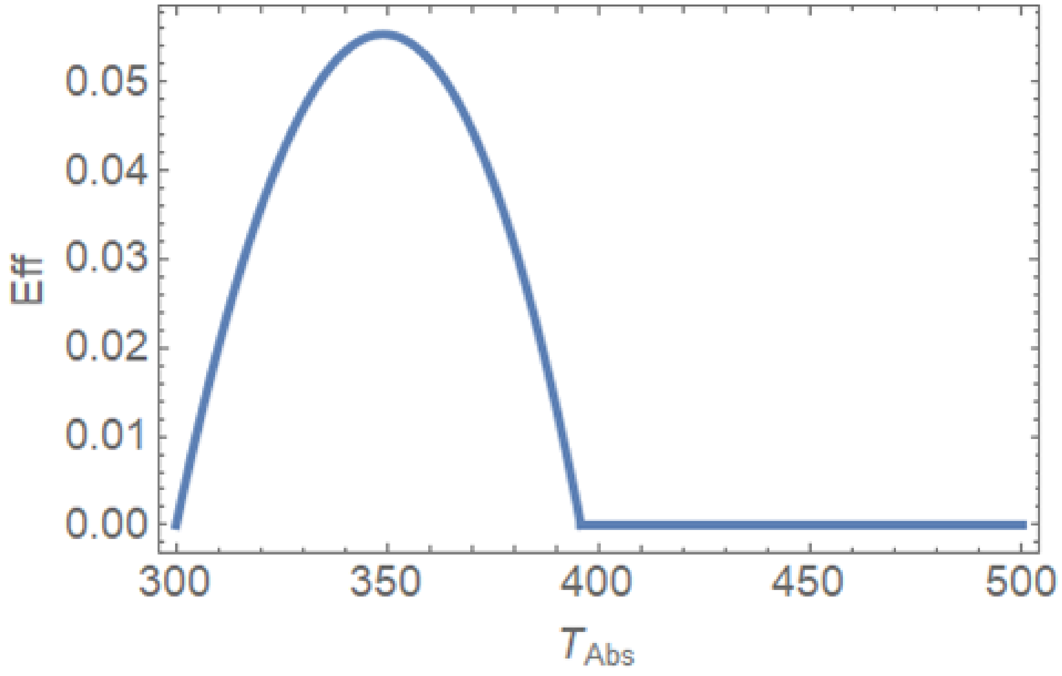
$$\dot{Q}_{\rm in} = \dot{Q}_{\rm sun} - \dot{Q}_{\rm rad}$$

$$\dot{Q}_{\rm out} = \frac{T_{\rm atmo}}{T_{\rm cell}} \dot{Q}_{\rm in}$$

$$\dot{W} = \dot{Q}_{\rm in} - \dot{Q}_{\rm out}$$

Ideal absorber (blackbody) + ideal converter (Carnot) = Muzer engine

$$\frac{\dot{W}}{\dot{Q}_{\rm sun}} = \left(1 - \frac{\pi}{\Omega_{\rm sun}} \frac{T_{\rm cell}^4}{T_{\rm sun}^4}\right) \left(1 - \frac{T_{\rm atmo}}{T_{\rm cell}}\right)$$



Bad trade off !

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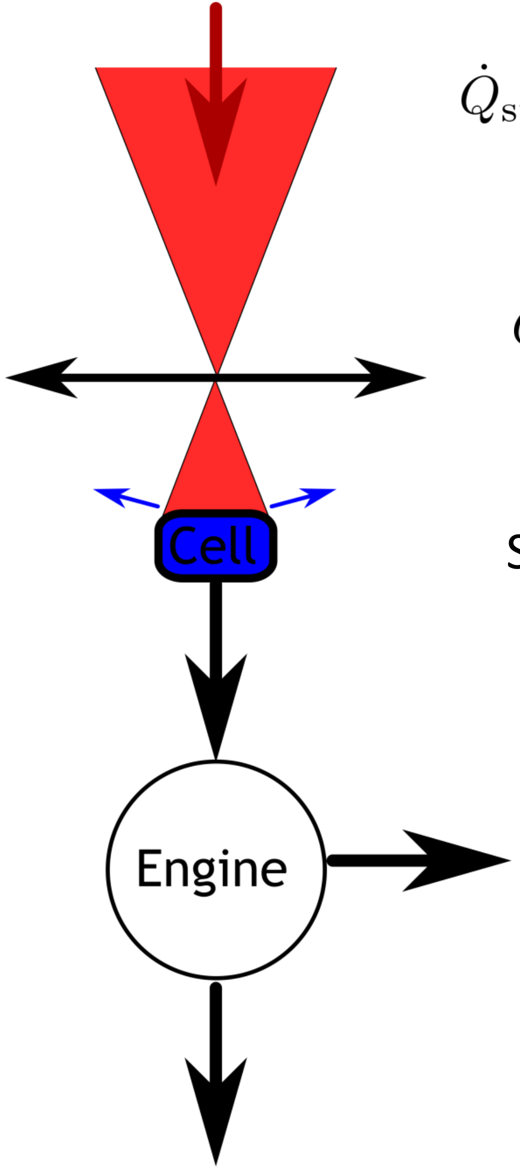
Option 1: light concentration



$$\dot{Q}_{\mathrm{sun}} = \frac{\Omega_{\mathrm{sun}}}{\pi} \times \sigma T^4_{\mathrm{sun}} dS$$

Size of the lens

Same power coming from the sun

$$\dot{Q}_{\mathrm{rad}} = \sigma T^4_{\mathrm{cell}} ds$$

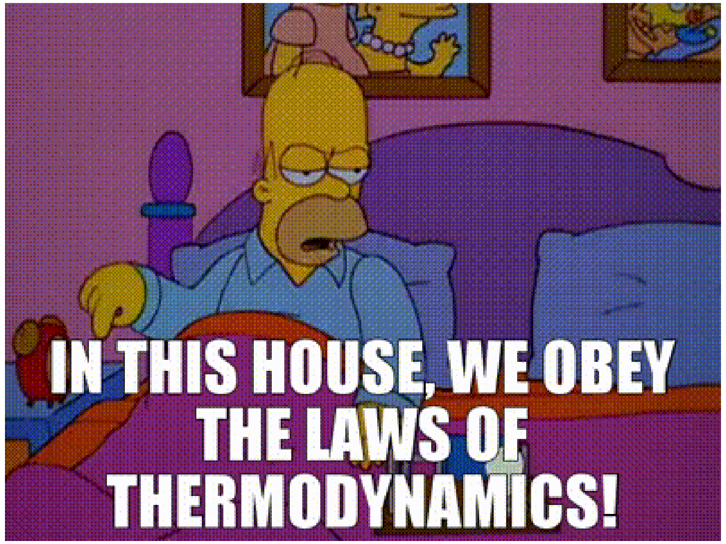
Size of the cell

Smaller absorber → less emission

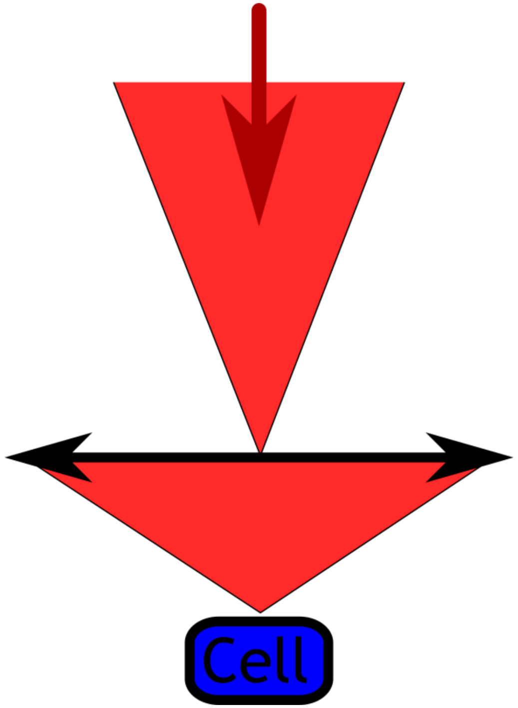
Size of the cell = size of the image of the Sun through the lens $ds = f^2 \Omega_{\mathrm{sun}}$

Steady state temperature

$$T_{\mathrm{cell}} \leq \left(\frac{\Omega_{\mathrm{sun}}}{\pi} \frac{dS}{ds} \right)^{1/4} T_{\mathrm{sun}} = \left(\frac{dS}{\pi f^2} \right)^{1/4} T_{\mathrm{sun}}$$



Optical concentration - solution



You can't make an arbitrarily small image because
optical étendue is conserved (or increased) but never reduced

$$\text{etendue} = \sin^2\theta_{\text{sun}} dS = \text{cste} = \sin^2\theta_{\text{lens}} ds \qquad ds = \frac{\Omega_{\text{sun}}/\pi}{\sin^2\theta_{\text{lens}}} dS$$

Low concentration $\sin^2\theta_{\text{lens}} \sim \frac{r_{\text{lens}}^2}{f^2}$ $ds = f^2\Omega_{\text{sun}}$

Large concentration $\sin^2\theta_{\text{lens}} \sim 1$ $ds = \frac{\Omega_{\text{sun}}}{\pi} dS$

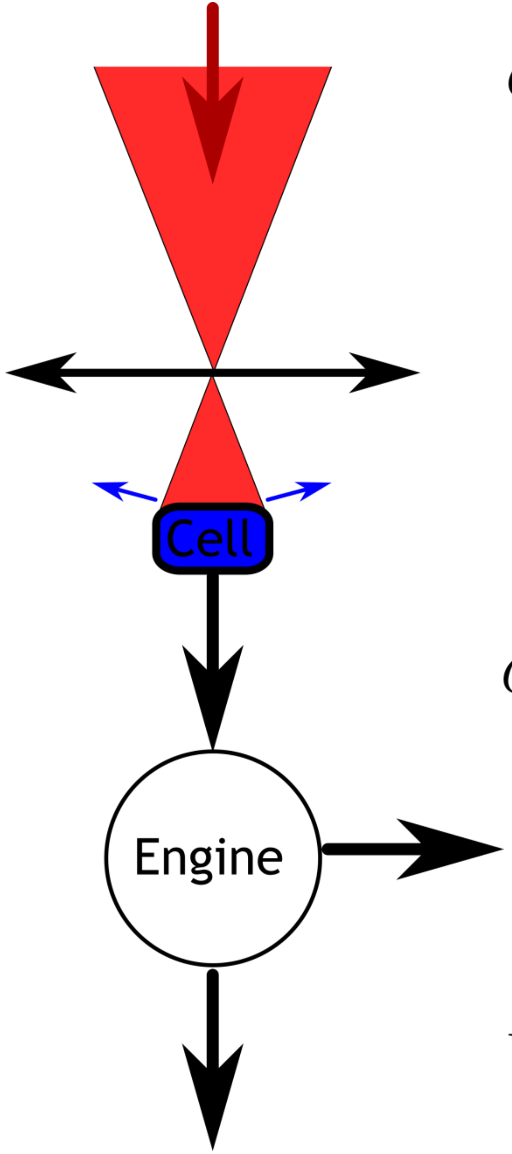
$$T_{\text{cell}} \leq \left(\frac{\Omega_{\text{sun}}}{\pi}\frac{dS}{ds}\right)^{1/4} T_{\text{sun}} = (\sin^2\theta_{\text{lens}})^{1/4} \times T_{\text{sun}} \leq T_{\text{sun}}$$

what if?

Can you use a magnifying glass
and moonlight to light a fire?

Concentration factor $1 \leq \frac{1}{\sin^2\theta_{\text{lens}}} \leq \frac{\pi}{\Omega_{\text{sun}}} = 46\,000$

Optical concentration



$$\dot{Q}_{\text{sun}} = \frac{\Omega_{\text{sun}}}{\pi} \times \sigma T_{\text{sun}}^4 dS$$

Power absorbed from the Sun

$$\dot{Q}_{\text{rad}} = \sigma T_{\text{cell}}^4 ds = \sigma T_{\text{cell}}^4 \frac{dS}{C}$$

Power radiated by the absorber

$$1 \leq C \leq \frac{\pi}{\Omega_{\text{sun}}} = 46\,000$$

$$\dot{Q}_{\text{in}} = \dot{Q}_{\text{sun}} - \dot{Q}_{\text{rad}}$$

The remaining power is provided to a Carnot Engine

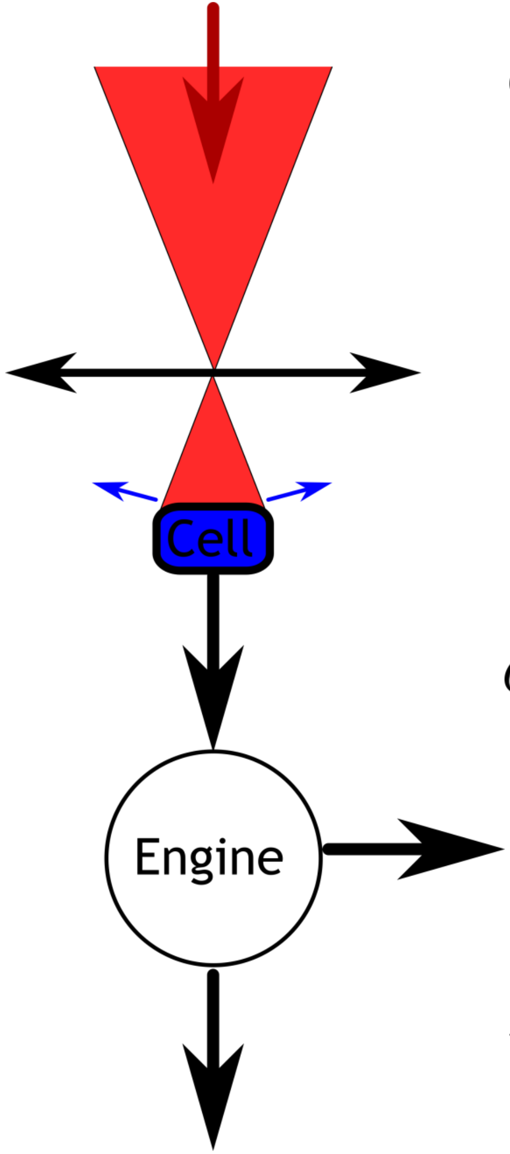
$$\dot{Q}_{\text{out}} = \frac{T_{\text{atmo}}}{T_{\text{cell}}} \dot{Q}_{\text{in}}$$

Heat must be expelled such that S_{in} = S_{out}

$$\dot{W} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}$$

The remaining power can be converted into work

Concentrated Solar Power = Solar Thermal Electricity



$$\dot{Q}_{\text{sun}} = \frac{\Omega_{\text{sun}}}{\pi} \times \sigma T_{\text{sun}}^4 dS$$

$$\dot{Q}_{\text{rad}} = \sigma T_{\text{cell}}^4 ds = \sigma T_{\text{cell}}^4 \frac{dS}{C}$$

$$1 \leq C \leq \frac{\pi}{\Omega_{\text{sun}}} = 46\,000$$

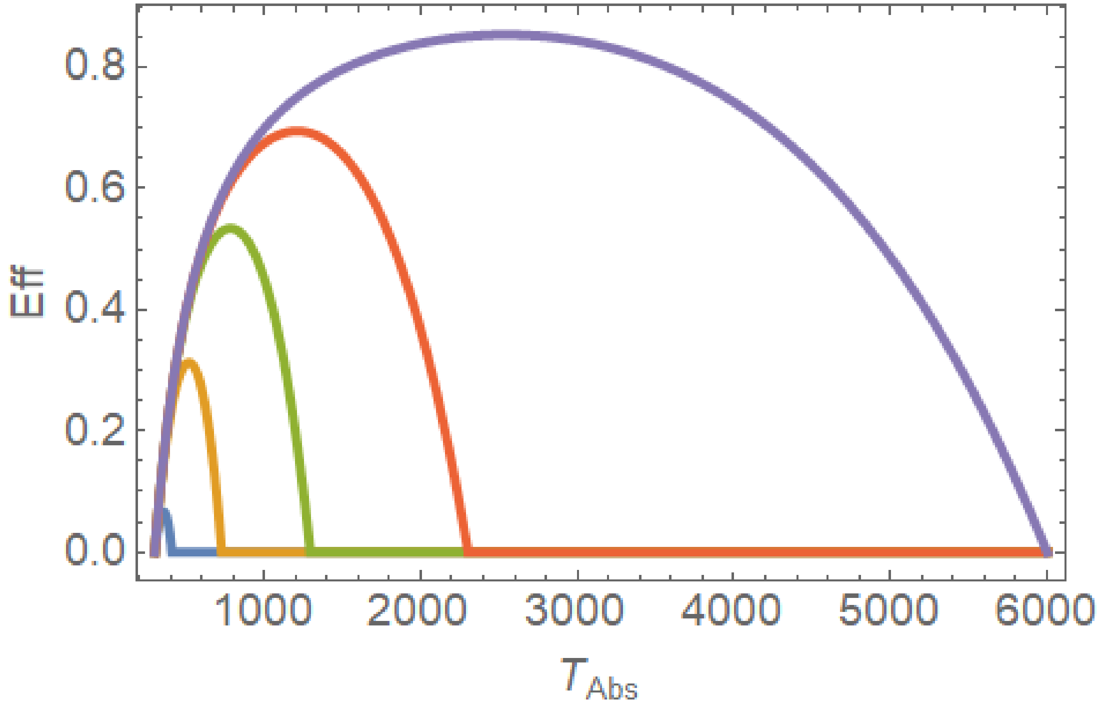
$$\dot{Q}_{\text{in}} = \dot{Q}_{\text{sun}} - \dot{Q}_{\text{rad}}$$

$$\dot{Q}_{\text{out}} = \frac{T_{\text{atmo}}}{T_{\text{cell}}} \dot{Q}_{\text{in}}$$

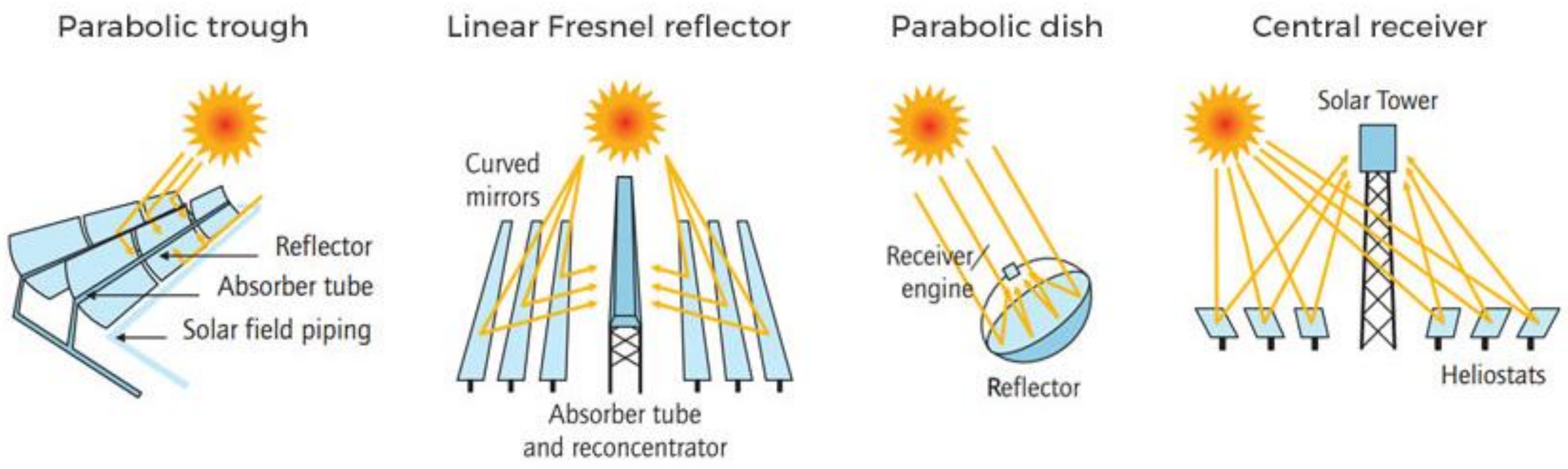
$$\dot{W} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}$$

Muzer engine under concentration

$$\frac{\dot{W}}{\dot{Q}_{\text{sun}}} = \left(1 - C \times \frac{\pi}{\Omega_{\text{sun}}} \frac{T_{\text{cell}}^4}{T_{\text{sun}}^4}\right)\left(1 - \frac{T_{\text{atmo}}}{T_{\text{cell}}}\right)$$



Concentrators technologies



C = 30 - 80

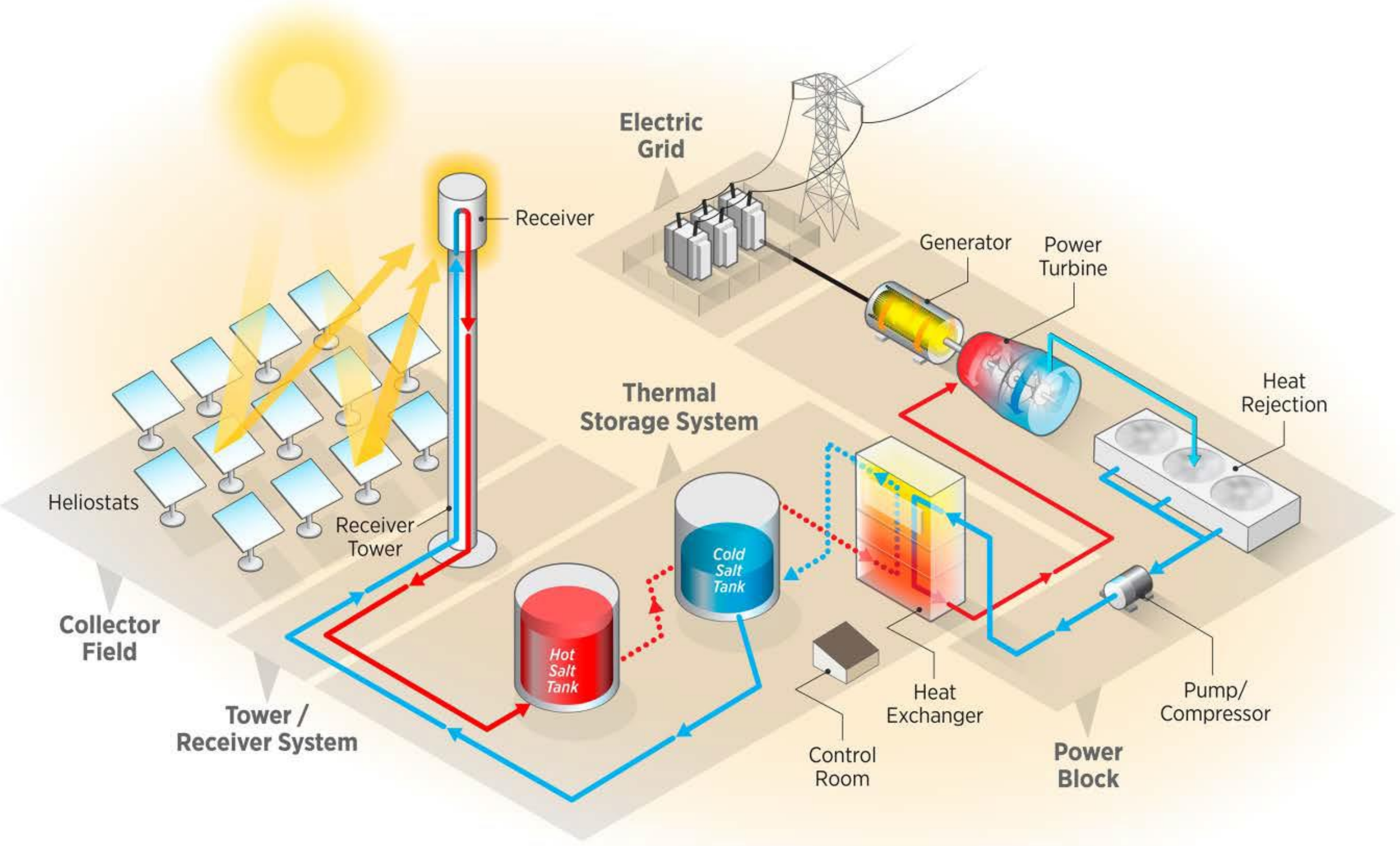
C = 30 - 80

C = 1000 - 3000

C = 200 - 1000

Historical installations : parabolic trough, with no thermal storage
Current projects : solar tower, with thermal storage

Concentrated solar power plant



NREL

Built in energy storage (thermal)

No high-tech materials involved
(mirrors, pipes, turbine, generator)

Pretty impressive powers

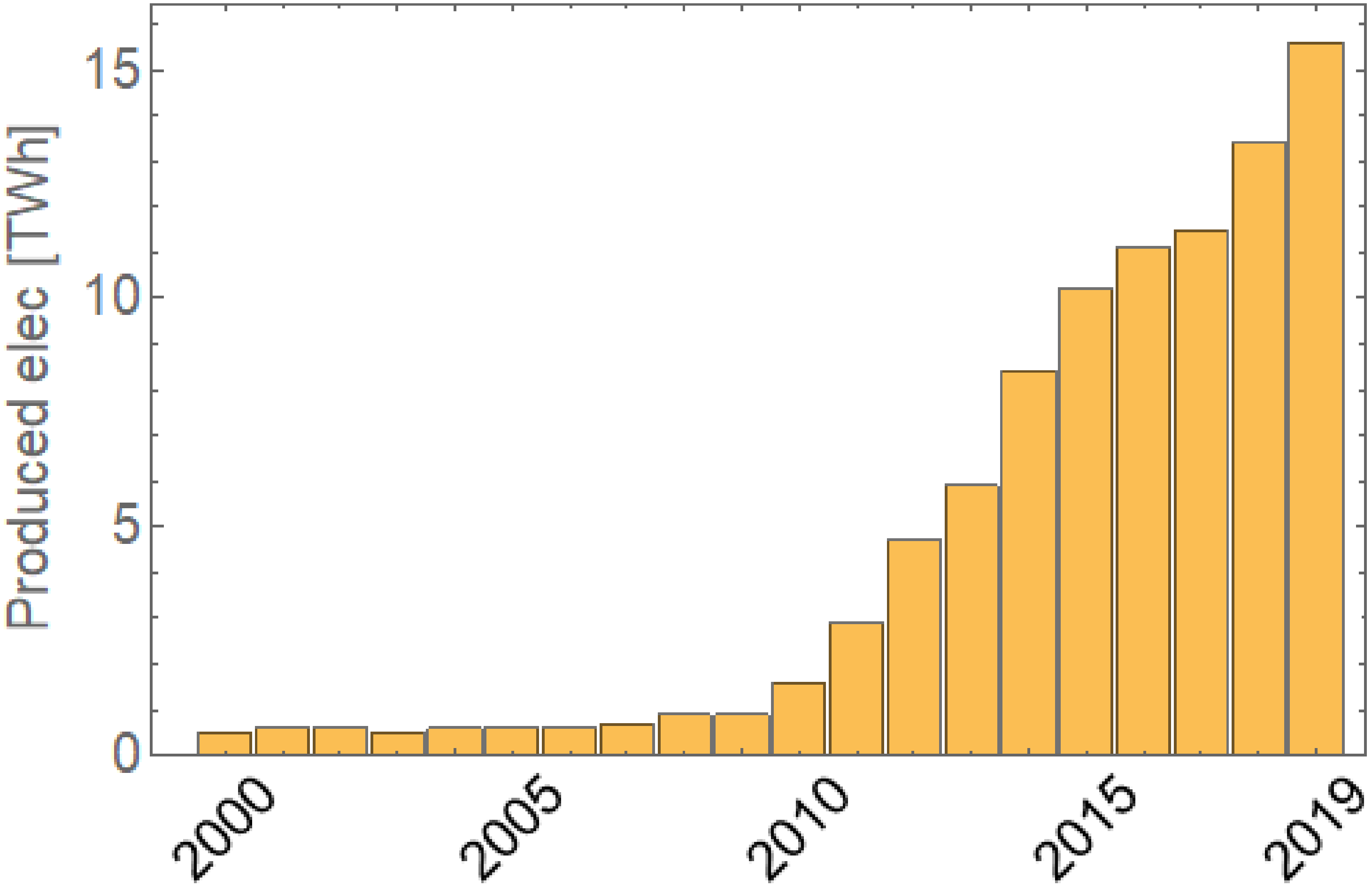
Require direct illumination
(can’t concentrate diffuse light)

Need tracking (mechanics)

More expensive than solar PV
(storage **not** included)

Need large installations to optimize infrastructures

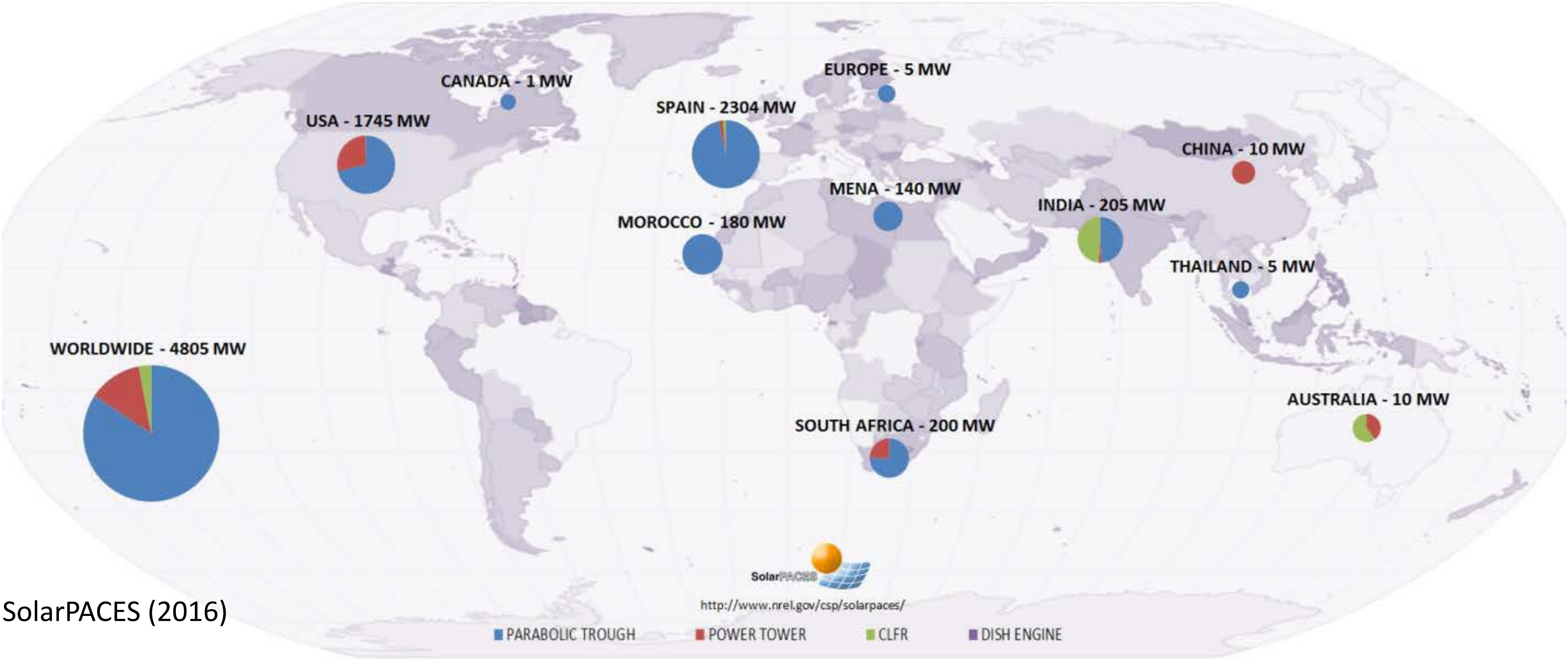
CSP production



World electricity in 2019 = 26 000 TWh
Solar electricity = 700 TWh
CSP = 16 TWh

Installed capacity = 5 GW
Load factor = 16/5*8.76 = 25%

CSP today



SolarPACES (2016)

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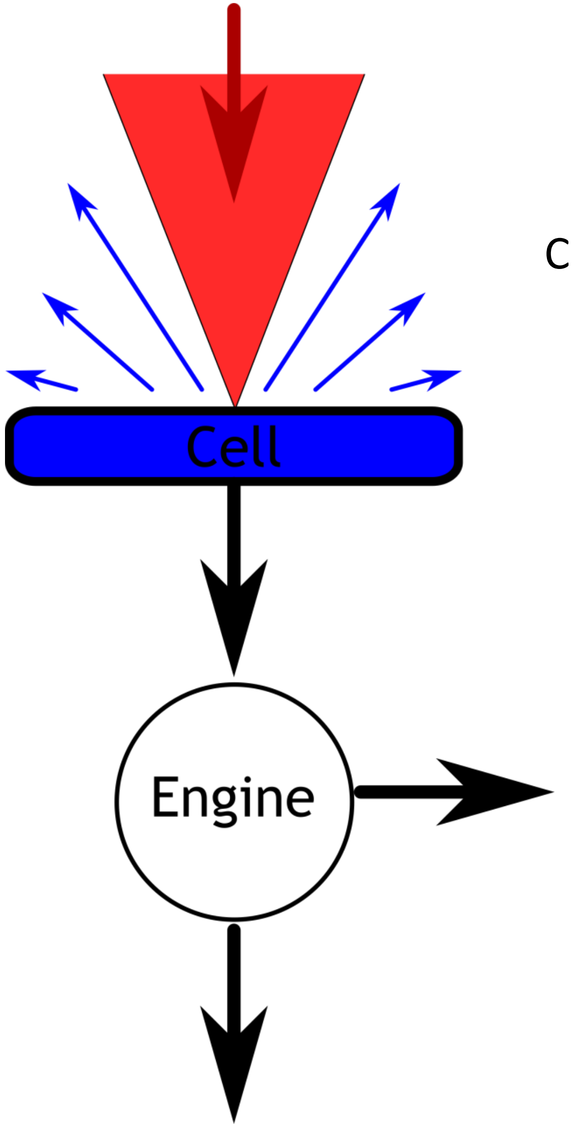
Option 2: introduce a gap



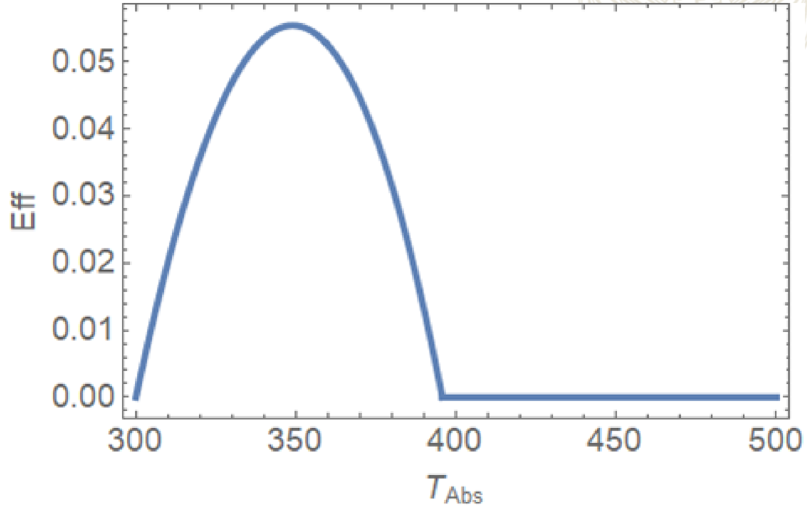
Back to the Muzer problem

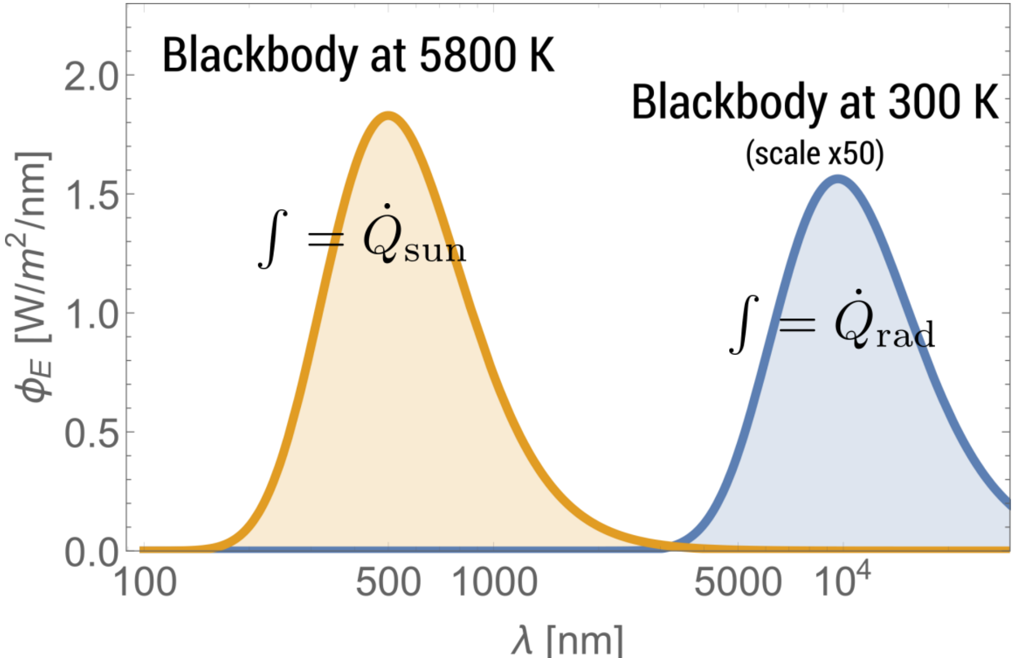
Can we prevent the cell from emitting radiations ?

Kirchhoff: absorptivity = emissivity
at each wavelength

But well distinct spectral regions !

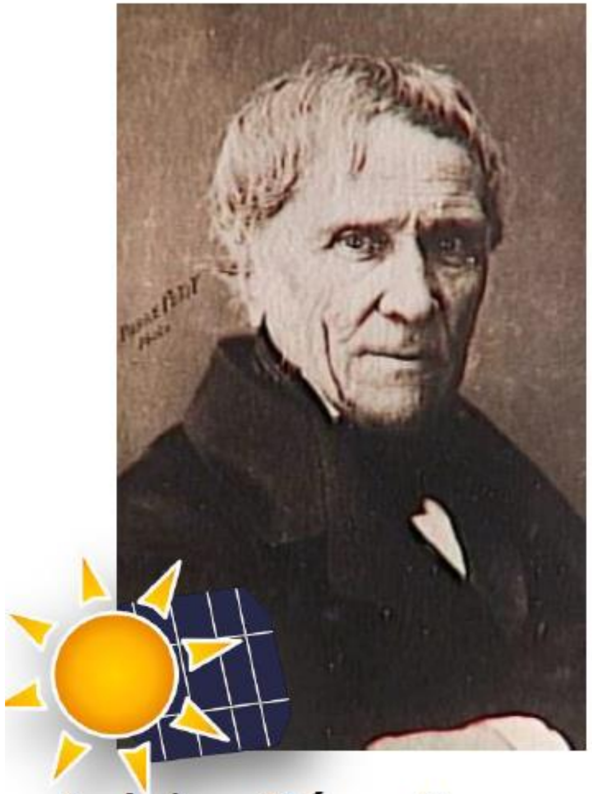
Introduce a gap
If hν < Eg, A = 0
If hν > Eg, A = 1





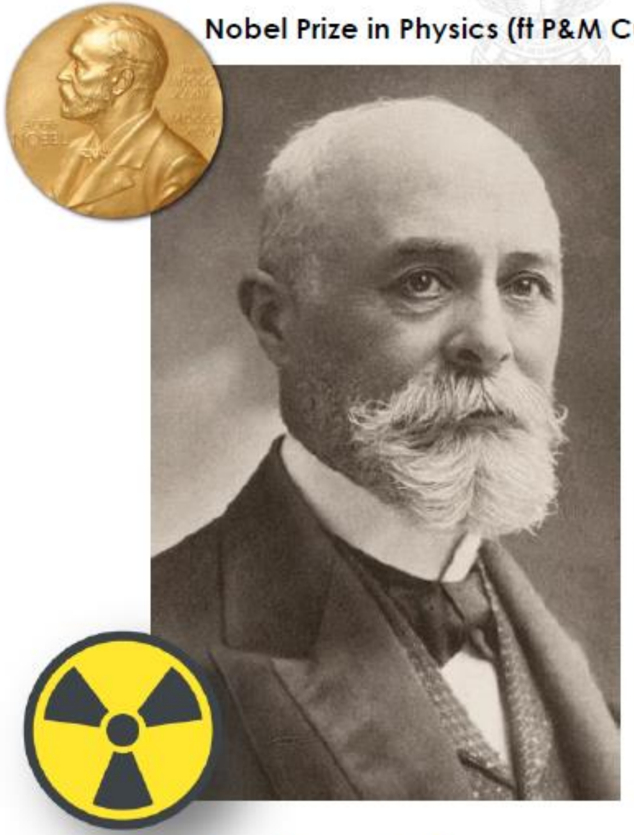
Solar cell : the origins

The photovoltaic effect was discovered in 1839 by the Frenches Antoine and Alexandre Edmond Becquerel (father and son respectively)



Antoine César Becquerel
[1788-1878]

Alexandre Edmond Becquerel
[1820 -1891]

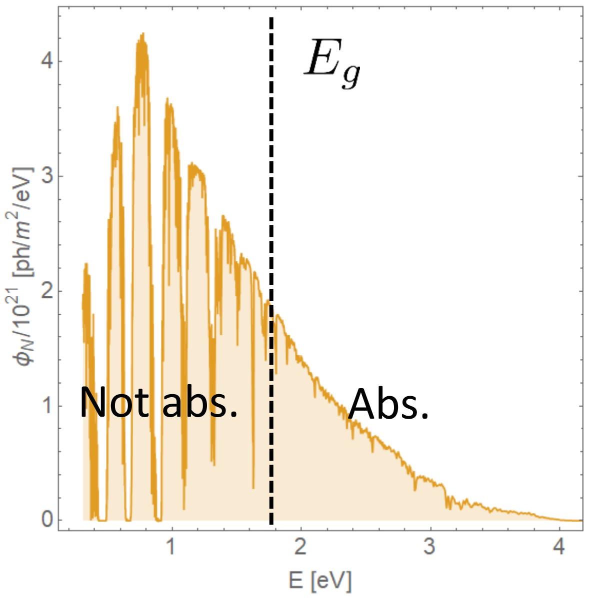


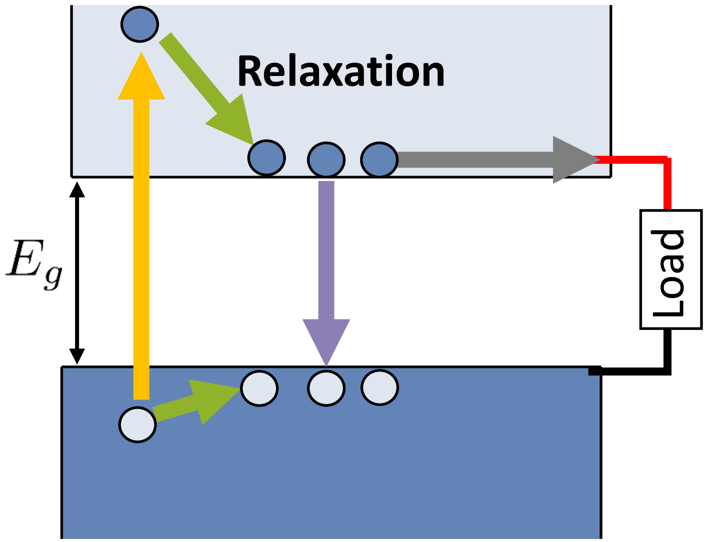
Nobel Prize in Physics (ft P&M Curie)

Antoine Henri Becquerel
[1852-1908]

A.-E. Becquerel, "Mémoire sur les effets électriques produits sous l'influence des rayons solaires," *Comptes rendus hebdomadaires des séances de l'Académie des sciences,* vol. 9, pp. 561–567, séance du Lundi4 novembre, 1839

What do you need to make a solar cell?





4 key functions :

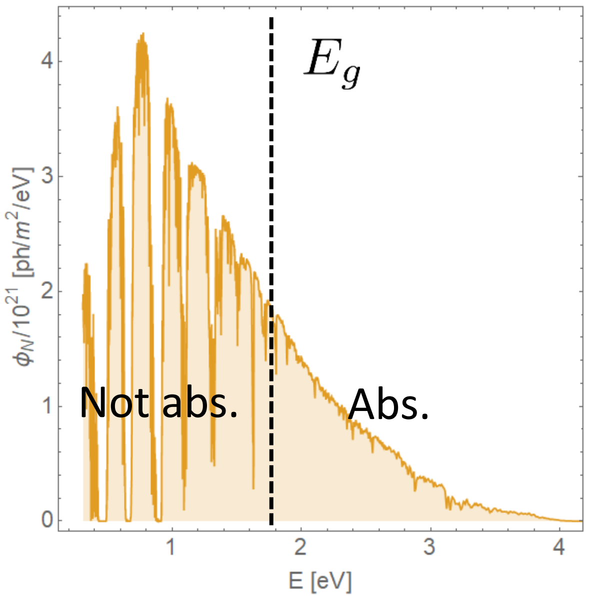
Absorb light

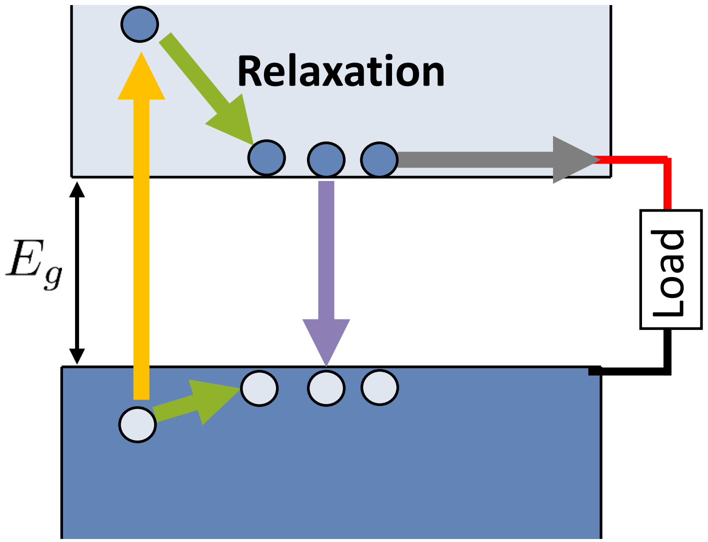
Prevent electrons from recombining

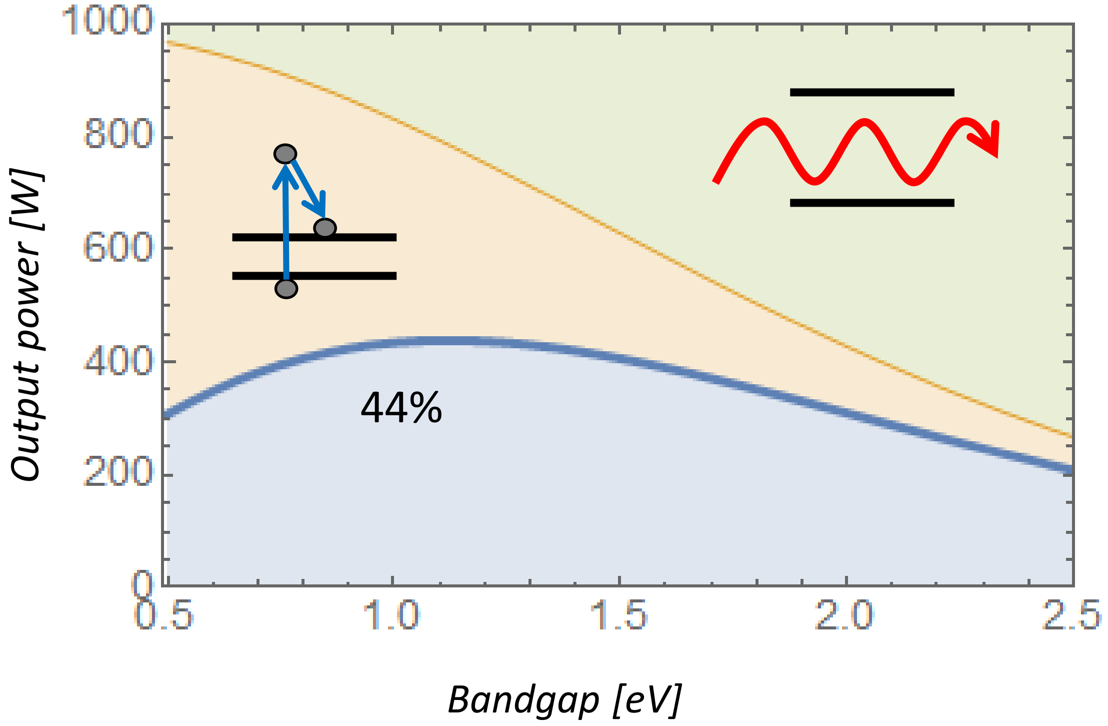
Transport carriers to the contacts

Provide carrier selectivity

The handwaving approach







Nb of electrons generated / sec

$$I \propto q \int_{\hbar\omega \geq E_g} \phi_{\text{sun}}(\hbar\omega) d\omega$$

Energy per electron

$$\sim E_g$$

Out power :

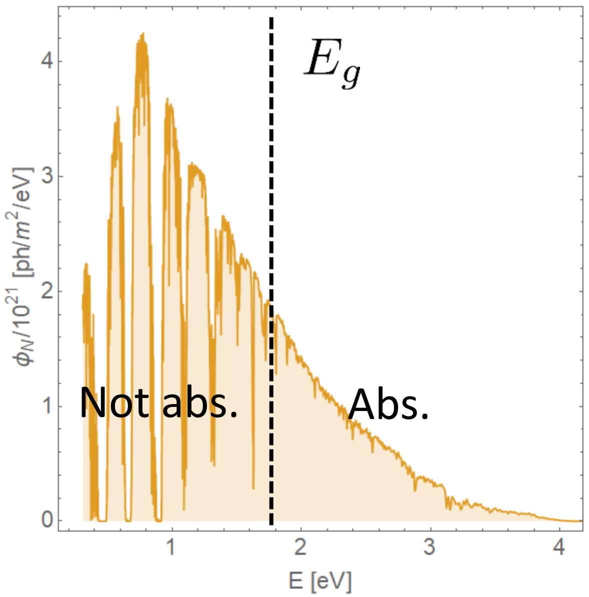
$$P = \int_{\hbar\omega \geq E_g} \phi_{\text{sun}}(\hbar\omega) d\omega \times E_g$$

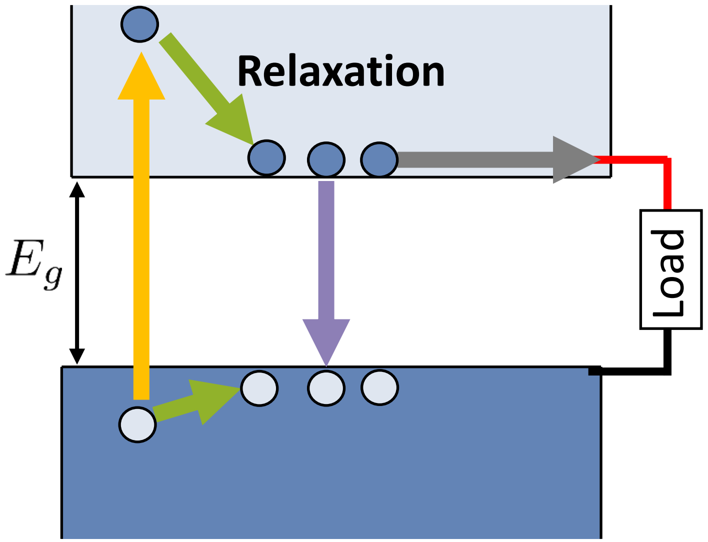
Rolle’s theorem: there has to be an optimal gap !

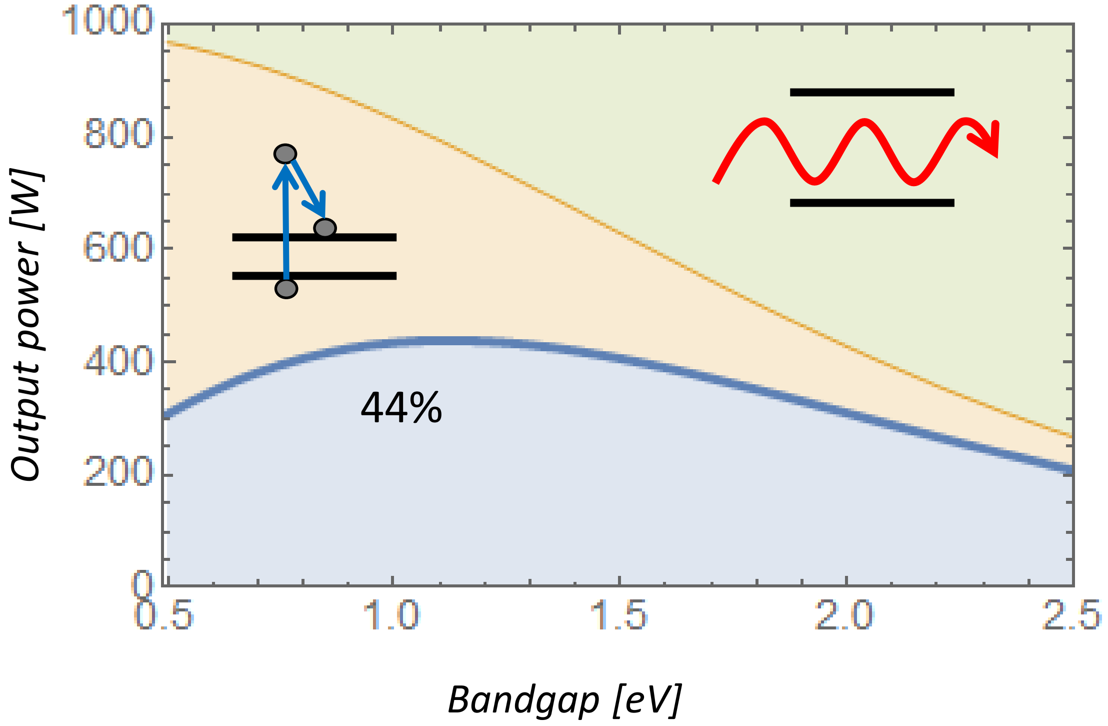
First trade off
bewteen absorption and energy
Leads to optimal gap

See PC 8

Thermo’s back !







WAIT ! PV : not just total output power! Output ***useful, electrical*** *power*.

Extracted energy

$$\dot{E} = \dot{N} \times Eg$$

Electrical power

$$P = I \times V$$

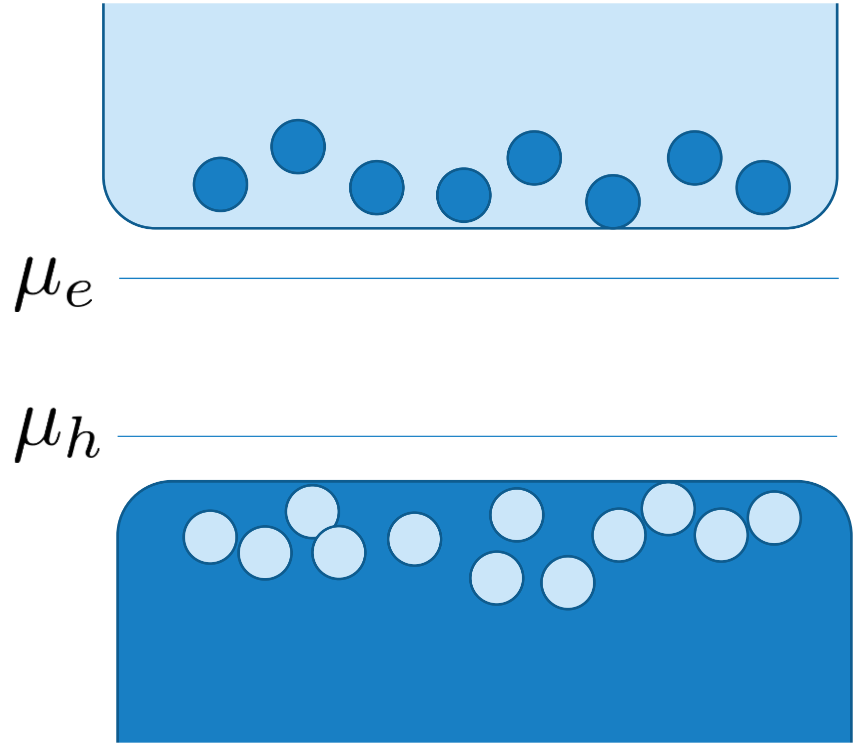
Thermodynamics

$$\Delta E = W + Q$$

Chemical potentials (again !)

1/ At thermal equilibrium, a population is entirely defined by two quantities

Temperature (T), chemical potential (µ)



Average energy per electron $\sim \frac{3}{2} k_B T$

Number of elecrons $\sim N_C \exp\left(\frac{\mu - E_C}{k_B T}\right)$

2/ µ = variation of the free energy when adding/removing 1 particle

$$\mu_e = \left.\frac{\partial F}{\partial N_e}\right|_{T,V,N_h}$$

Change in free energy = maximal amount of work recoverable over the transformation !

Transformation = remove 1 electron from CB, add 1 electron to VB $W_{\text{out}} = \Delta F = \mu_e - \mu_h$

$$qV = \Delta\mu$$

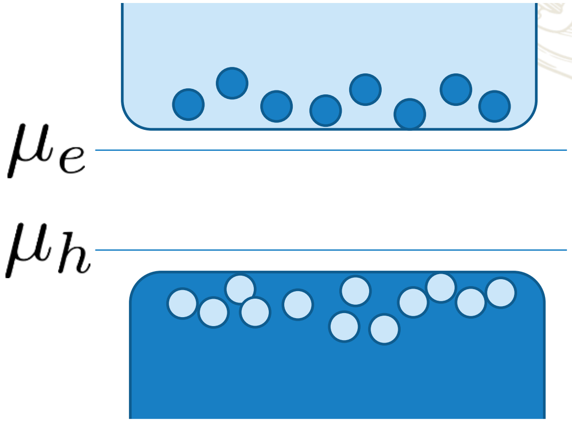
The thermodynamic approach

PV : not just total output power! Output ***useful*** *power*.

Electrical engineering : $P = I \times V$

Thermodynamics: $\Delta E = W + Q$

$$W = \Delta\mu = qV$$

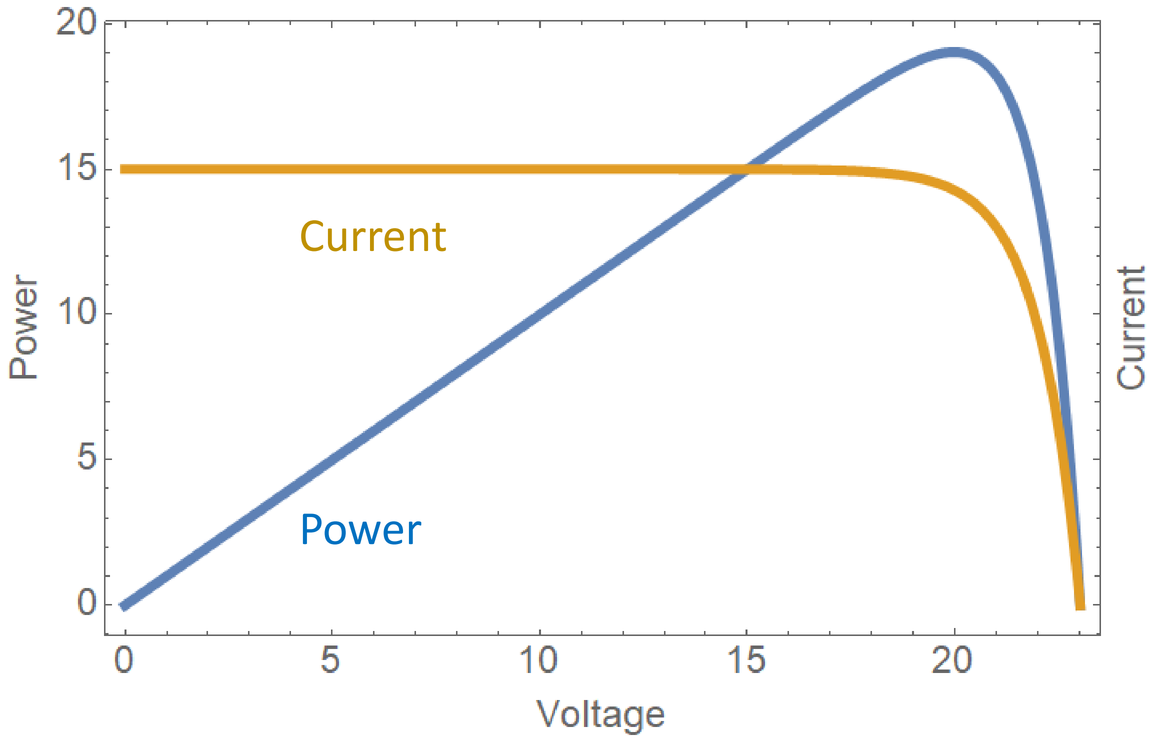


More particles → Larger Δμ → More V, no I

Extract particles → Decrease Δμ → More I, Less V

Second trade off
bewteen voltage and current
Leads to maximal power point

See PC 8



The thermodynamic approach (contd.)

Extracted energy

$$\dot{E} = \dot{N} \times Eg$$

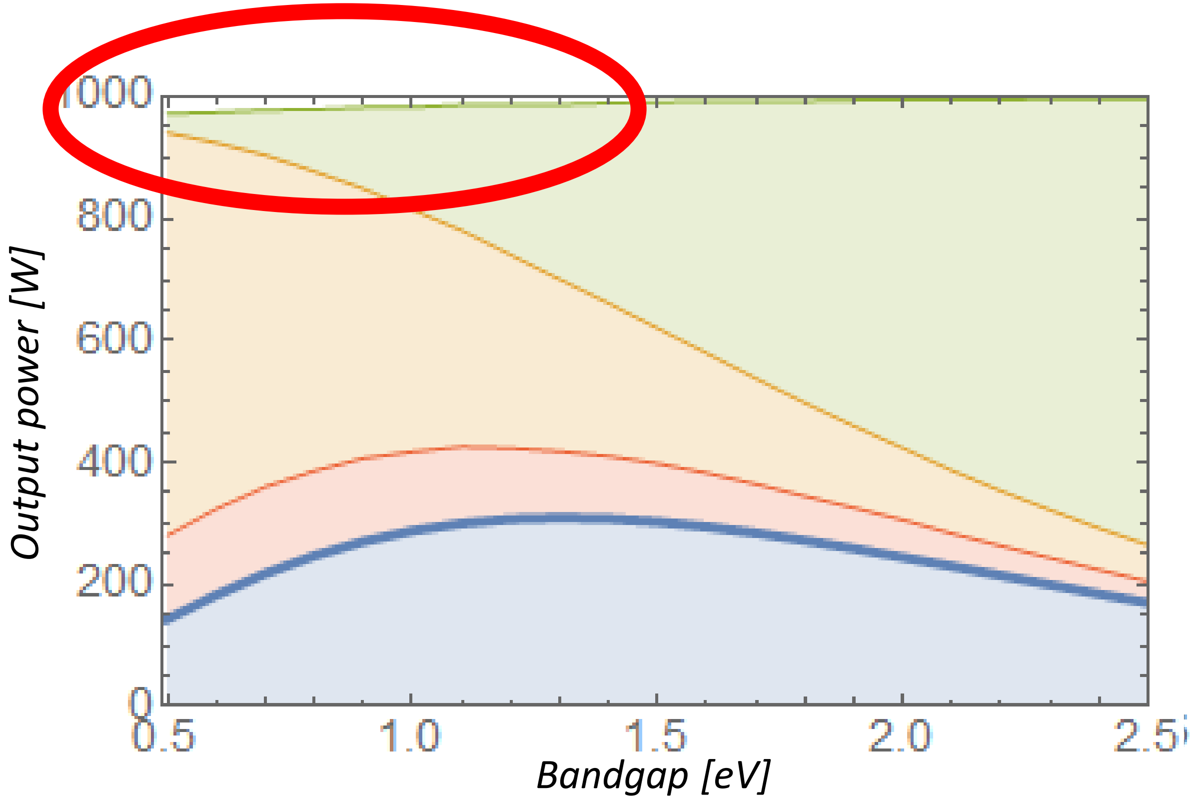
Electrical power

$$P = I \times V$$

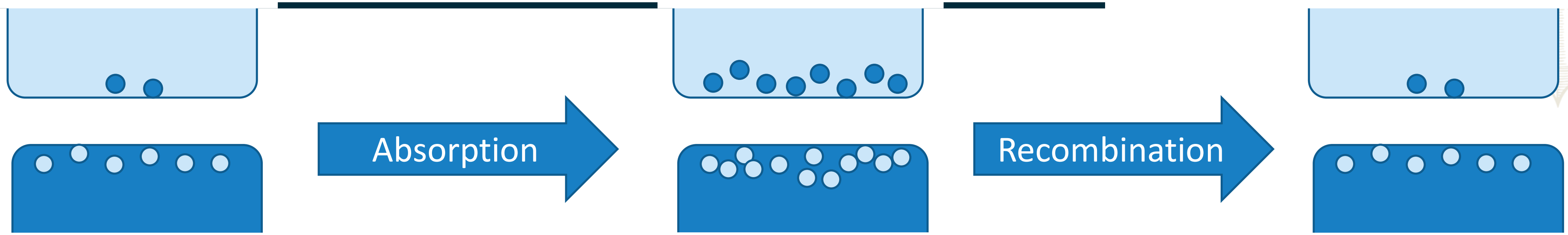
Thermodynamics

$$\Delta E = W + Q$$

$$P = \dot{N} \times \Delta\mu$$



The detailed balance approach



Absorption

Recombination

Thermal
Cold, few carriers

Thermal
Cold, many carriers

Thermal
Cold, few carriers

How much energy is actually radiated by the converter ?

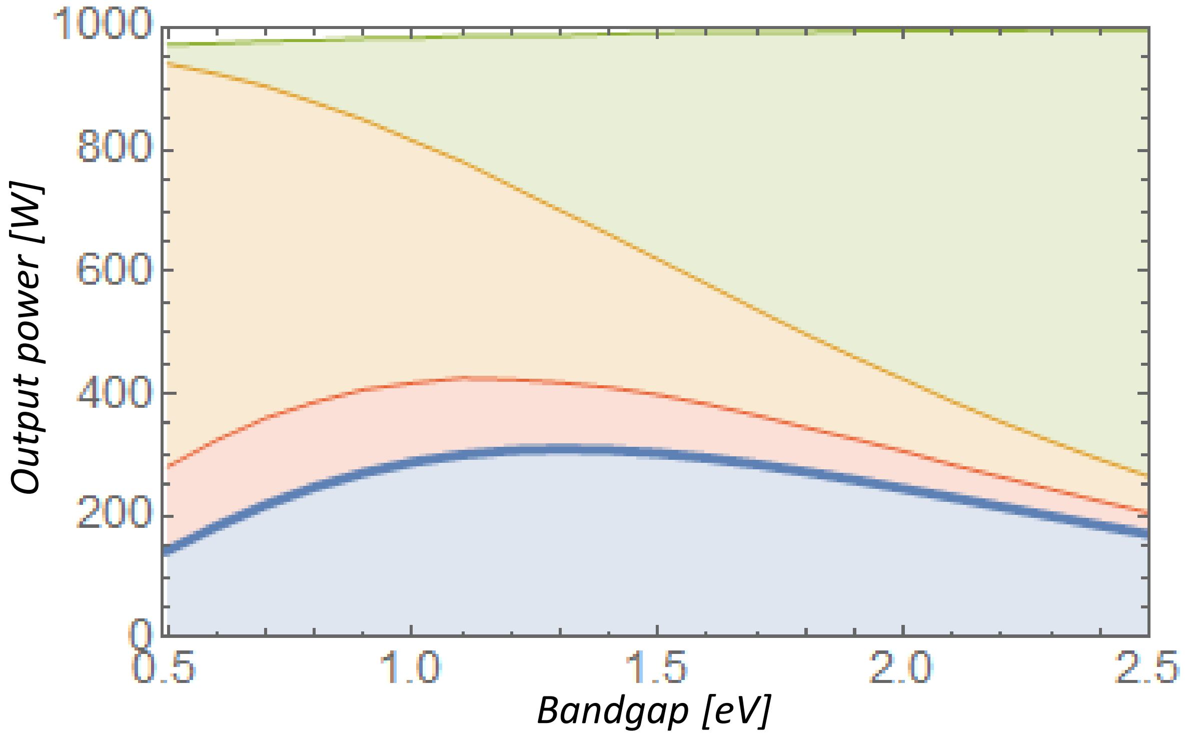
$$R \propto n \times p \propto \mathcal{E}(E) \frac{E^2}{\exp\left(\frac{E-\Delta\mu}{k_B T}\right)-1}$$

Kirchoff's law :

If a system can absorb a radiation at wavelength λ, it can also emit a radiation at the same wavelength.

$$\mathcal{E}(E) = \mathcal{A}(E)$$

Detailed balance
Transitions *to* a band = Transitions *from* the band



Shockley & Queisser, 1961

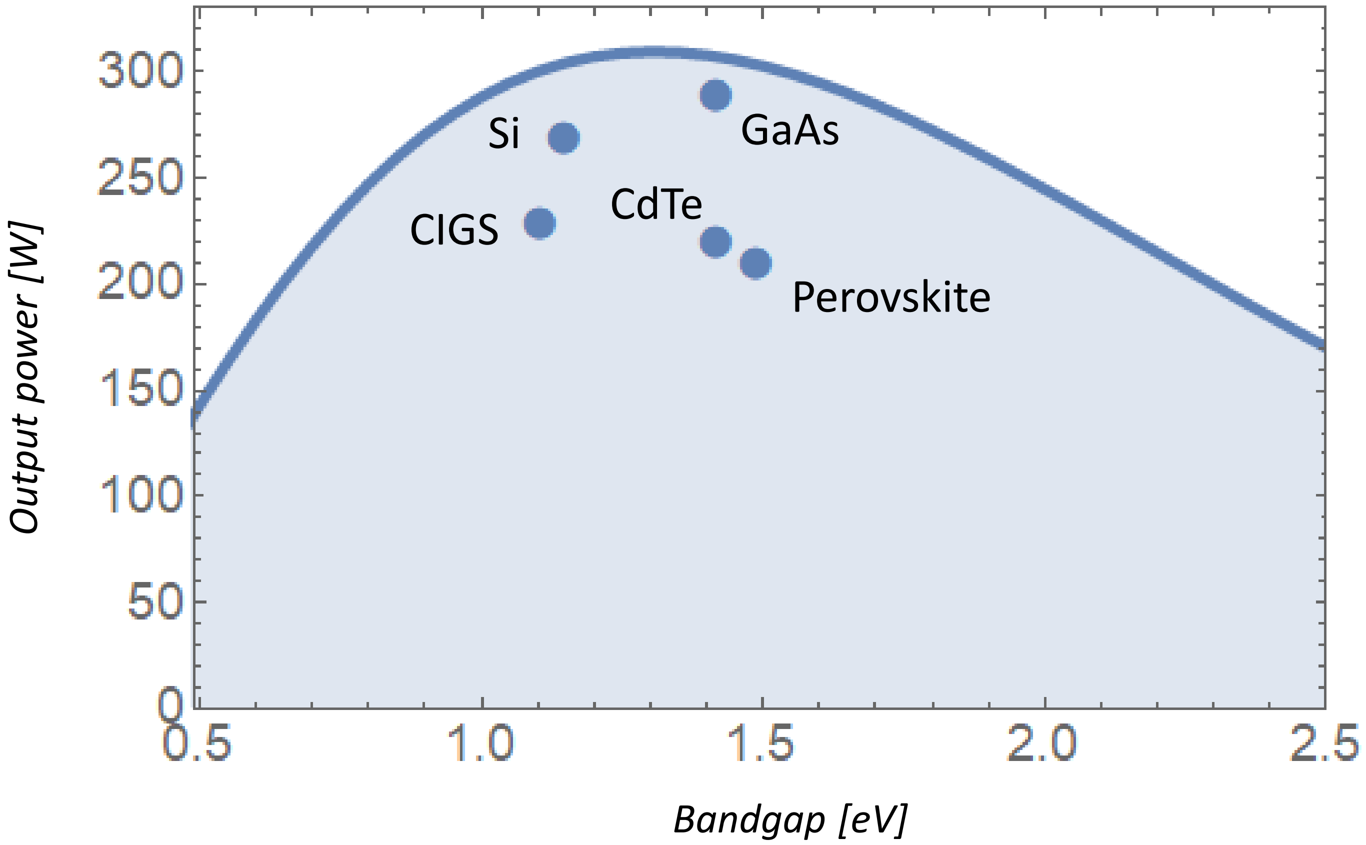
The limits of Shockley-Queisser

Underlying assumption:

Full absorption Step like absorptivity	No light management (ARC, texturing, back mirror…)
Ideal transport Infinite mobility	No thickness (ultra thin films…)
Perfect contact Flat band & selective	No interface optimization (series resistance, passivation…)
Radiative regime Radiative recombination only	No defects, No interactions between carriers

J.F. Guillemoles et al., Guide for the perplexed to the Shockley–Queisser model for solar cells, Nature (2019)

A very simple mode, and yet…



J.F. Guillemoles et al., Guide for the perplexed to the Shockley–Queisser model for solar cells, Nature (2019)

I. Solar energy resource

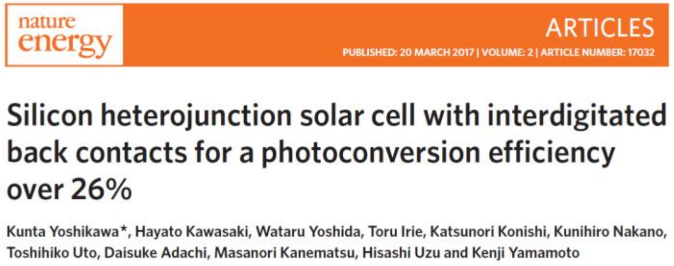
II. Thermodynamics of solar energy conversion
  A. Solar heating
  B. Concentrated solar power
  C. Photovoltaics

III. Overview of the silicon PV technology

IV. PV today and tomorrow


Omanobserver

Conversion efficiencies



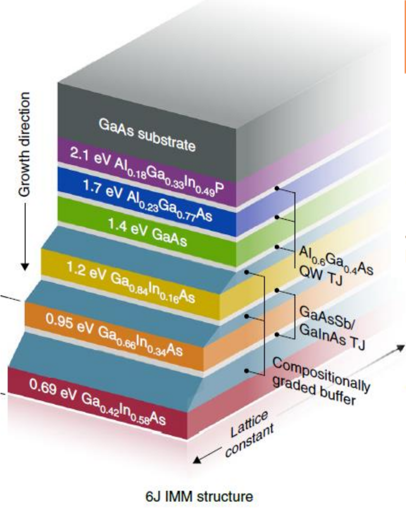
nature energy

ARTICLES

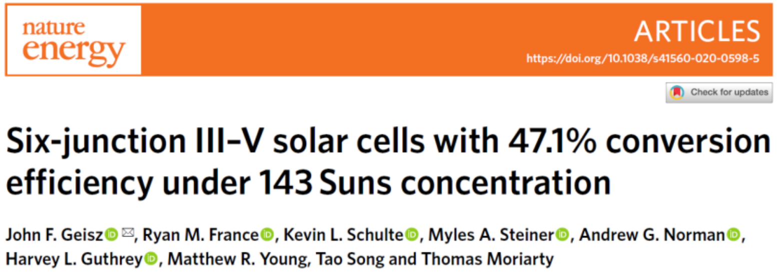
PUBLISHED: 20 MARCH 2017 | VOLUME: 2 | ARTICLE NUMBER: 17032

Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%

Kunta Yoshikawa*, Hayato Kawasaki, Wataru Yoshida, Toru Irie, Katsunori Konishi, Kunihiro Nakano, Toshihiko Uto, Daisuke Adachi, Masanori Kanematsu, Hisashi Uzu and Kenji Yamamoto



6J IMM structure



nature energy

ARTICLES

https://doi.org/10.1038/s41560-020-0598-5

Check for updates

Six-junction III–V solar cells with 47.1% conversion efficiency under 143 Suns concentration

John F. Geisz, Ryan M. France, Kevin L. Schulte, Myles A. Steiner, Andrew G. Norman, Harvey L. Guthrey, Matthew R. Young, Tao Song and Thomas Moriarty

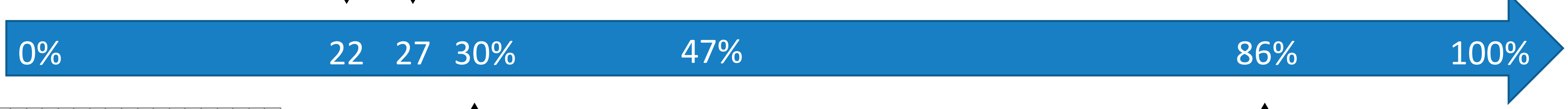
Commercial systems

Silicon record

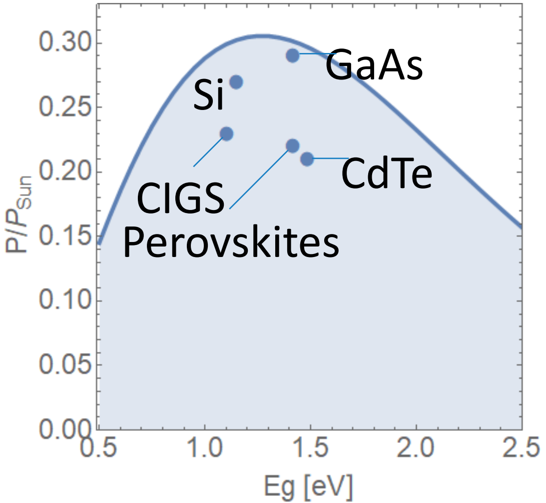
(Yoshikawa et al., Nature Energy (2017))

Overall record (multijonction)

Geisz JF, Nature Energy (2020)



0% 22 27 30% 47% 86% 100%

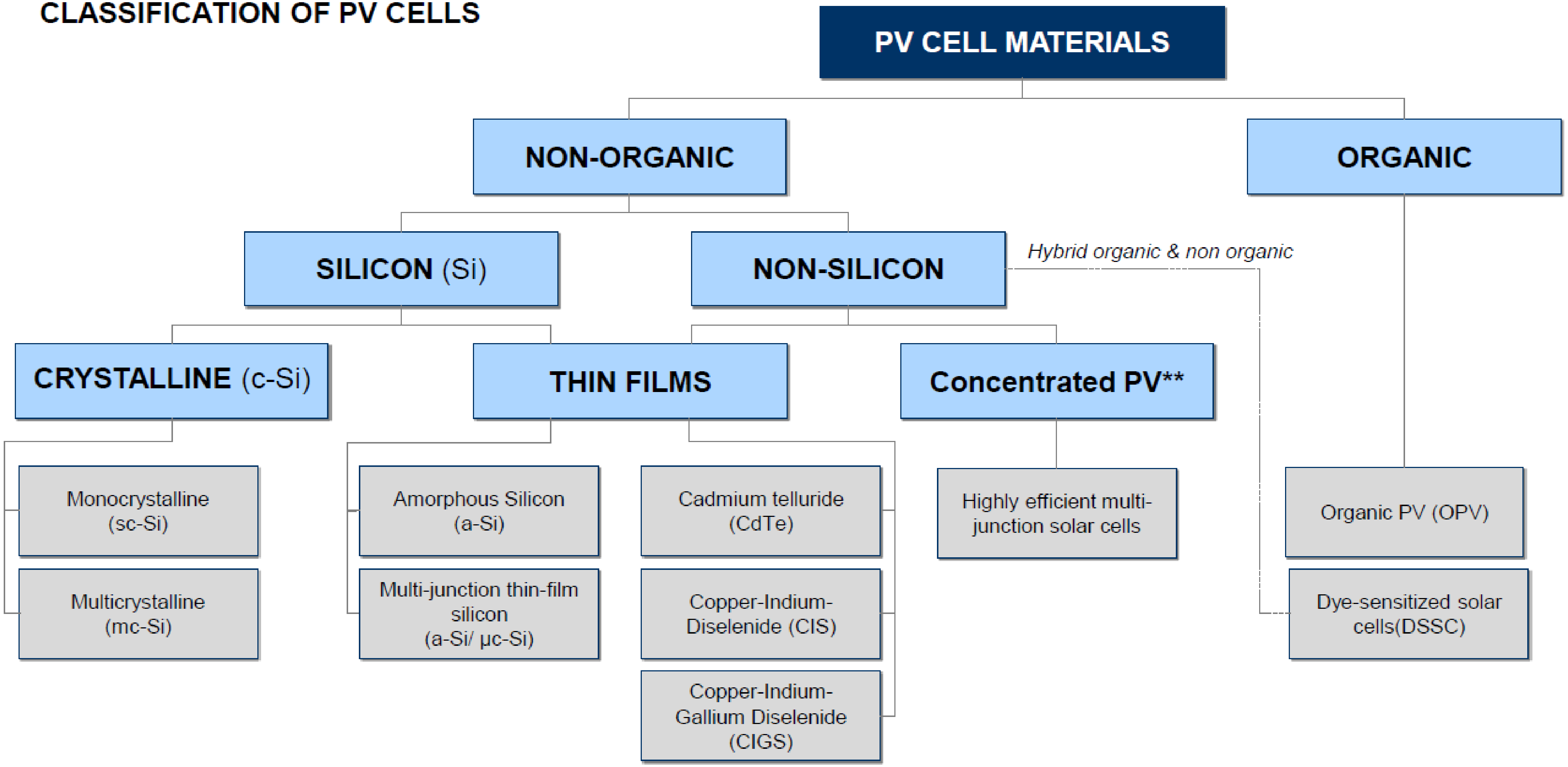


Theoretical limit for single junctions *(limite de Shockley Queisser)*

Thermodynamic upper bond

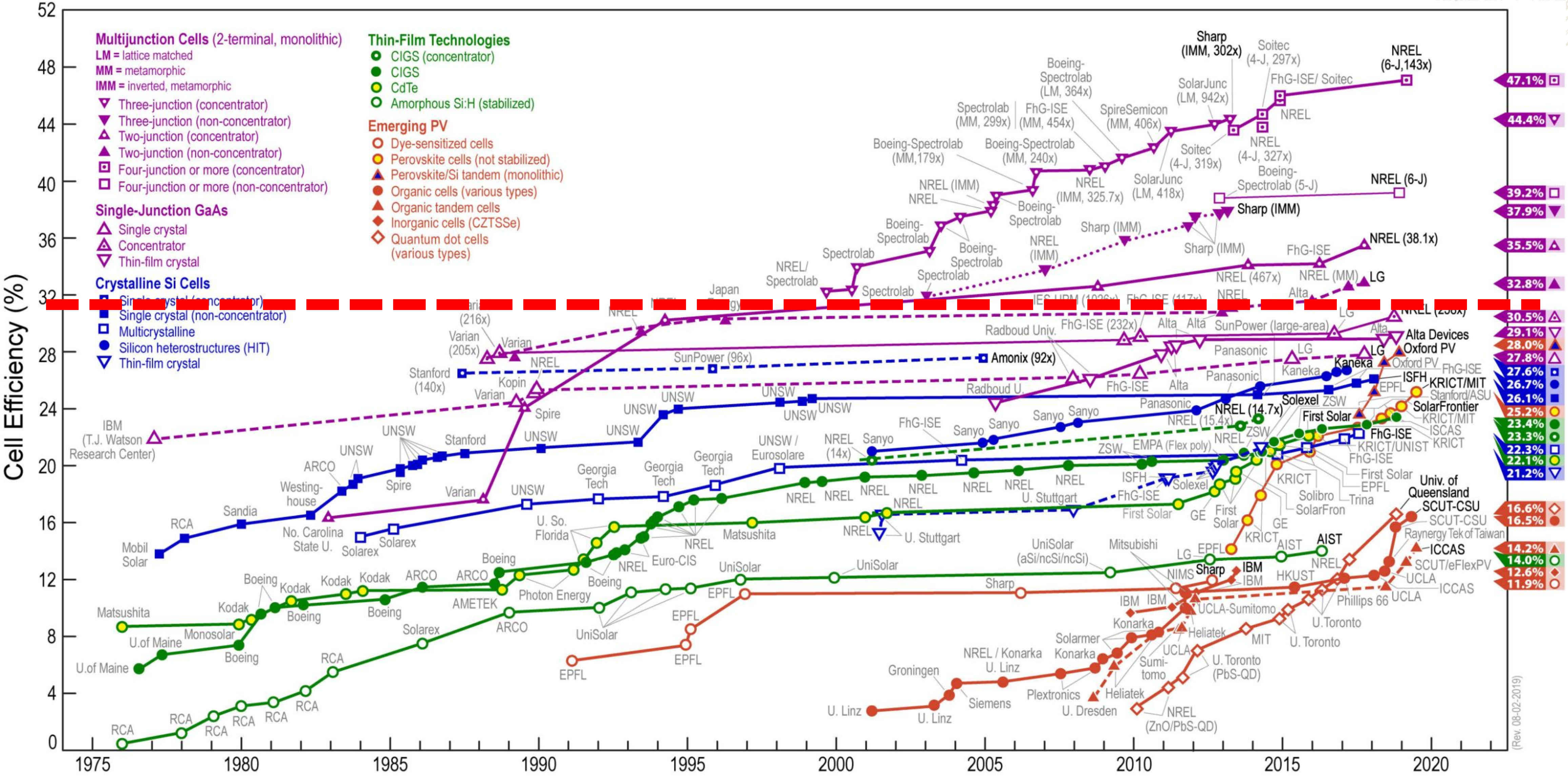
PV technologies

CLASSIFICATION OF PV CELLS



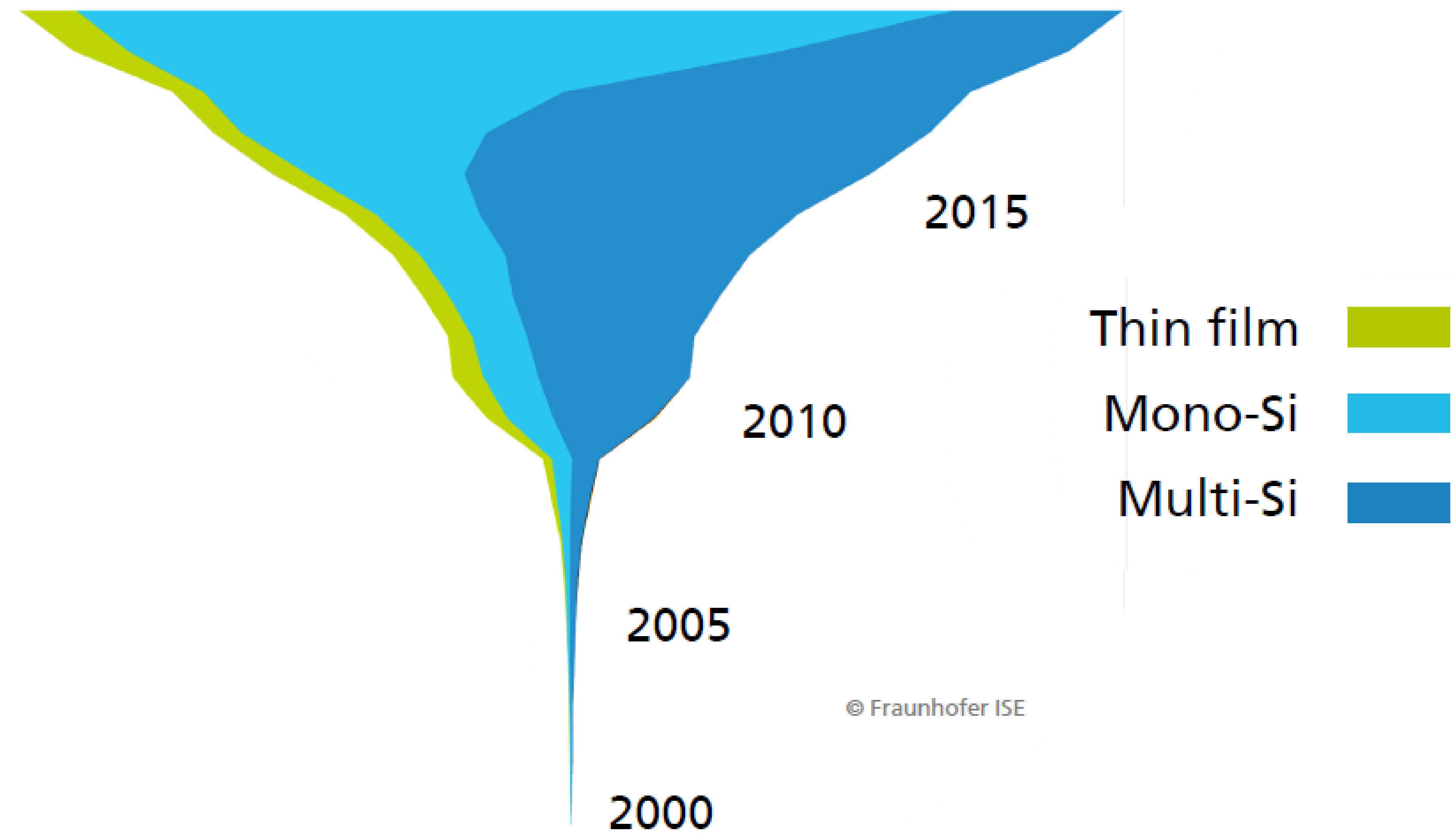
- **PV CELL MATERIALS**
  - **NON-ORGANIC**
    - **SILICON** (Si)
      - **CRYSTALLINE** (c-Si)
        - Monocrystalline (sc-Si)
        - Multicrystalline (mc-Si)
      - **THIN FILMS**
    - **NON-SILICON**
      - **THIN FILMS**
        - Amorphous Silicon (a-Si)
        - Multi-junction thin-film silicon (a-Si/ µc-Si)
        - Cadmium telluride (CdTe)
        - Copper-Indium-Diselenide (CIS)
        - Copper-Indium-Gallium Diselenide (CIGS)
      - **Concentrated PV****
        - Highly efficient multi-junction solar cells
      - *Hybrid organic & non organic*
        - Dye-sensitized solar cells(DSSC)
  - **ORGANIC**
    - Organic PV (OPV)
    - Dye-sensitized solar cells(DSSC)

Welcome to the jungle



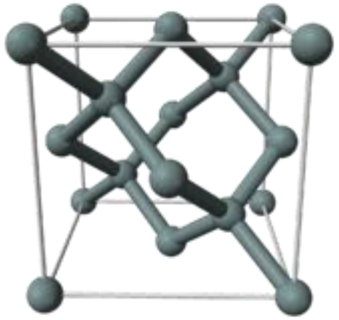
1st order: PV = silicon technologies

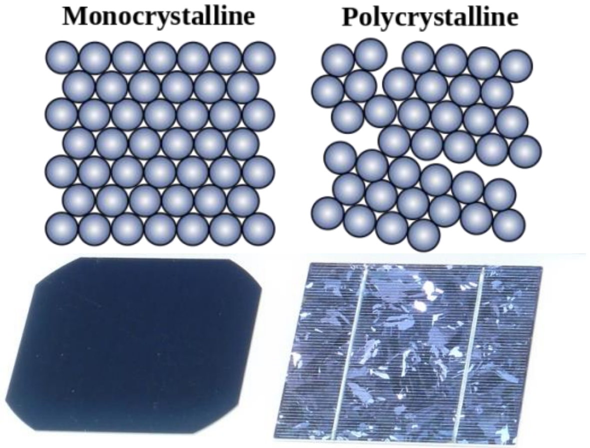
About 150* GWp PV module production in 2020



© Fraunhofer ISE

Techno overview: silicon





Silicon is the historical backbone of PV

1954 : First cell >6% efficiency
1960s' : First commercial systems

(actually, two types of crystals, very similar behavior)

c-Si [Crystalline Silicon]

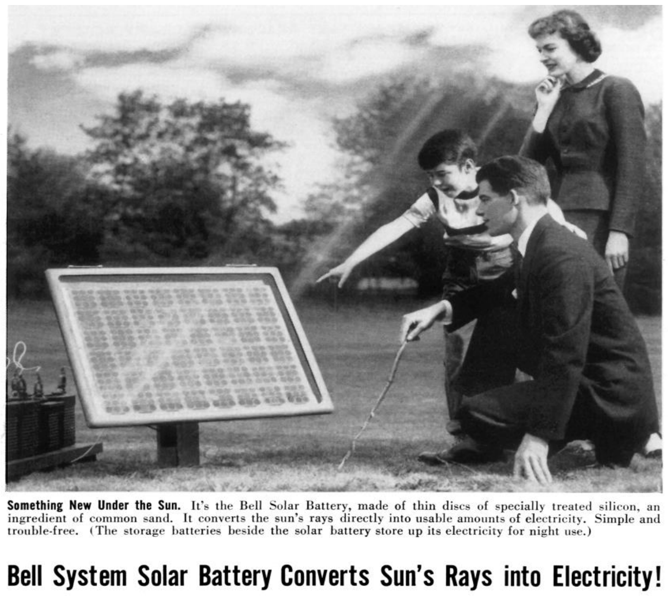
multi/poly-Si [multi/poly crystalline Silicon]

Silicon PV originates in the electronics industry.

Excellent electronic properties (mobility, lifetime),
Not so good optical properties, but ideal gap

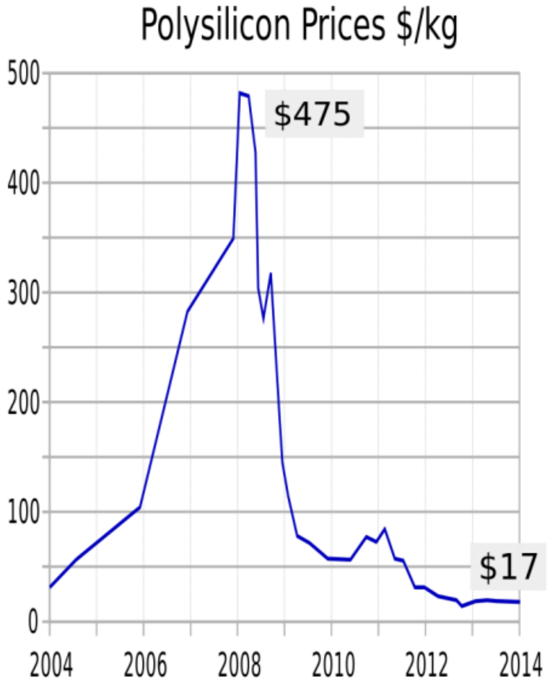
Benefitted from the experience curve of electronics

''Silicon shortage'' in 2006 – 2010
→ emergence of a dedicated market

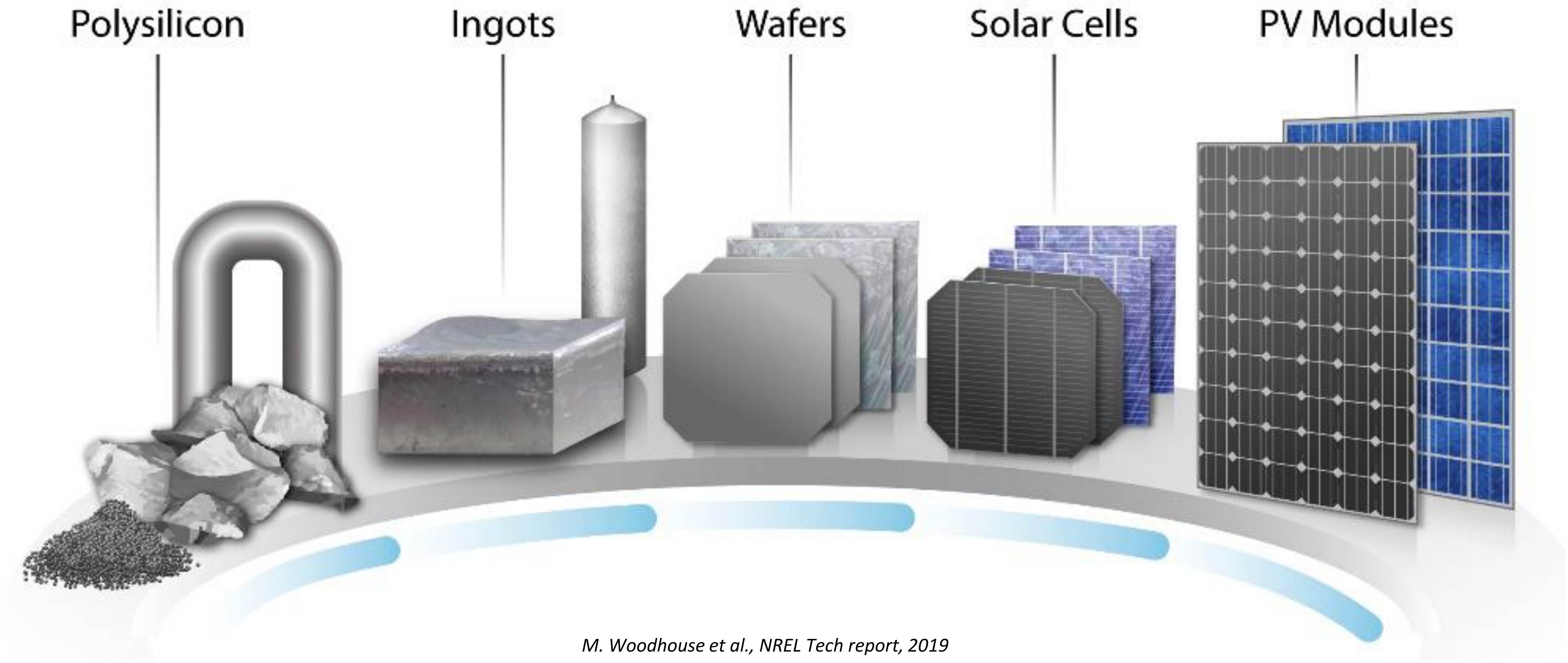


Something New Under the Sun. It's the Bell Solar Battery, made of thin discs of specially treated silicon, an ingredient of common sand. It converts the sun's rays directly into usable amounts of electricity. Simple and trouble-free. (The storage batteries beside the solar battery store up its electricity for night use.)

Bell System Solar Battery Converts Sun's Rays into Electricity!



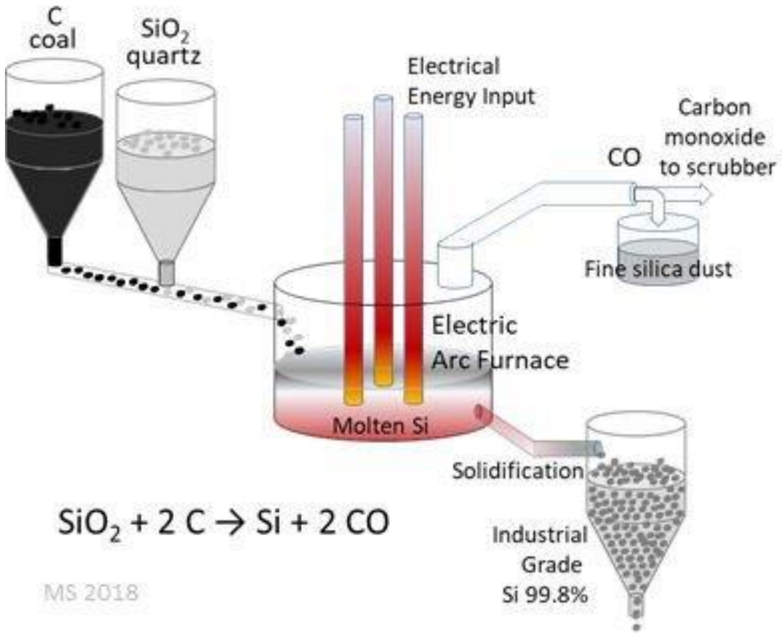
From quartzite to pure silicon



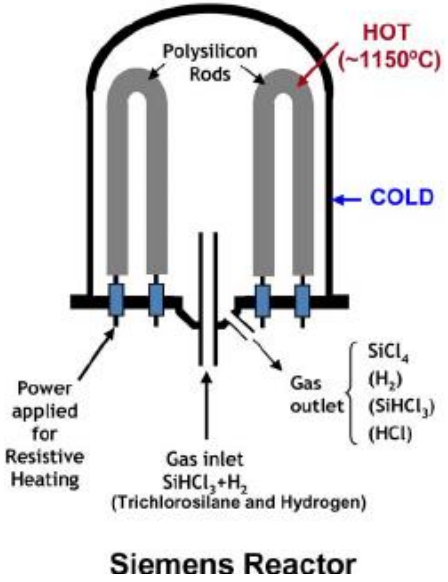
M. Woodhouse et al., NREL Tech report, 2019

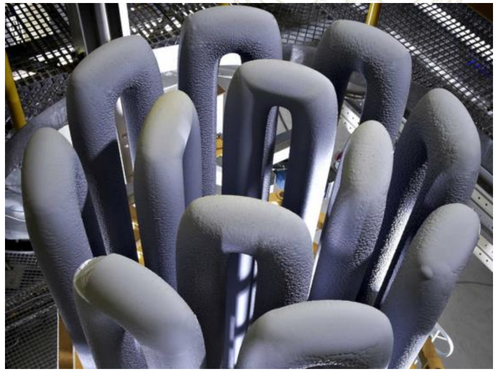
From quartzite to pure silicon

SiO_2 - quartzite



$$SiO_2 + 2\,C \rightarrow Si + 2\,CO$$



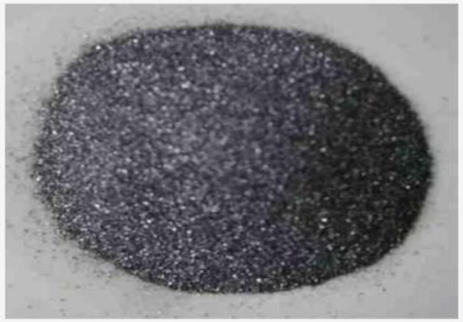


Electronic grade poly-Si

(9N) 99.9999999%

(4.5N) 99.995%

Electronics
Solar cells

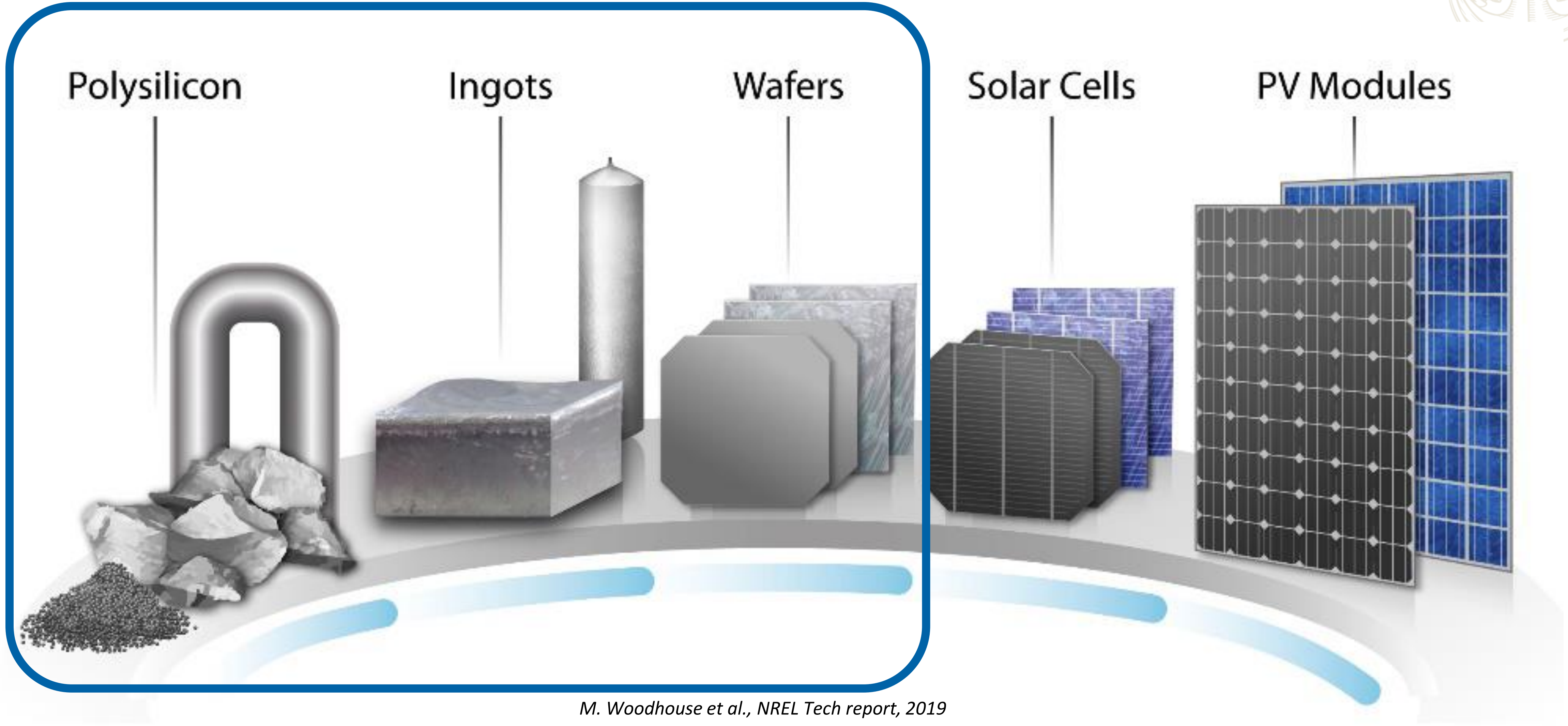


Metallurgic grade

98.5-99.5%

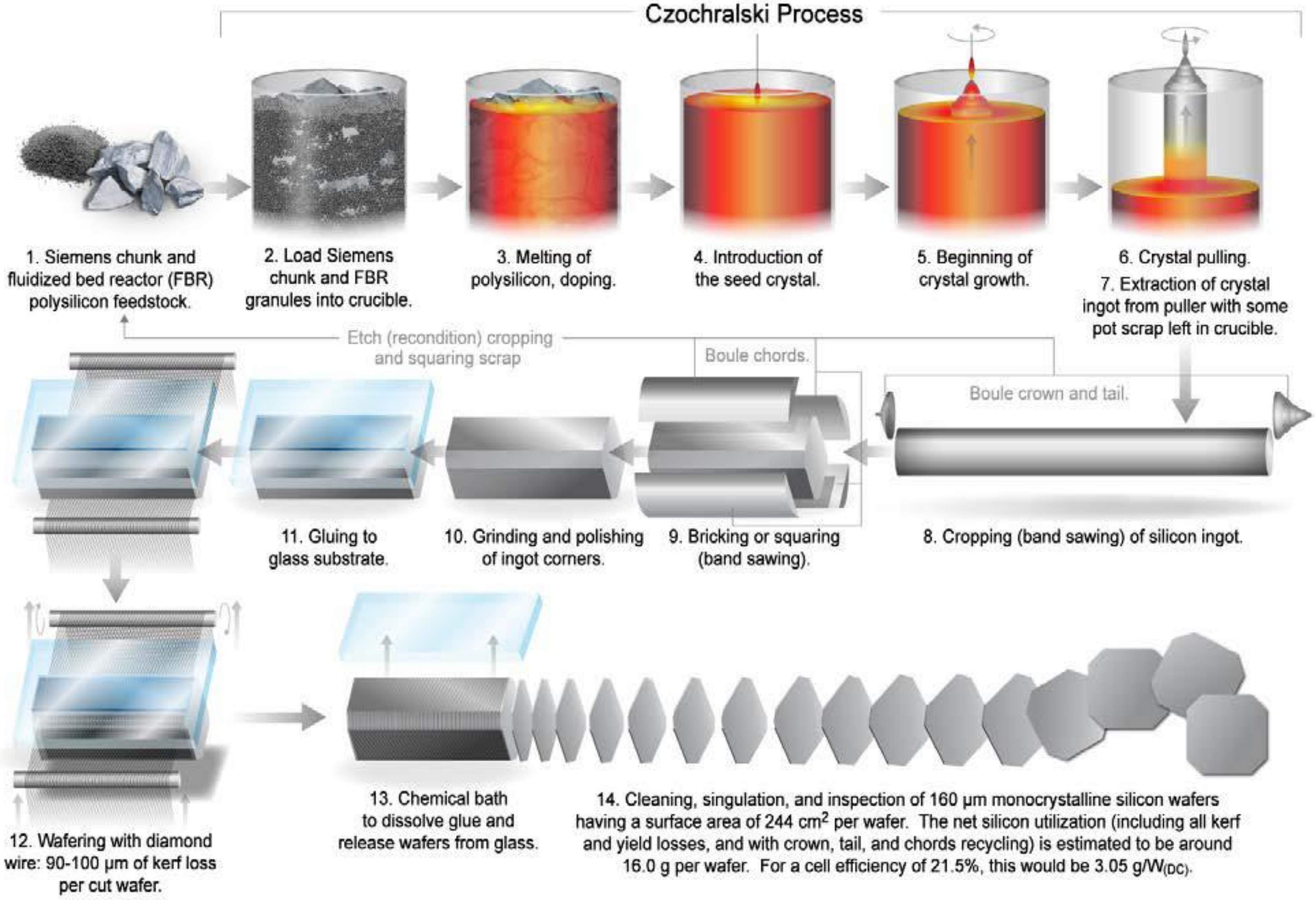
Alluminium
Steel
Silicone
…

From silicon to wafers



M. Woodhouse et al., NREL Tech report, 2019

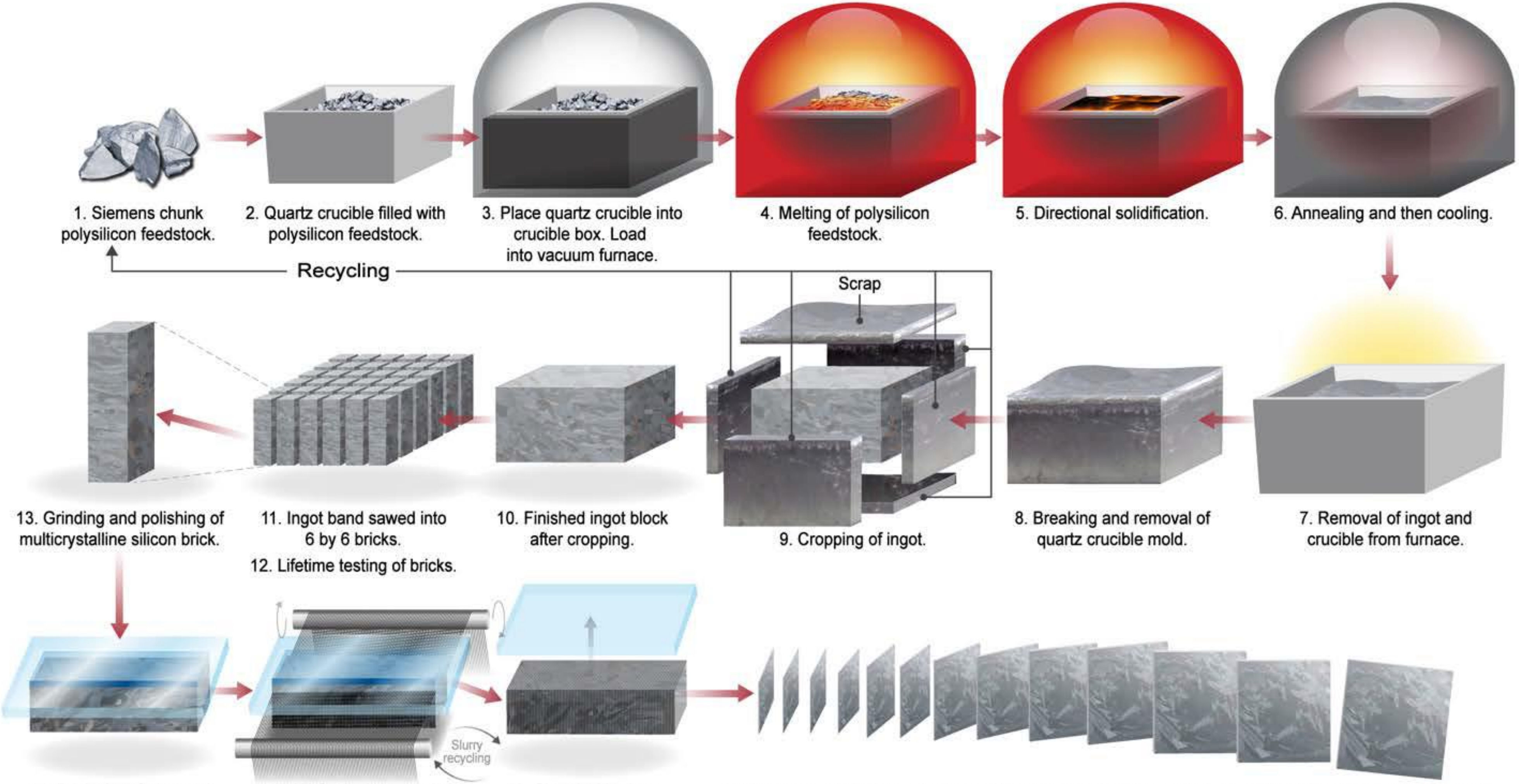
Monocrystaline wafers



1. Siemens chunk and fluidized bed reactor (FBR) polysilicon feedstock.
2. Load Siemens chunk and FBR granules into crucible.
3. Melting of polysilicon, doping.
4. Introduction of the seed crystal.
5. Beginning of crystal growth.
6. Crystal pulling.
7. Extraction of crystal ingot from puller with some pot scrap left in crucible.
8. Cropping (band sawing) of silicon ingot.
9. Bricking or squaring (band sawing).
10. Grinding and polishing of ingot corners.
11. Gluing to glass substrate.
12. Wafering with diamond wire: 90-100 µm of kerf loss per cut wafer.
13. Chemical bath to dissolve glue and release wafers from glass.
14. Cleaning, singulation, and inspection of 160 µm monocrystalline silicon wafers having a surface area of 244 cm^2 per wafer. The net silicon utilization (including all kerf and yield losses, and with crown, tail, and chords recycling) is estimated to be around 16.0 g per wafer. For a cell efficiency of 21.5%, this would be 3.05 $g/W_{(DC)}$.

M. Woodhouse et al., NREL Tech report, 2019

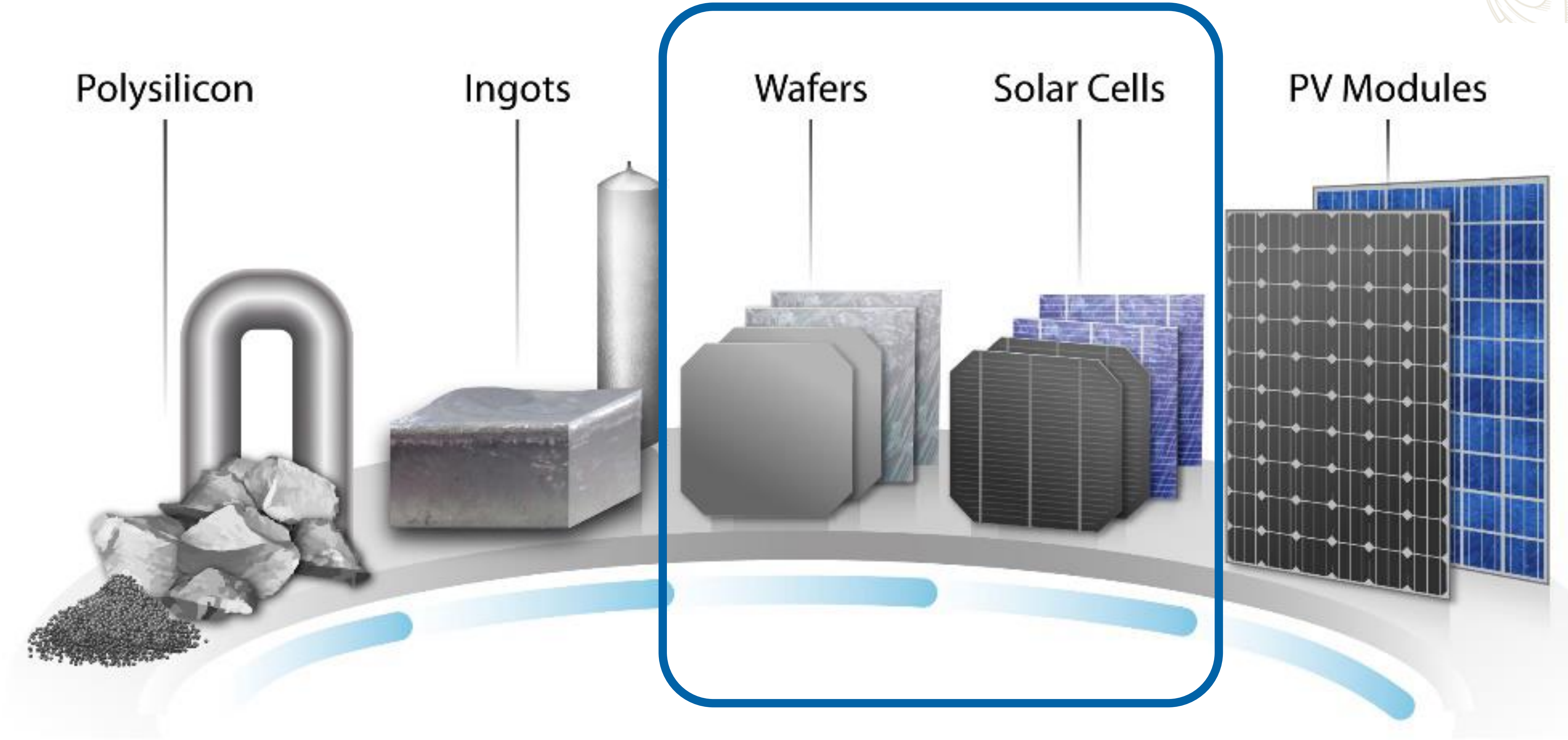
Multi-crystalline wafers



1. Siemens chunk polysilicon feedstock.
2. Quartz crucible filled with polysilicon feedstock.
3. Place quartz crucible into crucible box. Load into vacuum furnace.
4. Melting of polysilicon feedstock.
5. Directional solidification.
6. Annealing and then cooling.
7. Removal of ingot and crucible from furnace.
8. Breaking and removal of quartz crucible mold.
9. Cropping of ingot.
10. Finished ingot block after cropping.
11. Ingot band sawed into 6 by 6 bricks.
12. Lifetime testing of bricks.
13. Grinding and polishing of multicrystalline silicon brick.
14. Brick chamfering and gluing to glass substrate.
15. Wafering (wire sawing): 150 μm kerf per cut wafer.
16. Chemical bath to dissolve glue and release wafers from glass.
17. Cleaning, singulation, and inspection of 180 μm multicrystalline silicon wafers having a surface area of 246 cm^2 per wafer. The net silicon utilization (including all kerf and yield losses, and with partial ingot recycling) is estimated to be around 16.9 g per wafer. For a cell efficiency of 20.5%, this would be 3.35 $\text{g/W}_{\text{(DC)}}$.

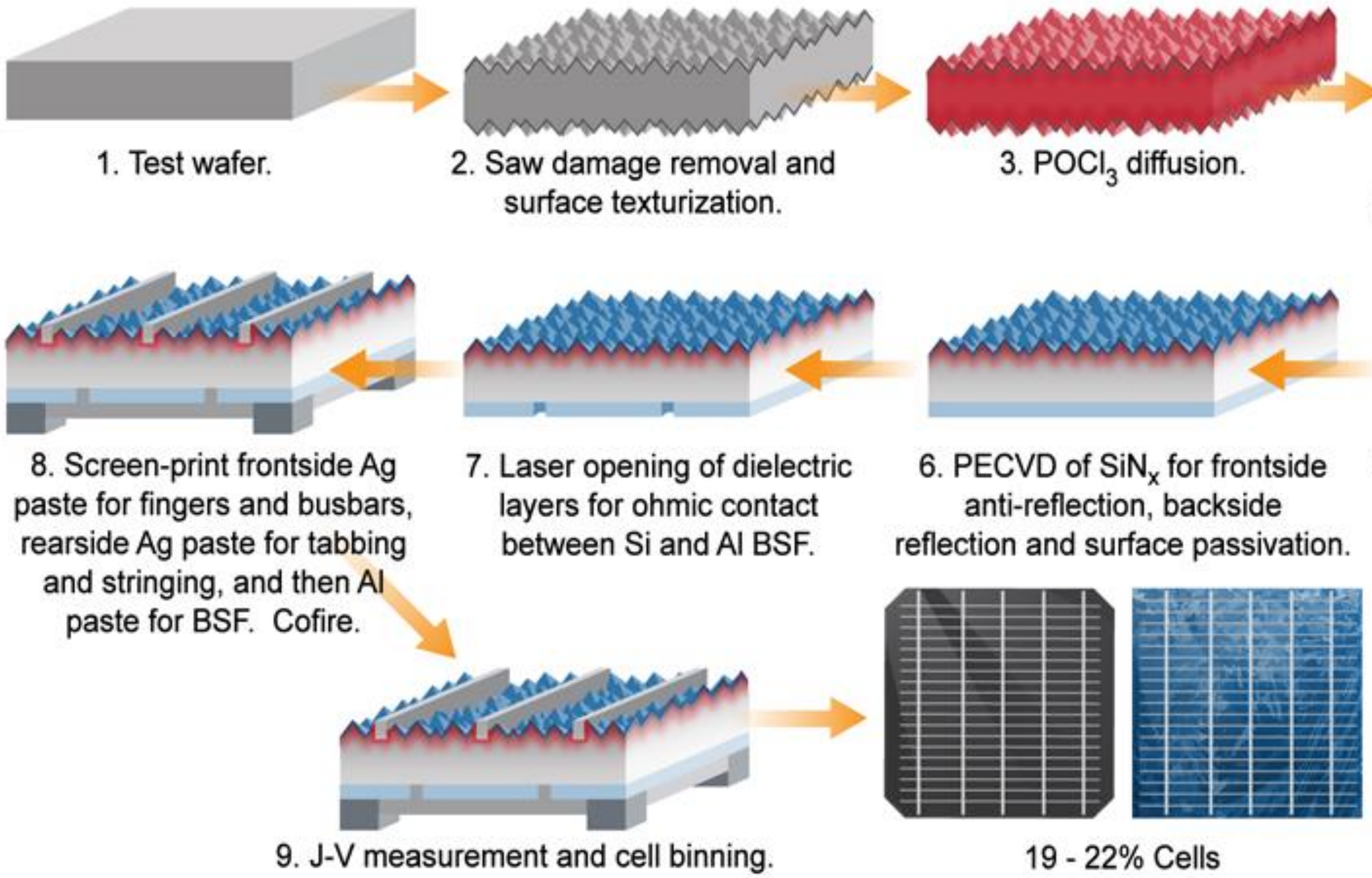
M. Woodhouse et al., NREL Tech report, 2019

From wafers to cells



M. Woodhouse et al., NREL Tech report, 2019

Inside a solar cell



1. Test wafer.

2. Saw damage removal and surface texturization.

3. $POCl_3$ diffusion.

4. PSG removal, rear side planarization, and edge isolation by single-side etching.

5. Rear-side deposition of silicon oxide or aluminum oxide layer.

6. PECVD of SiN_x for frontside anti-reflection, backside reflection and surface passivation.

7. Laser opening of dielectric layers for ohmic contact between Si and Al BSF.

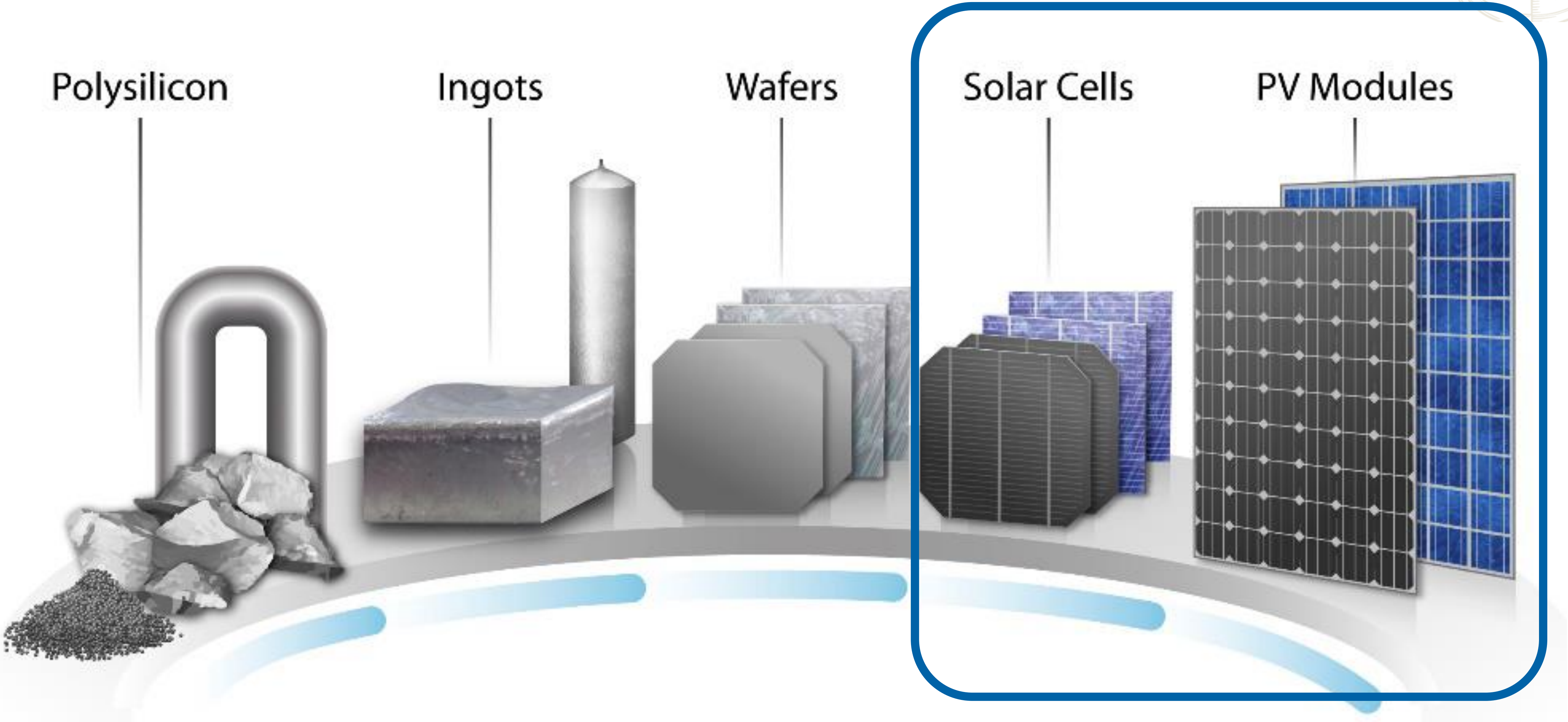
8. Screen-print frontside Ag paste for fingers and busbars, rearside Ag paste for tabbing and stringing, and then Al paste for BSF. Cofire.

9. J-V measurement and cell binning.

19 - 22% Cells

M. Woodhouse et al., NREL Tech report, 2019

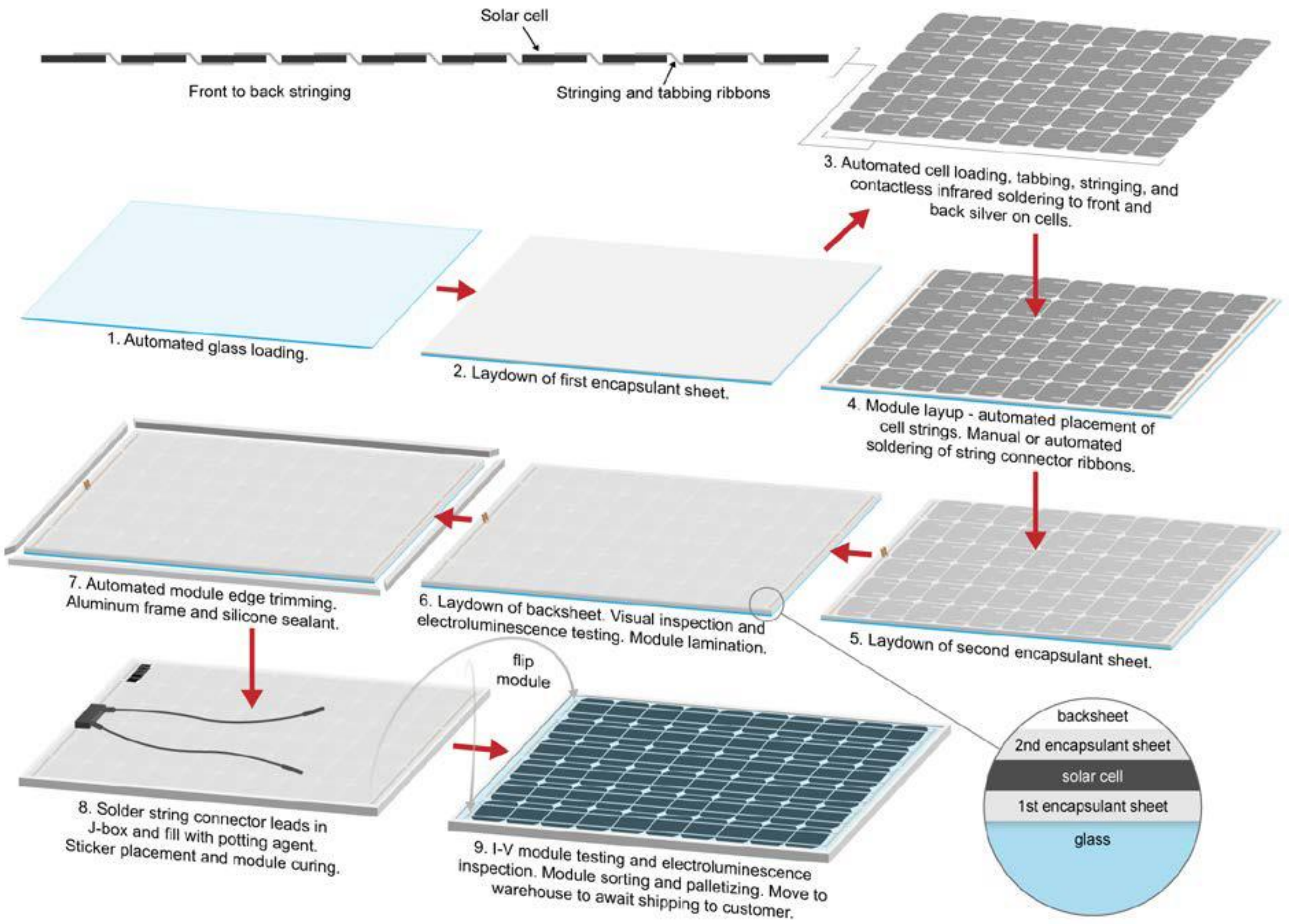
From cells to modules



M. Woodhouse et al., NREL Tech report, 2019

Moduling

M. Woodhouse et al., NREL Tech report, 2019



1. Automated glass loading.

2. Laydown of first encapsulant sheet.

3. Automated cell loading, tabbing, stringing, and contactless infrared soldering to front and back silver on cells.

4. Module layup - automated placement of cell strings. Manual or automated soldering of string connector ribbons.

5. Laydown of second encapsulant sheet.

6. Laydown of backsheet. Visual inspection and electroluminescence testing. Module lamination.

7. Automated module edge trimming. Aluminum frame and silicone sealant.

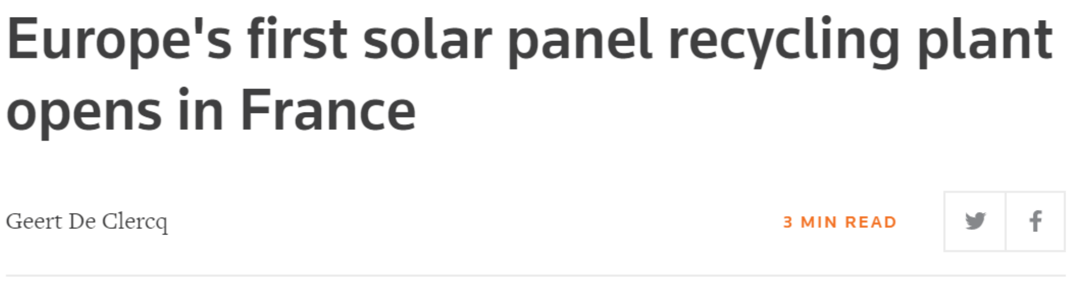
8. Solder string connector leads in J-box and fill with potting agent. Sticker placement and module curing.

9. I-V module testing and electroluminescence inspection. Module sorting and palletizing. Move to warehouse to await shipping to customer.

Solar cell shopping list

Poids en gramme	par m²	par Wc efficacité : 20%	par kWh ensoleillement 1700 kWh/m²/an facteur de perf. 85% 25 ans, -0.5%/an
Silicium	600	3	0.1
Gallium	0.000 2	0.000 001	0.000 000 003
Argent	4	0.02	0.000 6
Aluminium	1 600	8	0.24
Plastique	1 700	8.5	0.25
Verre	8 000	40	1.2
Cuivre	900	4.5	0.14
Béton	12 000	60	1.8
Acier	14 000	70	2.1
CO_2	50	1 000	30
Energie primaire [MJ]	3 000	15	0.45

Recyling



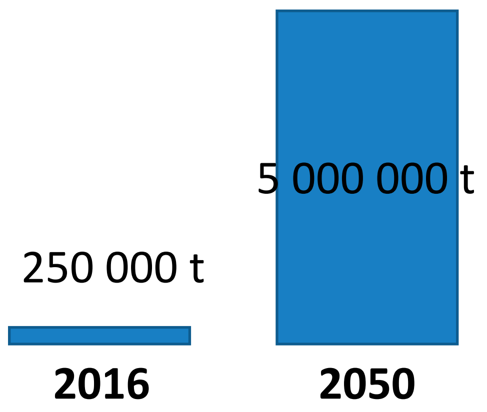
Europe's first solar panel recycling plant opens in France

Geert De Clercq

3 MIN READ

> *"This is the* ***first*** *dedicated solar panel recycling plant in Europe, possibly* ***in the world****," Gilles Carsuzaa, head of electronics recycling at Veolia, told reporters.*

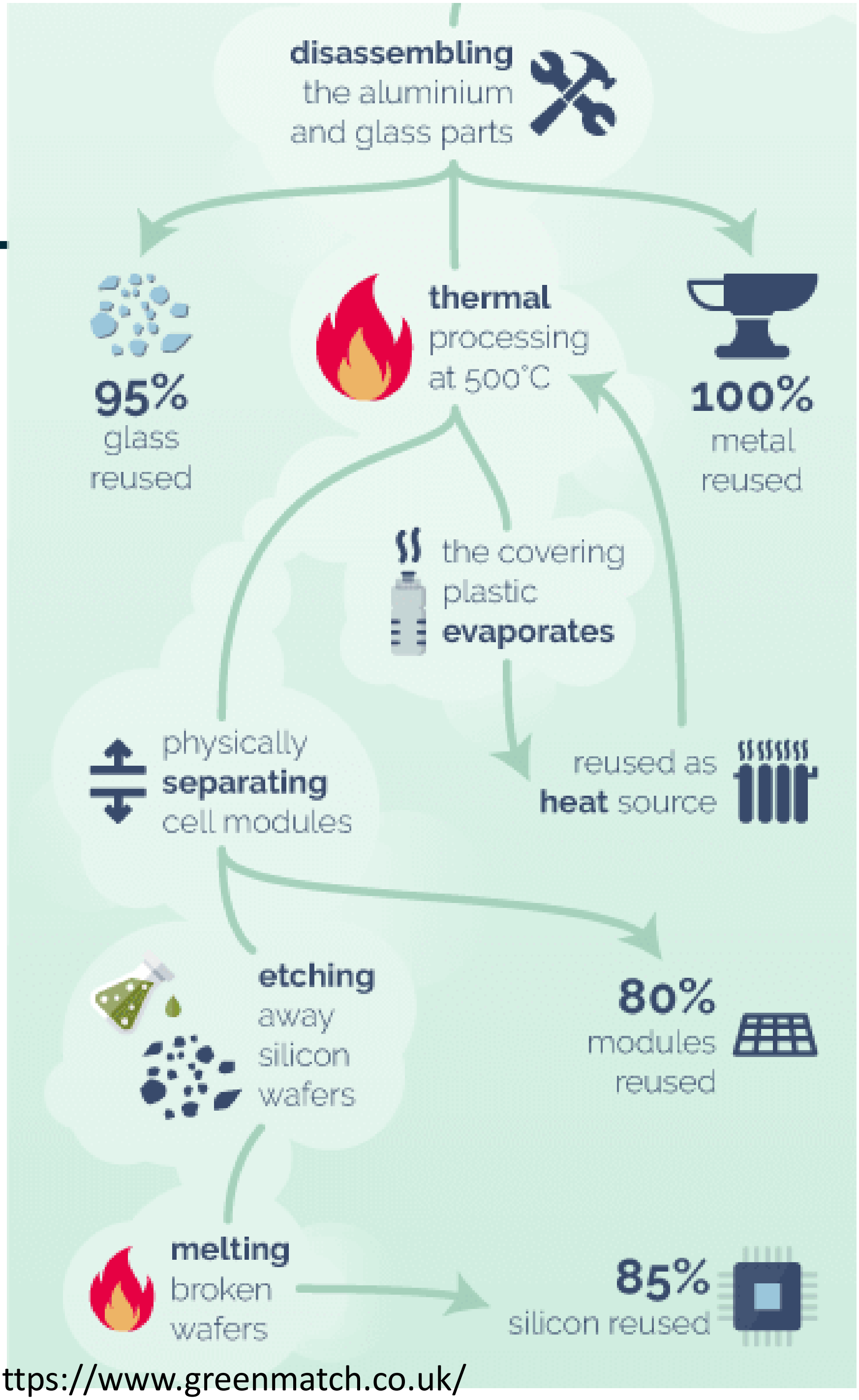
G. De Cleerq, Reuters, *June 2018*



End of life management, IEA – IRENA, 2016

Recycling Or downcycling ?

Recycling of non-Si techno ?



https://www.greenmatch.co.uk/

Lecture 6 – solar energy

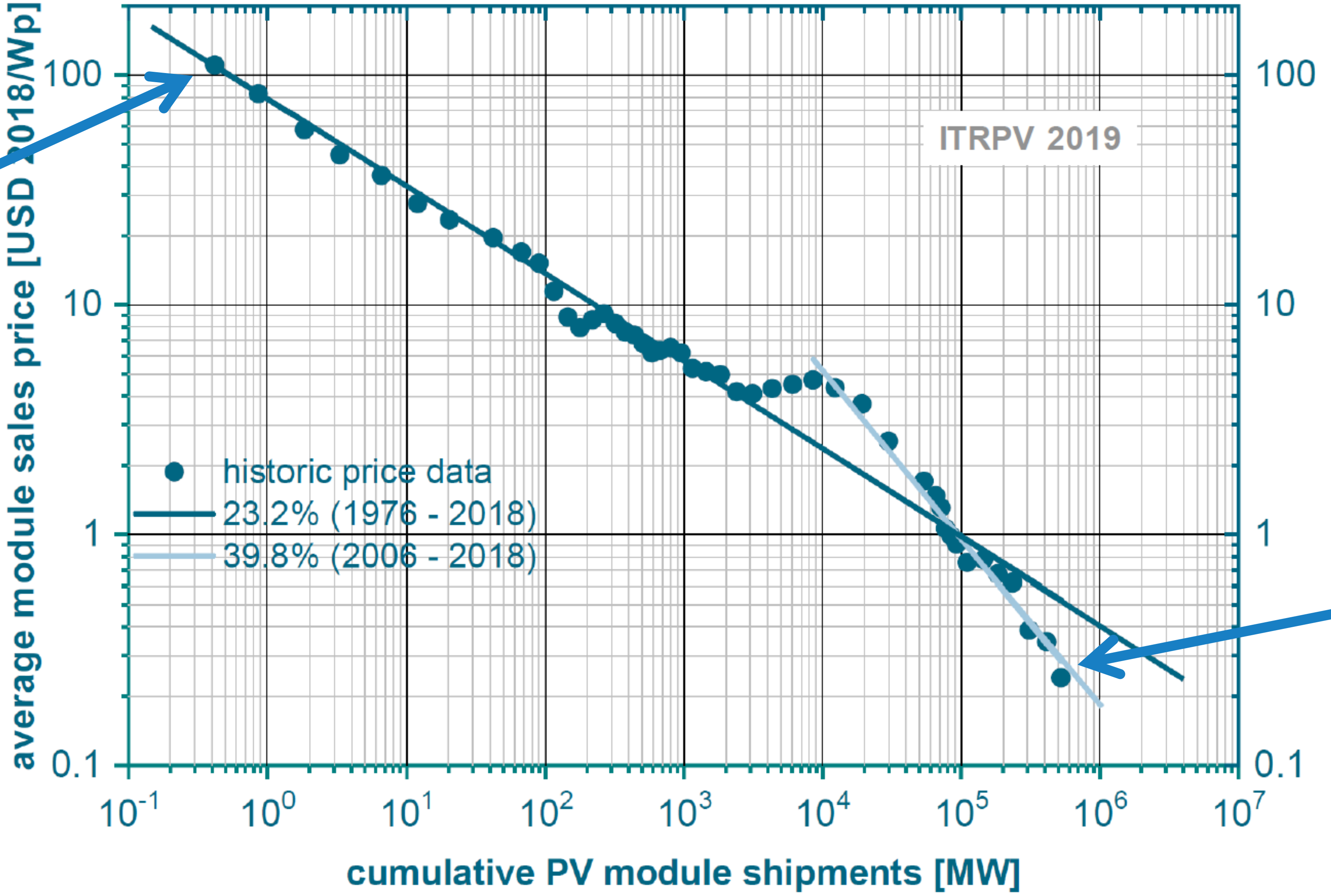
I. Solar energy resource

II. Thermodynamics of solar energy conversion
  A. Solar heating
  B. Concentrated solar power
  C. Photovoltaics

III. Overview of the silicon PV technology

IV. PV today and tomorrow

Cost evolution

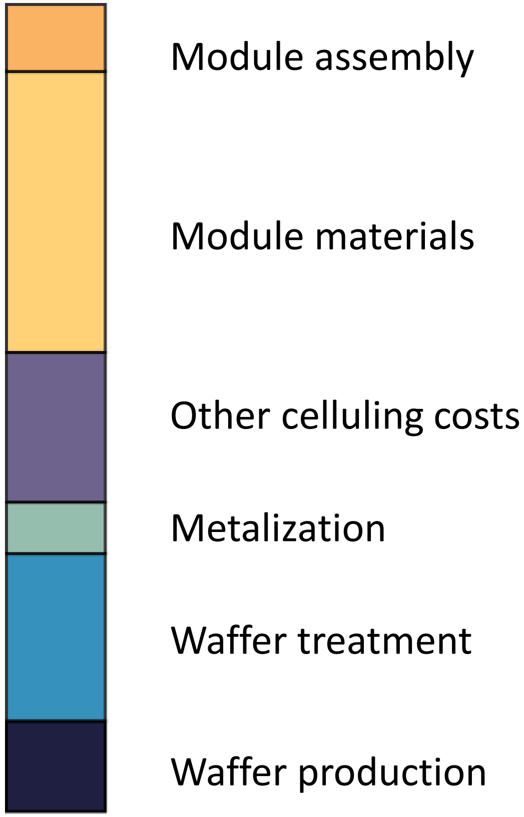


1976
100$/W

2019
0.2$/W

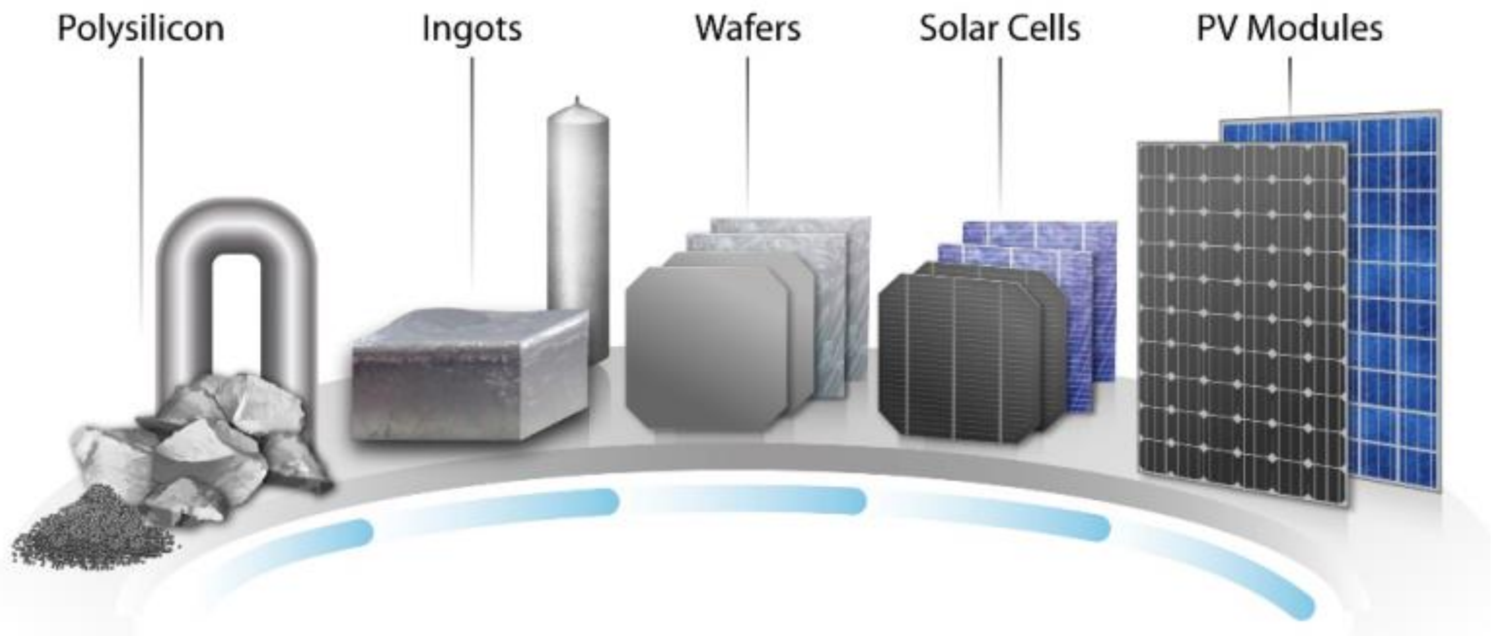
Module cost

Module cost



0.24 $/W

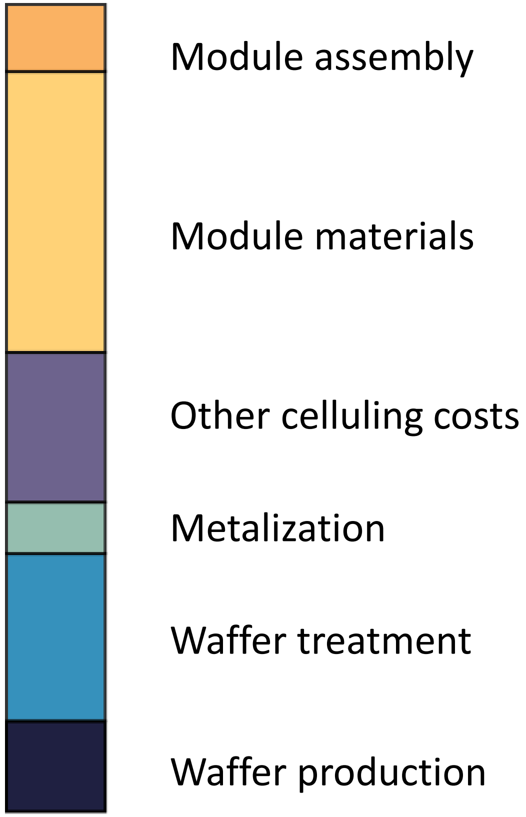
NREL (2019)



M. Woodhouse et al., NREL Tech report, 2019

Installed cost

Module cost



Module assembly

Module materials

Other celluling costs

Metalization

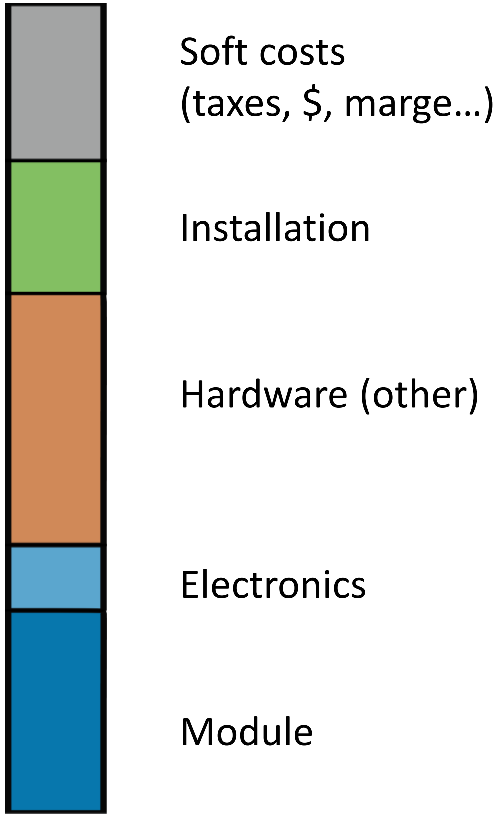
Waffer treatment

Waffer production

0.24 $/W

NREL (2019)

Installed cost



Soft costs
(taxes, $, marge…)

Installation

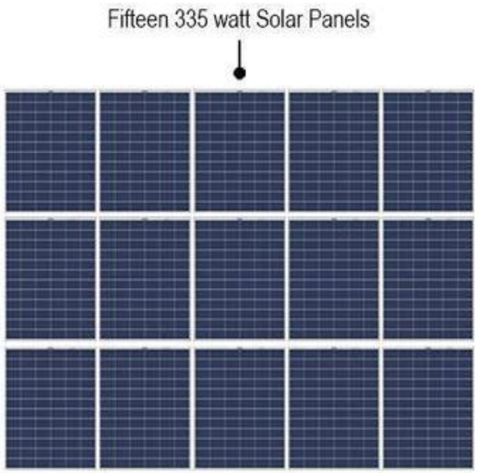
Hardware (other)

Electronics

Module

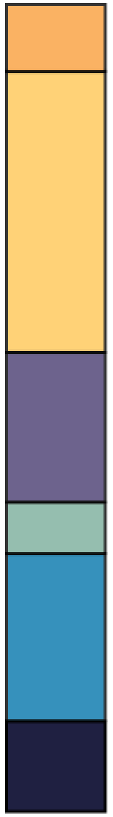
1.07$/W

IRENA (2019)



Levelized cost

Module cost



Module assembly

Module materials

Other celluling costs

Metalization

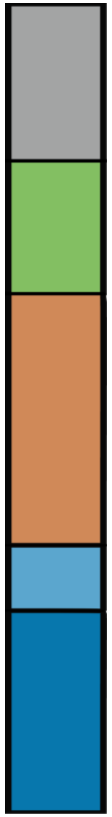
Waffer treatment

Waffer production

0.24 $/W

NREL (2019)

Installed cost



Soft costs
(taxes, $, marge…)

Installation

Hardware (other)

Electronics

Module

1.07$/W

IRENA (2019)

Levelized cost of electricity

About 1/3 of electricity bills (J. Percebois)

Maintenance

Illumination

Degradation

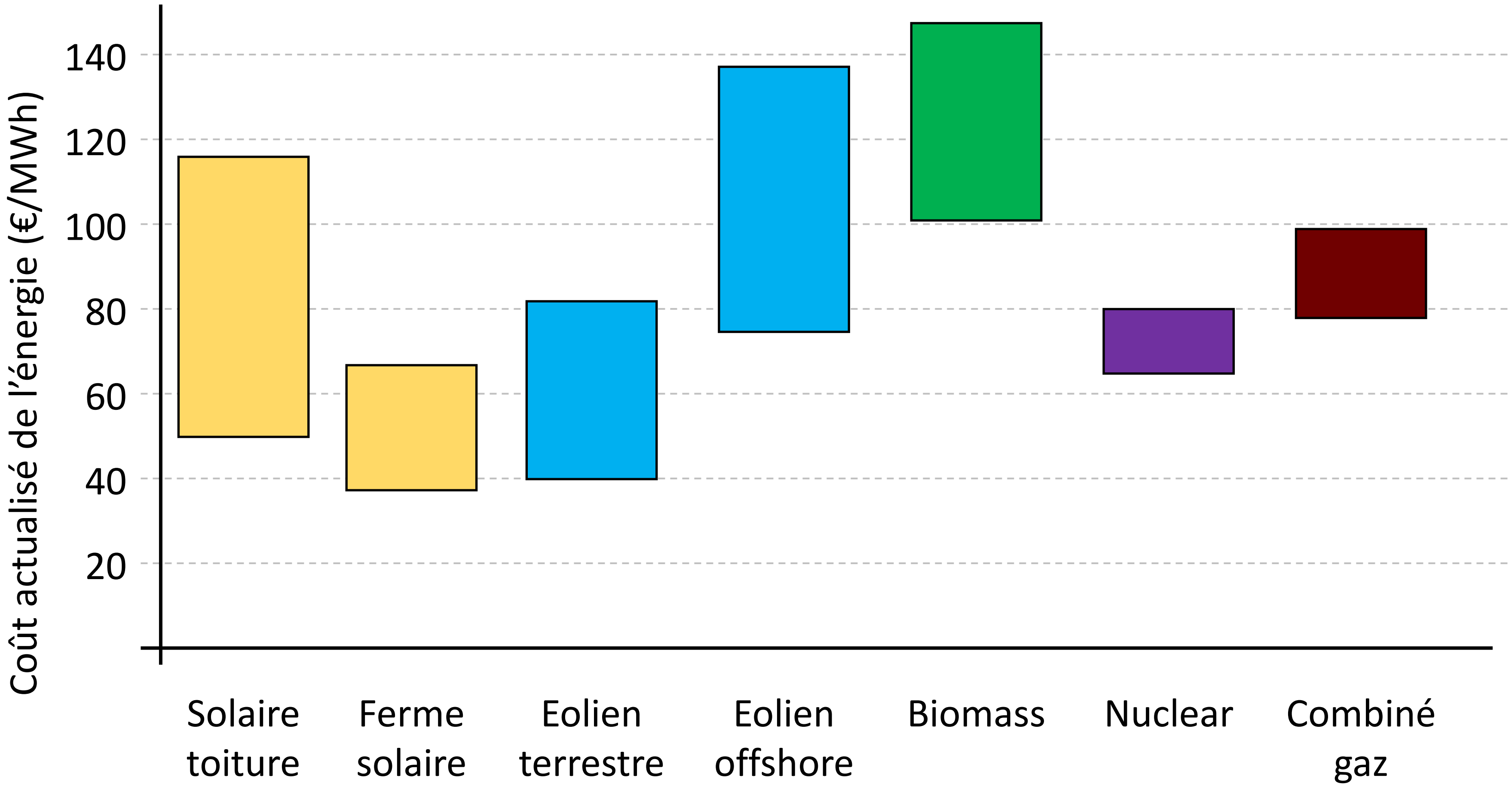
-0,5% /an

**Efficiency: 20% → 17%
in 30 yrs**

40-60 $/MWh

ITRPV (2019)

Levelized cost (continued)



Fraunhofer ISE, Levelized cost of electricity – renewable energy technologies (2018)

EIA, Levelized Cost and Levelized Avoided Cost of New Generation (2019)

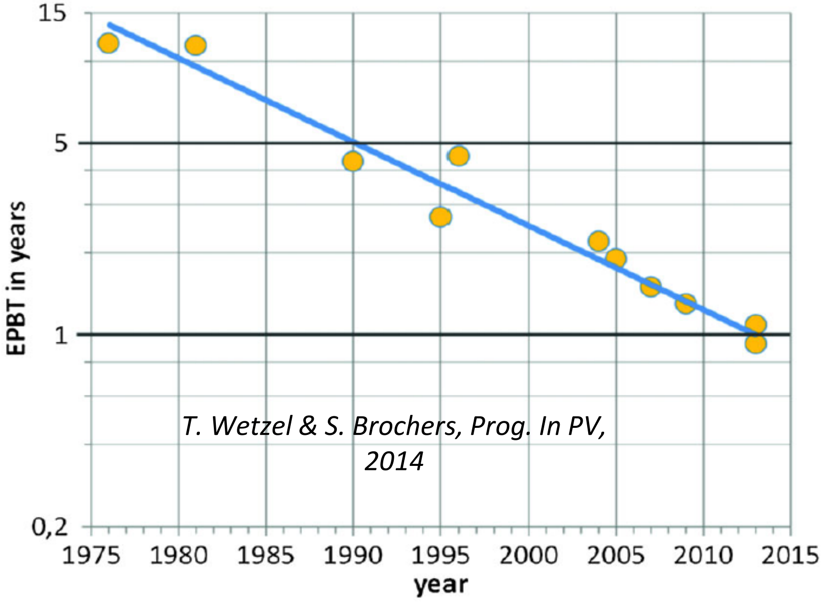
Energy pay back


Progress in PHOTOVOLTAICS
PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2014)

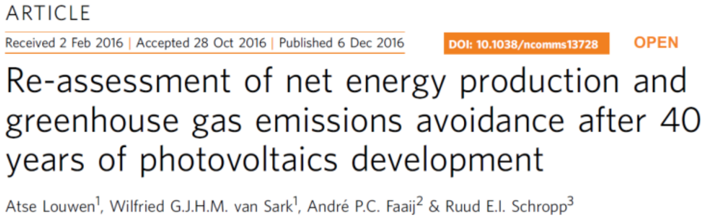
BROADER PERSPECTIVES

Update of energy payback time and greenhouse gas emission data for crystalline silicon photovoltaic modules

Thomas Wetzel* and Stephanie Borchers



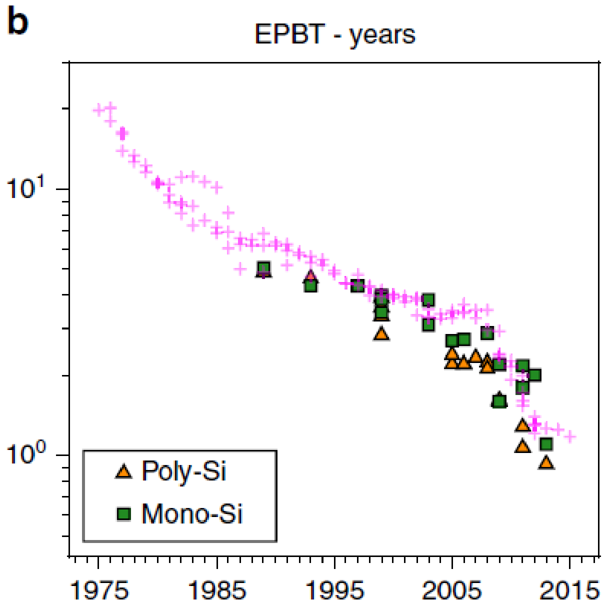
T. Wetzel & S. Brochers, Prog. In PV, 2014

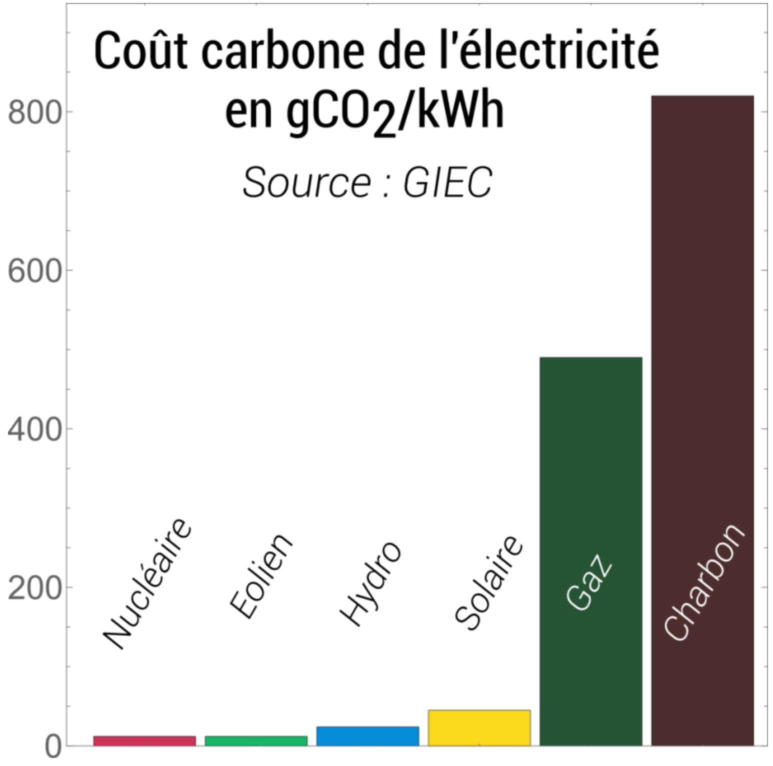

ARTICLE

Received 2 Feb 2016 | Accepted 28 Oct 2016 | Published 6 Dec 2016
DOI: 10.1038/ncomms13728
OPEN

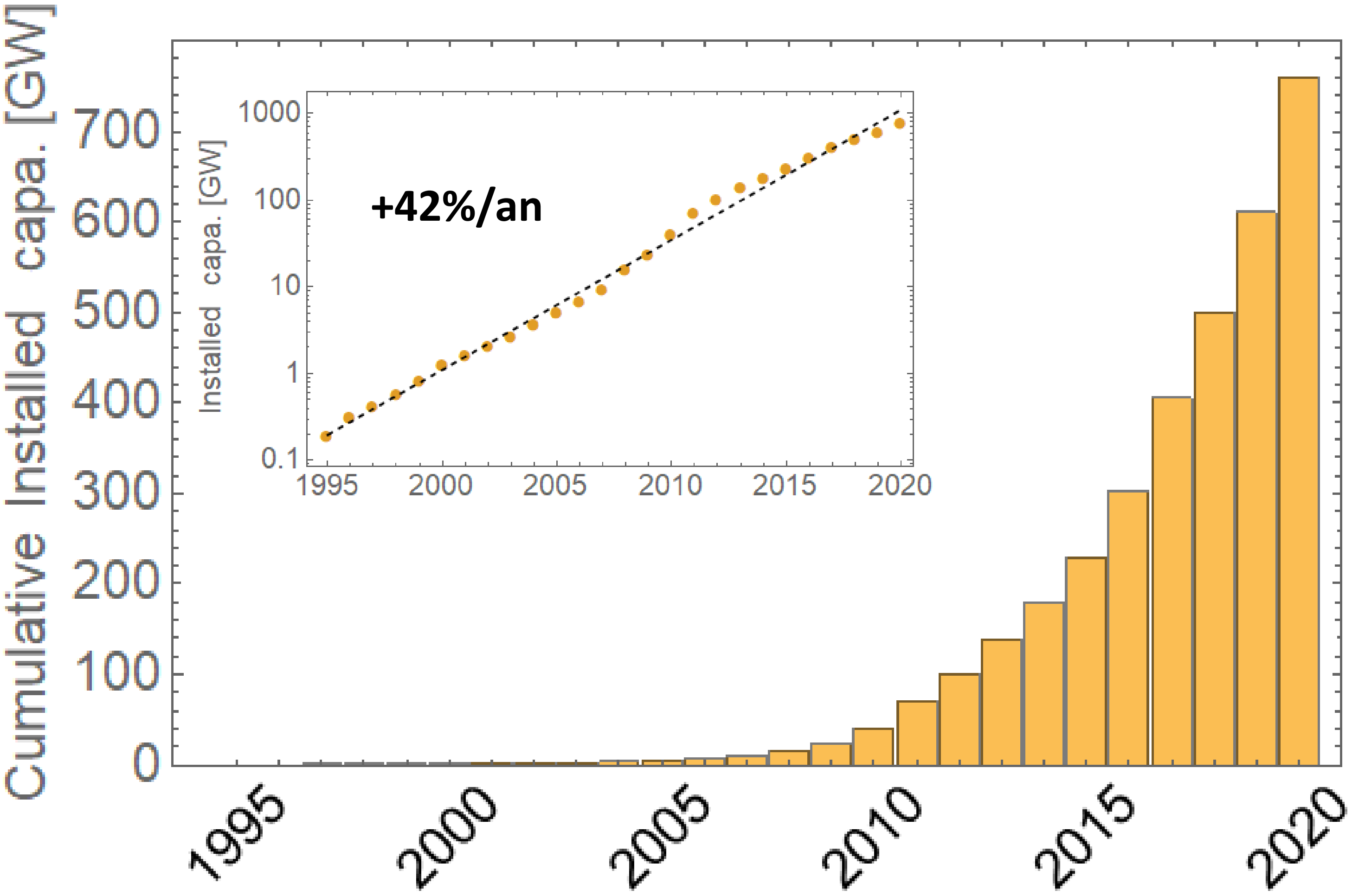
Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development

Atse Louwen[1], Wilfried G.J.H.M. van Sark[1], André P.C. Faaij[2] & Ruud E.I. Schropp[3]





Installed PV capacity



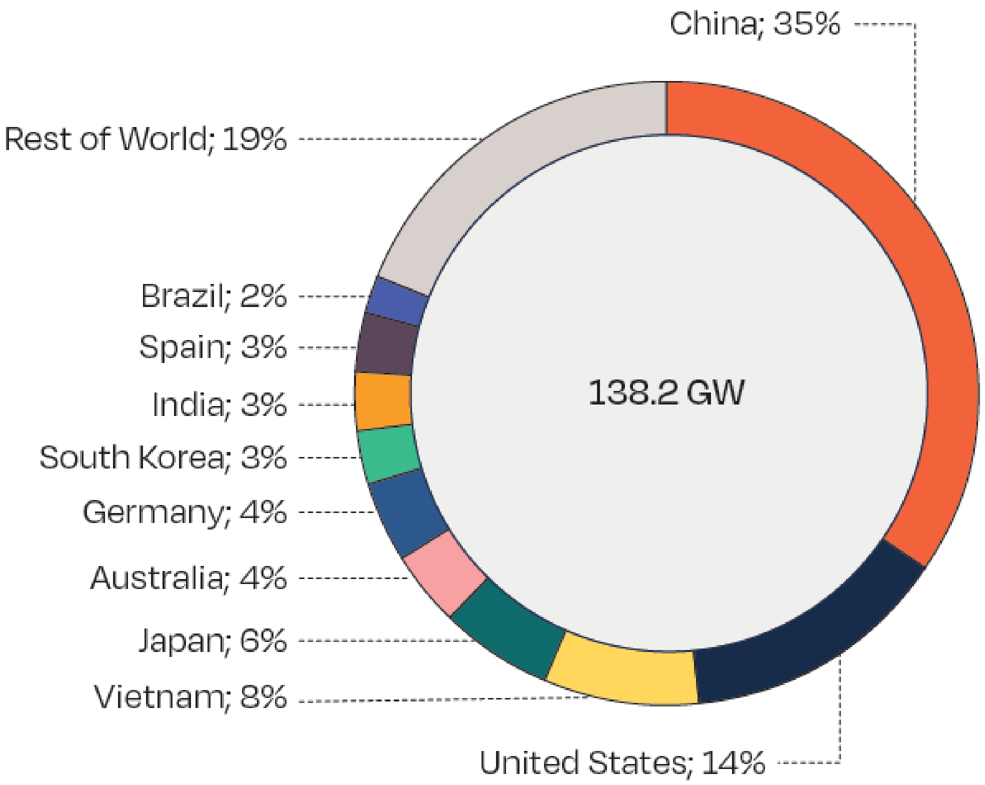
BP (2015) & IEA-PVPS (2019)

In 2018,
World :
500GW installed
650 TWh actually produced
(=2.5% of the world production)

France :
8.5 GW installed
10 TWh actually produced
(= 2% of the French production)

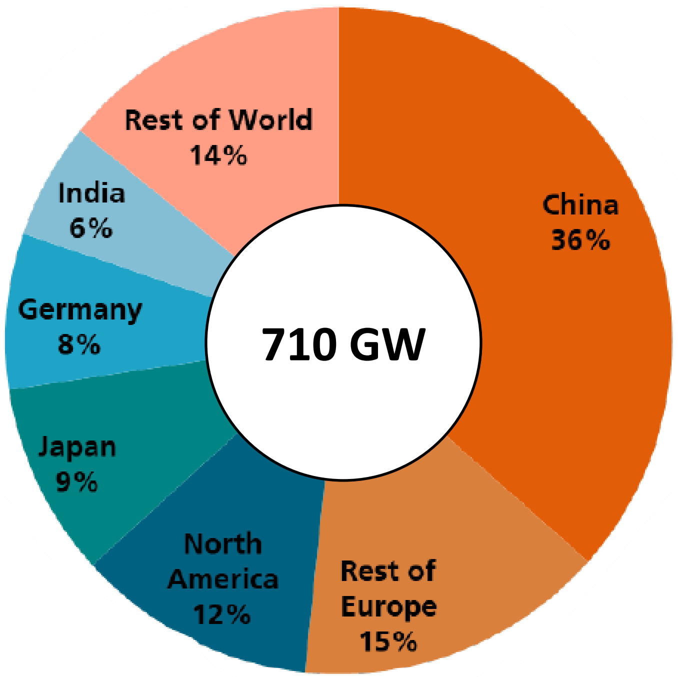
PV distribution

Installed power in 2020

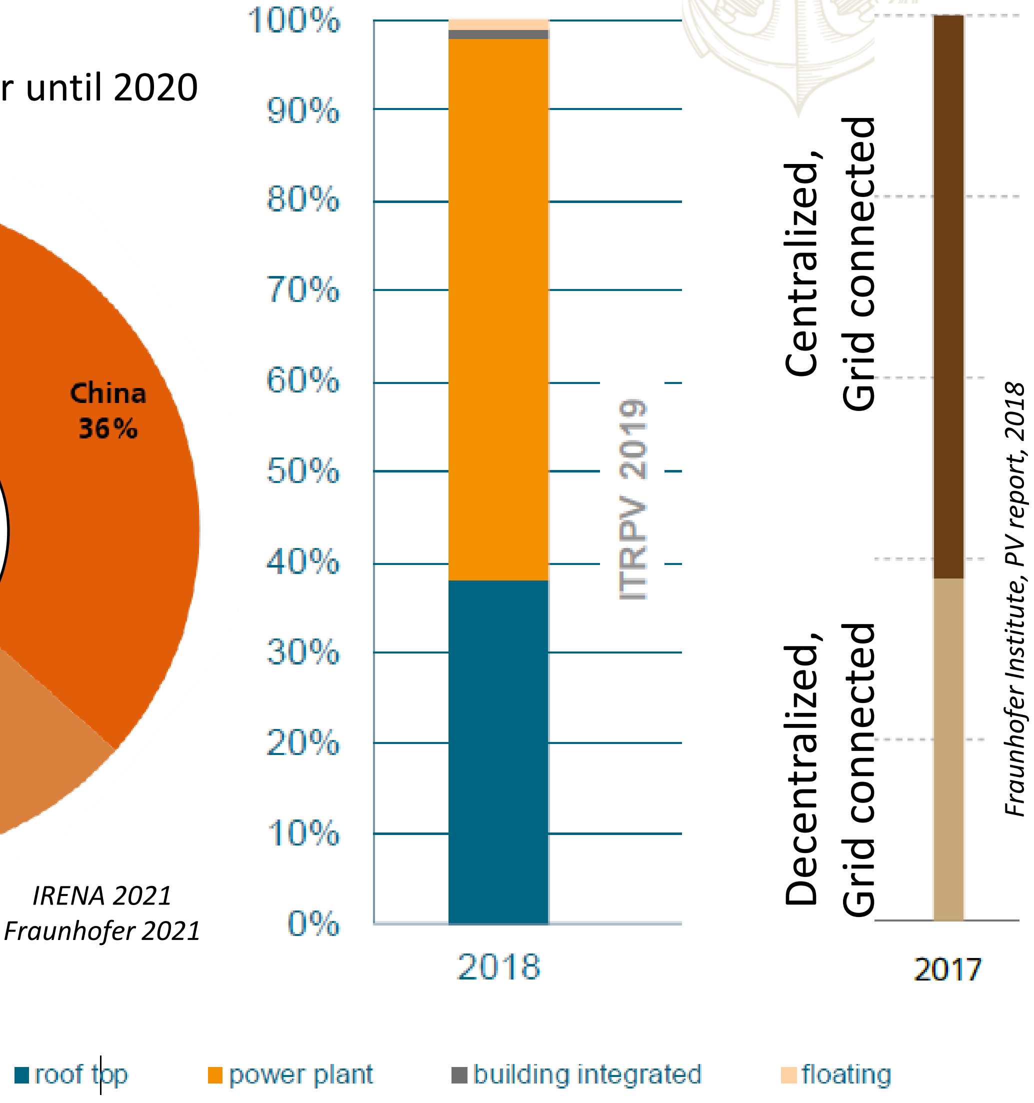


SOLARPOWER EUROPE 2021

Cumulative installed power until 2020

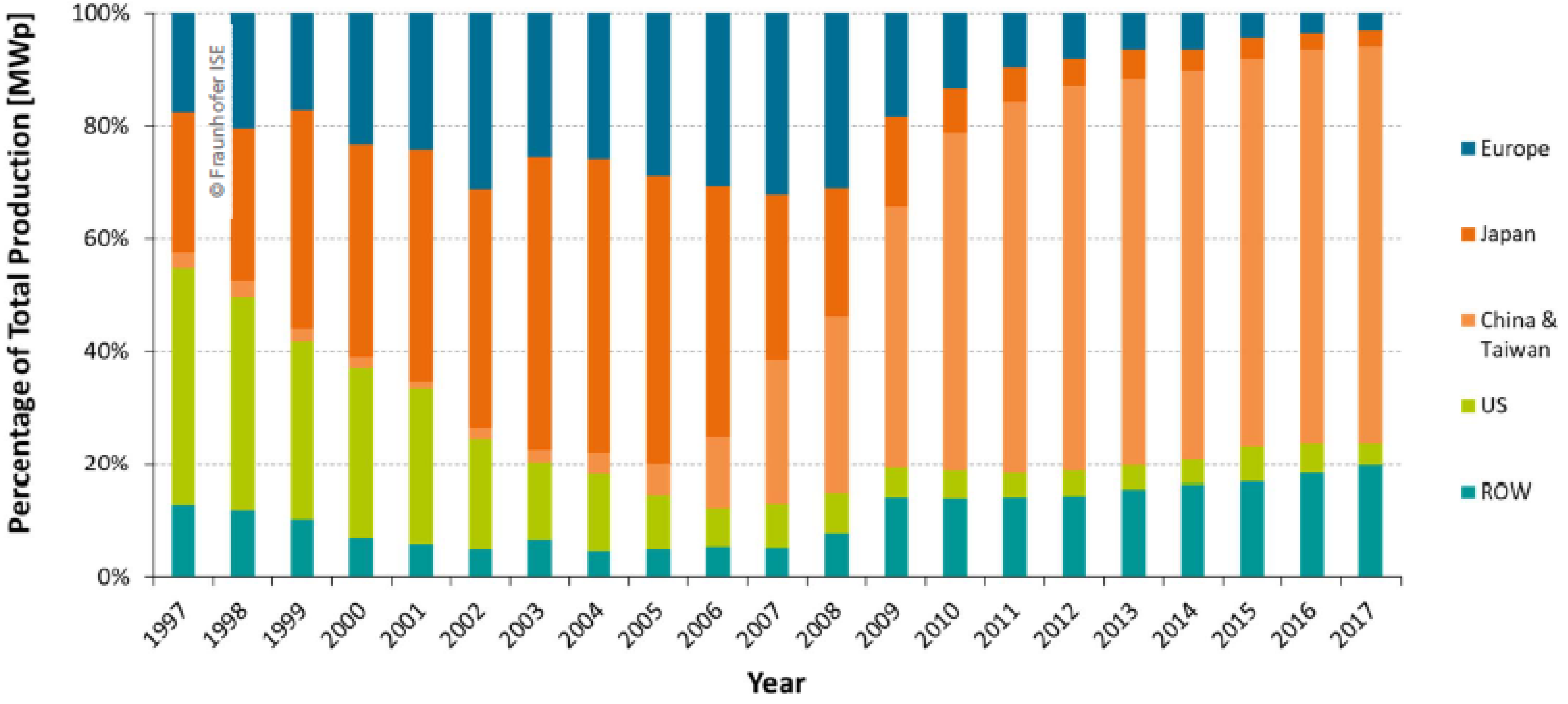


IRENA 2021
Fraunhofer 2021

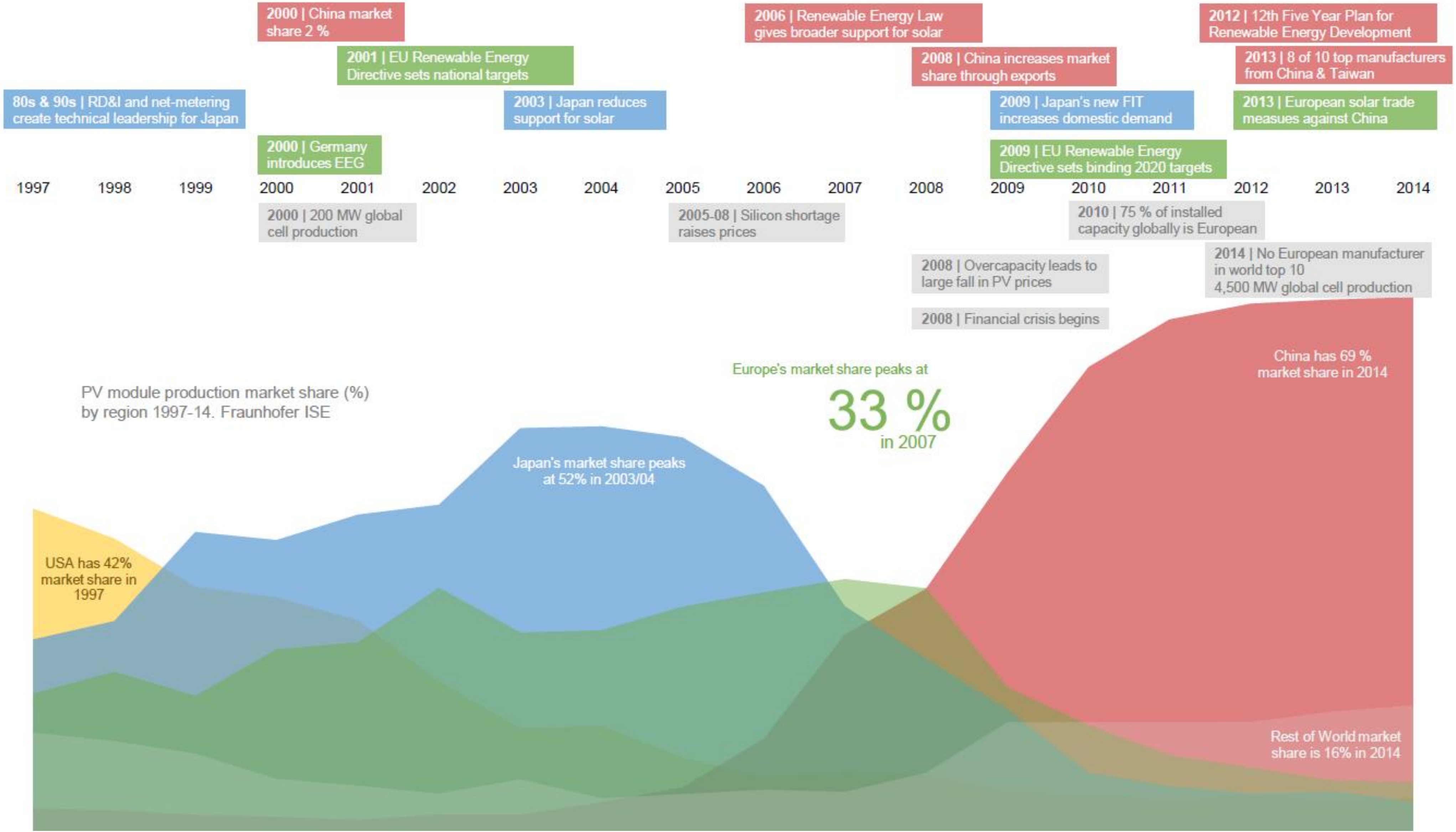


Fraunhofer Institute, PV report, 2018

Solar module production



Timeline of PV in Europe



Assessment of Photovoltaics European Commission (2017)

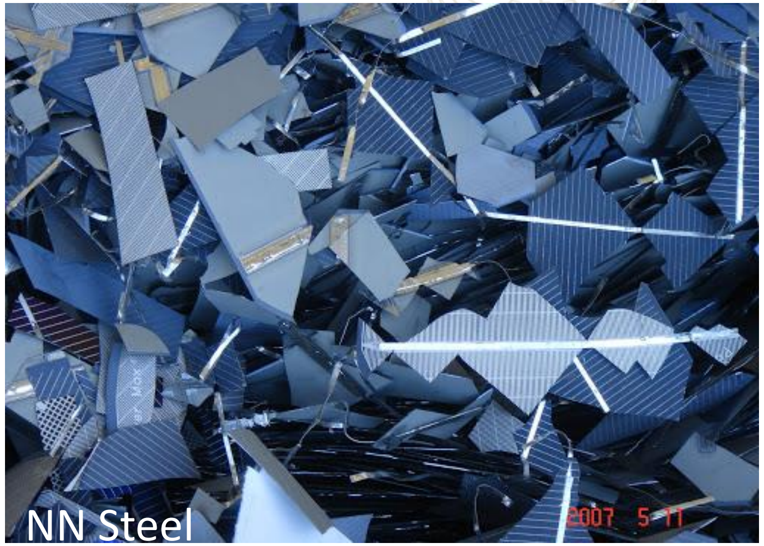
Industrial processes

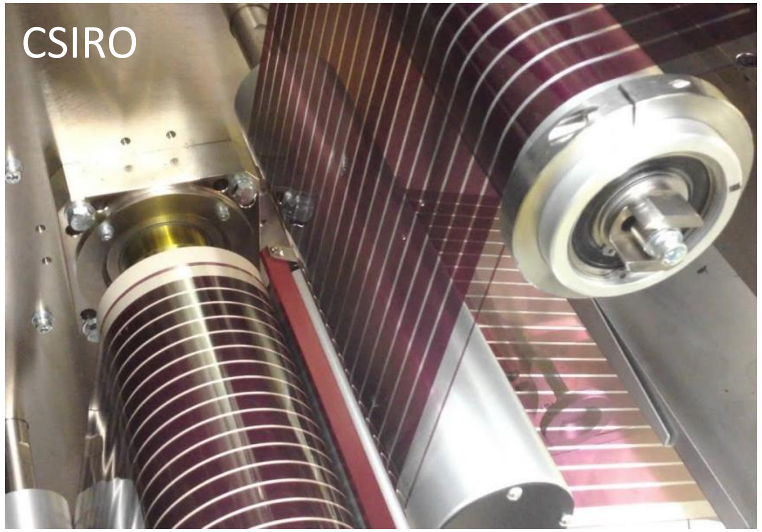
Scale up (european)
production capacities
(aiming at TW scale)

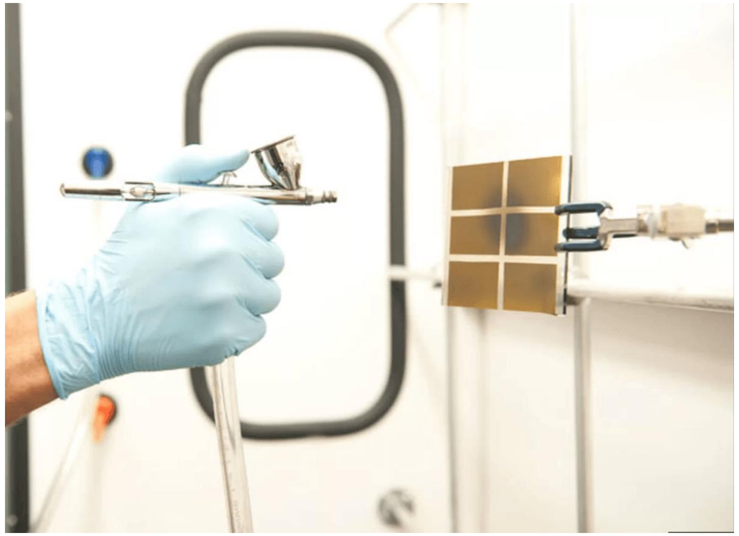
Paving technologies
→
Coating technologies ?

Consider end-of-life at
conception stages


Reuters


NN Steel

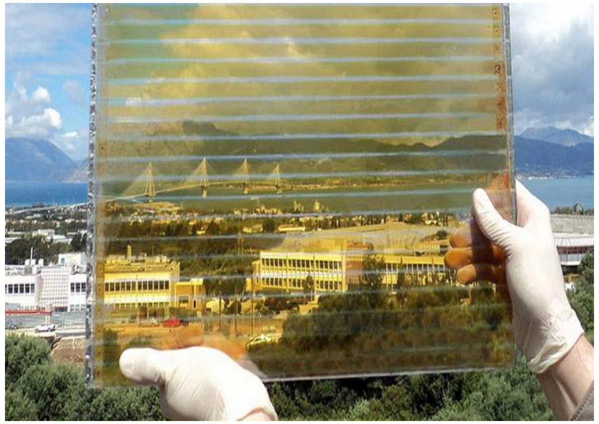

CSIRO

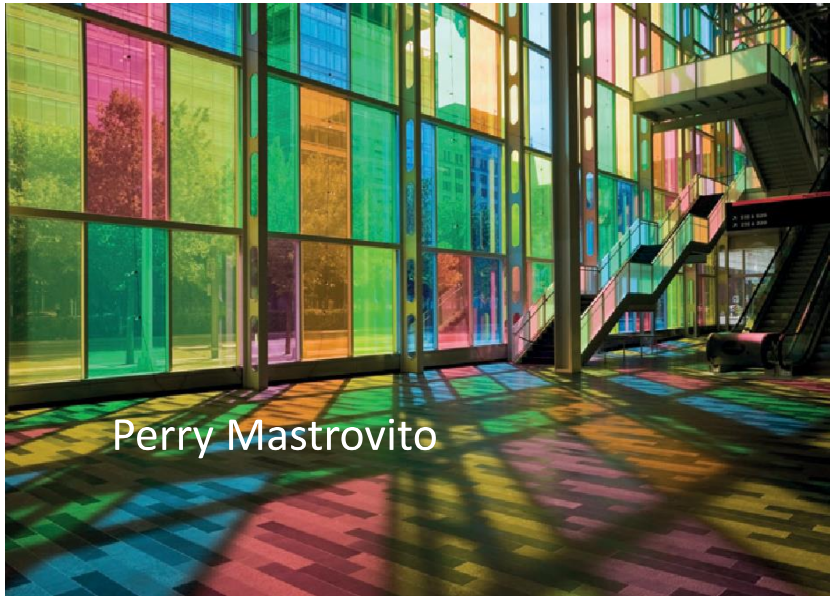


Broader applications

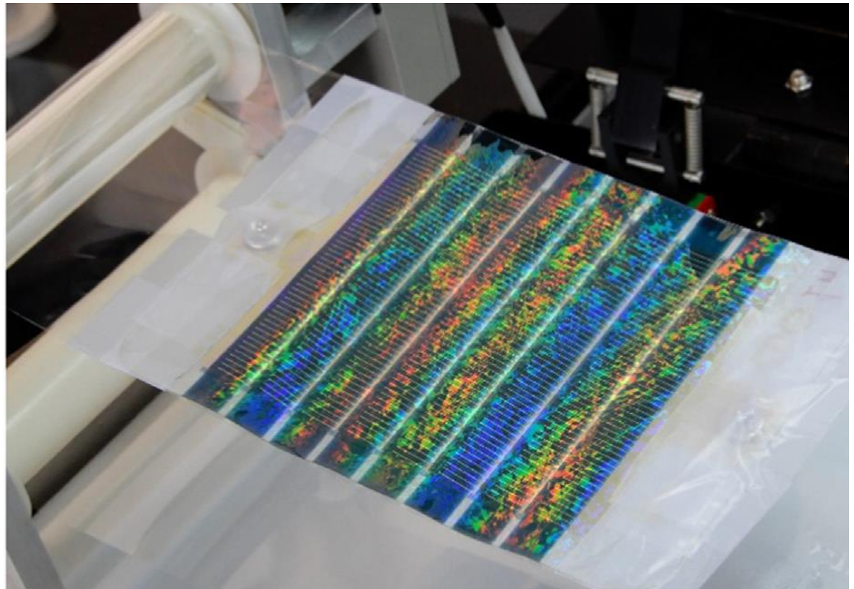
Mechanical properties

Optical properties





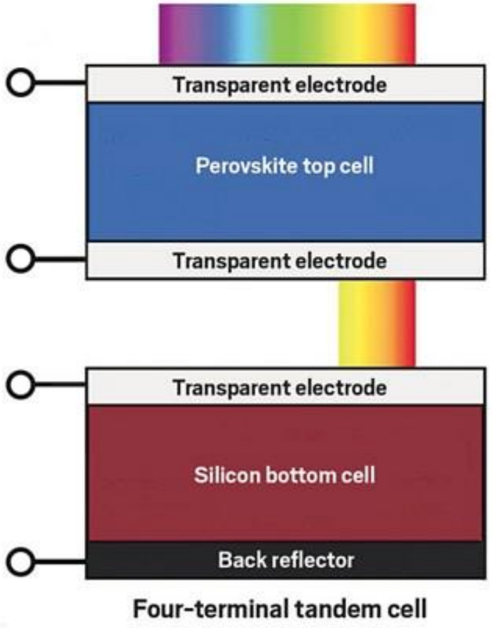
Perry Mastrovito



The quest for high efficiencies

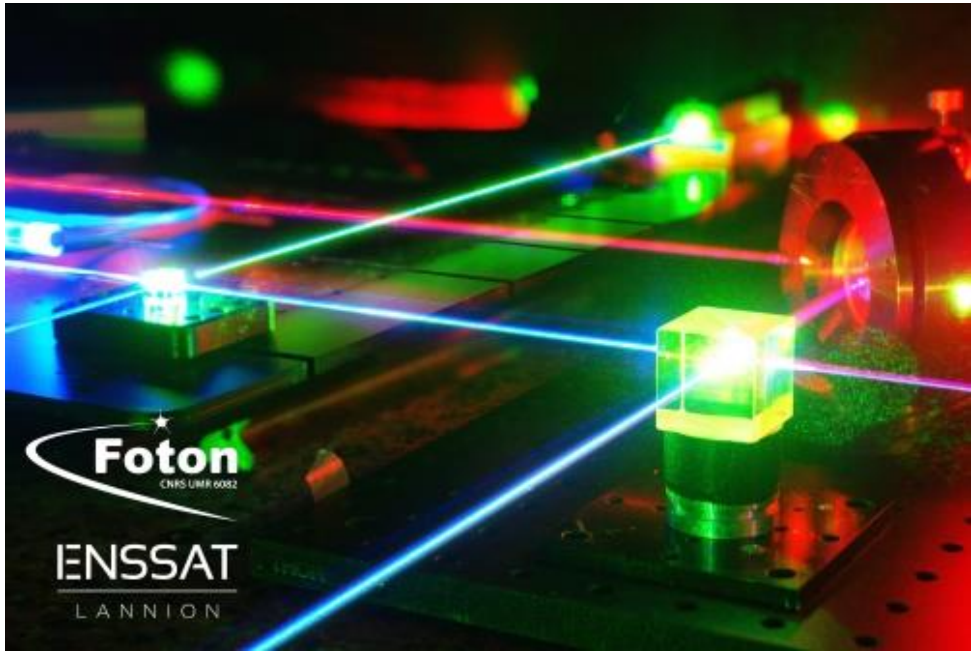
How to overcome the 30% Shockley-Queisser limit
and aim at much higher efficiencies?

Architecture

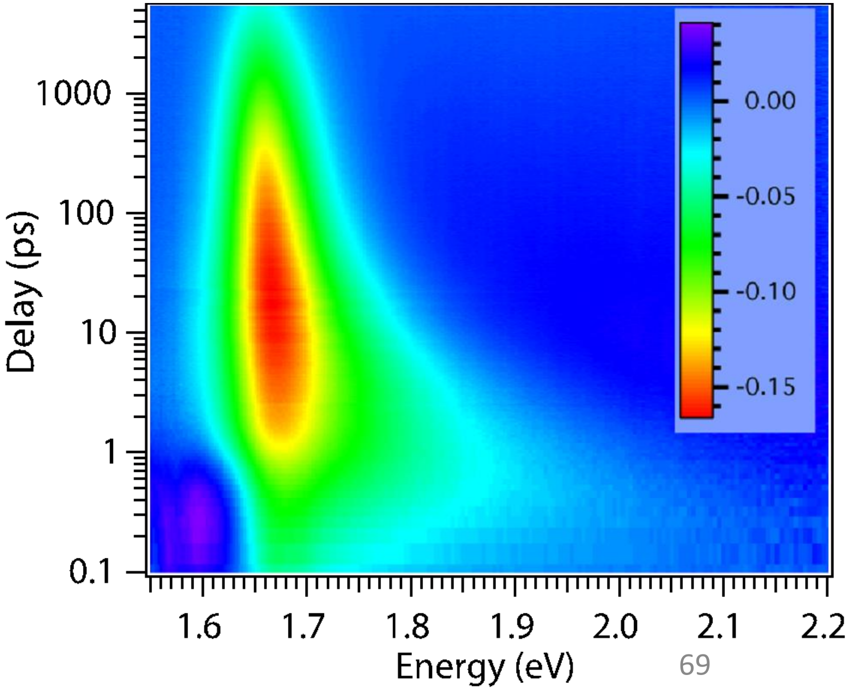


Wernet et al., Adv. Mat. (2018)

Light



Carriers

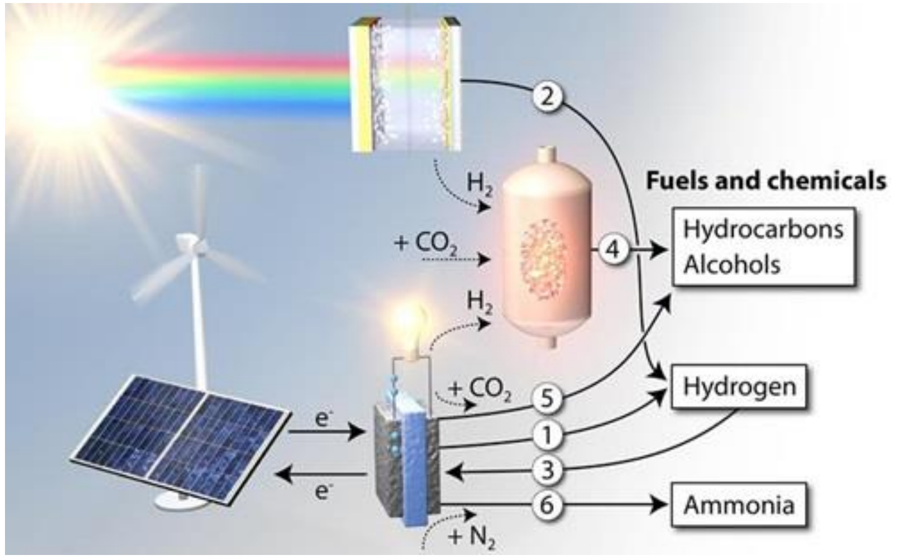


Yang et al., Nat. Photonics. (2016)

Grid integration

Multi-vectors

Solar
↓
Chemical (H_2 …)

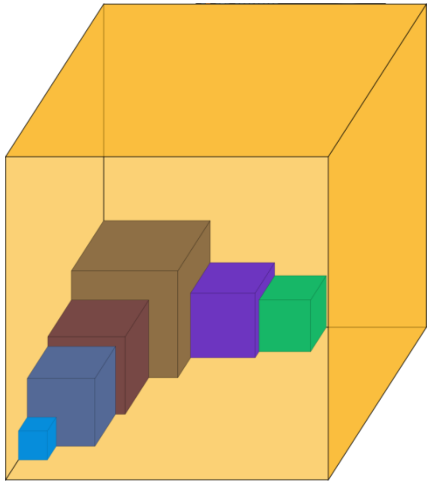


Solar
↓
Thermal

Match supply and consumption

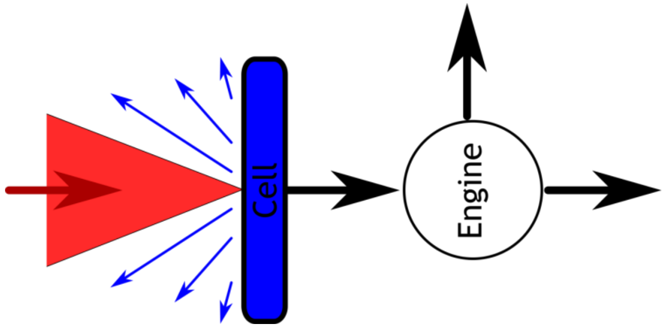
Take home message

Orders of magnitude

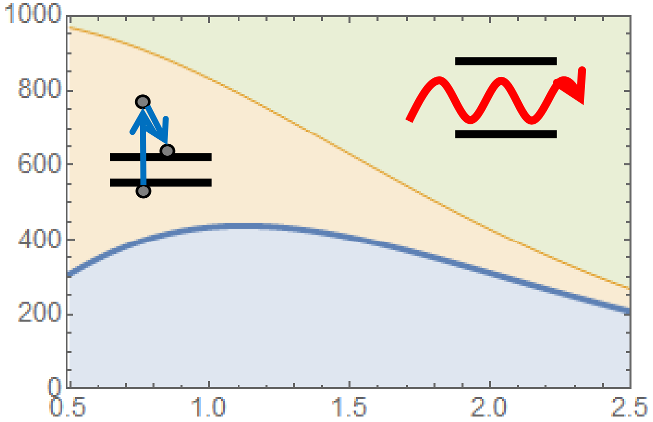


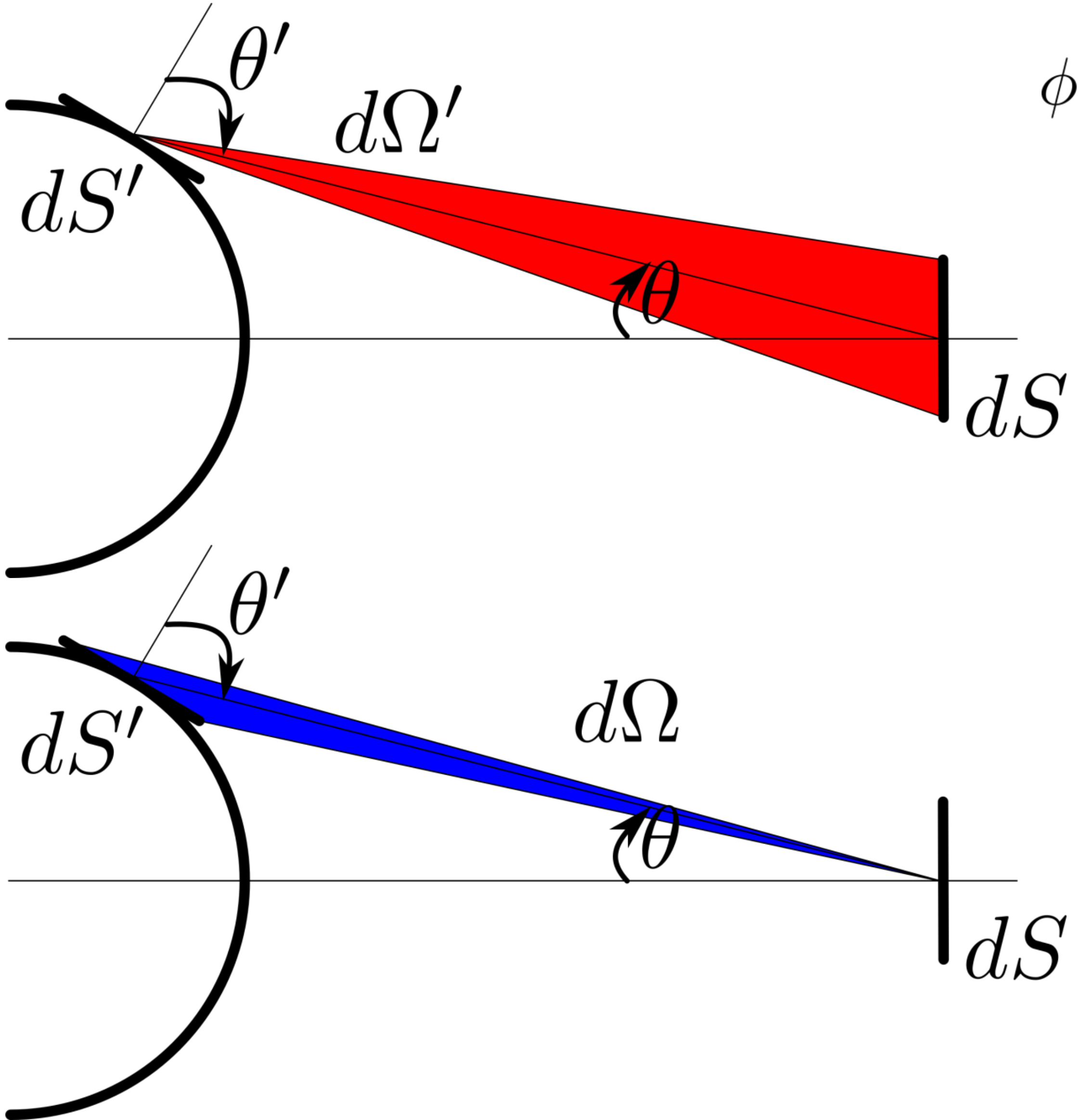
Different ways to convert solar energy

Thermodynamics with radiative heat exchange



Basic solar cell physics





$$\phi_E(\Omega) = \int dE \phi_E(E,\, \Omega) = \frac{\cos\theta}{\pi}\sigma T^4$$

$$\begin{aligned} dI &= \frac{\cos\theta'}{\pi}\sigma T_{\rm sun}^4 dS' d\Omega' \\ &= \frac{\cos\theta'}{\pi}\sigma T_{\rm sun}^4 dS' \frac{dS\cos\theta}{D^2} \\ &= \frac{\cos\theta}{\pi}\sigma T_{\rm sun}^4 dS \frac{dS'\cos\theta'}{D^2} \\ &= \frac{\cos\theta}{\pi}\sigma T_{\rm sun}^4 dS d\Omega \end{aligned}$$

$$\begin{aligned} I &= \frac{1}{\pi}\int \cos\theta d\Omega \times \sigma T^4 \\ &= \sin^2\theta_{\rm sun} \times \sigma T^4 \end{aligned}$$