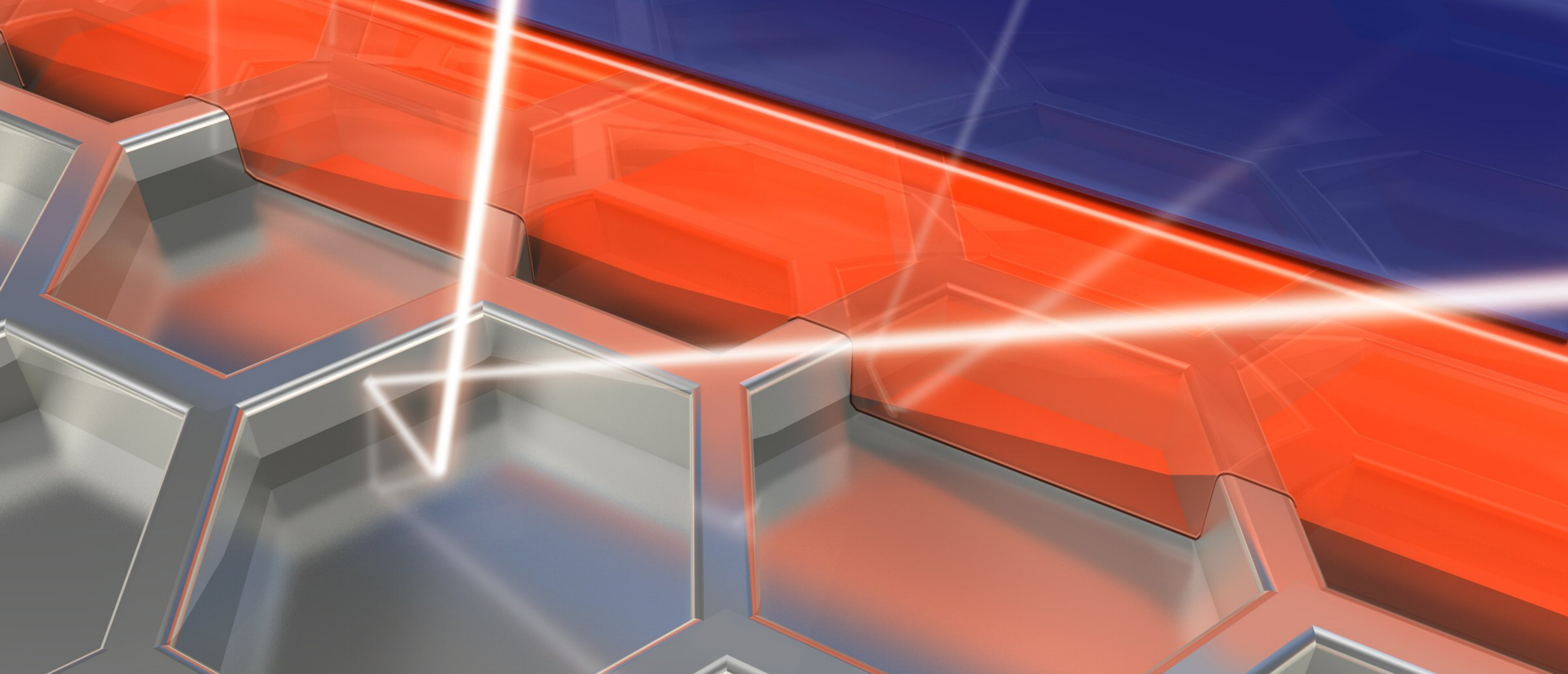
FOM Institute AMOLF

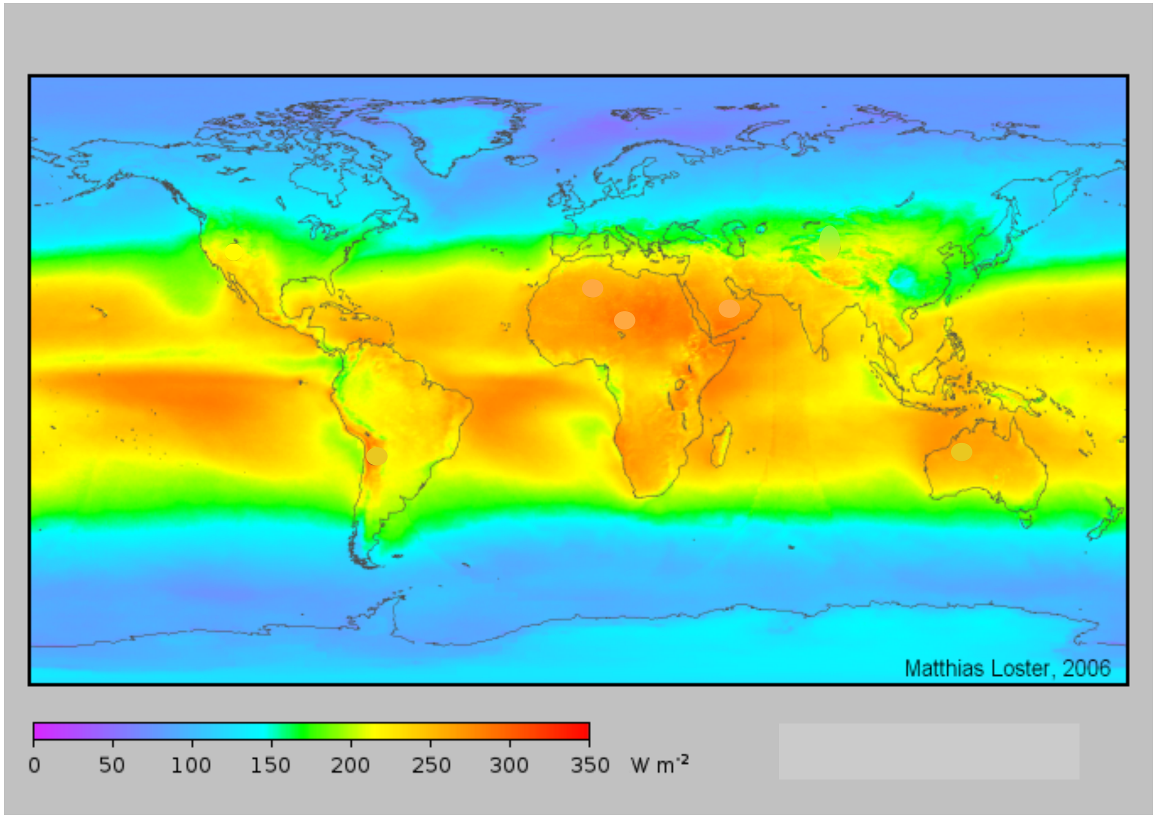
Photovoltaic solar energy conversion

Albert Polman

FOM Institute AMOLF



Solar irradiance on earth



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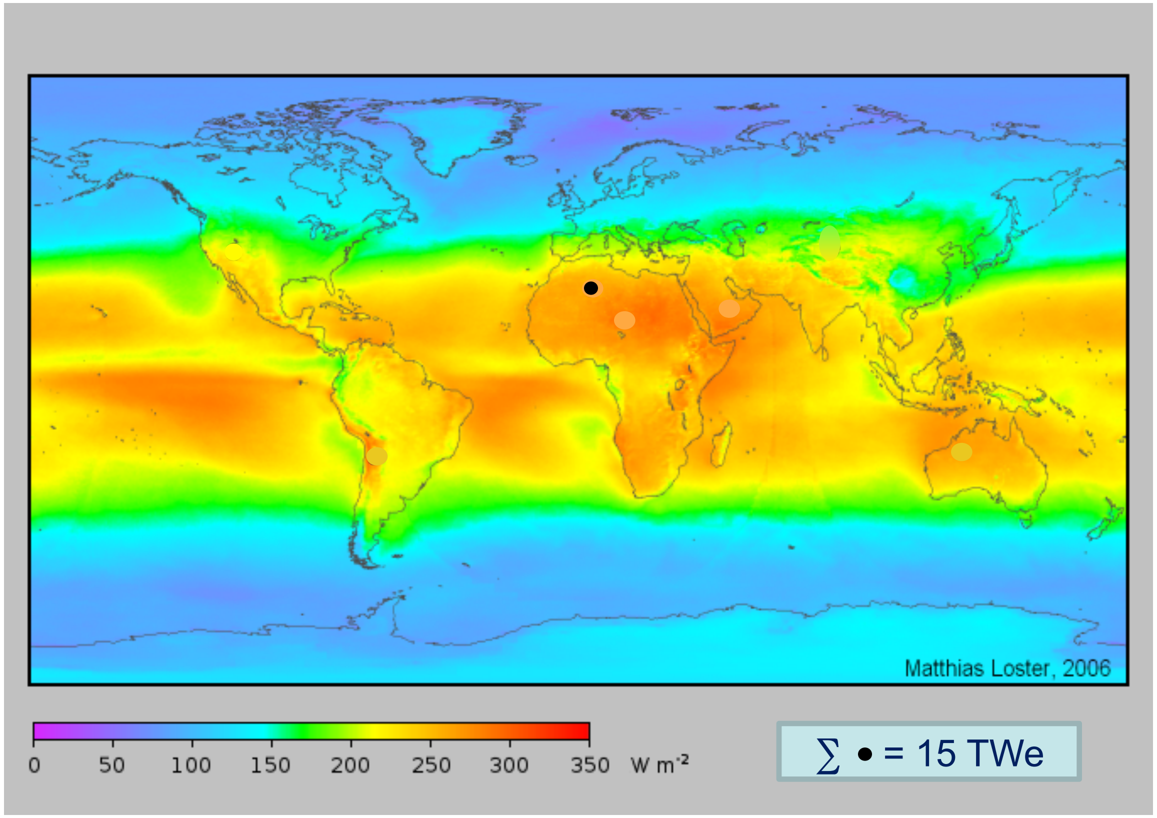
Solar irradiance on earth



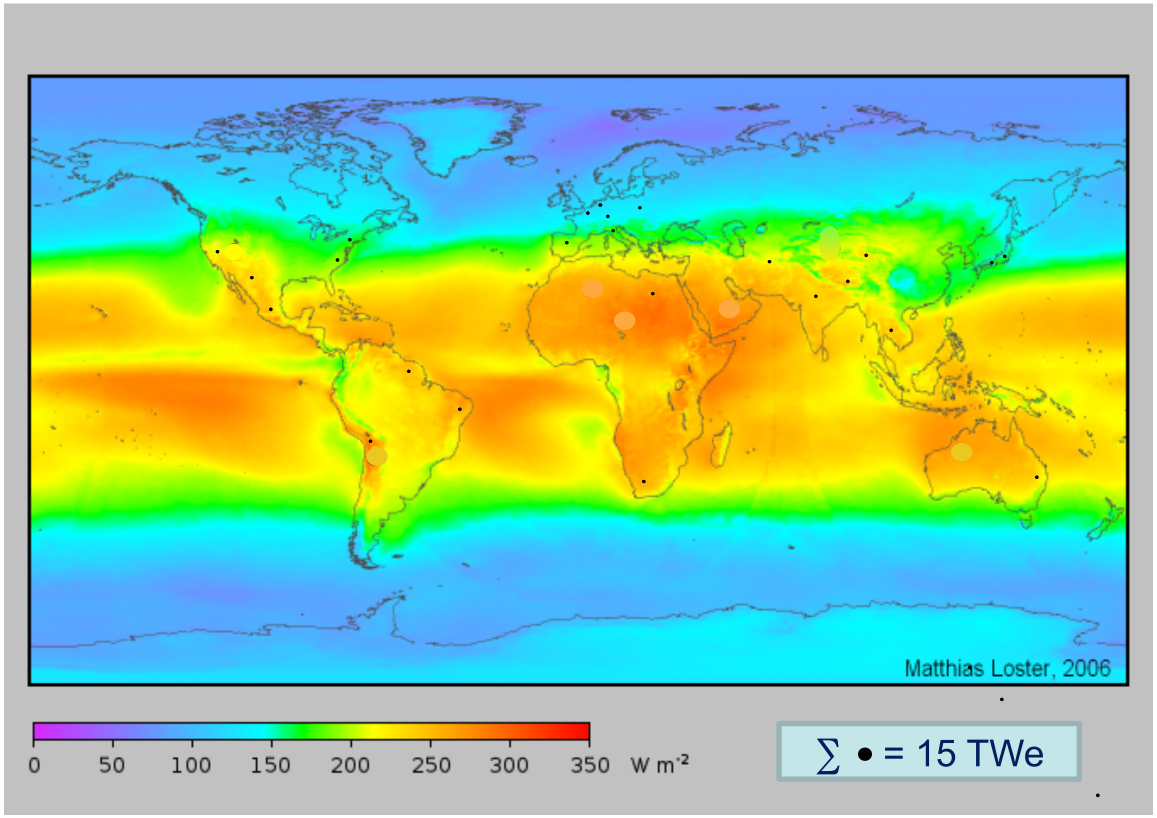
assuming 30 %
efficient solar panels

Black dot:

area of solar panels needed to generate all of the worlds primary energy

(all energy consumed: electricity, heat, fossil fuels)

Solar irradiance on earth



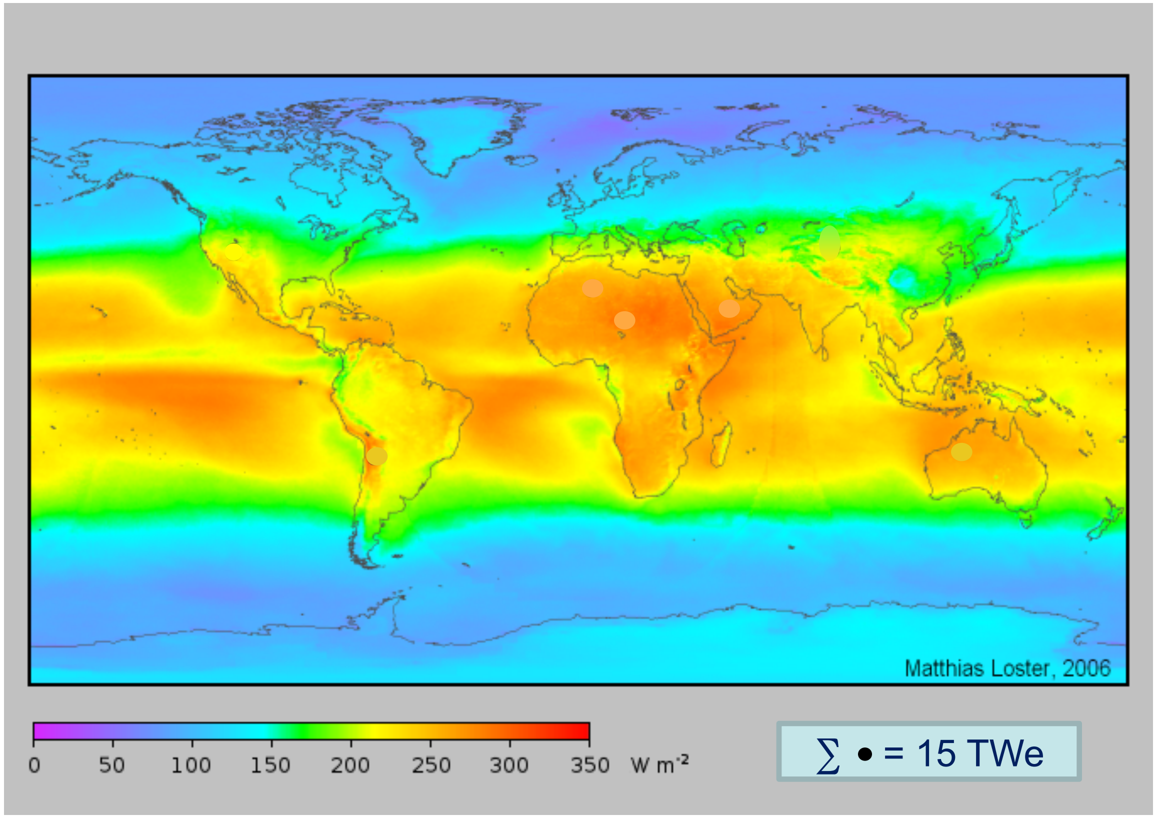
assuming 30 %
efficient solar panels

20 black dots:

area of solar panels needed to generate all of the worlds primary energy

(all energy consumed: electricity, heat, fossil fuels)

Solar irradiance on earth



assuming 30 %
efficient solar panels

1000 black dots:

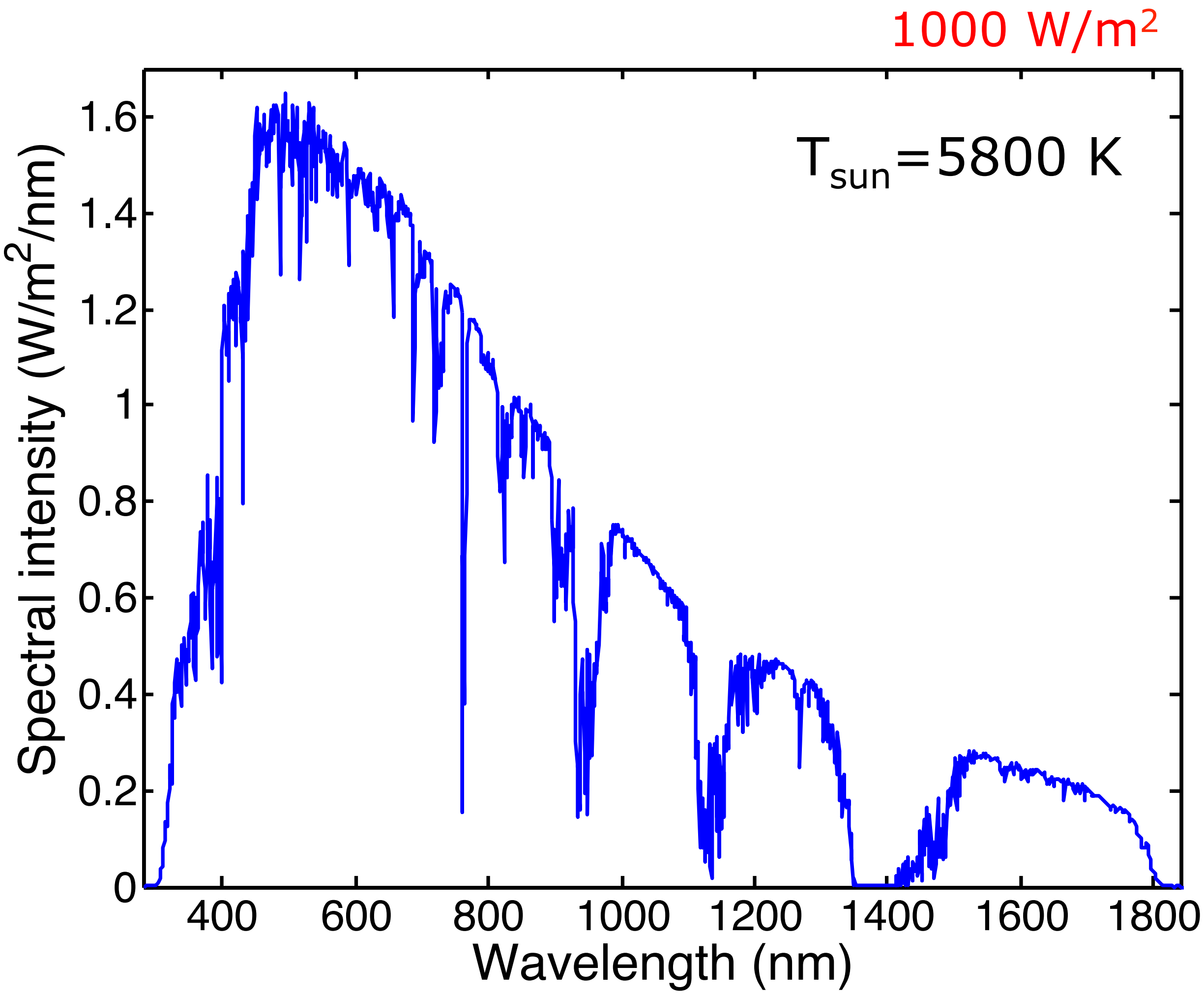
area of solar panels needed to generate all of the worlds primary energy

(all energy consumed: electricity, heat, fossil fuels)

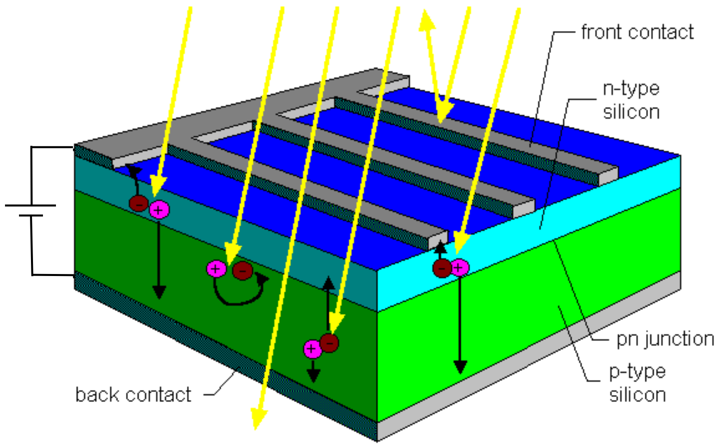
Needed:
1) Lower costs
2) Higher efficiency

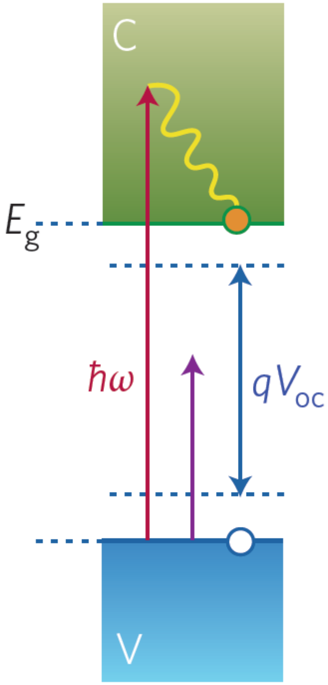

Earth

The solar spectrum

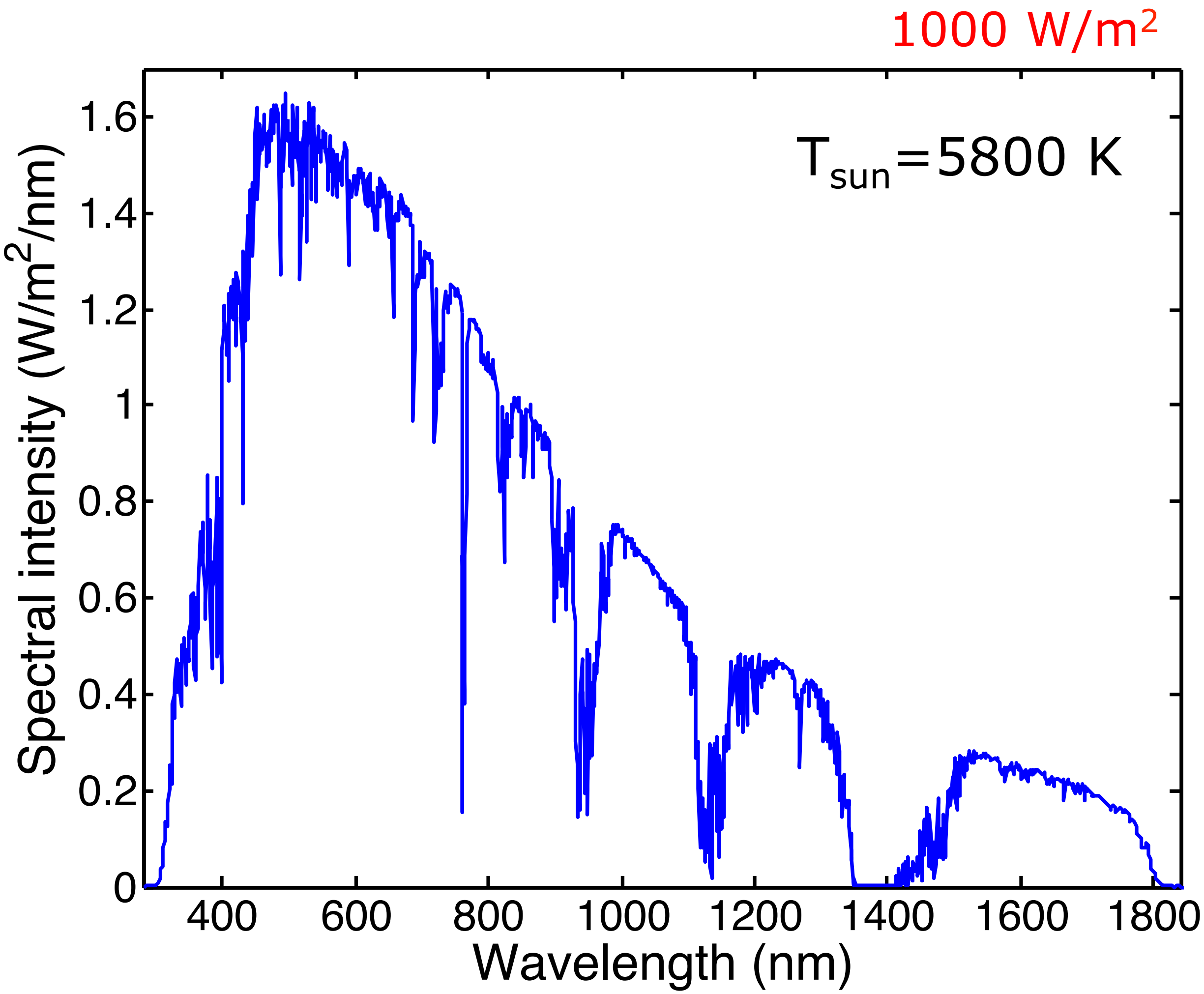


Solar cell basic design

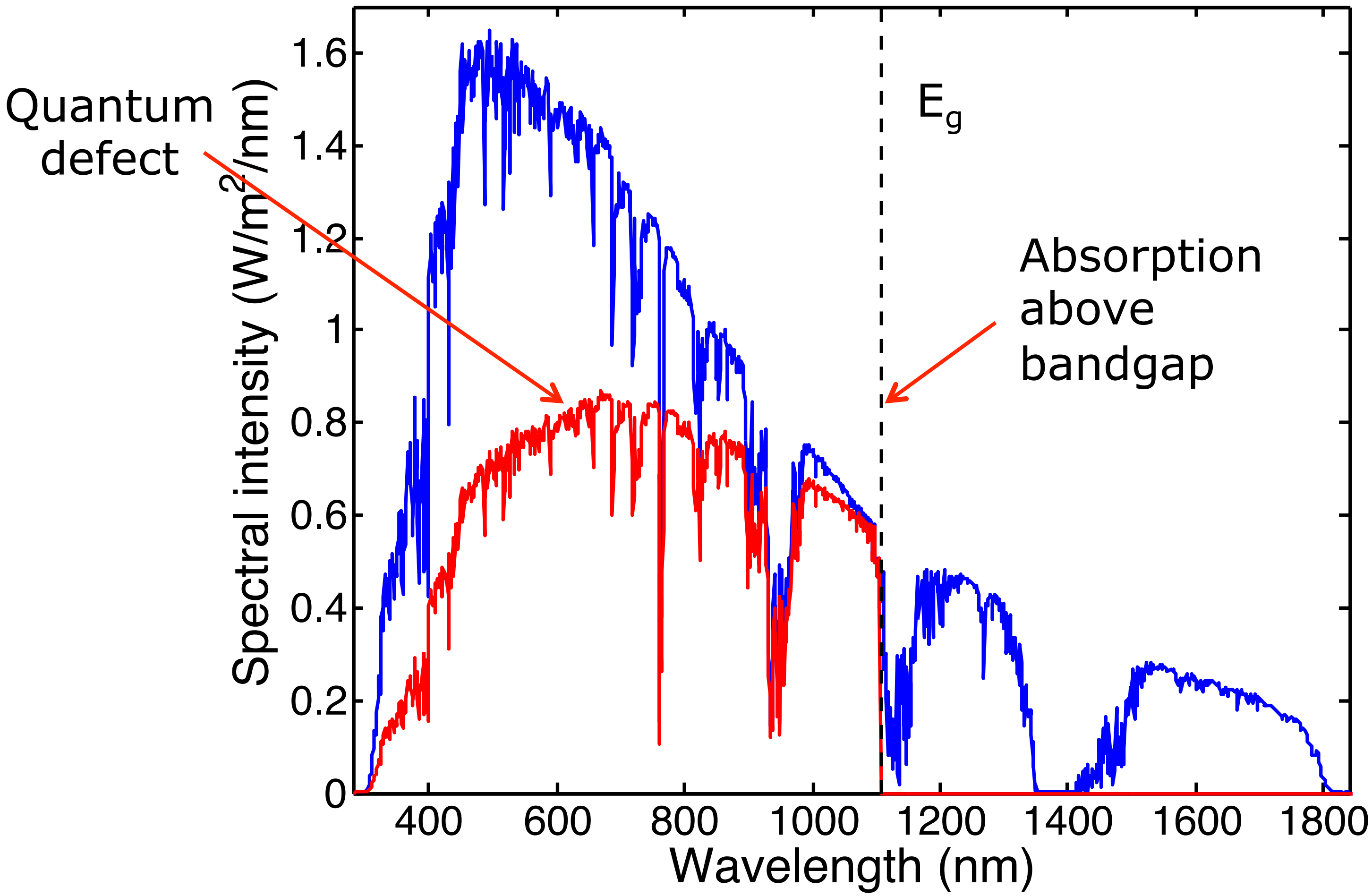




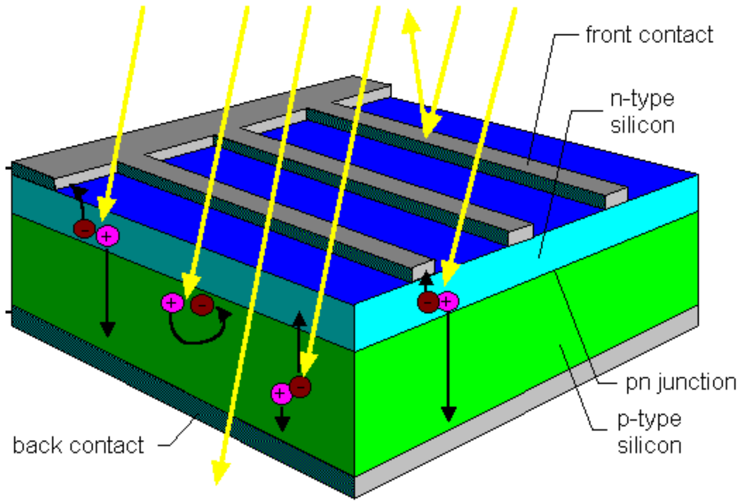
The solar spectrum

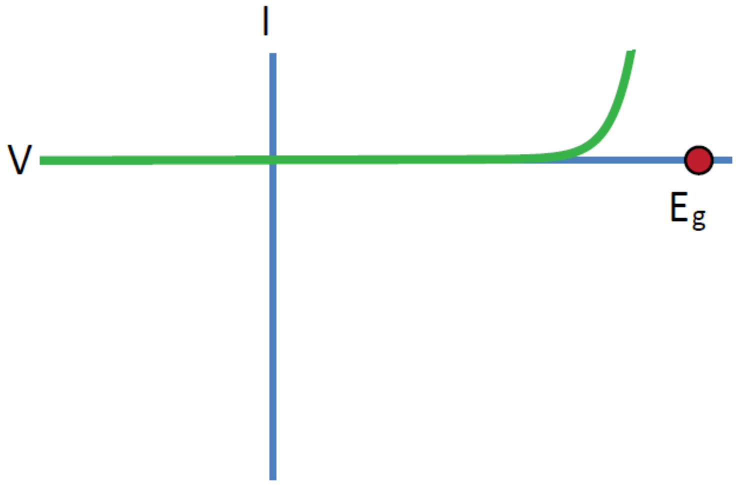


Absorption edge and quantum defect



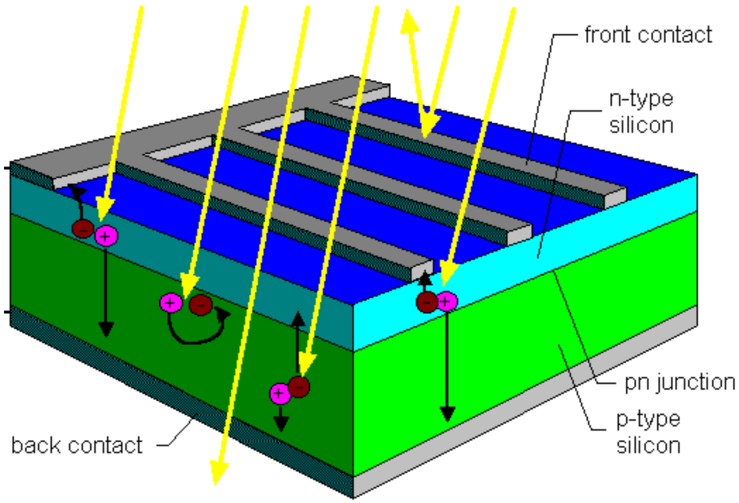
Voltage is lower than bandgap energy

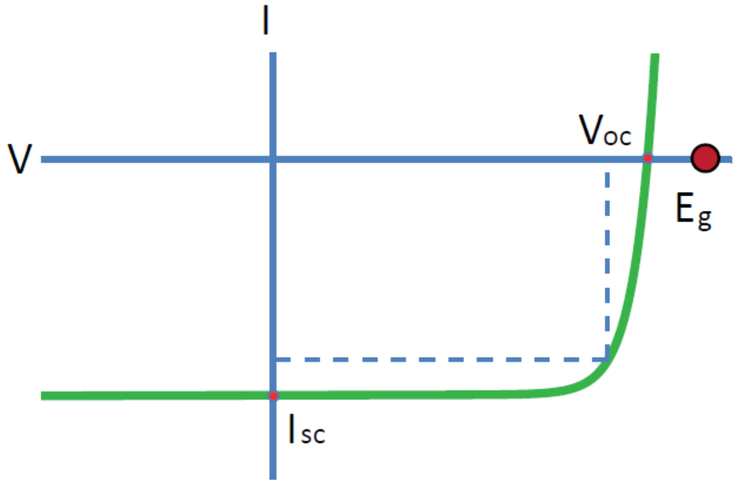




$$I_{ext} = I_0 \exp(V/kT)$$

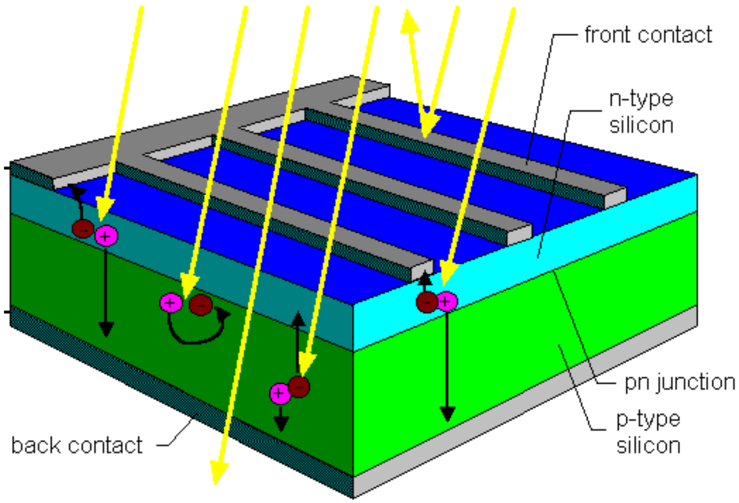
Voltage is lower than bandgap energy

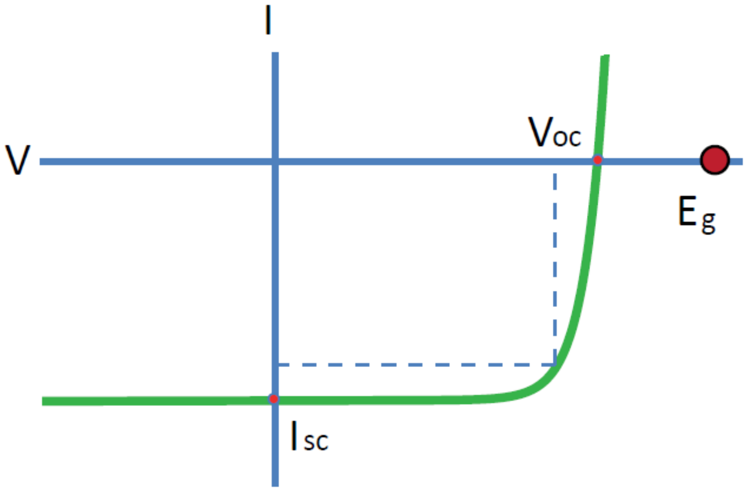




$$I_{ext} = I_0 \exp(V/kT) - I_{SC}$$

Voltage is lower than bandgap energy





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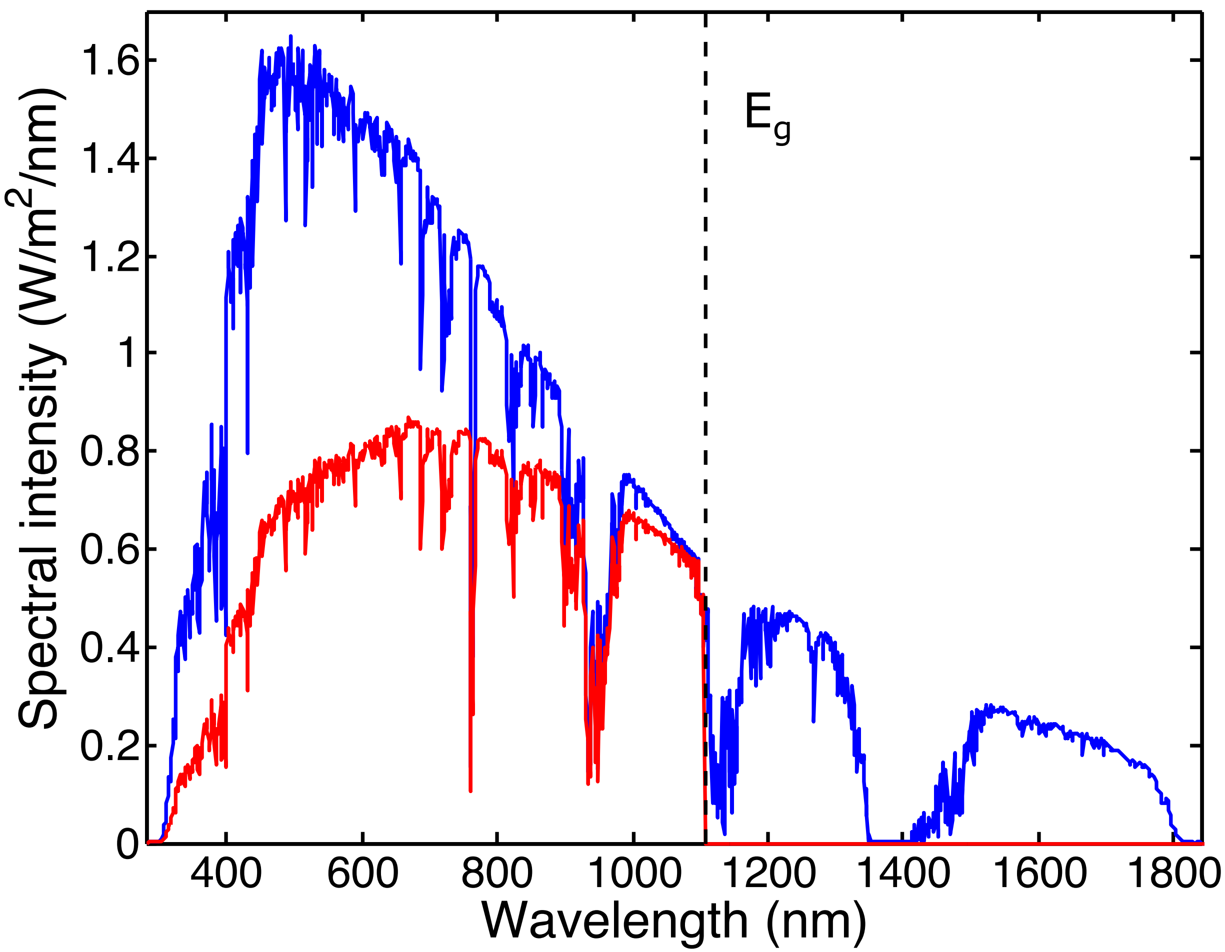
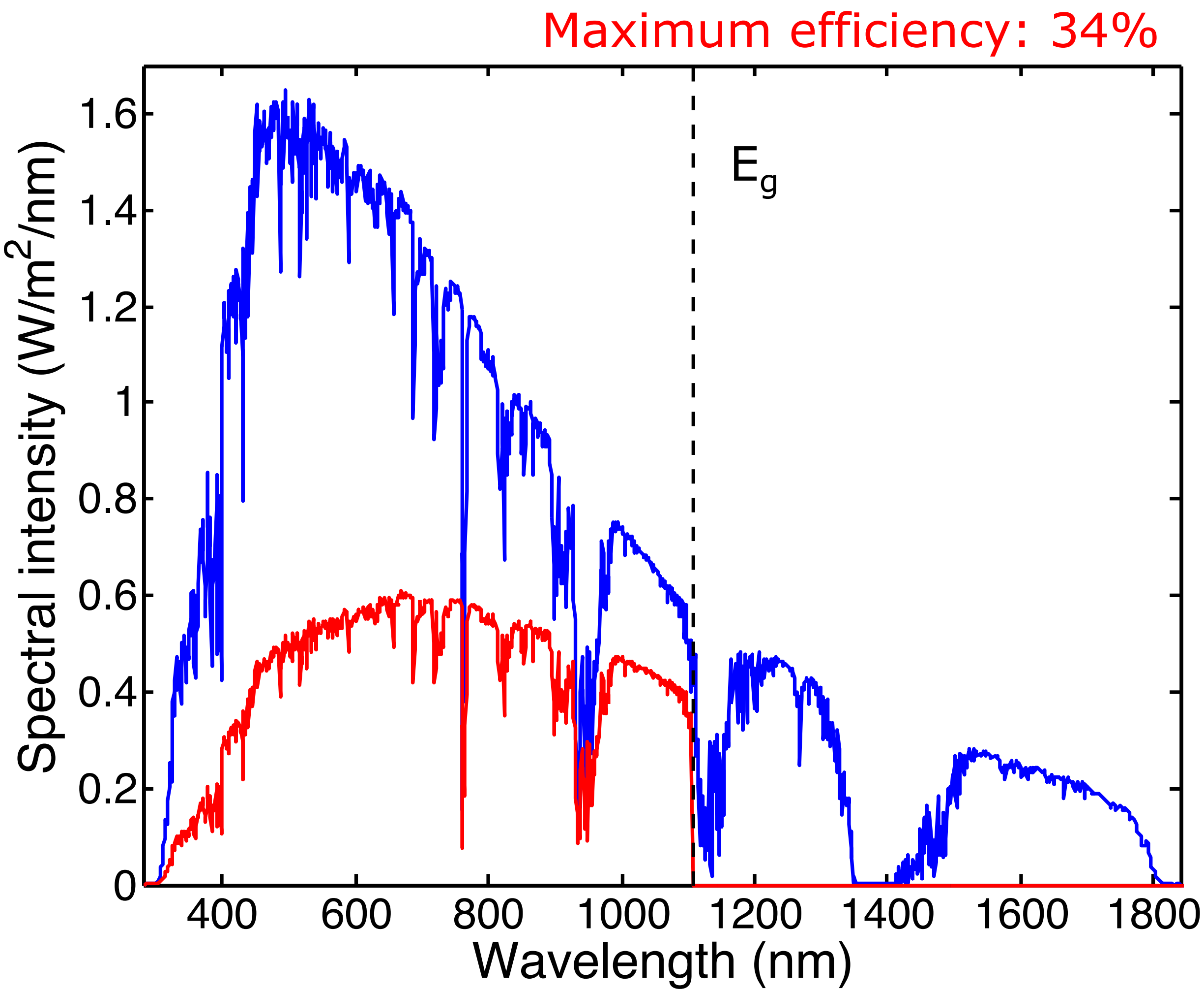
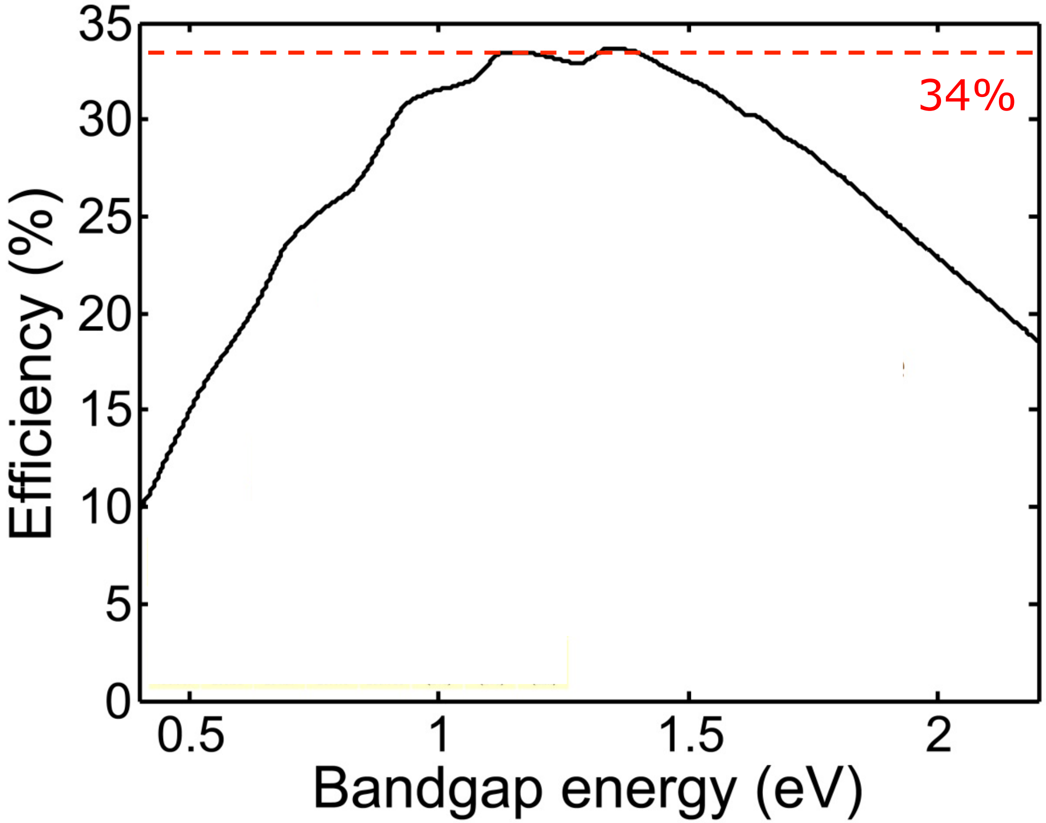


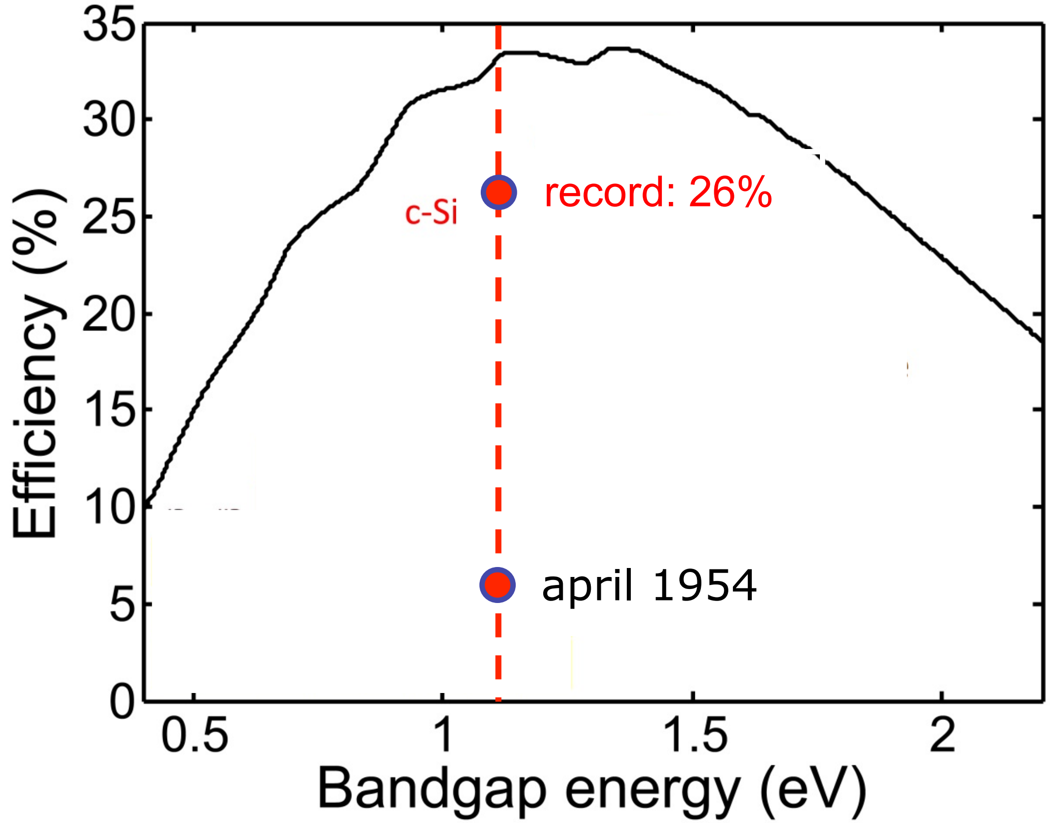
Voltage is lower than bandgap energy



Shockley-Queisser efficiency limit: 34%



Silicon is ideal: SQ limit = 33 %



The silicon solar cell turned 60 !

April 25, 1954

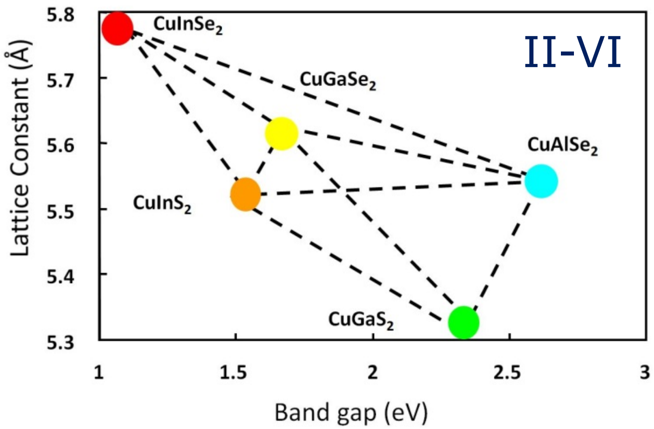
New York Times: *the beginning of a new era, leading eventually to the realization of one of mankind's most cherished dreams – the harnessing of the almost limitless energy of the sun for the uses of civilization*

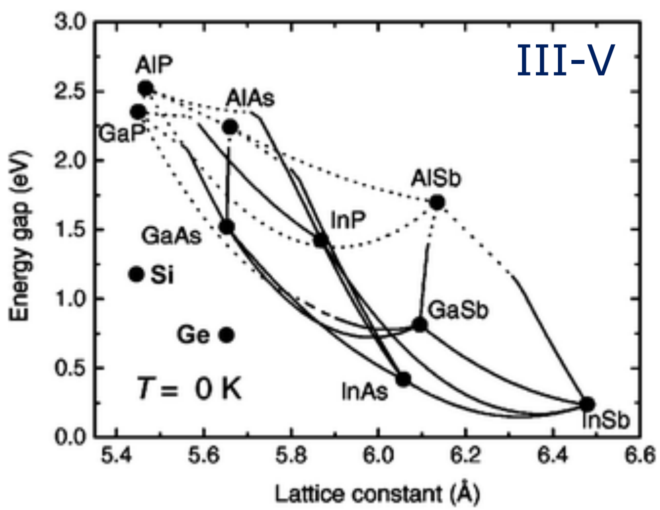
The first practical solar cell
Si: 6 % efficiency

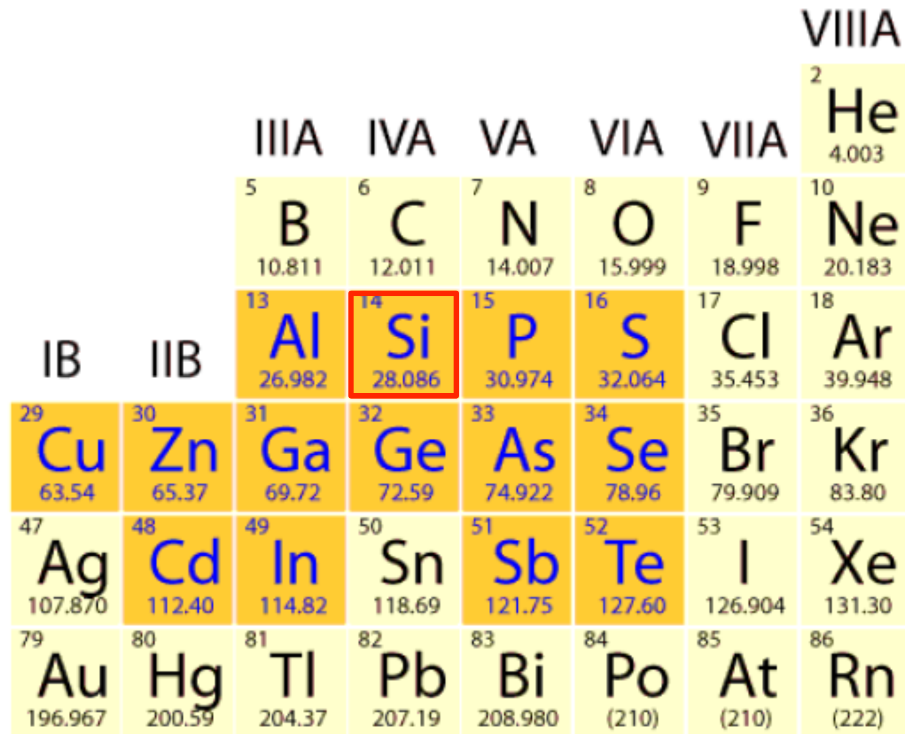
Vanguard satellite 1958

2014

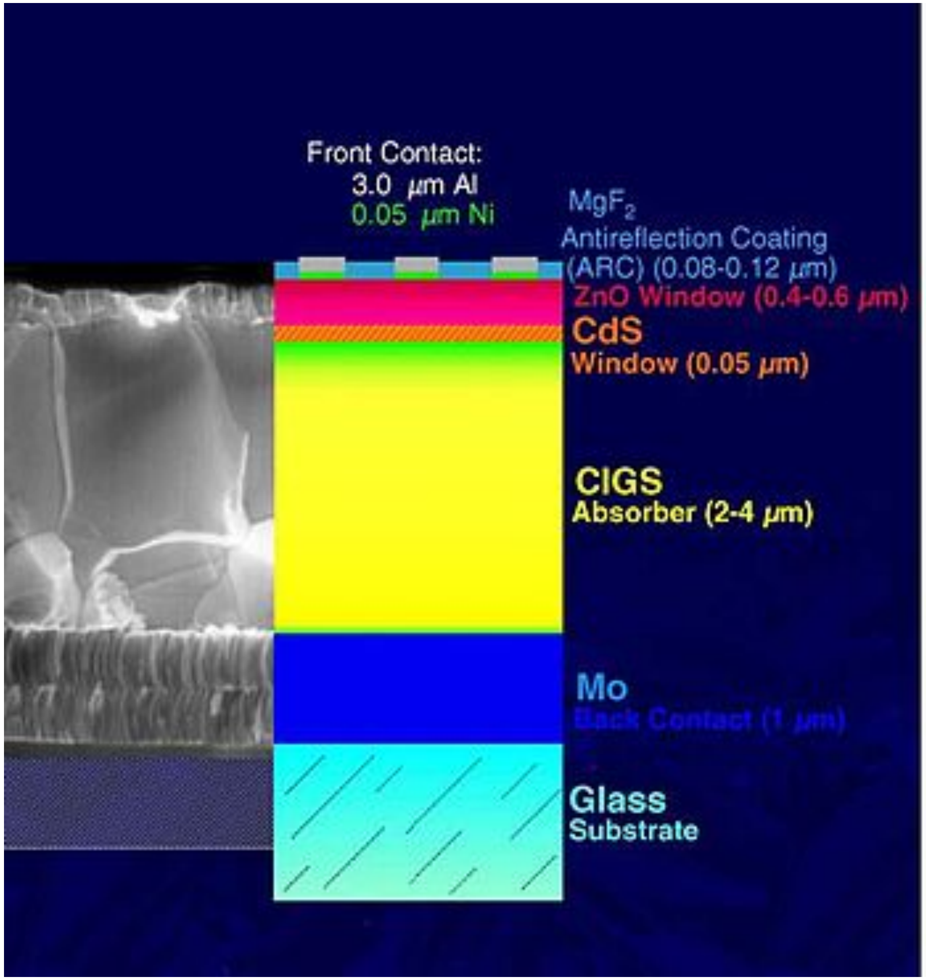
Periodic Table of solar elements

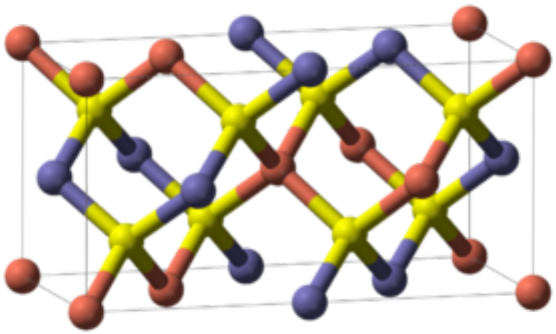




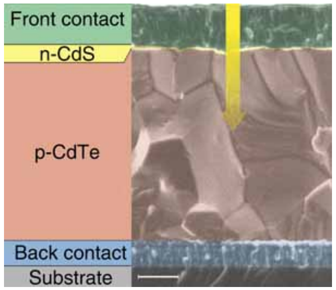


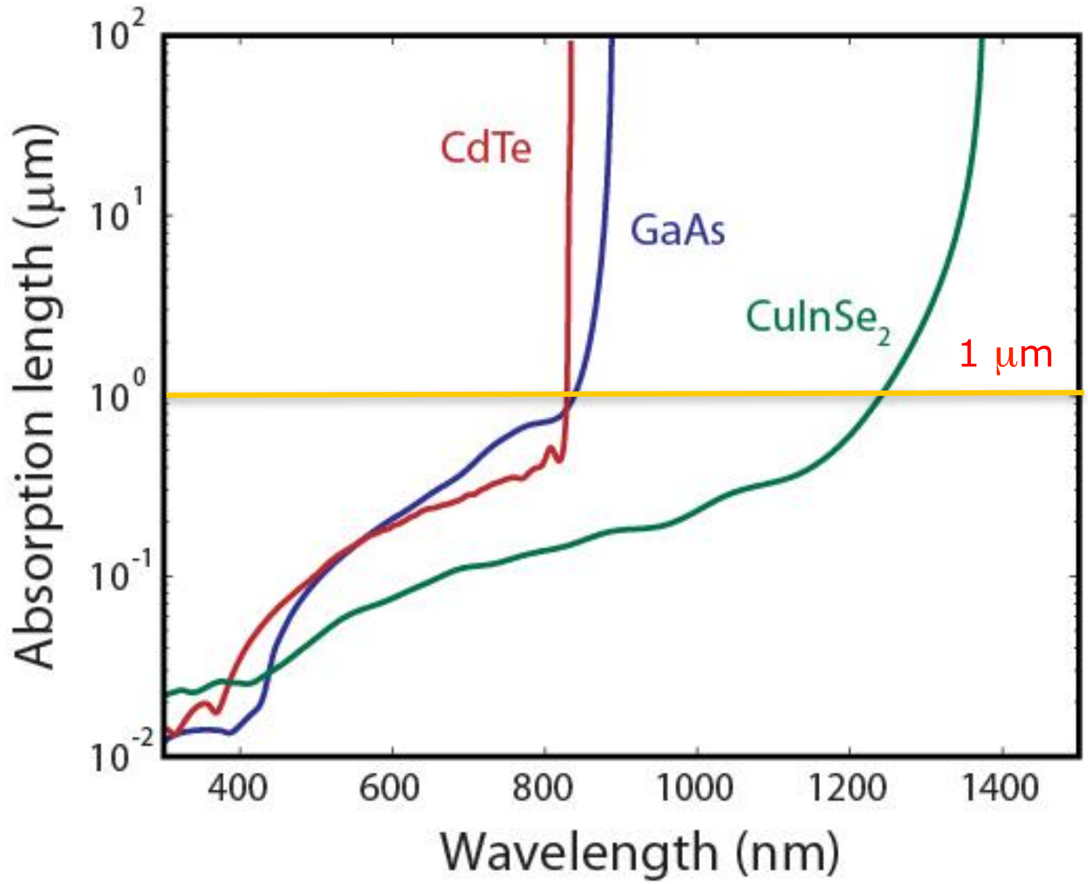
$CuIn_xGa_{(1-x)}Se_2$ (CIGS) cells: 20.8%

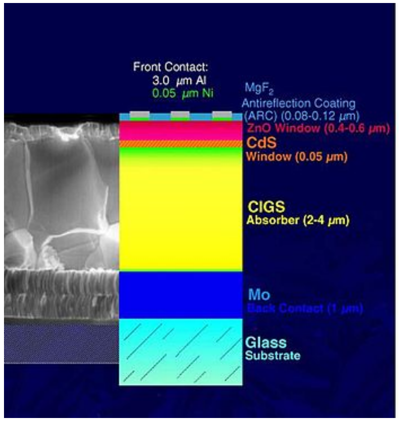




Absorption length in compound semiconductors

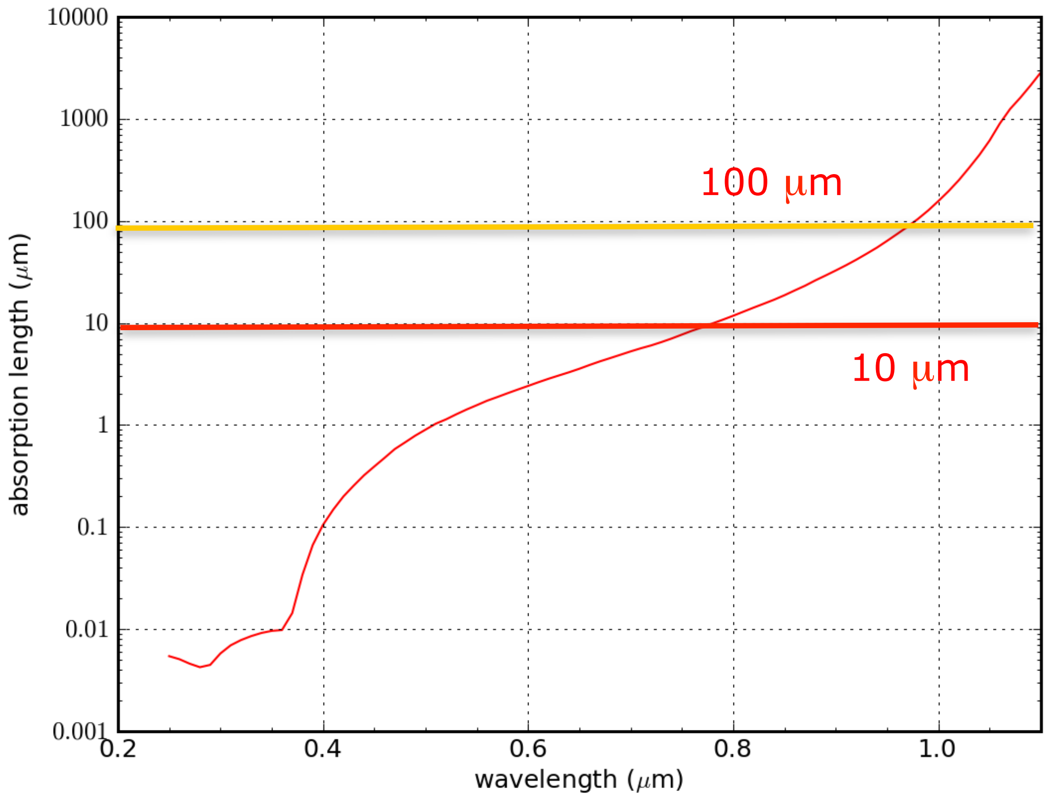


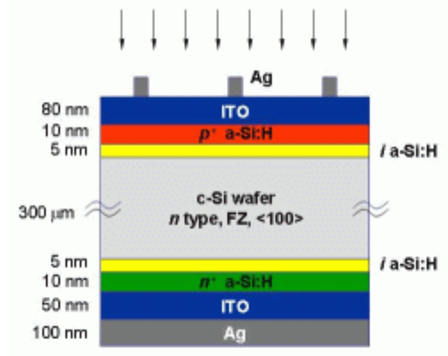


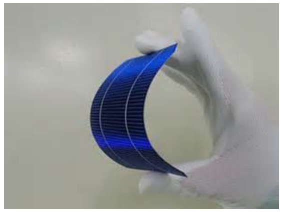


Kranz *et al*., Nature Comm. 4, 2306 (2013)
wikipedia.org

Absorption length in silicon







physics.ucsd.edu
japantechniche.com, pvlab.epfl.edu

Si solar cell efficiencies

expensive

cheap

Material	Thickness	Efficiency	Source
Monocrystalline Si	260 μm	25.6 %	Panasonic (Jap)
Polycrystalline Si	99 μm	20.4 %	FhG-ISI (Ger)
Nanocrystalline Si	2 μm	10.1 %	Kaneka (Jap)
Amorphous Si	300 nm	10.1 %	Oerlikon (Swi)

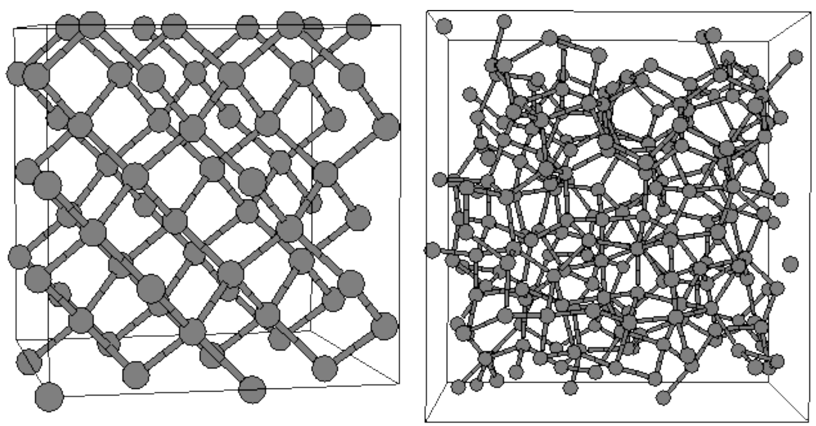
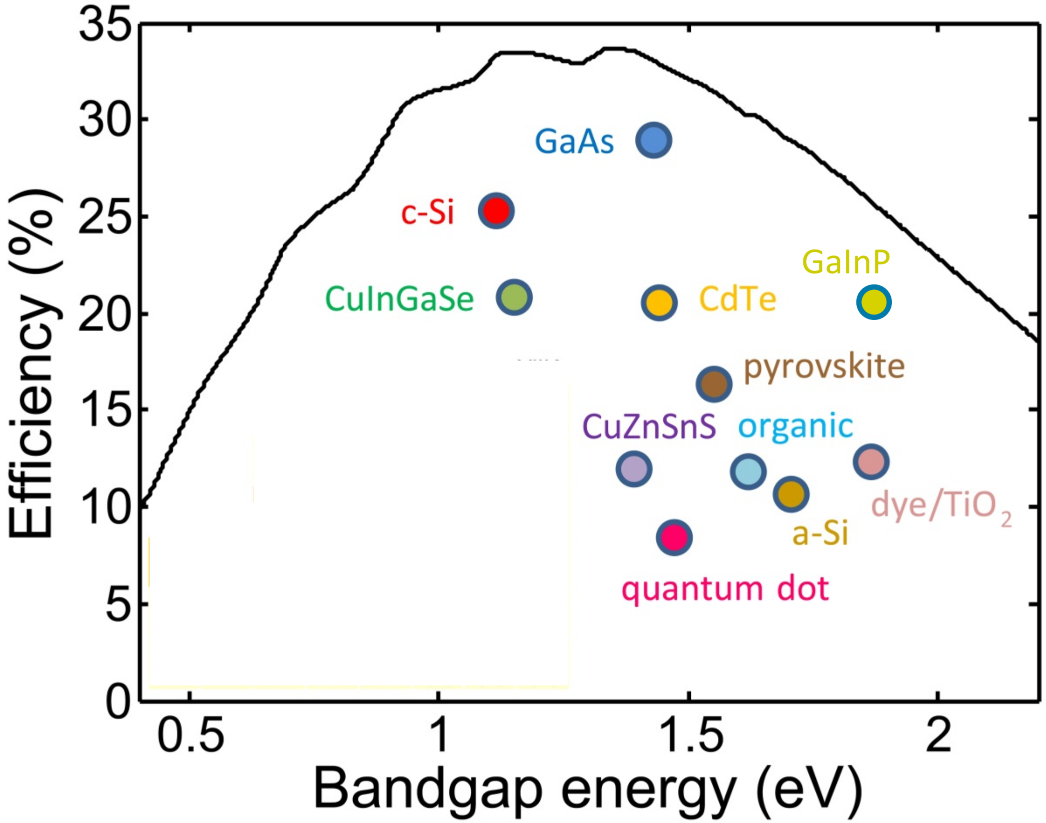


Figure 1.1: **Crystalline Si and CRN amorphous Si models. Left: 64 atom model of crystalline silicon; right: 216 atom CRN model of amorphous silicon.**

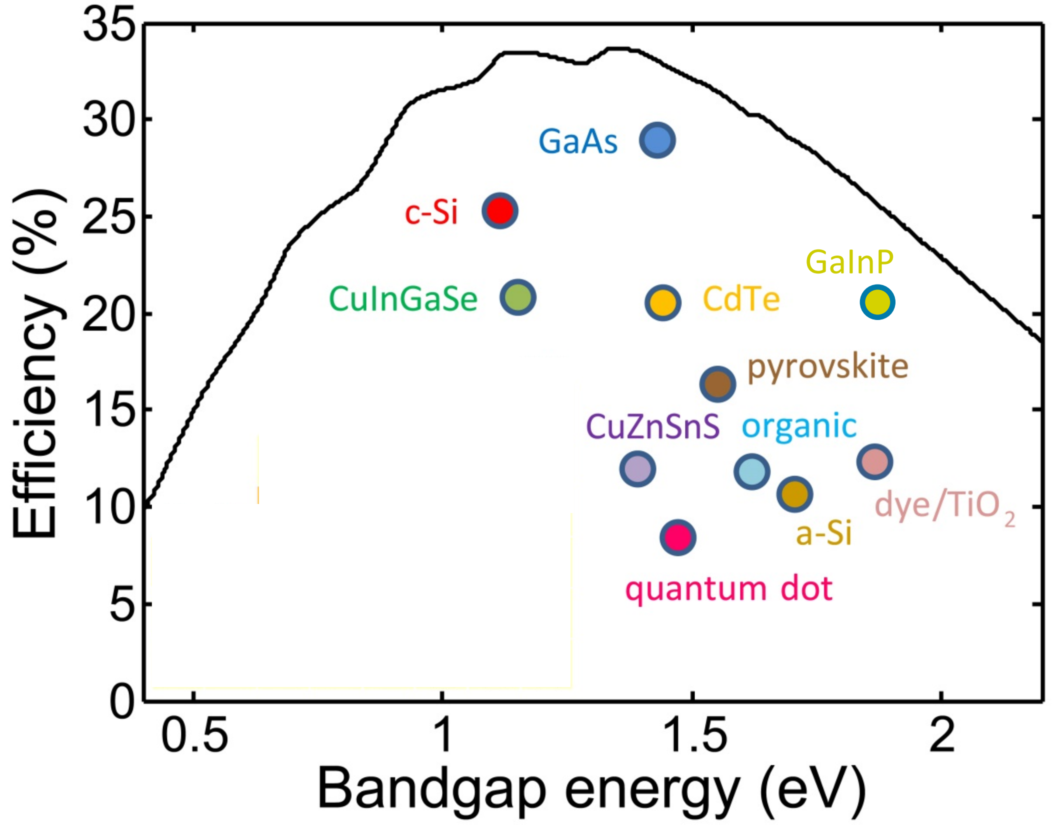
http://www.physics.rutgers.edu/~nakhmans/Pro/thesis/node6.html

M.A. Green *et al*., Prog. Photovolt. Res. Appl. **20**, 12 (2011)

Demonstrated solar cell efficiencies



Despite 60 years of research: No material reaches the thermodynamic limit !

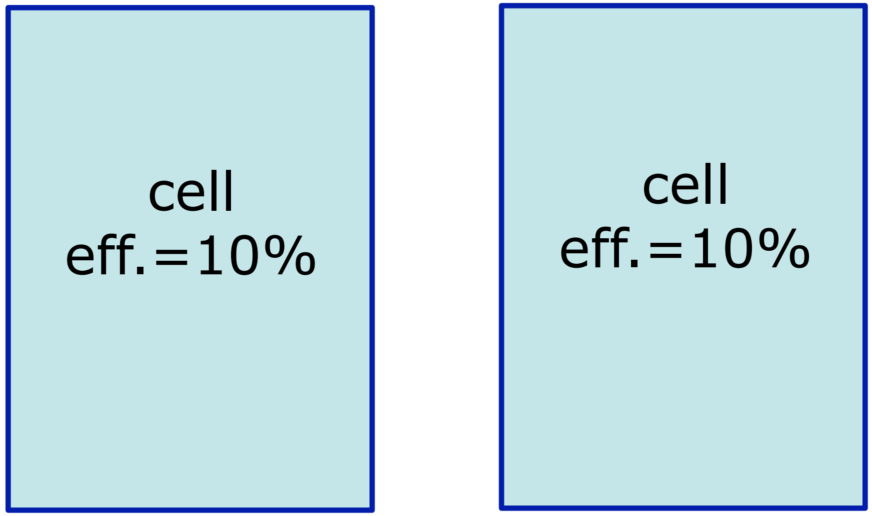


Solar power generation system = cells + panel + inverter + system + installation + land

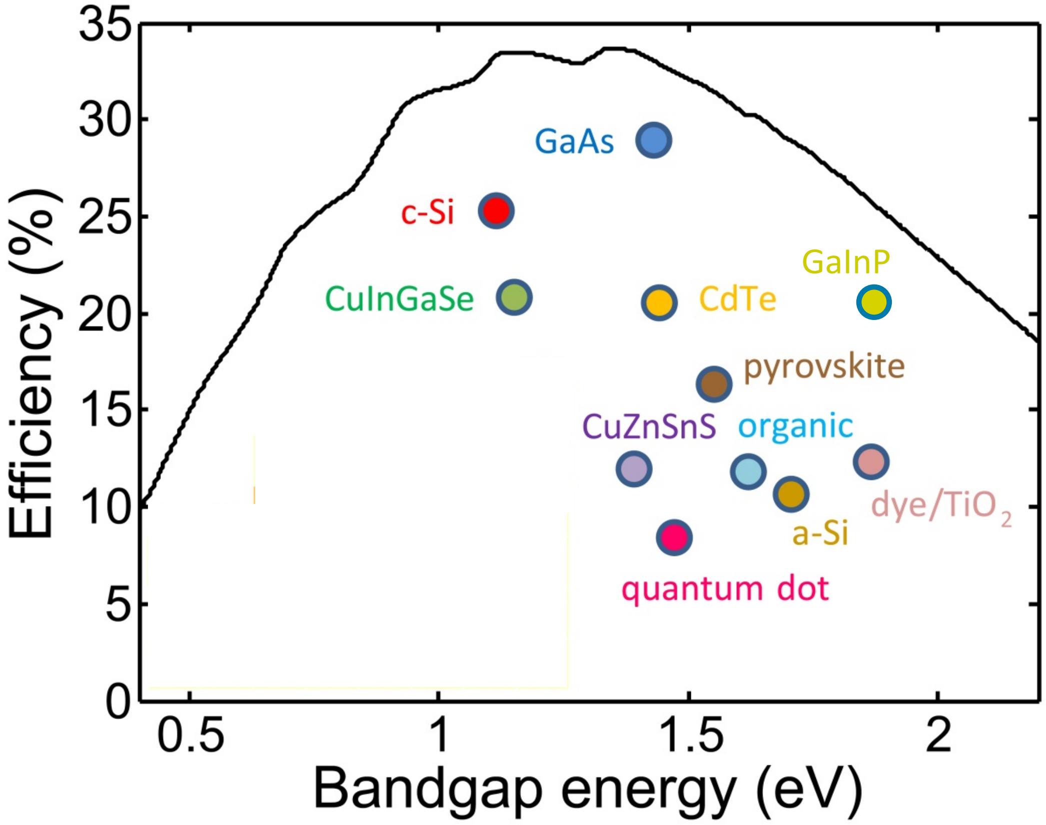
cell
eff.=20%

panel	€ 100
cells	€ 100
Total	€ 200

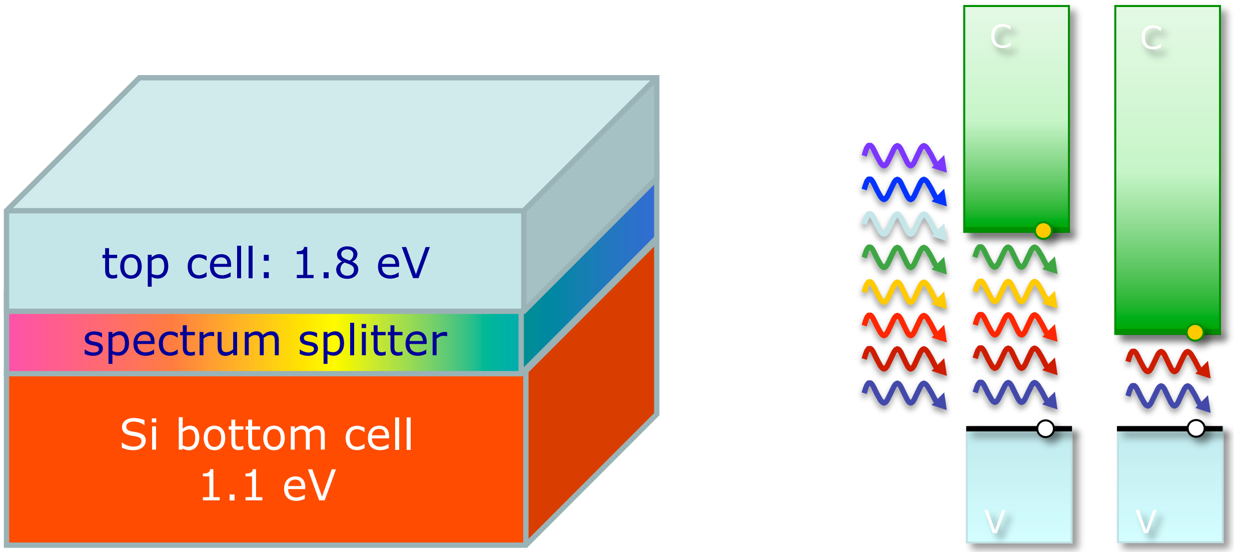
Solar power generation system = cells + panel + inverter + system + installation + land



High efficiency is “more important” than low cost



Dual-junction solar cell: thin-film-on-silicon
SQ limit: 44%



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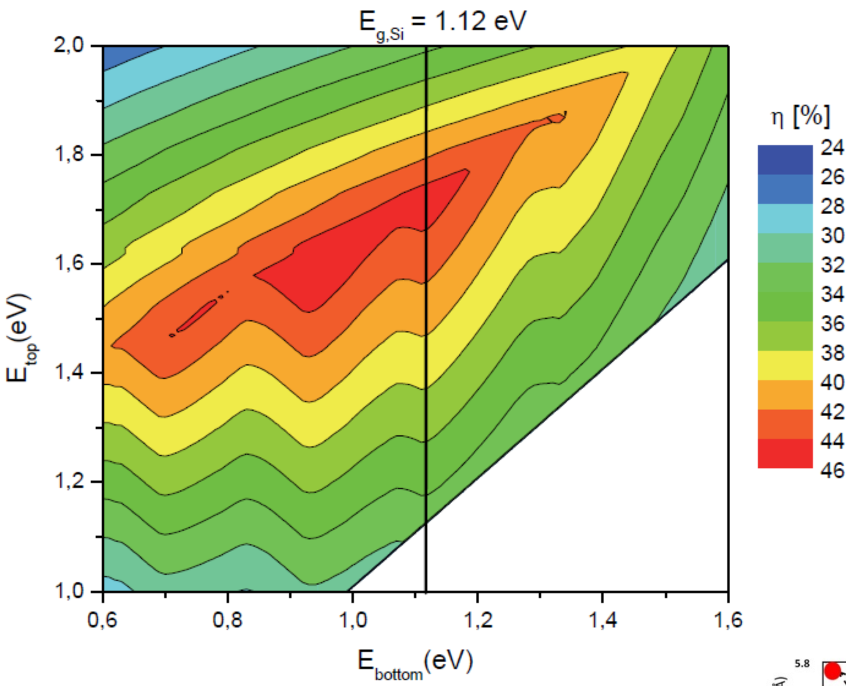
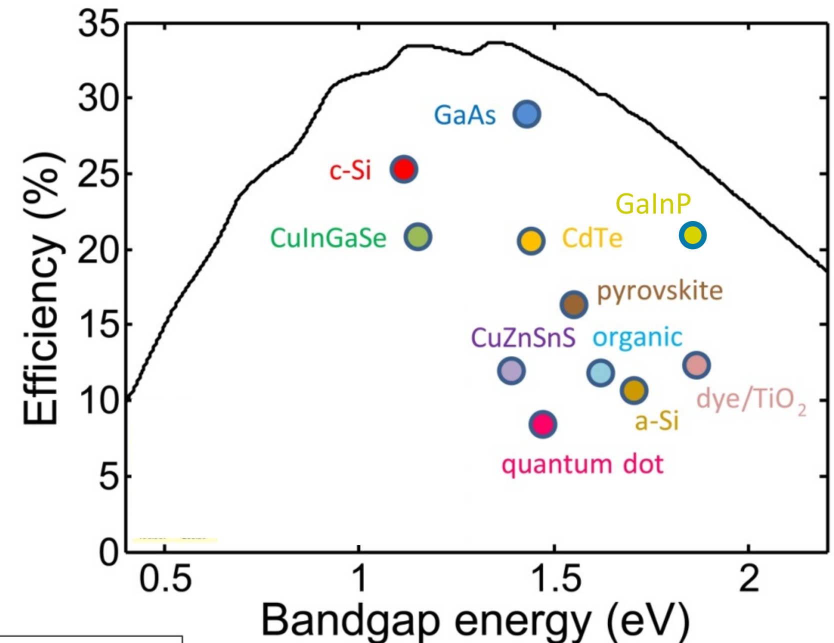
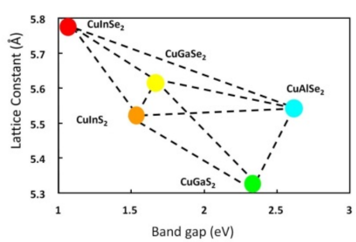
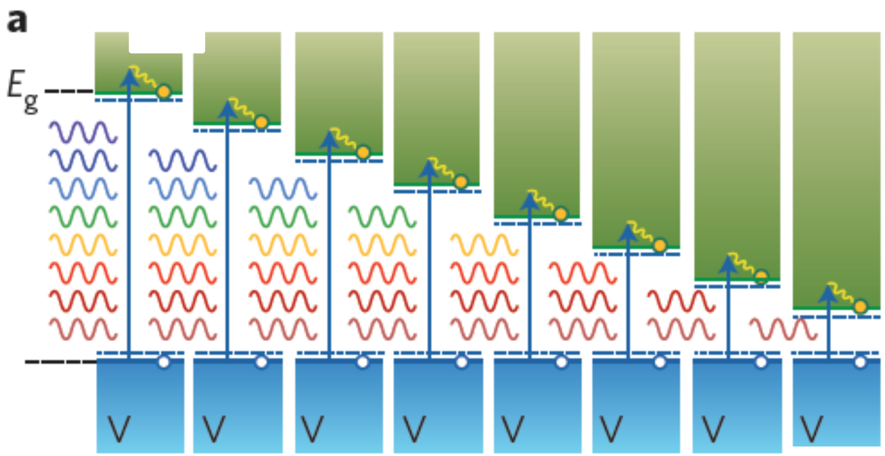


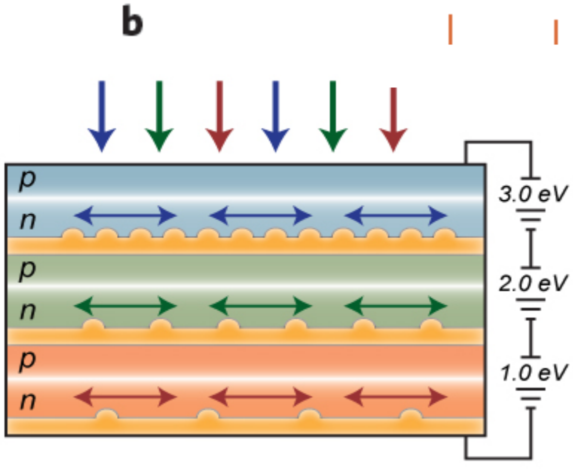




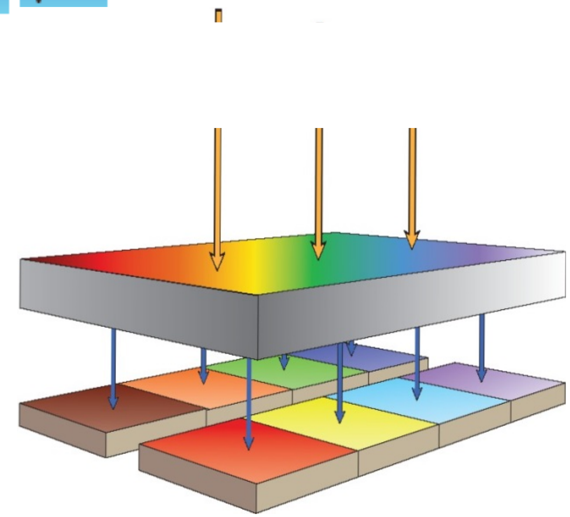
Multi-bandgap solar cell designs



Efficiency potential
> 50%



spectrum
splitting



series-connected

parallel-connected

A. Polman and H.A. Atwater
Nature Mater. **11**, 174 (2012)

Strategies towards high efficiency at low costs

1) Wafer-based Si solar cells (→25-29%)
- Reduce costs (=reduce wafer thickness: 10-20 μm)
- Decrease recombination at surface, junctions, contacts
- Increase light trapping, angular emission restriction,..

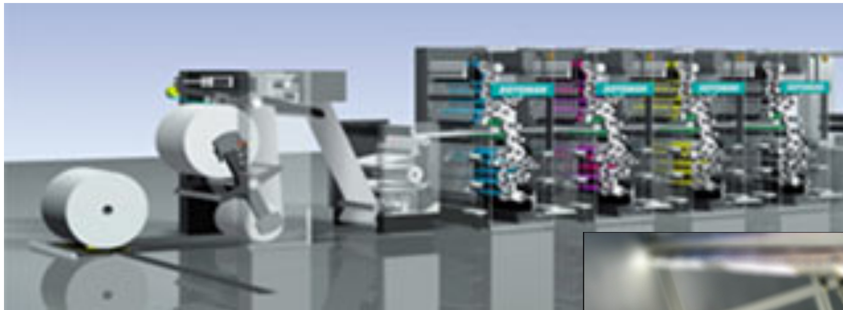
2) Thin-film solar cells
- Increase efficiency & reduce costs

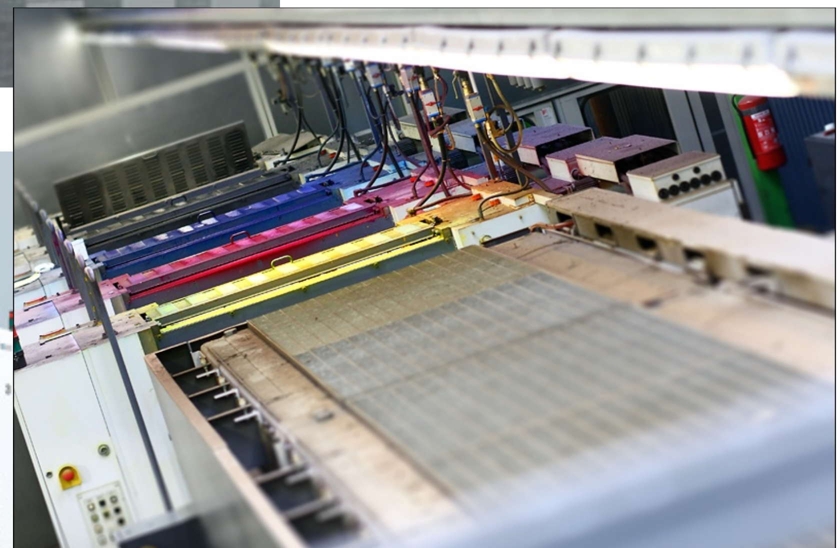
3) Dual-junction solar cells on silicon (→30-35%)
- Increase efficiency and bandgap of top cells
- Define spectral splitting architectures

4) New materials and designs (→>40%)
- Novel multijunction cell architectures
- Nanowire solar cells
- ….

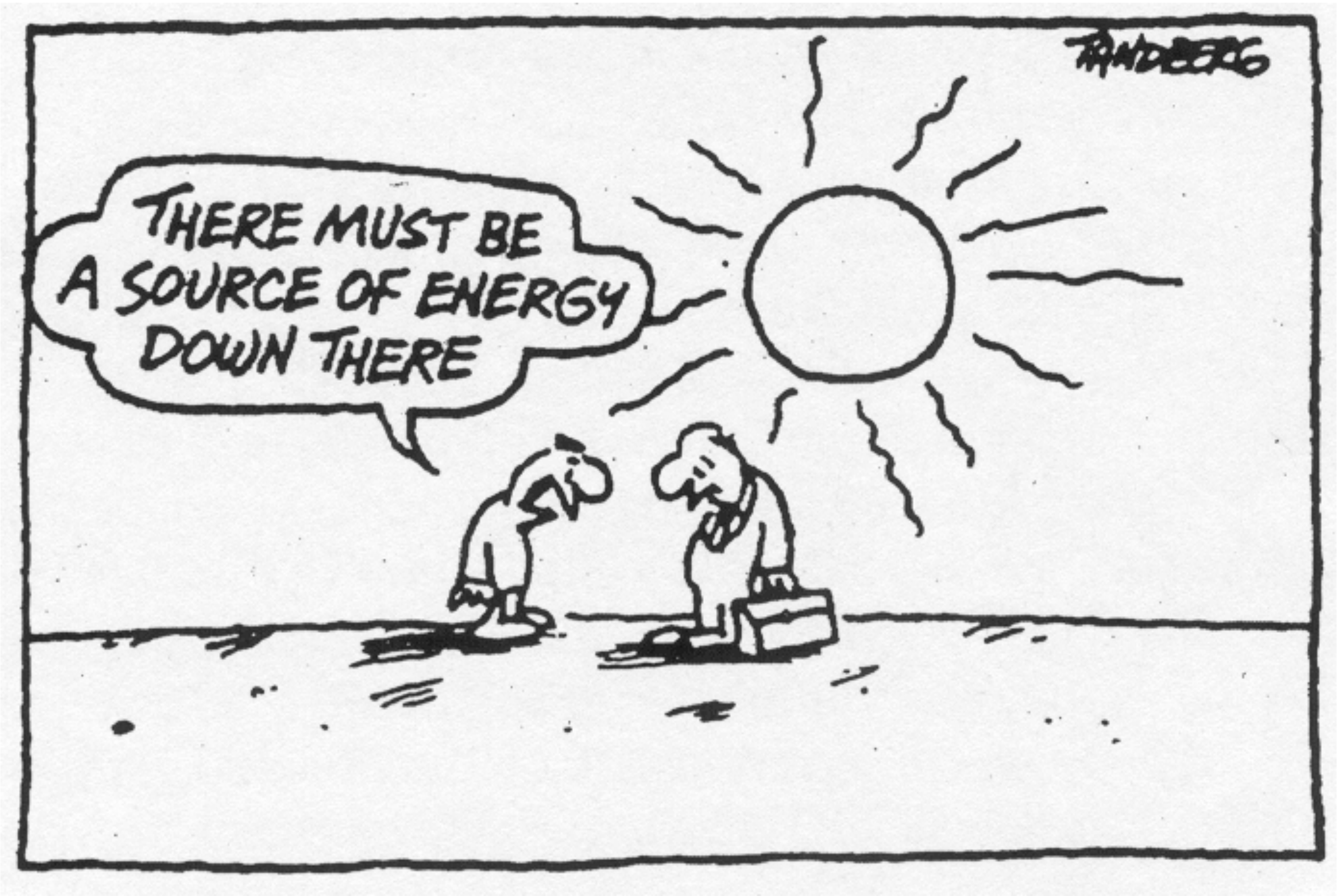
Towards ultra-large-area PV systems worldwide

Large-scale printing of solar cells





Energy from the sun



Energy from the sun

is a

science challenge
&
technology challenge
&
societal/political challenge


www.erbium.nl
Thank you