Photovoltaics, CSP and direct solar-to-fuel approaches

Peter C. K. Vesborg
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Global challenges related to future energy

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What we had to skip last time....

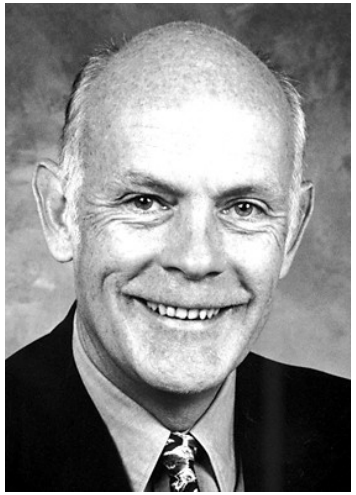
Table 1. World energy statistics and projections

Quantity	Definition	Units	2001*	2050†	2100‡
N	Population	B persons	6.145	9.4	10.4
GDP	GDP§	T $/yr	46	140¶	284‖
GDP/N	Per capita GDP	$/(person-yr)	7,470	14,850	27,320
$\dot{E}$/GDP	Energy intensity	W/($/yr)	0.294	0.20	0.15
$\dot{E}$	Energy consumption rate	TW	13.5	27.6	43.0
C/E	Carbon intensity	KgC/(W·yr)	0.49	0.40	0.31
$\dot{C}$	Carbon emission rate	GtC/yr	6.57	11.0	13.3
$\dot{C}$	Equivalent CO_2 emission rate	$GtCO_2$/yr	24.07	40.3	48.8

Richard Smalley

Nobel Laureate

1943-2005



Any future energy technology must be scalable to the TW level

Smalley *MRS Bull*. 2005

Ressources and availability

Back-of-an-envelope "1 TW benchmark"

How many square meters of water electrolyzer?

Reversible potential ca. 1.25 V, assume i = 1 A/cm^2

A = 10^{12} W /(1.25 V x 10^4 A/m^2) = 8 x 10^7 m^2 = **80 km**

How many square meters of photovoltaic array?

Avg. annual insolation in Spain: 1700 kWh/m^2yr

Assume a 10% efficiency.

A = 10^9 kW x 365 x 24 h/yr /(1700 kWh/m^2yr x 0.10) = 5.1 x 10^{10} m^2 = **51.000 km^2**

How many kg of photovoltaic absorber?

Assume absorber density of 5 g/cm^3 and a thickness of 1 μm

m = 5.1 10^{10} m^2 x 10^{-6} m x 5 t/m^3 = **260.000 t**

How much (material) is available?

And – do metals come from mines?

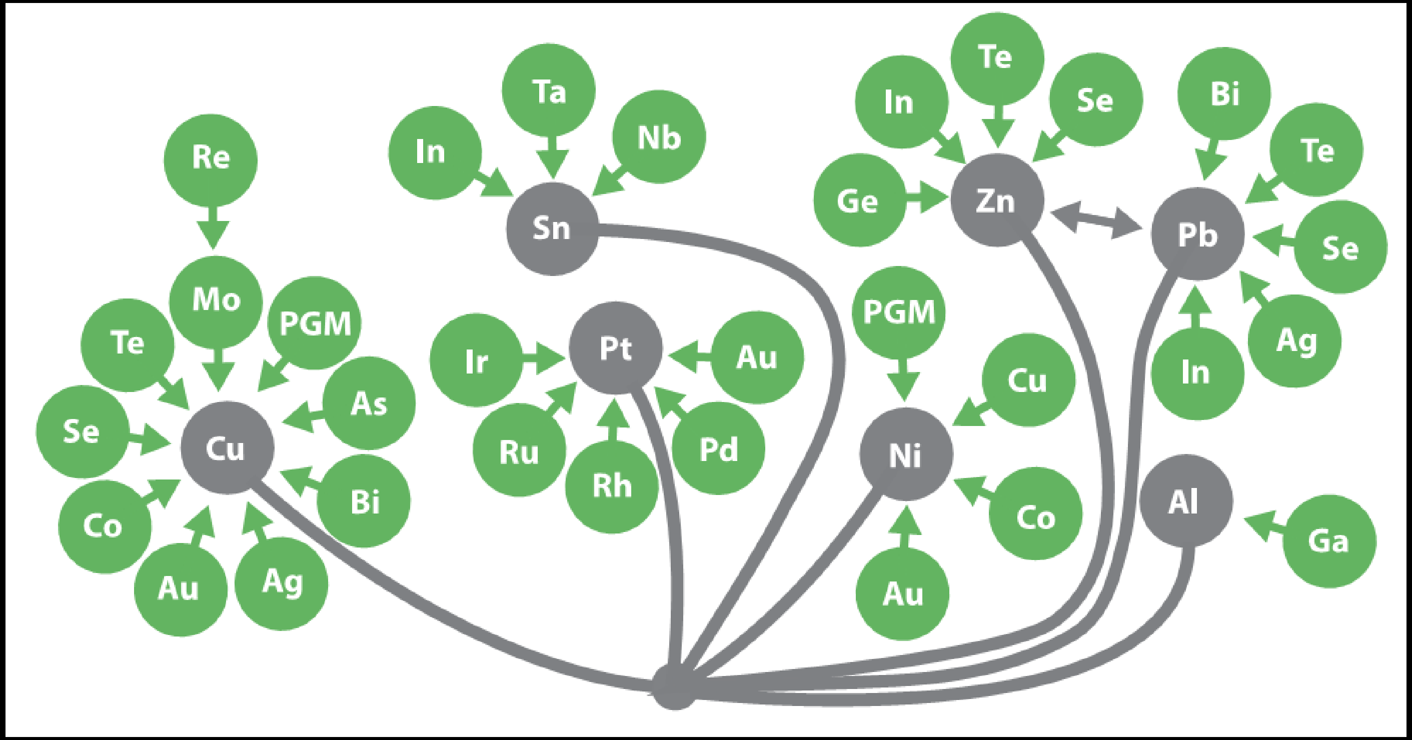
Underground

Open pit/strip

Only about 35 metals are mined directly

More than 30 metals have *no mines*

Where “stuff” originates



Primary products (elastic)

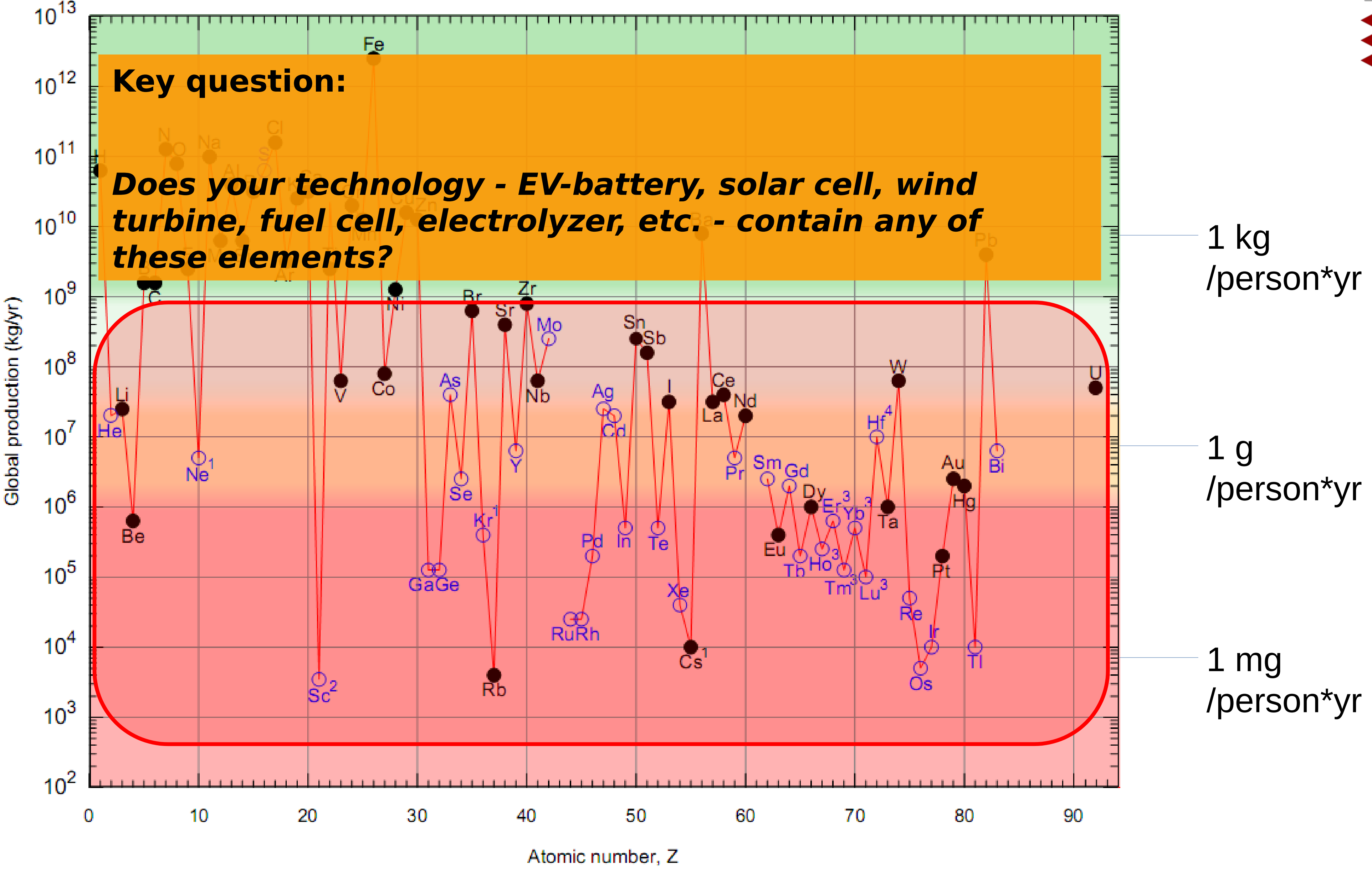
vs.

Bi-products (inelastic)

C. Hagelüken & C. Meskers, *MIT press, ISBN: 9780262013581*, p.163-197, (2010)

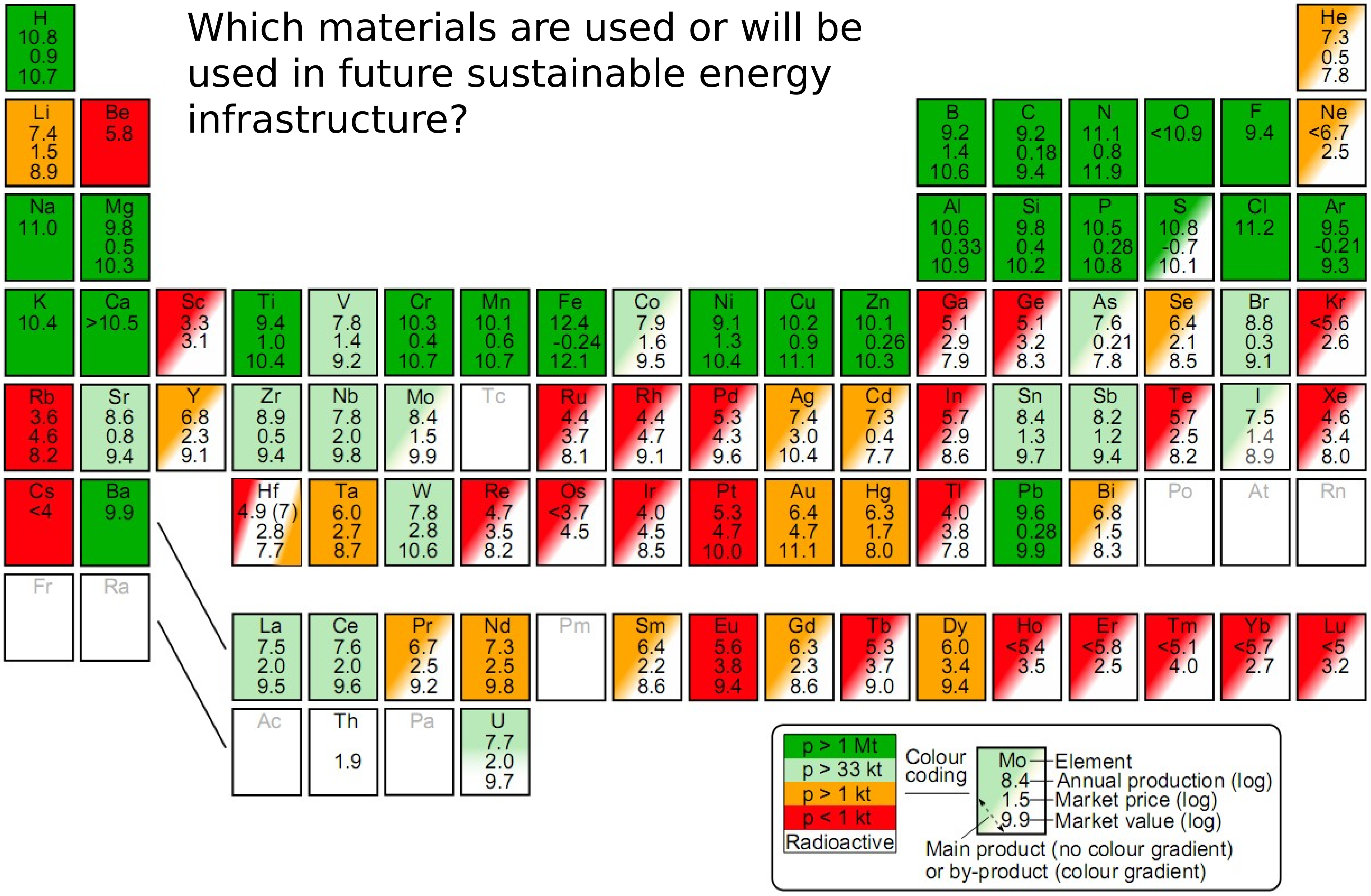
Key question:

Does your technology - EV-battery, solar cell, wind turbine, fuel cell, electrolyzer, etc. - contain any of these elements?

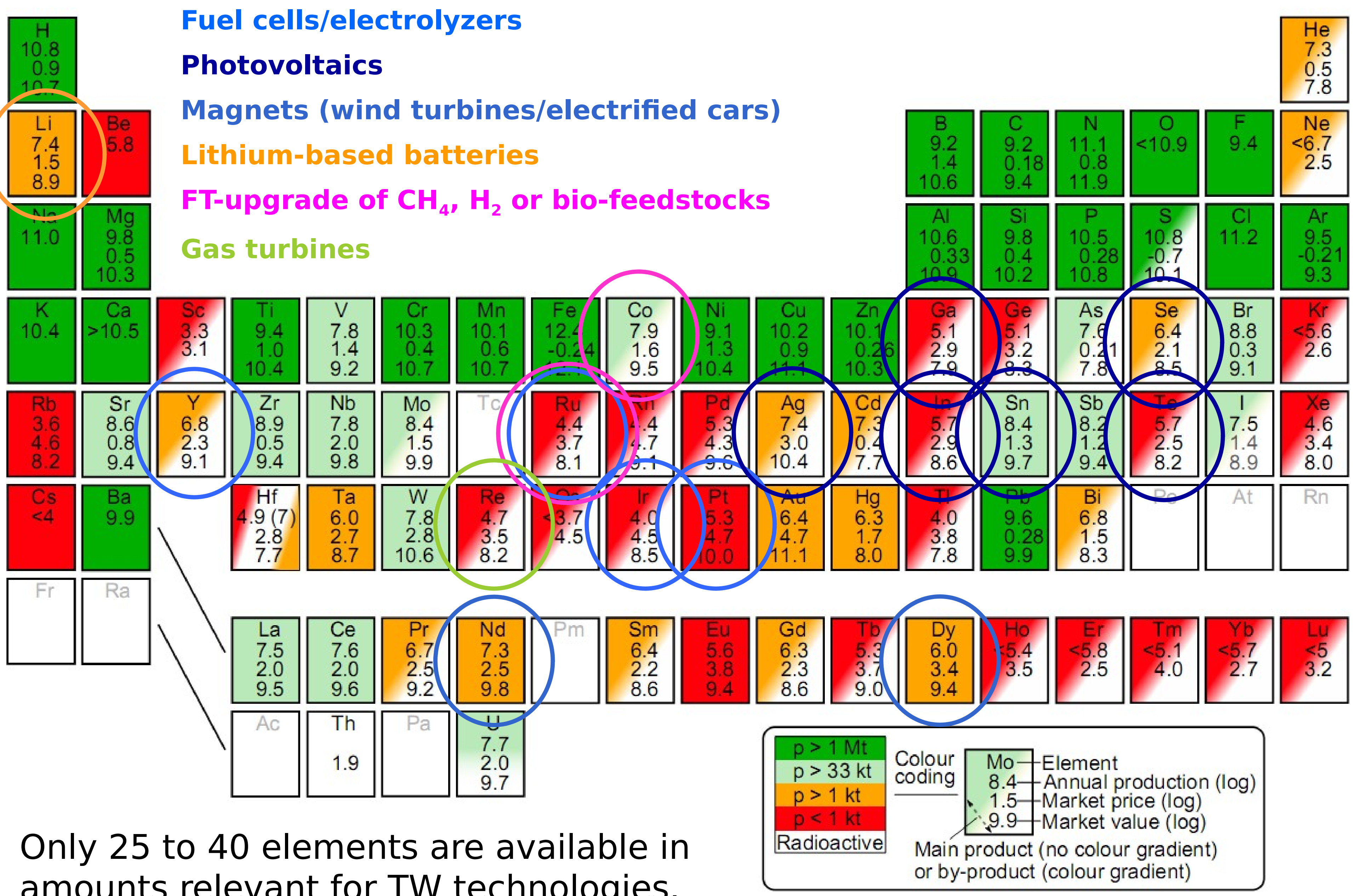


P.C.K. Vesborg & T.F. Jaramillo, *RSC Adv.*, 2, p.7933, (2012)

Which materials are used or will be used in future sustainable energy infrastructure?



P.C.K. Vesborg & T.F. Jaramillo, *RSC Adv.*, 2, p.7933, (2012)



Only 25 to 40 elements are available in amounts relevant for TW technologies.

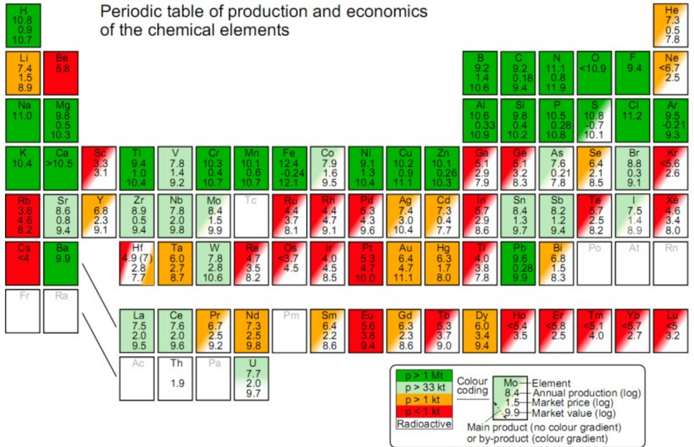
P.C.K. Vesborg & T.F. Jaramillo, *RSC Adv.*, 2, p.7933, (2012)

Time to reach 1 TW_{avg}

Technology	Material	Intensity $W_p\ kg^{-1}$	TW_p req. $\log(M/TW_p)$	Capacity factor	TW_{avg} req. $\log(M/TW_{avg})$	Years to reach 1 TW_{avg}
Wind Turbines	Steel/Fe	12	10.9	0.25	11.5	0.14
Wind (on-shore)	Cement[a]	20	10.7	0.25	11.3	0.06
Wind (PM-gen.)	Nd	5.3 k	8.3	0.25	8.9	45
Wind (PM-gen.)	Dy	80 k	7.1	0.25	7.7	50
Photovoltaics-c-Si	Glass	13	10.9	0.19	11.6	—
Photovoltaics-c-Si	Polymers	85	10.1	0.19	10.8	—
Photovoltaics-c-Si	Si[b]	250	9.6	0.19	10.3	3
Photovoltaics-c-Si	Cu	450	9.3	0.19	10.1	0.7
Photovoltaics-CdTe[c]	Te	14 k	7.9	0.2	8.6	700
Photovoltaics-CIGS[d]	In	50 k	7.3	0.2	8.0	200
Fuel Cells-SOFC[e,f]	Y	83 k	7.1	—	—	(1.8)
Fuel Cells-PEMFC[e,g]	Pt	1.25 M	5.9	—	—	(4)
Co-based FT	Co[h]	12 k	7.9	0.95	7.9	1
	Ru/Re[i]	590 k	6.2	0.95	6.3	75/38
Nuclear fission[j]	$U_{nat.}$	2.3 k	8.6	0.85	8.7	10

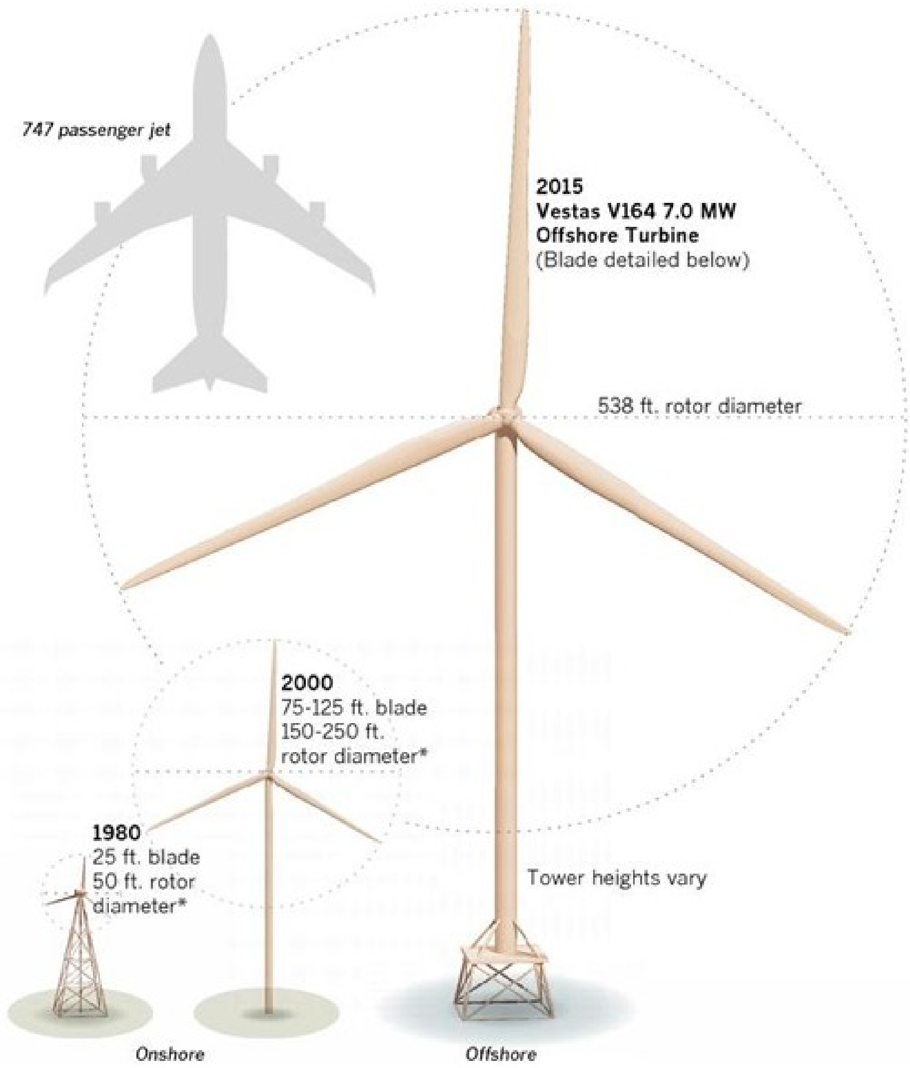
One key *sustainability challenge*:

To use (far) less of the “red” materials and only rely on the available, “green” materials!!



We need 28 TW$_{avg}$ by 2050

What if a single technology to provide 28 TW by 2050



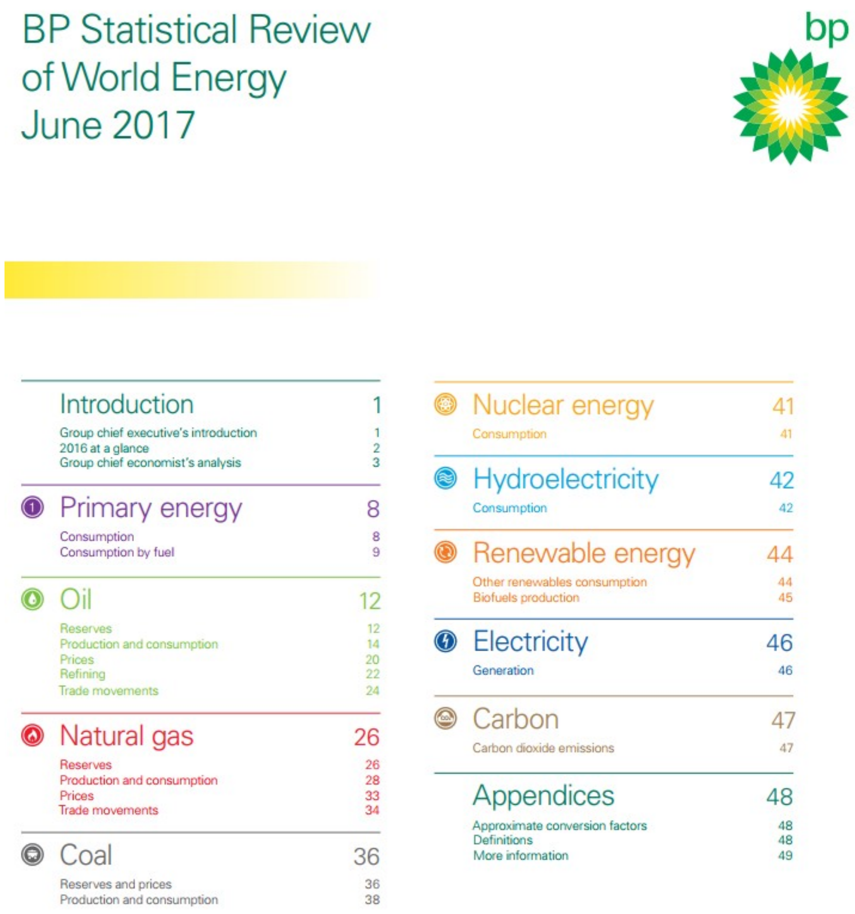
Where to find DATA – Energy 1

BP Statistical Review of World Energy

pdf, pptx, xlsx

Issued every year in June

Country-by-country data


BP Statistical Review
of World Energy
June 2017

bp

http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html

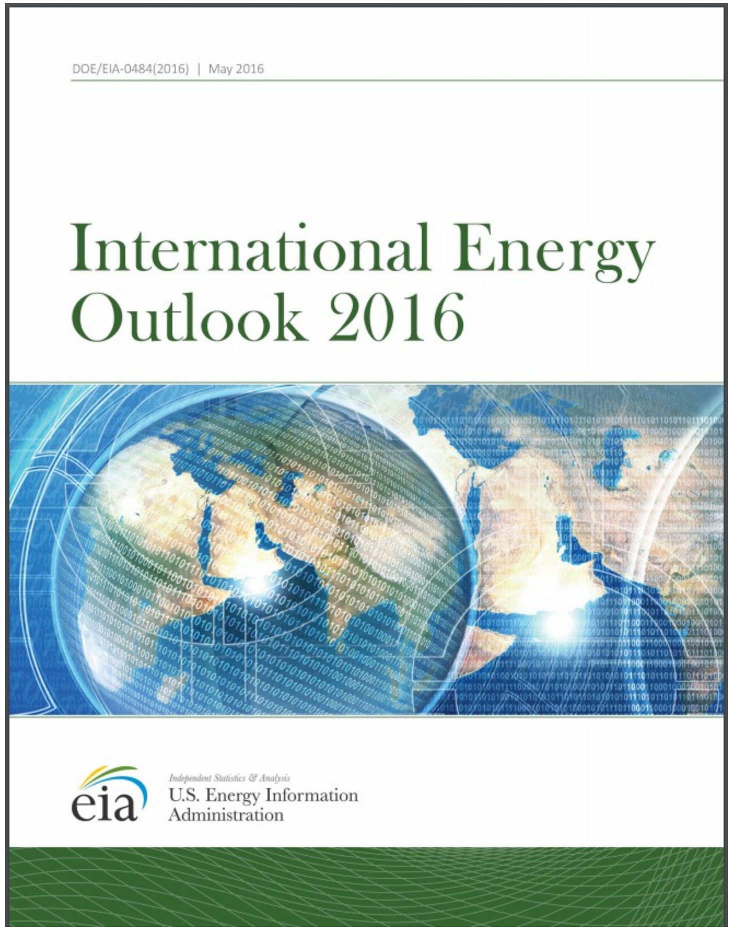
Where to find DATA – Energy 2

US Department of Energy (EIA)
International Energy Outlook
pdf, xlsx

Issued every year

Country-by-country data

Dubious ”proved reserves”



https://www.eia.gov/outlooks/ieo/

Where to find DATA – Energy 3

International Energy Agency (IEA)

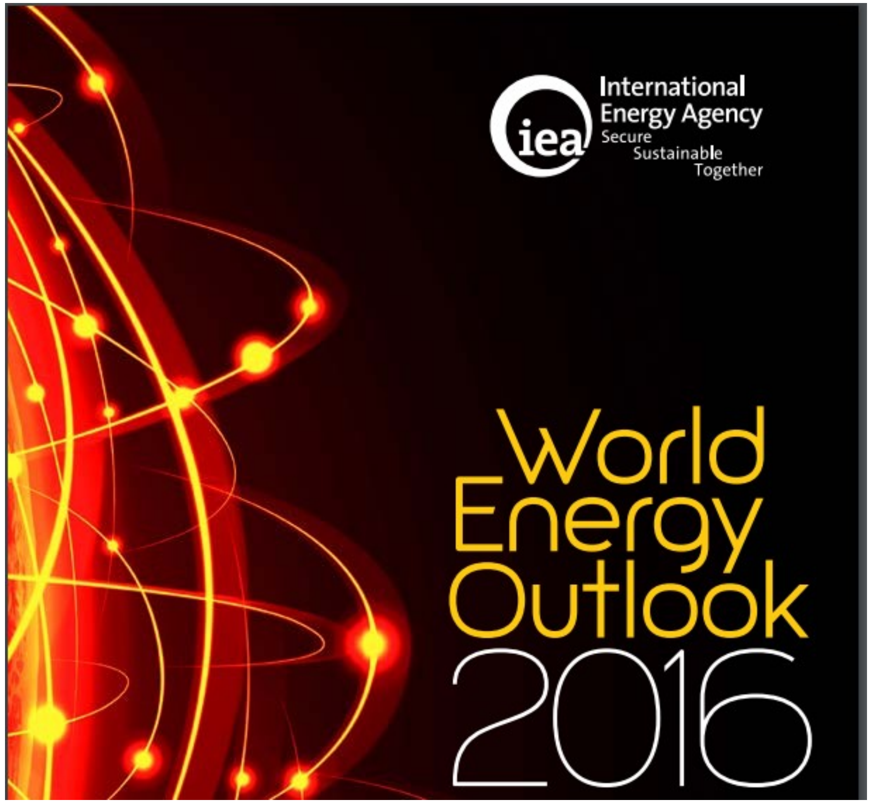
- **World Energy Outlook**
- pdf

Issued every year – but not free until a few years later

- Use DTU libary

Country-by-country data

Much more than energy flows!



https://www.iea.org/publications/freepublications/

Where to find DATA – Energy 4

International Energy Agency (IEA)

Oil Market Report

pdf

Issued every month (!)

Country-by-country data

https://www.iea.org/oilmarketreport/omrpublic/

Where to find DATA – Other stuff

Material flows

USGS Minerals Yearbook

https://minerals.usgs.gov/minerals/pubs/myb.html

Country statistics

Indexmundi

http://www.indexmundi.com/

FAO flagship reports

The Future of Food and Agriculture

The State of World Fisheries and Aquaculture

The State of the World's Forrests

Typical mistakes and ”tricks”

Mega ≠ Giga ≠ Tera

Reserves ≠ Ressources

Comparing stocks to flows
- E.g. B. Lomborg

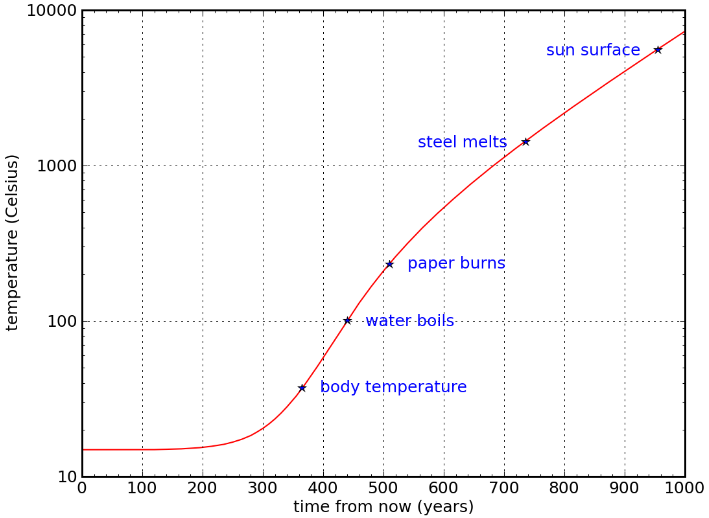
”Gigaton Carbon”
- 44 ≠ 12

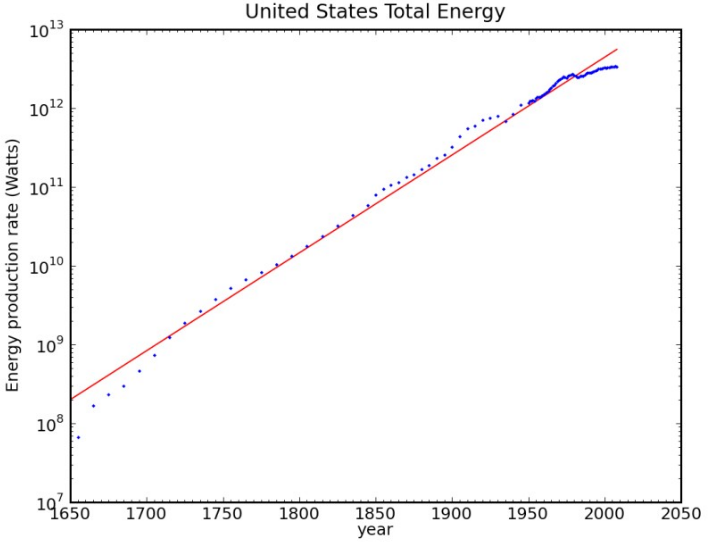
BO ≠ BOE ≠ Barrel of liquids
- Oil ≠ Natural gas
- Oil ≠ ”Liquids”

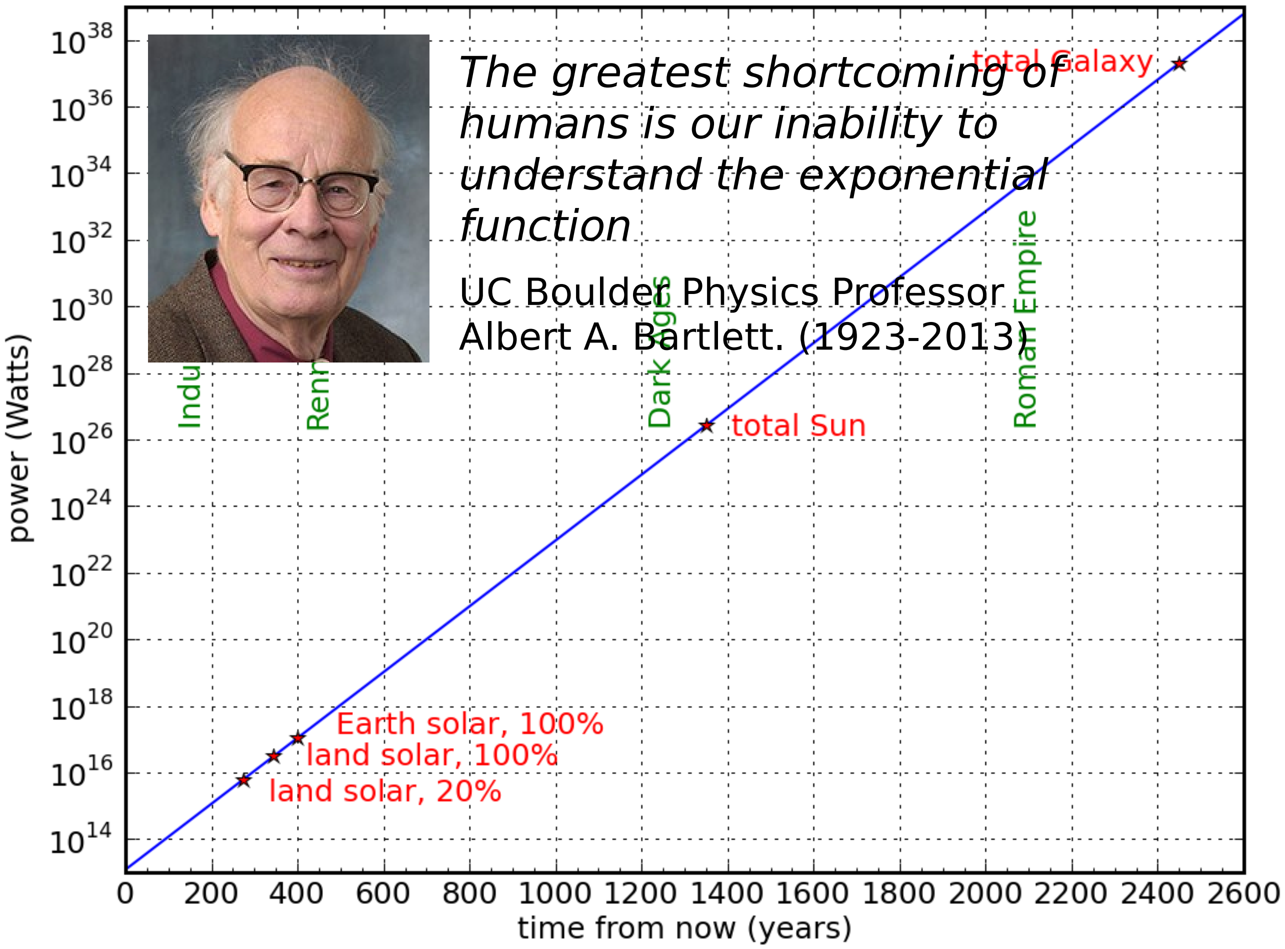
Afterthought - zooming out (in time)

Gedankenexperiment

Continued exponential growth for generations to come?

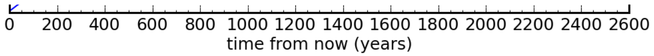


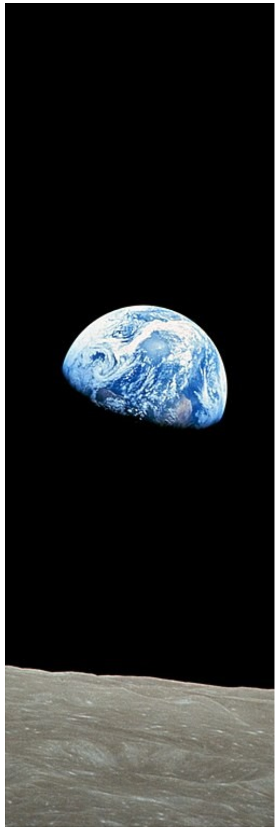




The greatest shortcoming of humans is our inability to understand the exponential function

UC Boulder Physics Professor Albert A. Bartlett. (1923-2013)





Credit: Thomas Murphy, UCSD
https://dothemath.ucsd.edu/

Photovoltaics, CSP and direct solar-to-fuel approaches

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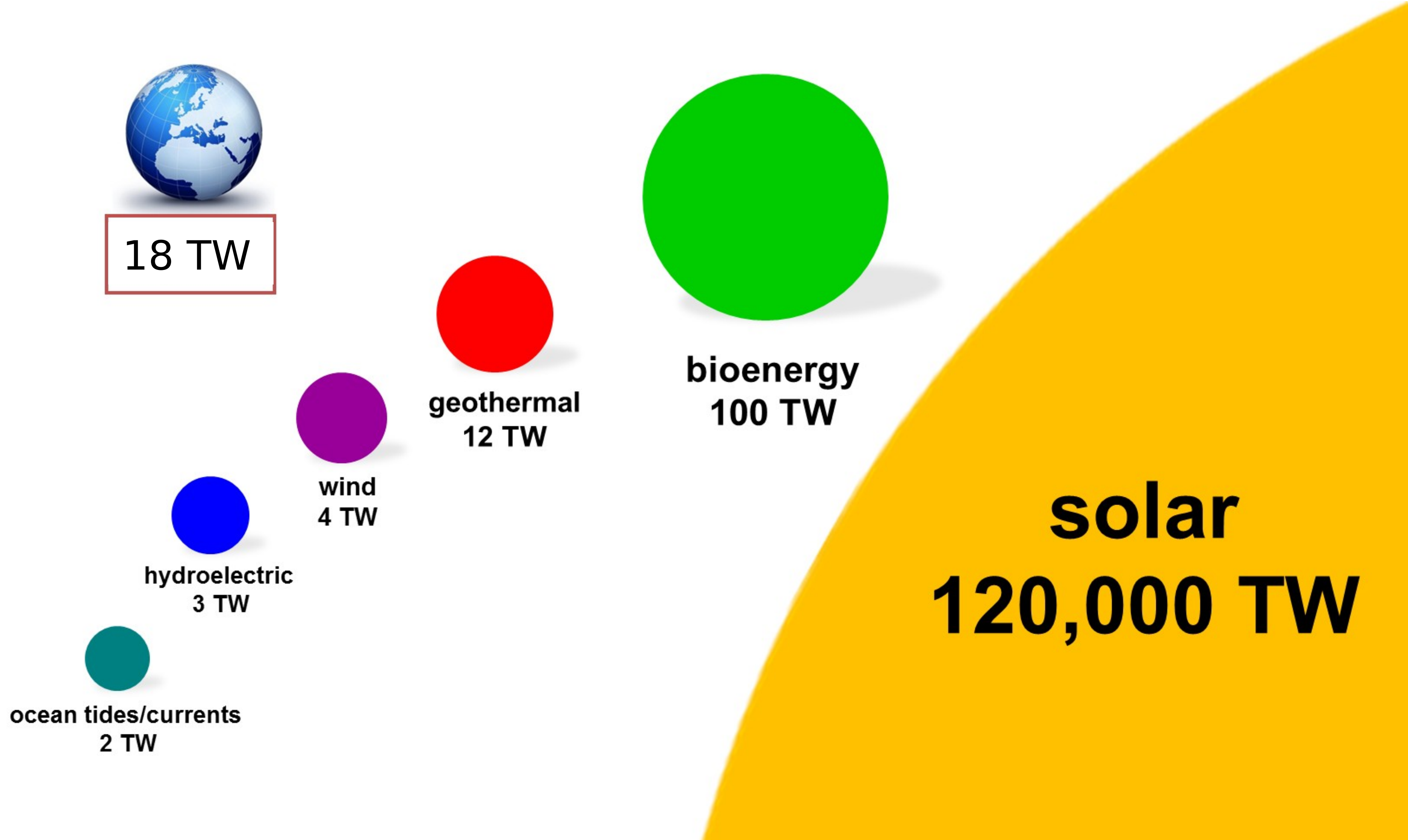
DTU Physics

A sustainable future energy infrastructure

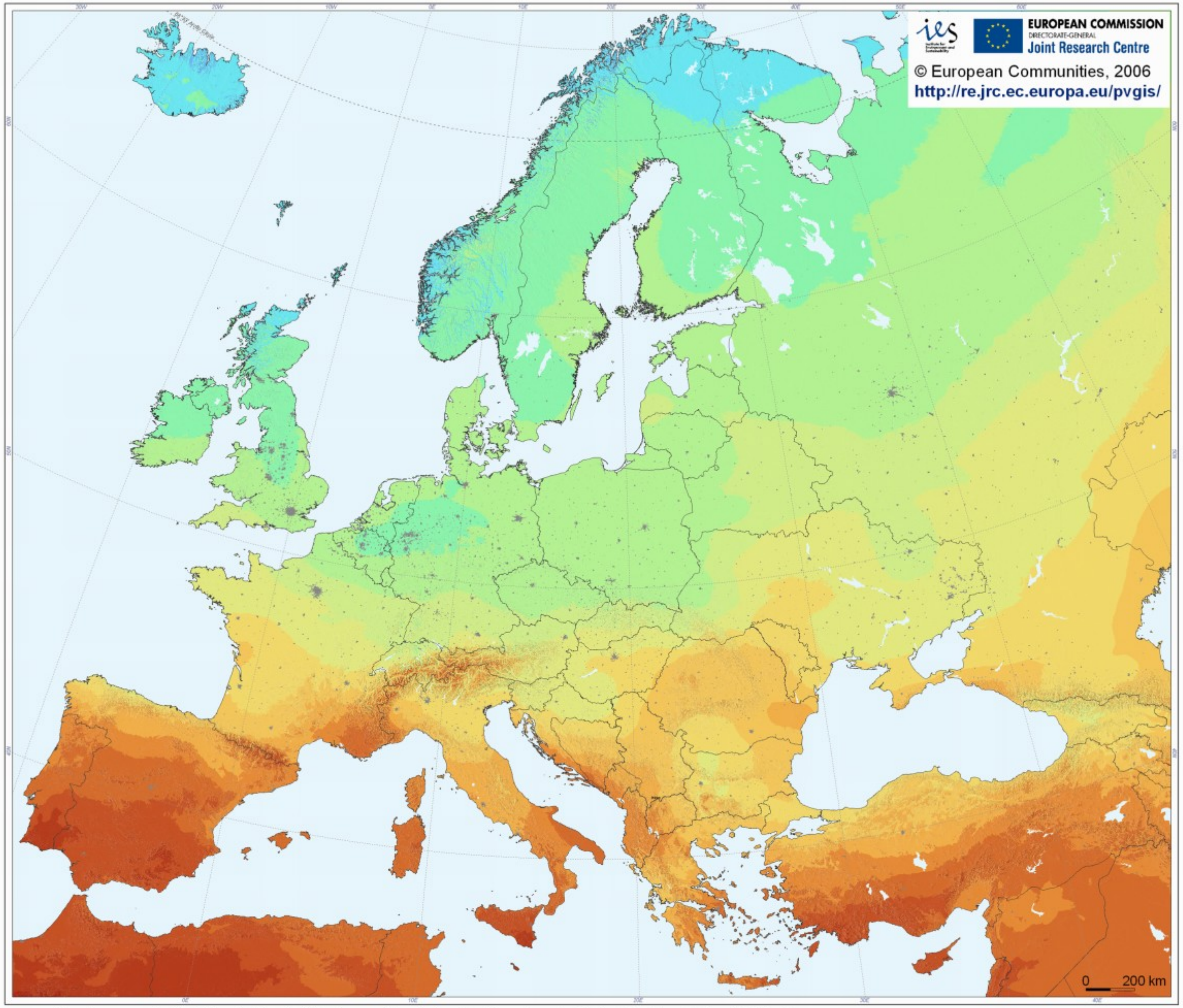
A fantastic resource



Photovoltatics

Quick intro to the physics of solar cells

Photovoltaic Solar Electricity Potential in European Countries



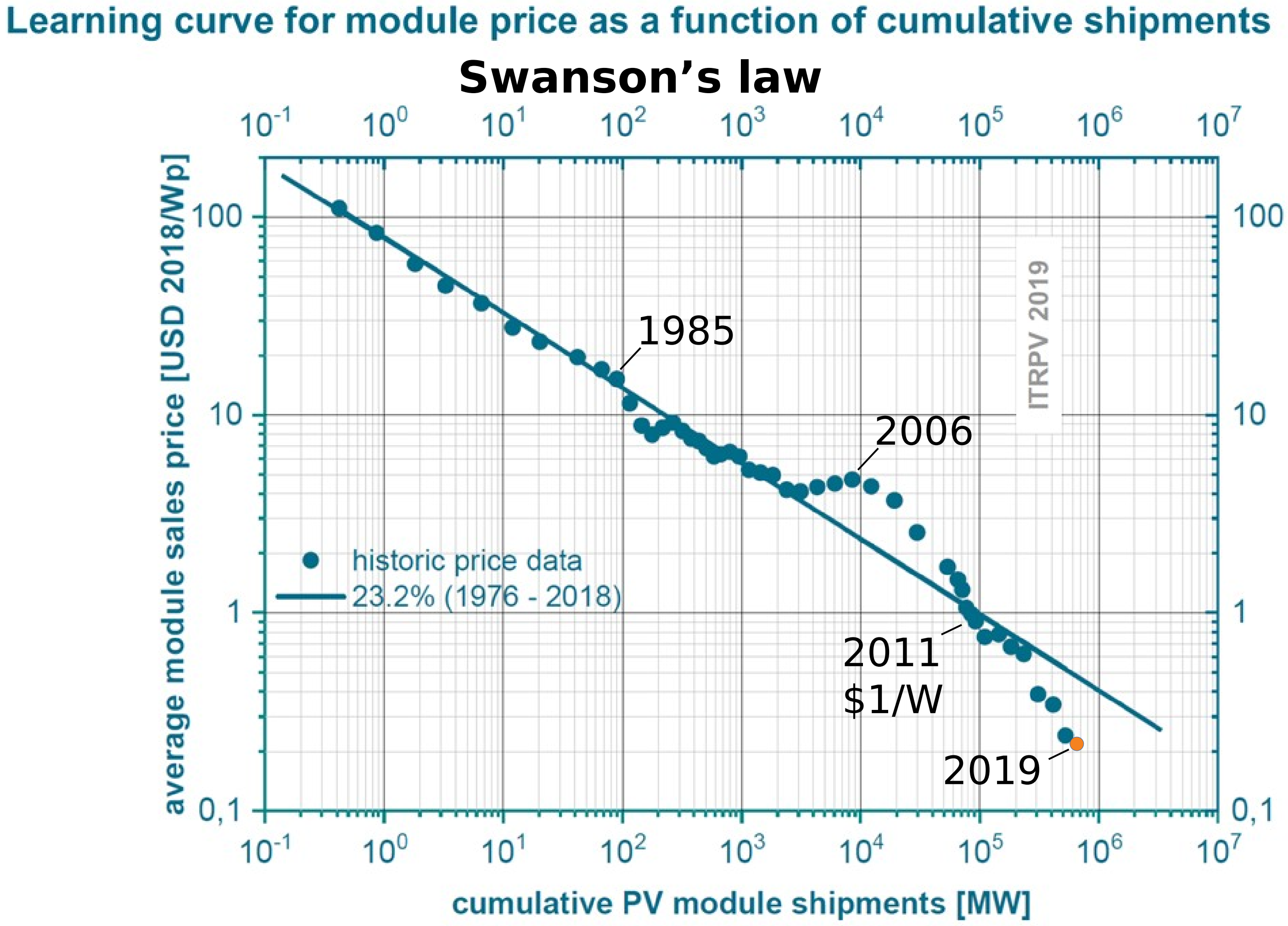
Yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules

Global irradiation [kWh/m²]
<600 800 1000 1200 1400 1600 1800 2000 2200>

Yearly sum of solar electricity generated by 1 kWp system with optimally-inclined modules and performance ratio 0.75

<450 600 750 900 1050 1200 1350 1500 1650>
Solar electricity [kWh/kWp]

Solar is highly competitive!



Abu Dhabi (350 MW PV plant)

Lowest bid: 2.42 US cents /kWh (2016)

http://www.thenational.ae

Denmark (600 MW offshore wind farm)

Lowest bid: 5.64 US cents /kWh (2016)

http://efkm.dk

Portugal (700 MW PV plant)

Lowest bid: 1.31 US cents /kWh (2020)

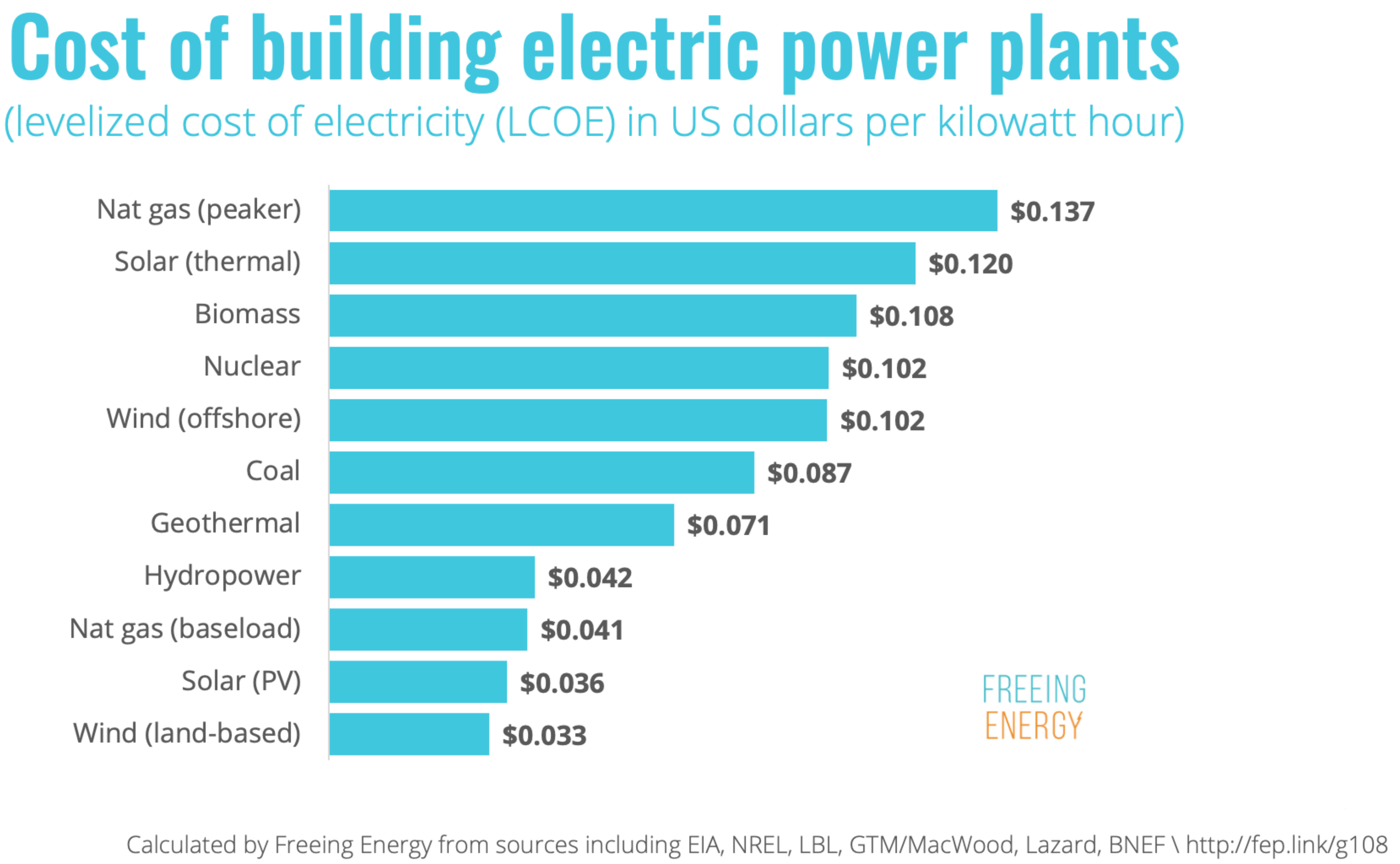
www.pv-tech.org/news/historic-result-as-portugal-claims-record-low-prices-in-700mw-solar-auction

Crude oil price:

~ 80 USD per barrel =
~ 4.7 US cents per kWh

Slide adapted from Jakob Kibsgaard, DTU Physics

LCOE of various technologies



LCOE of various technologies

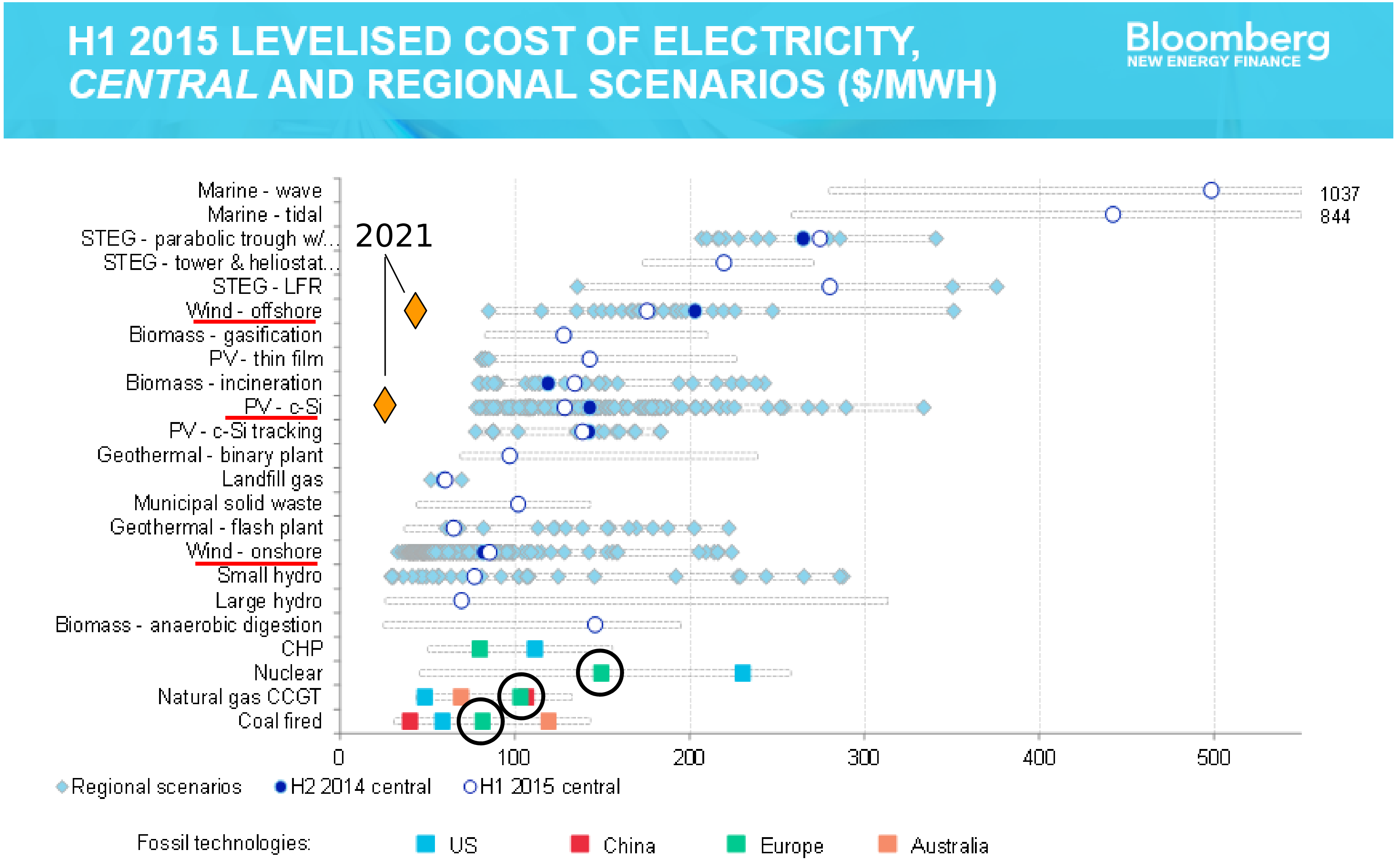
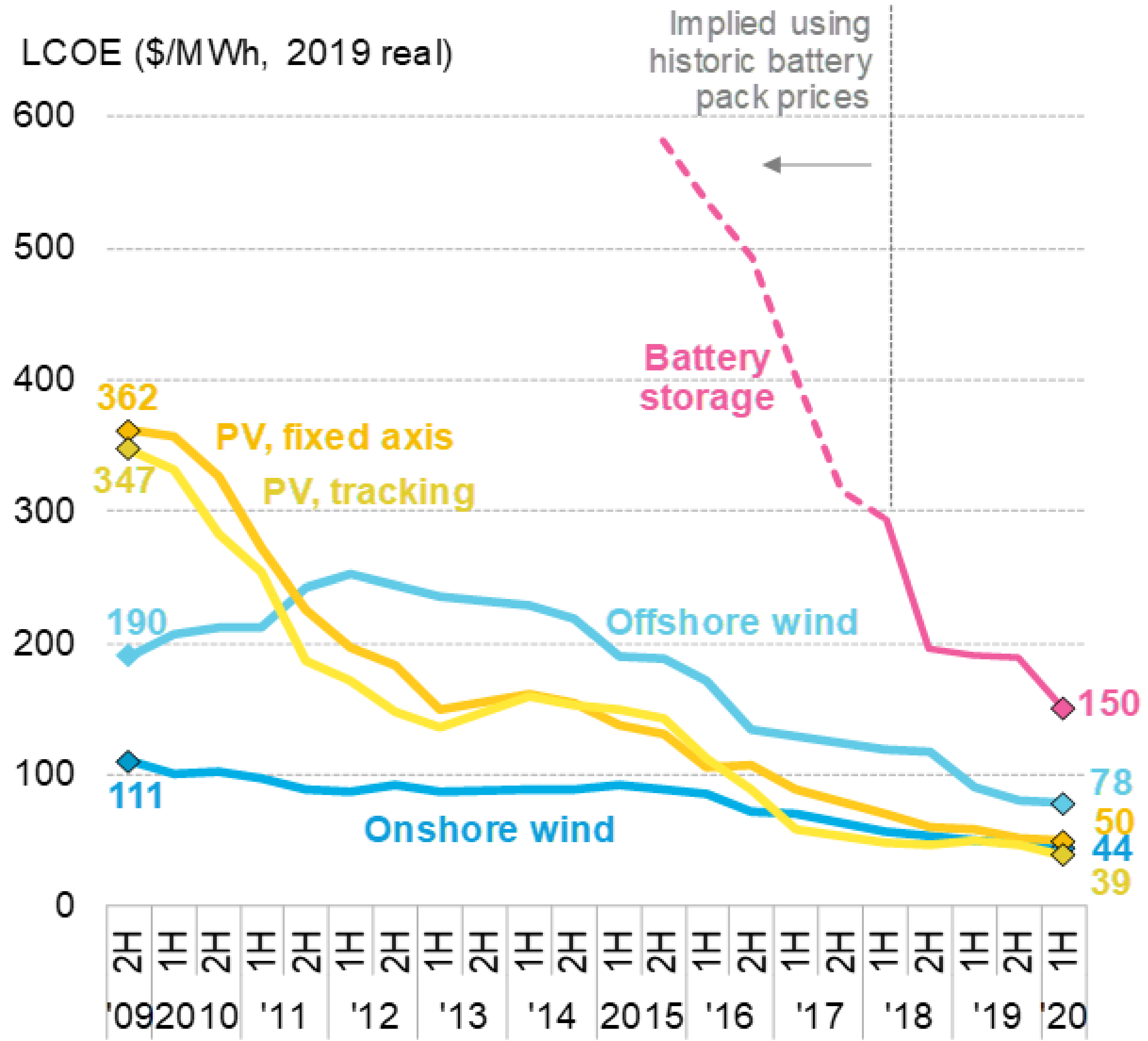


Figure 2: Global LCOE benchmarks – PV, wind and batteries

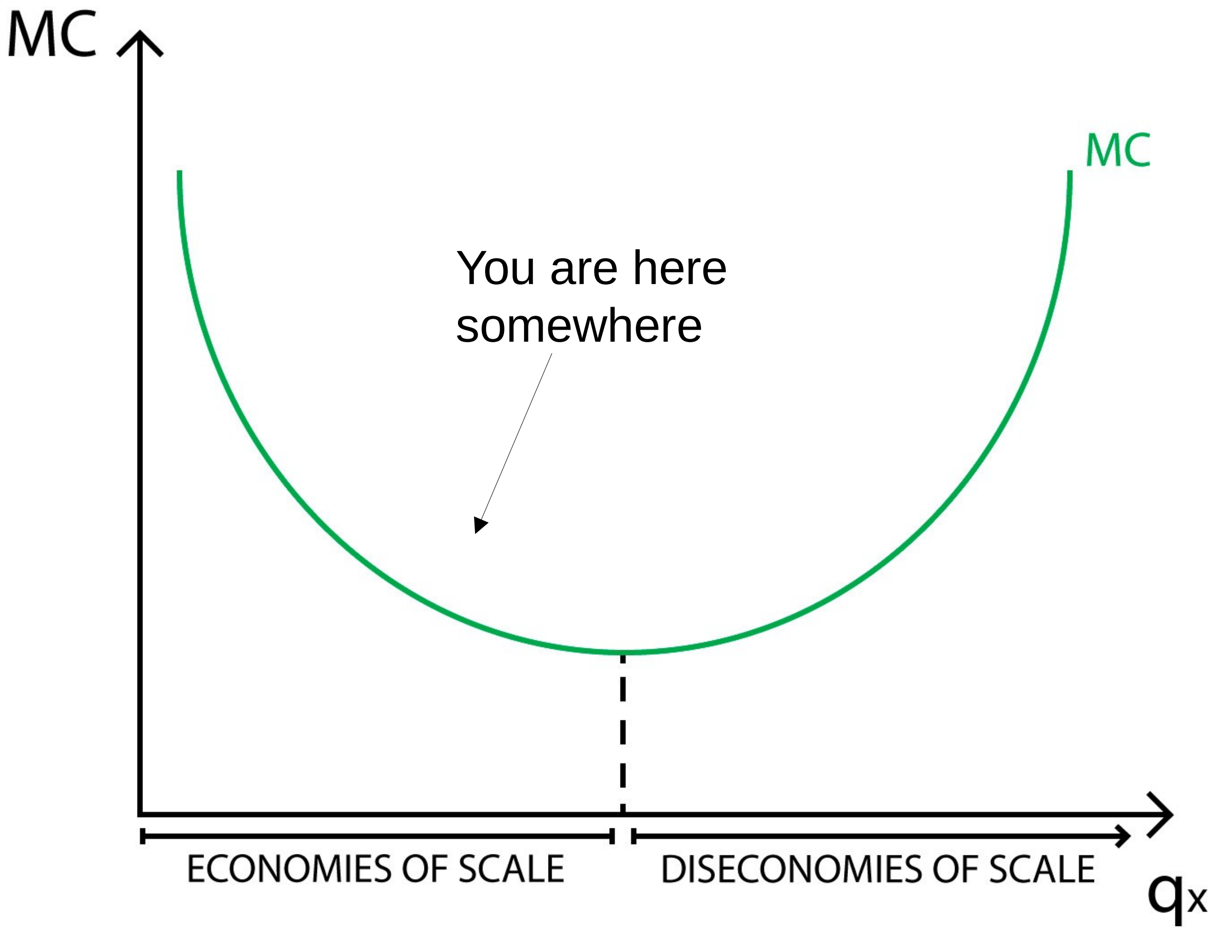


Source: BloombergNEF. Note: The global benchmark is a country weighted-average using the latest annual capacity additions. The storage LCOE is reflective of utility-scale projects with four-hour duration, it includes charging costs.

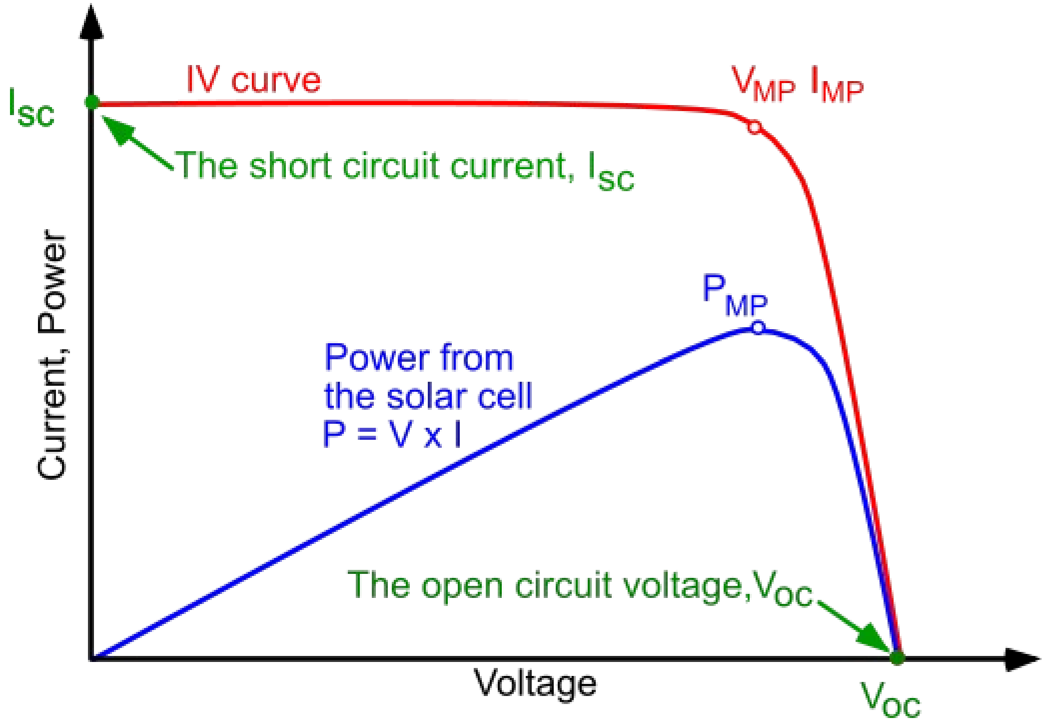
Two drivers

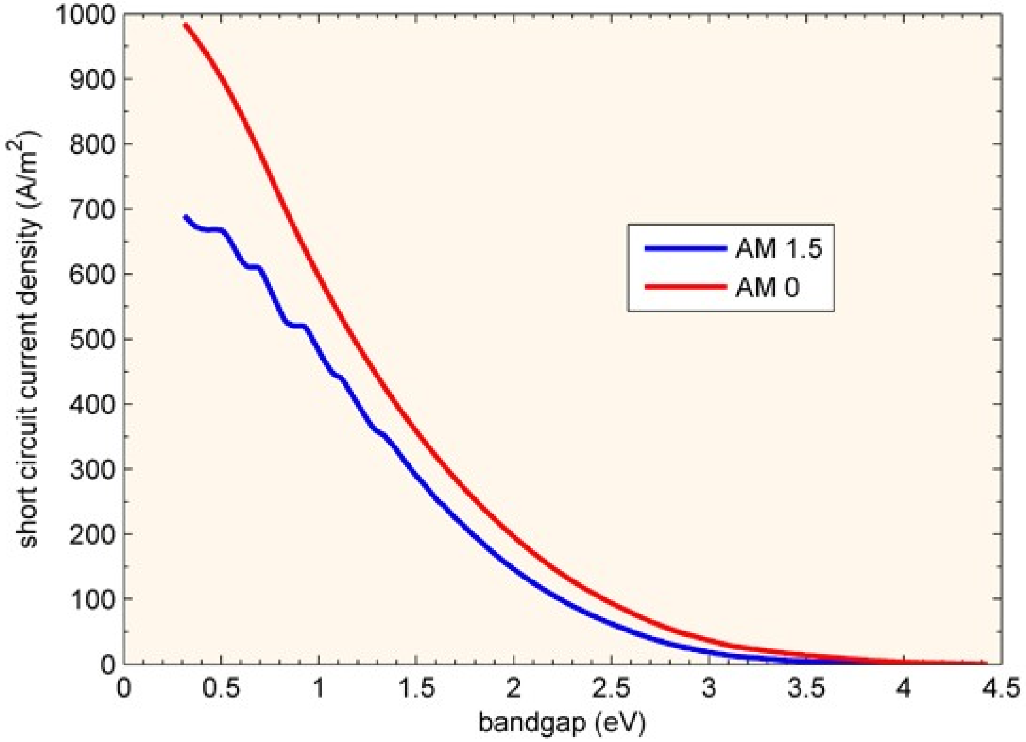
Better technology

Economics of scale

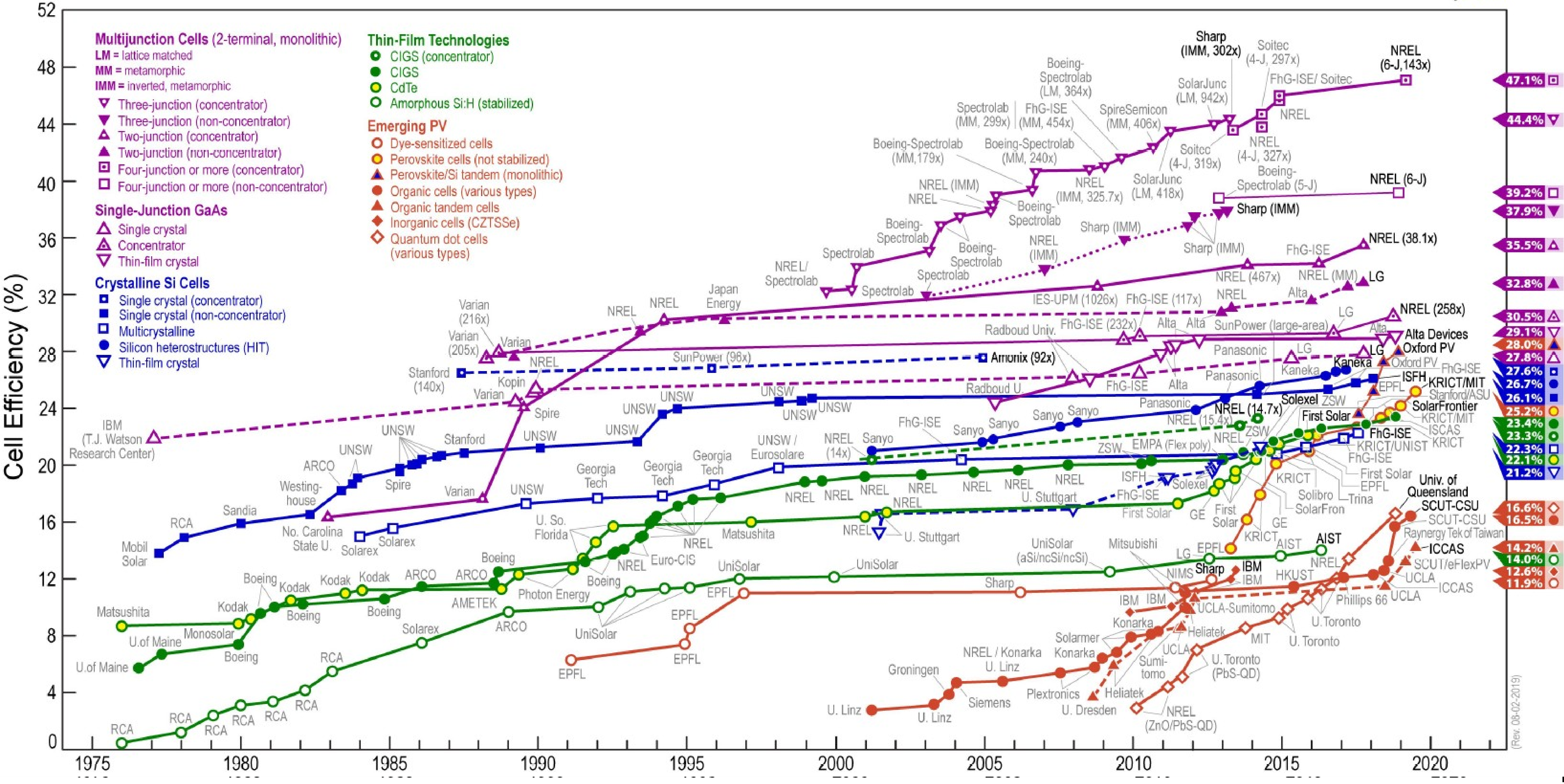


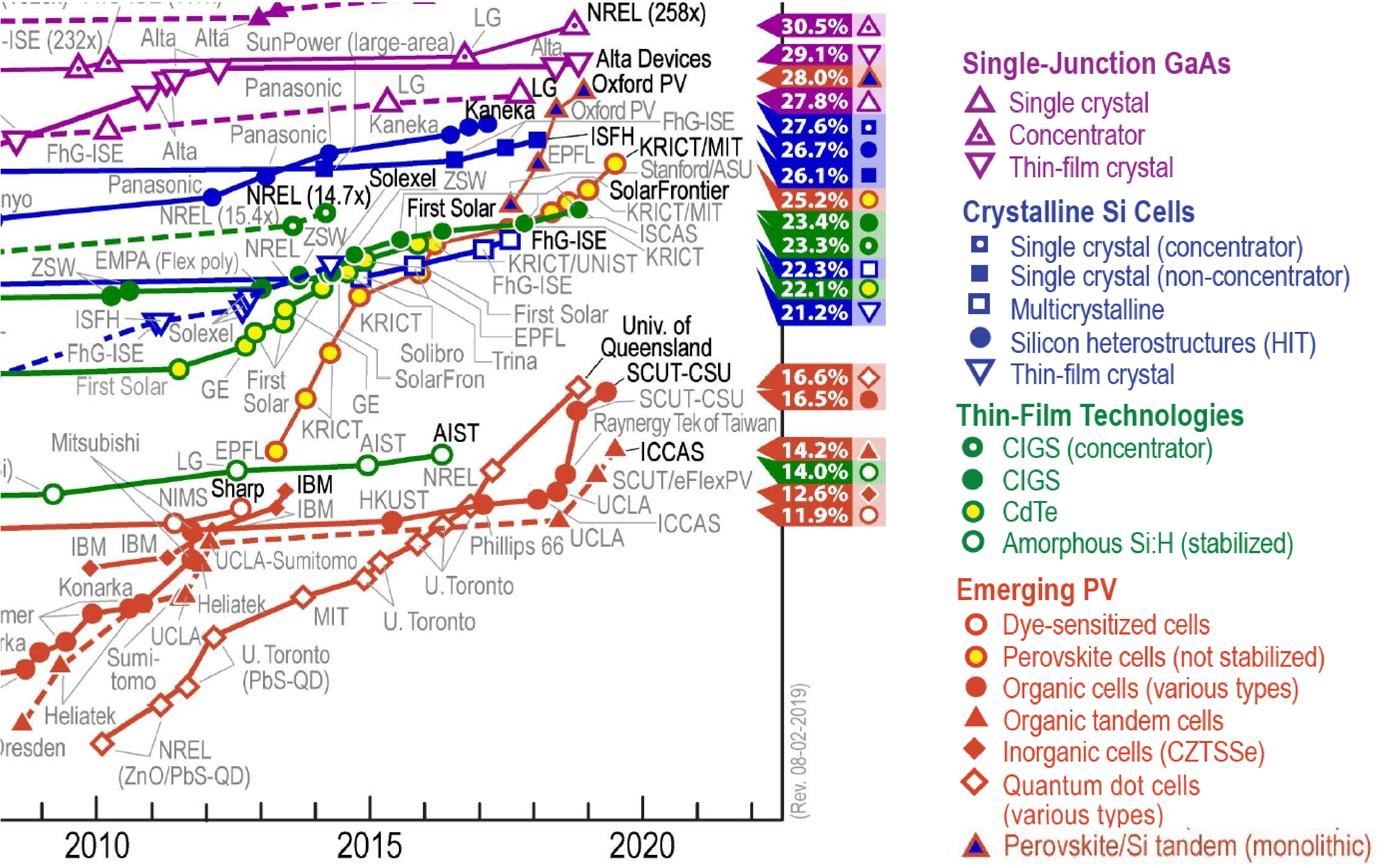
Solar cell models and parameters



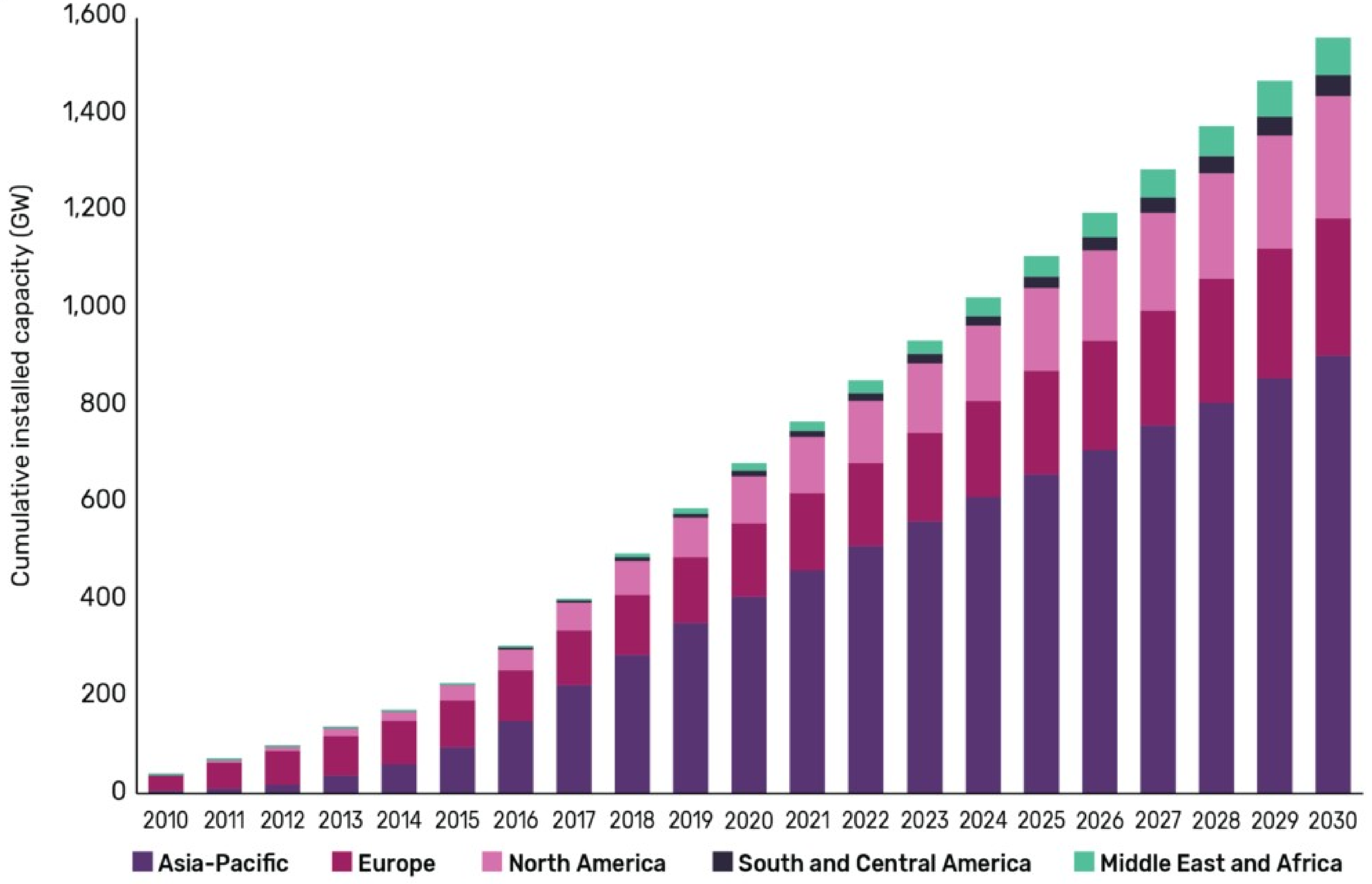


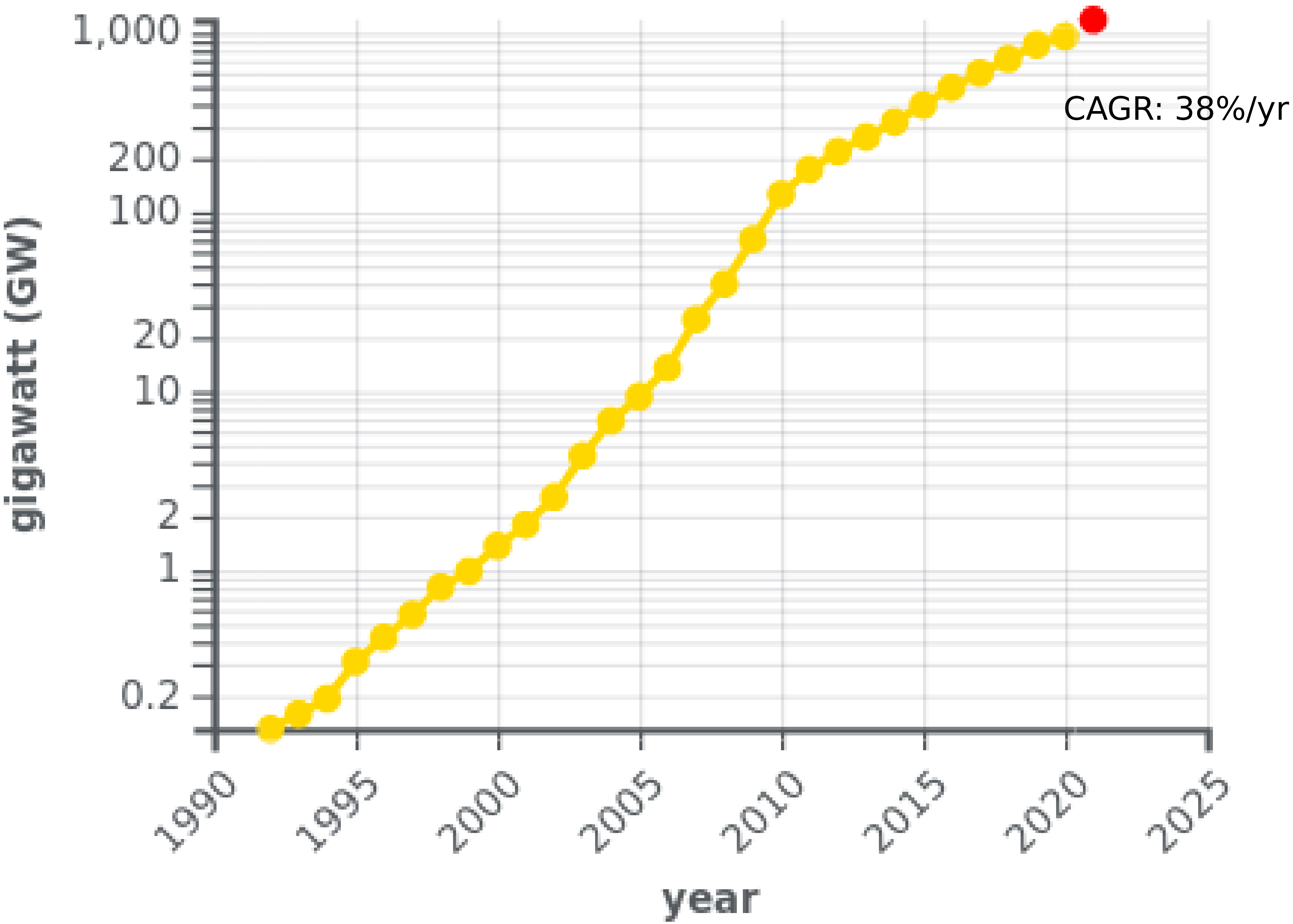
Best Research-Cell Efficiencies



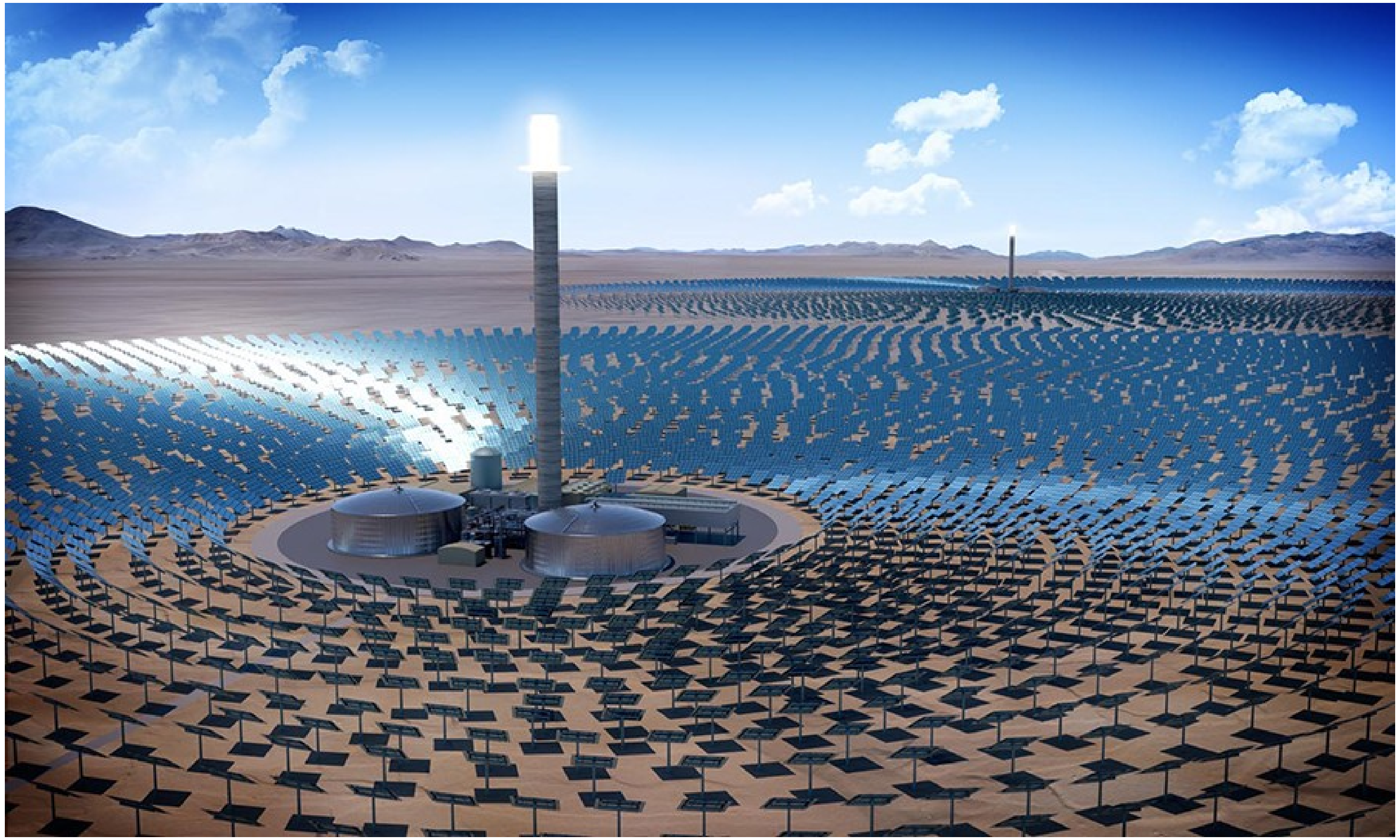

30.5%
29.1%
28.0%
27.8%
27.6%
26.7%
26.1%
25.2%
23.4%
23.3%
22.3%
22.1%
21.2%
16.6%
16.5%
14.2%
14.0%
12.6%
11.9%
2010
2015
2020
(Rev. 08-02-2019)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells
(various types)
Perovskite/Si tandem (monolithic)

Cumulative global solar PV installed capacity by region, 2010-2030



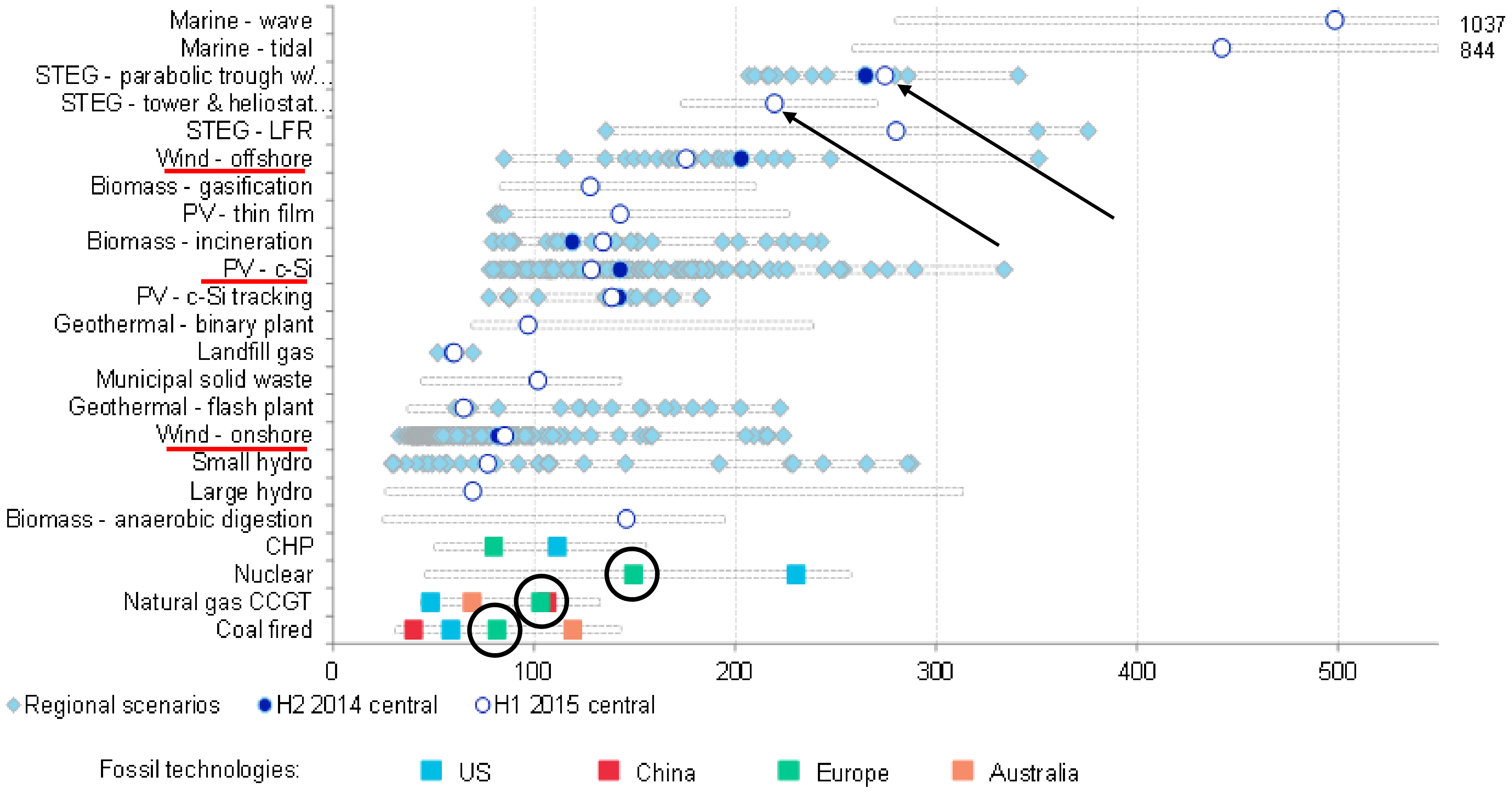

1,000
200
100
20
10
2
1
0.2
gigawatt (GW)
1990
1995
2000
2005
2010
2015
2020
2025
year
CAGR: 38%/yr

CSP

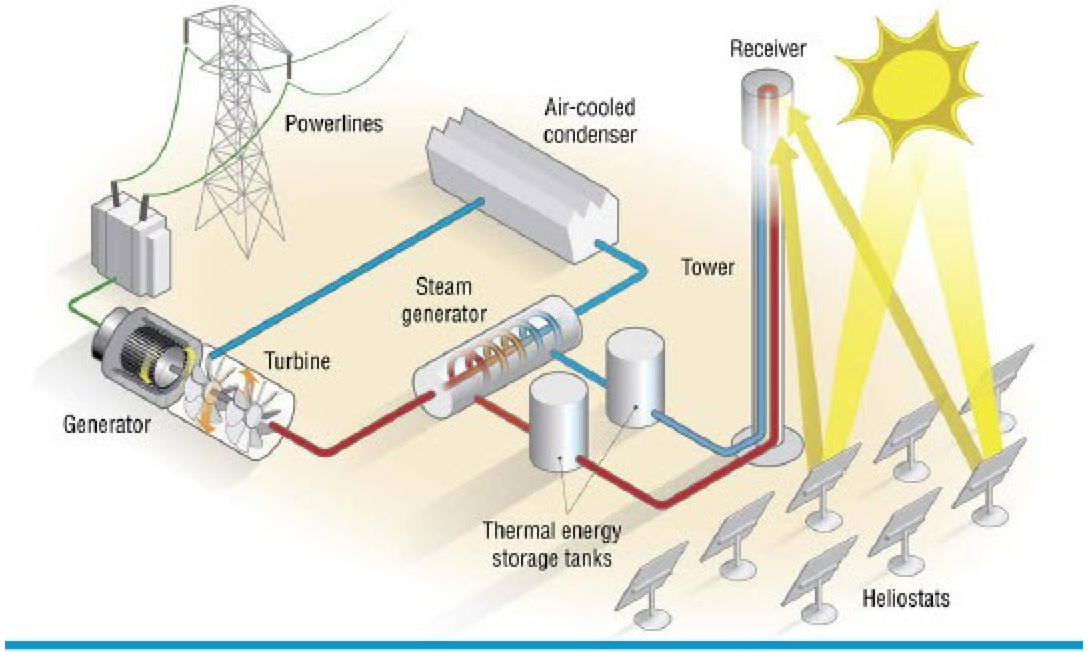


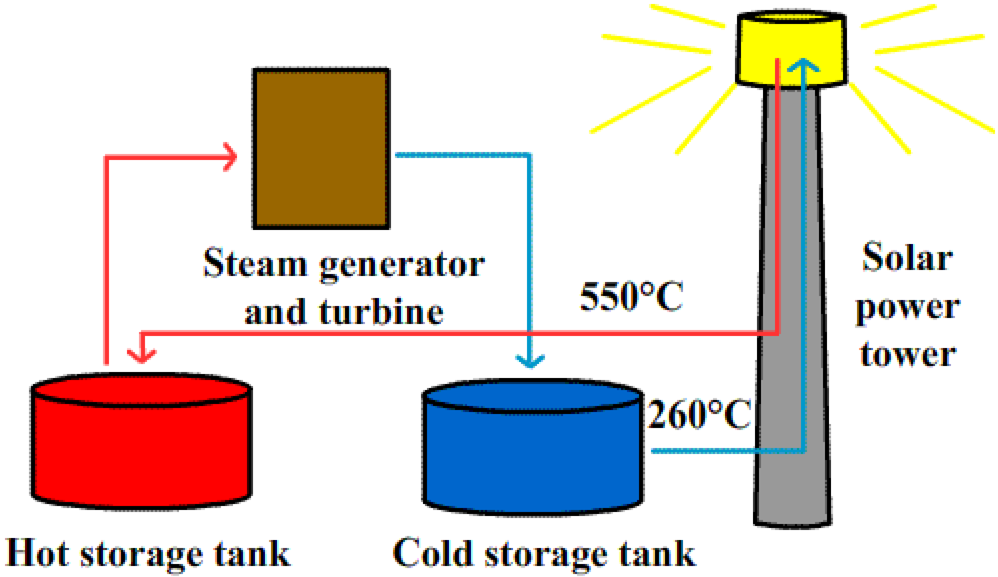
H1 2015 LEVELISED COST OF ELECTRICITY, *CENTRAL* AND REGIONAL SCENARIOS ($/MWH)

Bloomberg NEW ENERGY FINANCE



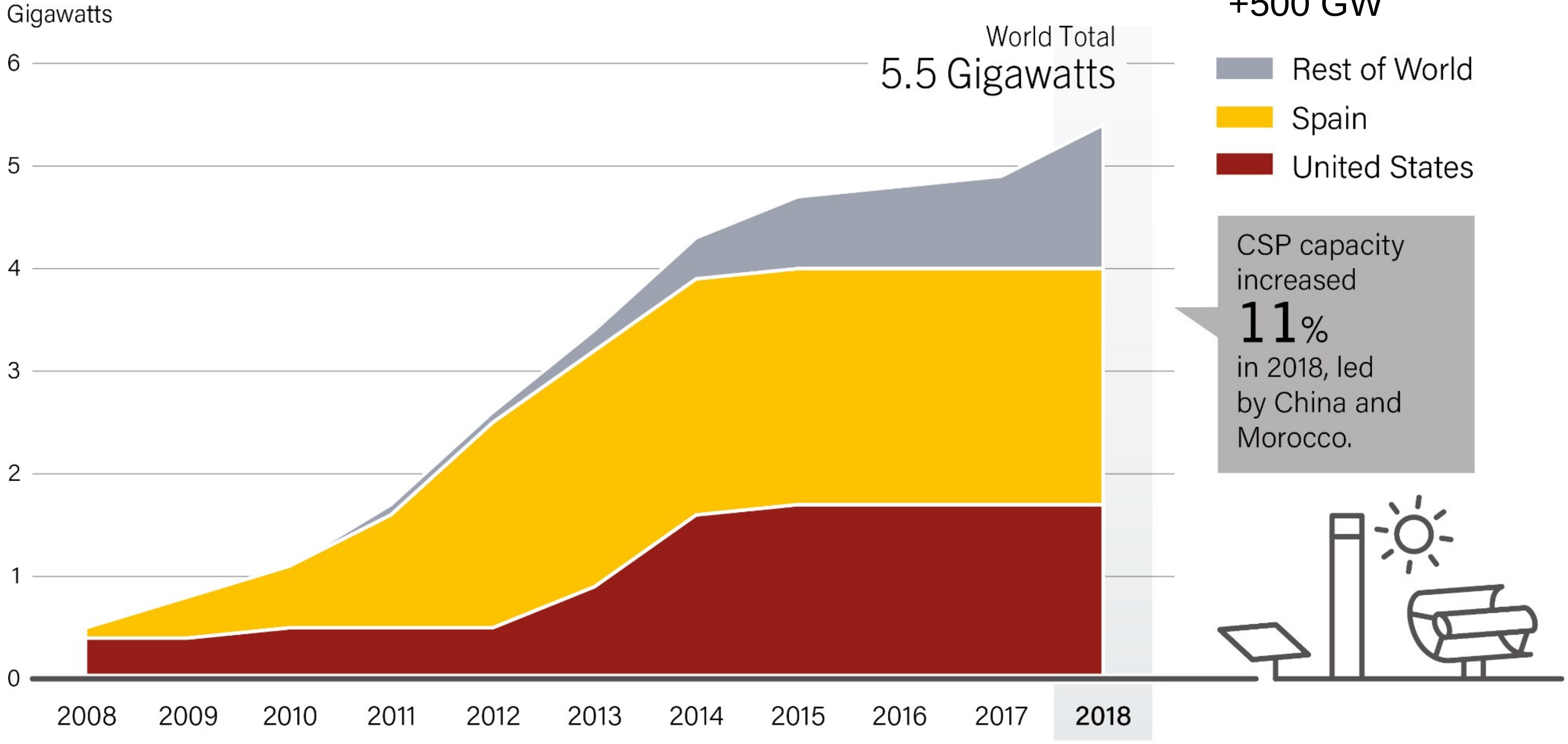
CSP can have storage!





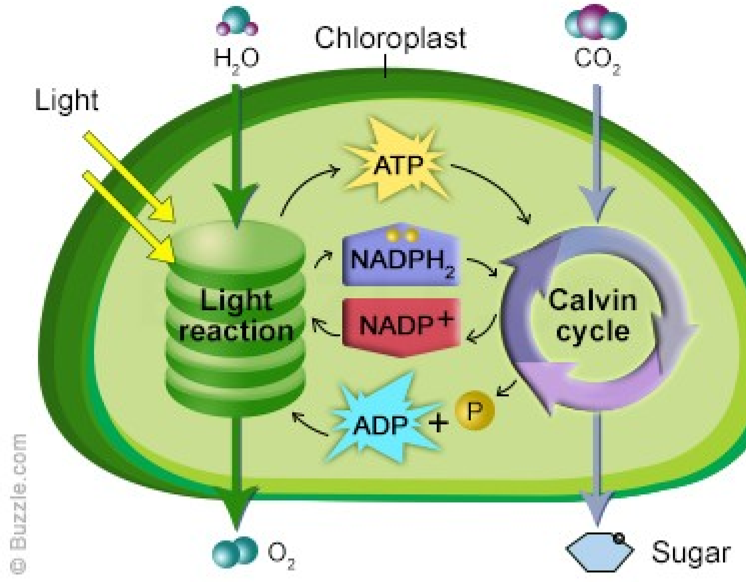
Concentrating Solar Thermal Power Global Capacity, by Country and Region, 2008-2018

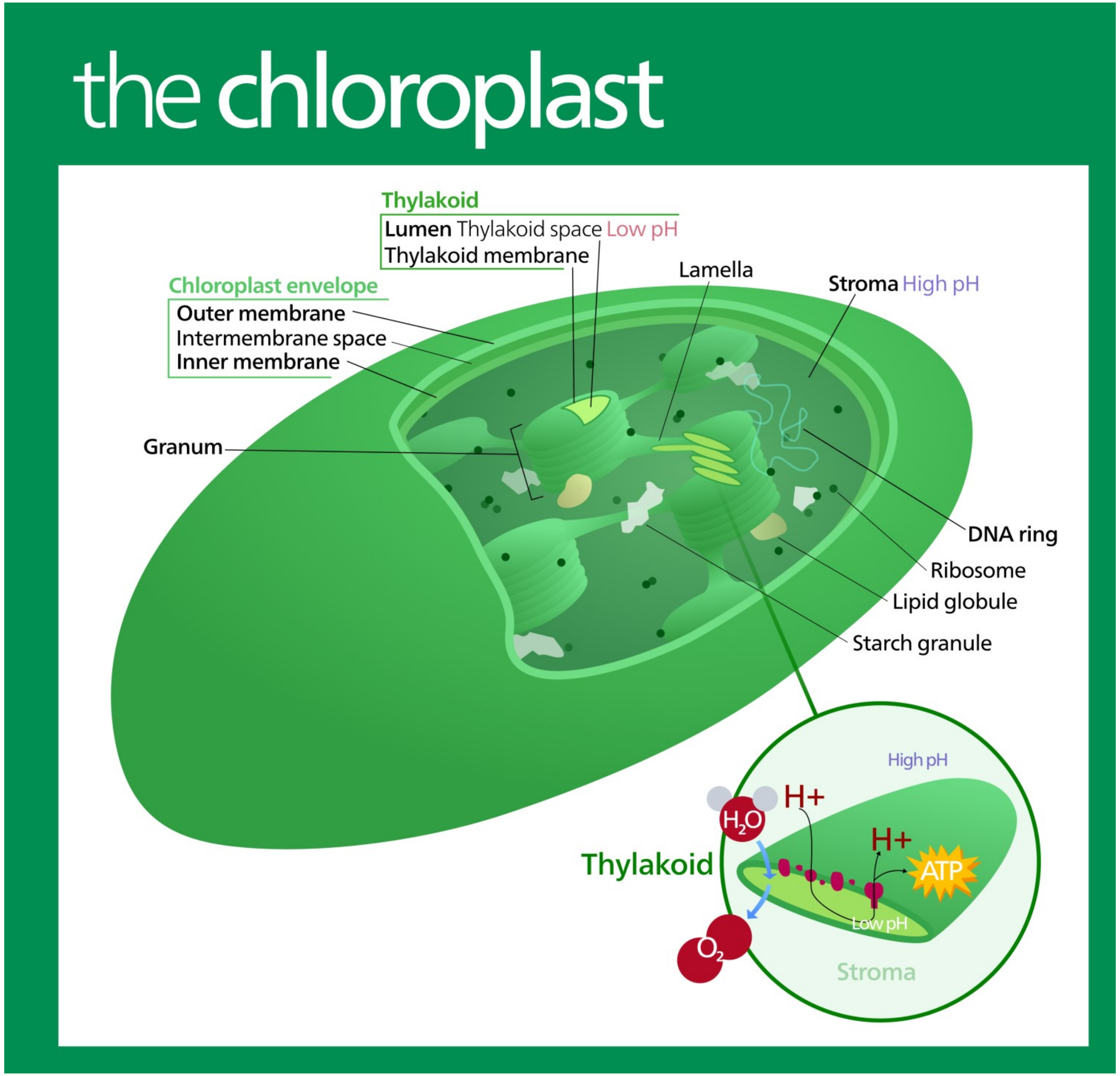
PV in 2018:
+500 GW



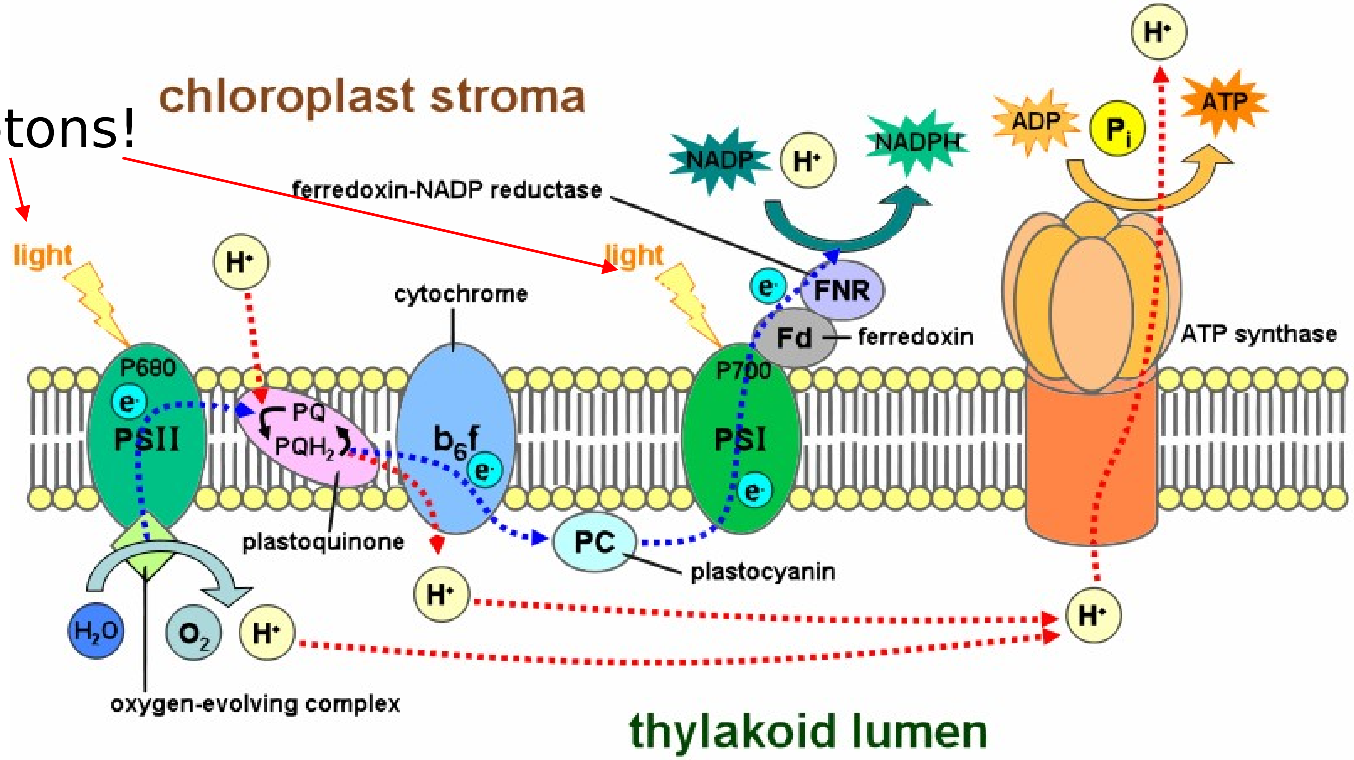
Direct solar-to-fuel

How does nature do it?

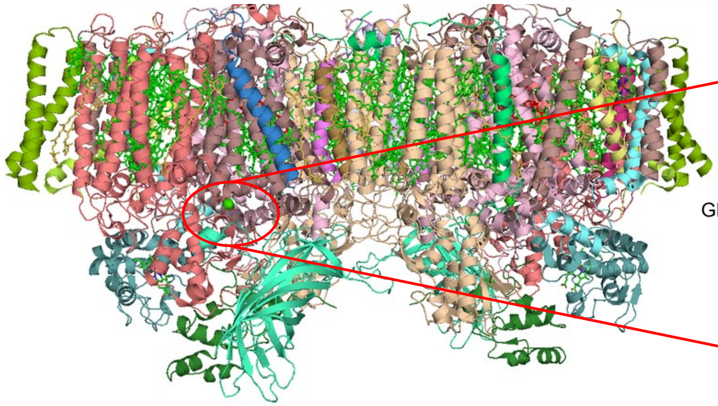


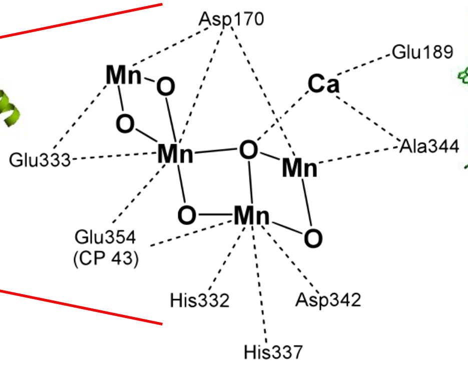


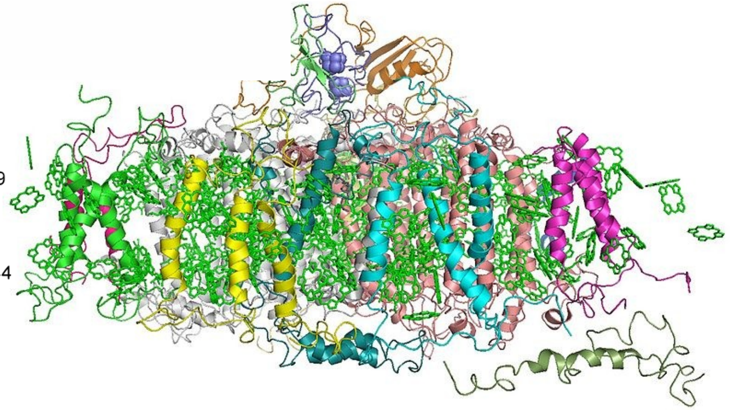
Two photons!



NB. Oxidation and reduction happens on opposite sides of the membrane!



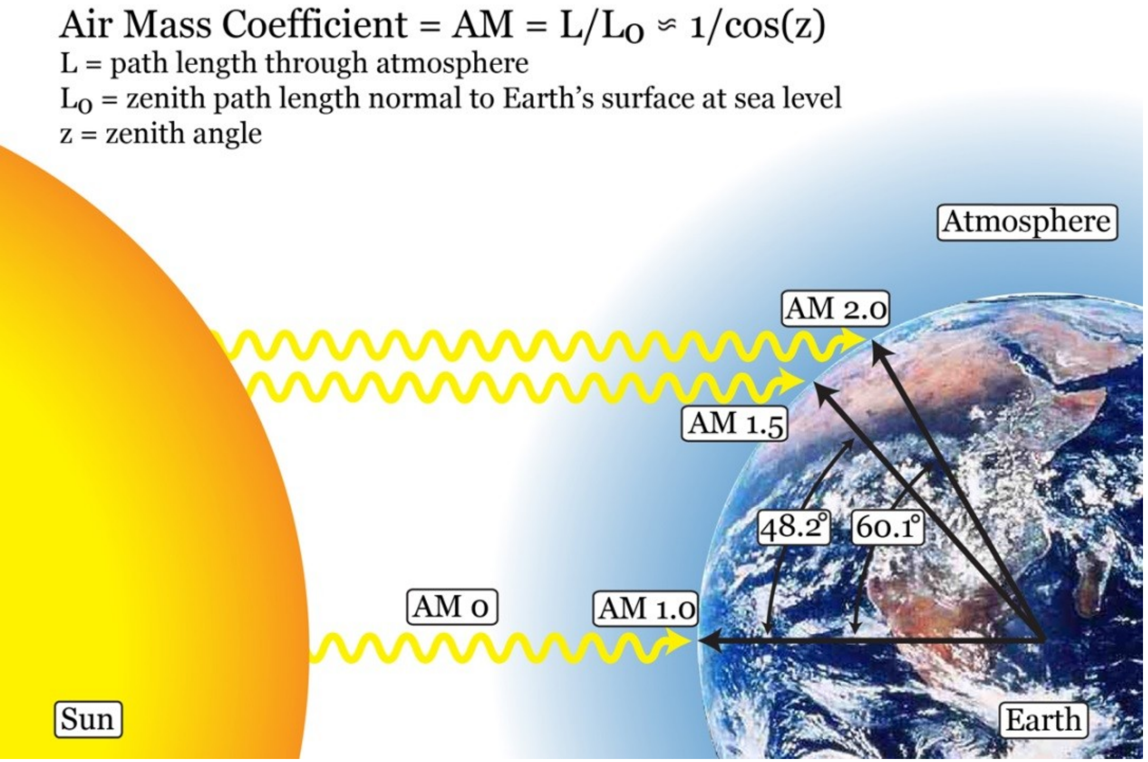


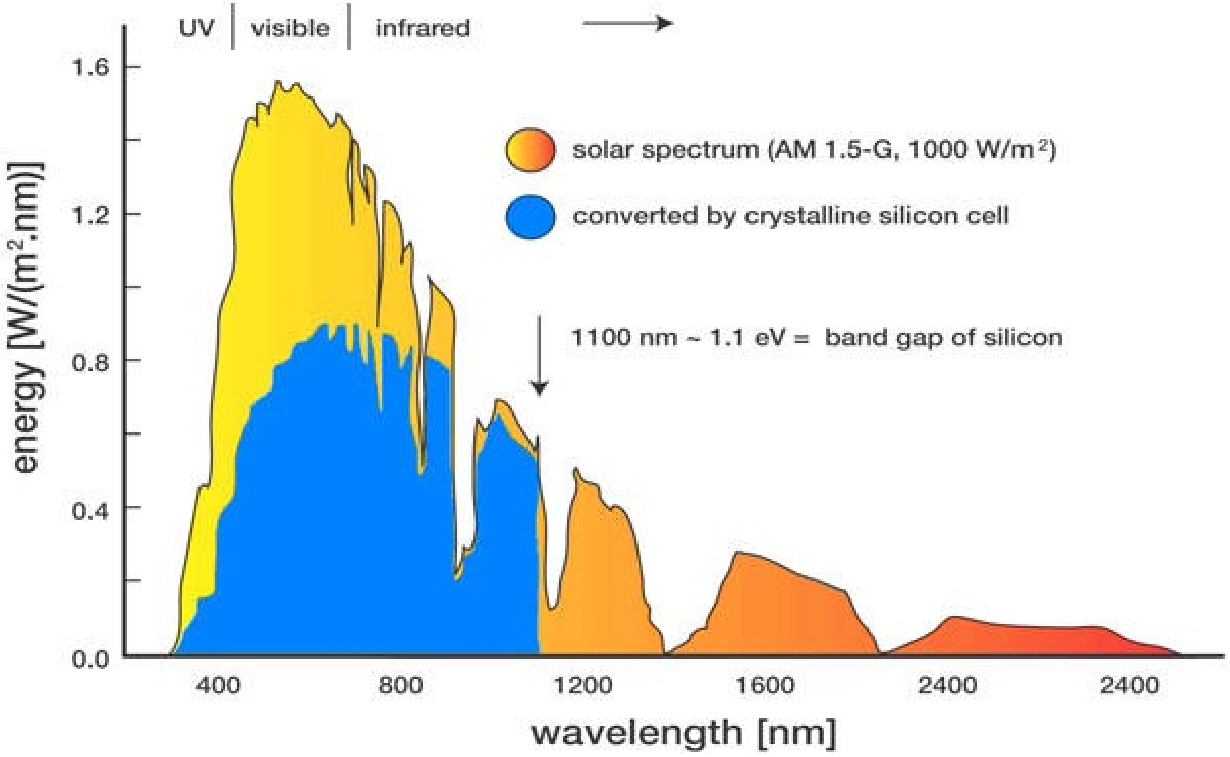


PS2

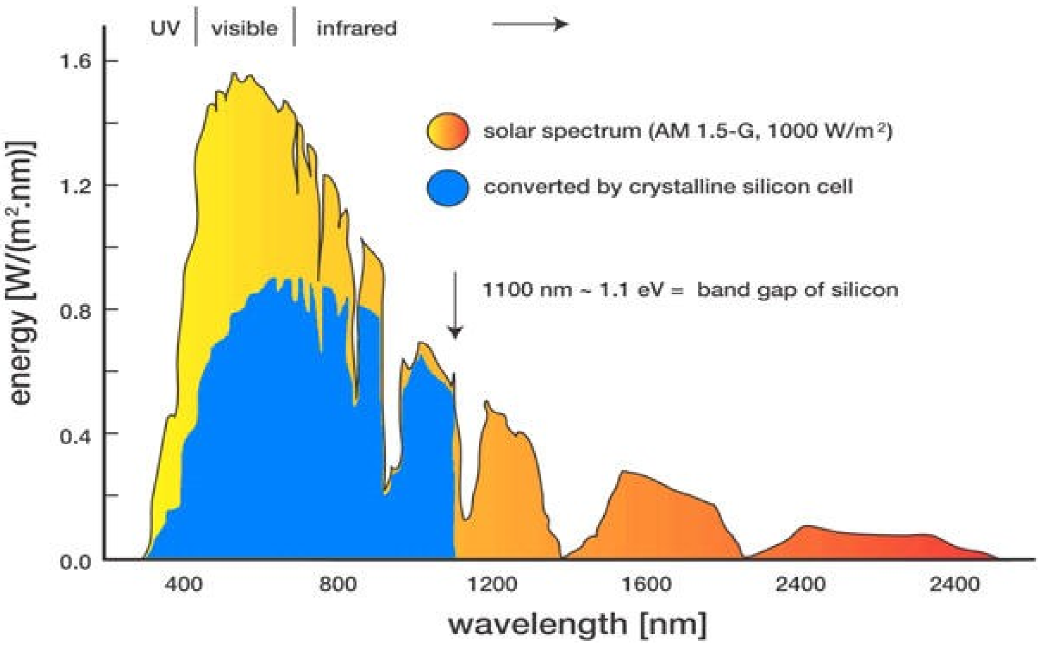
PS1

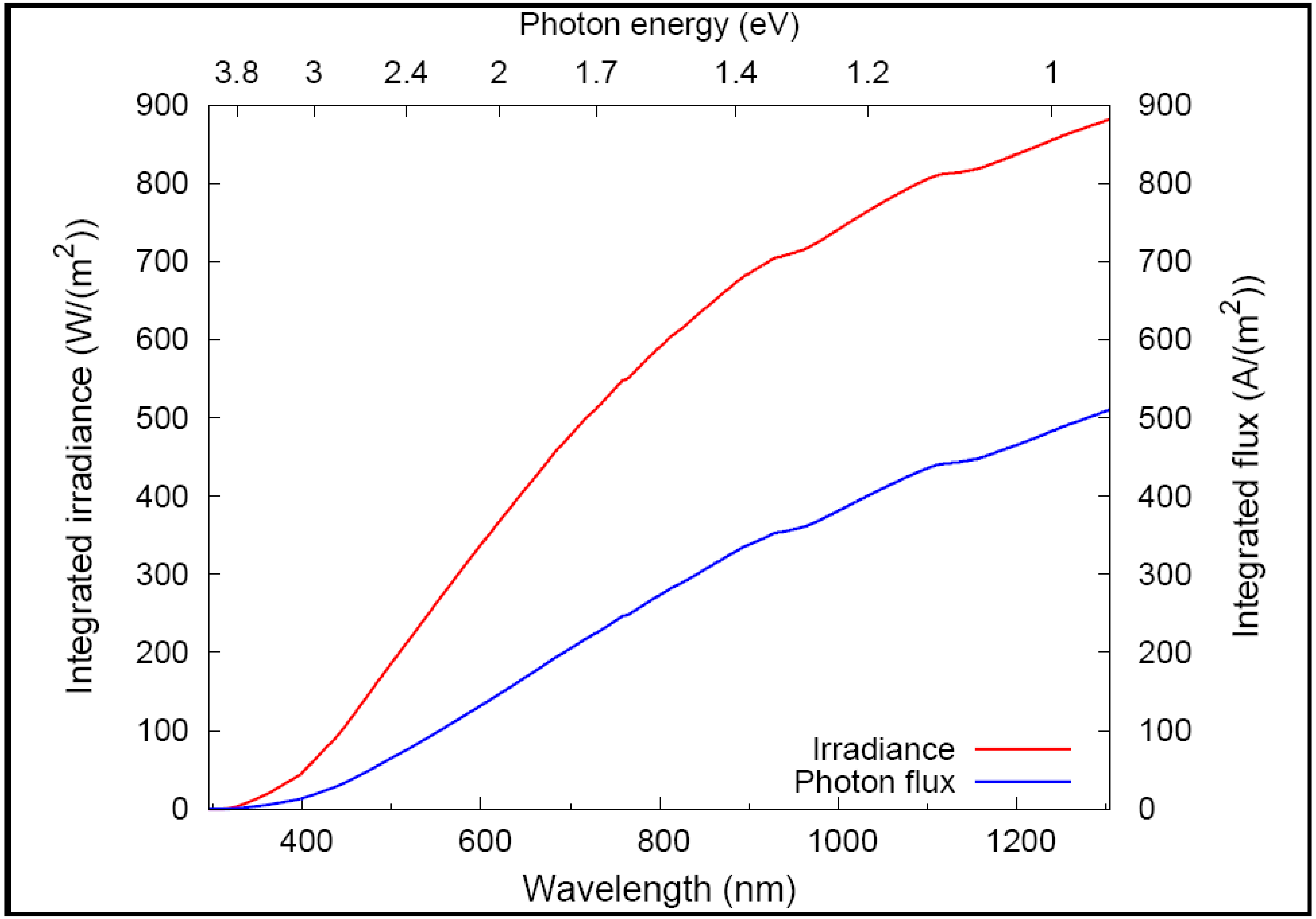
Why use two photons?



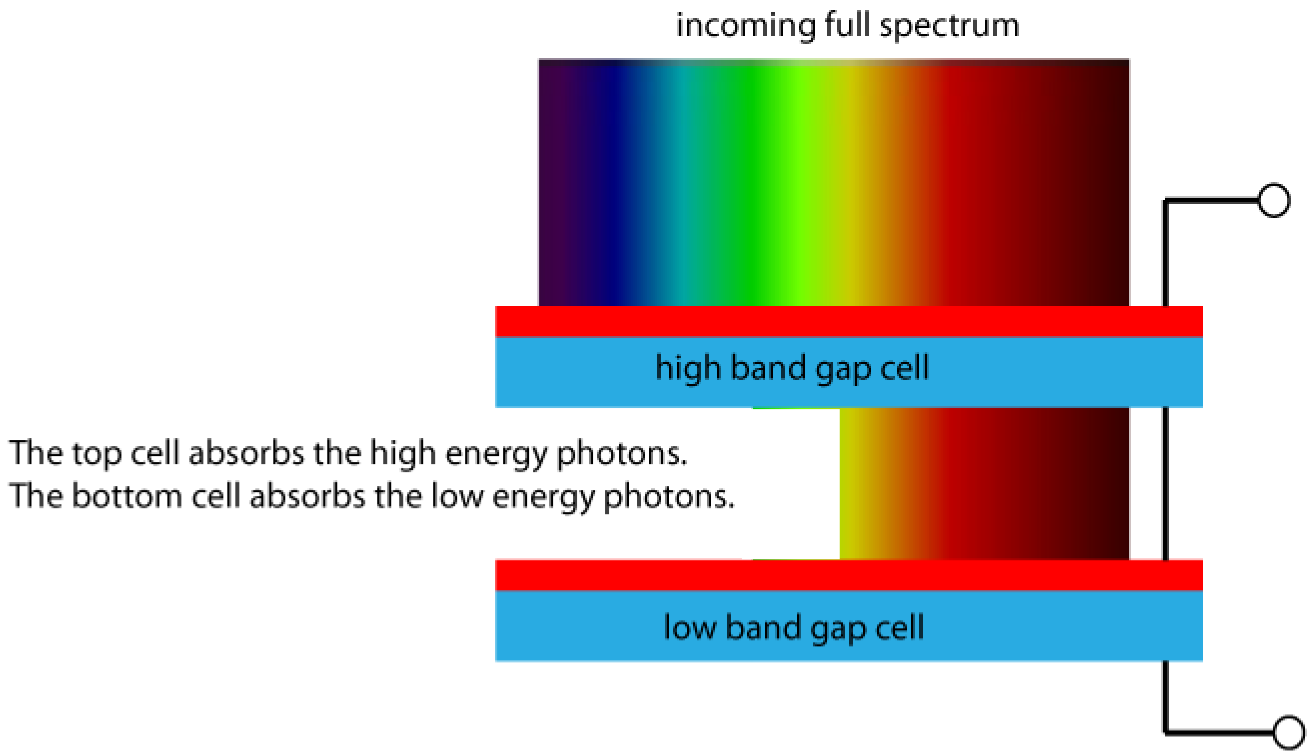


Integrated spectrum



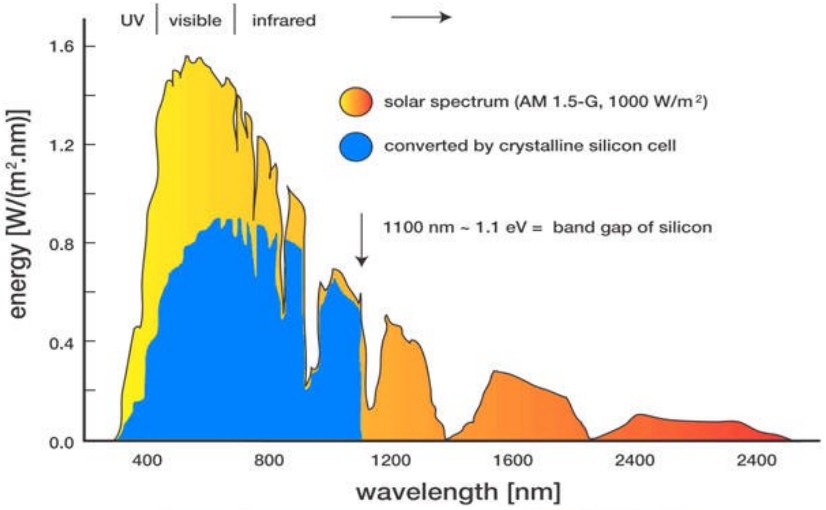


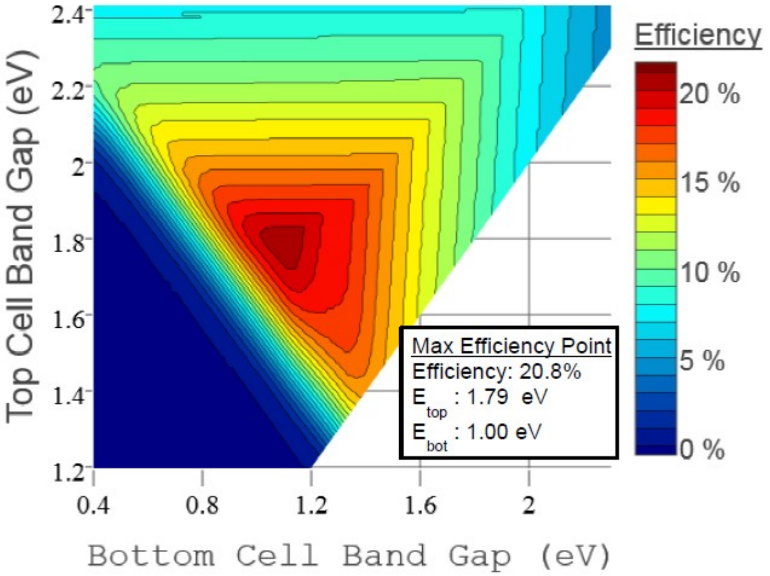
Divide and conquer

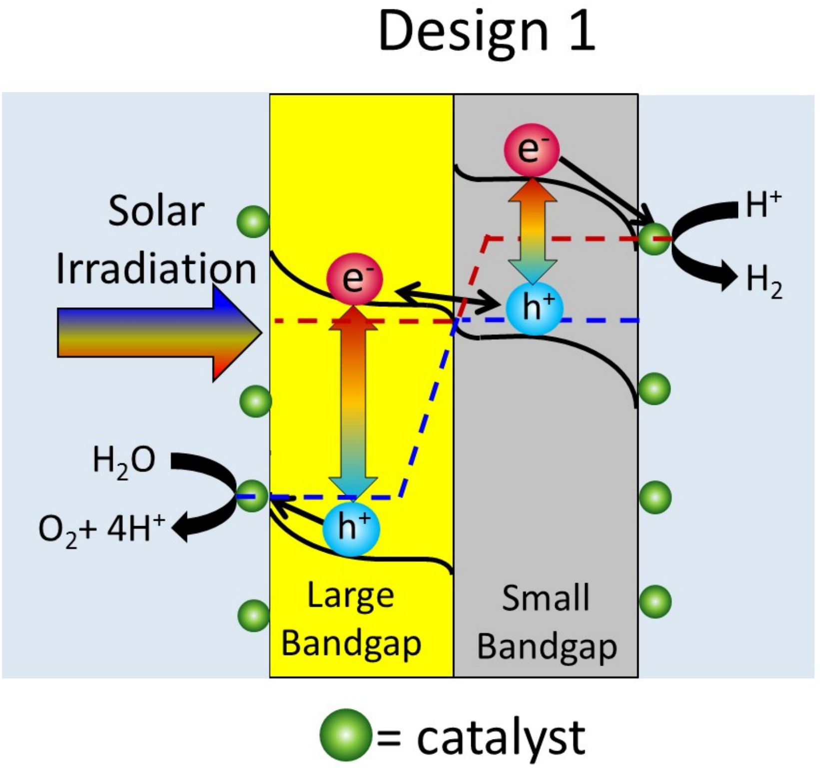


Almost cut the current in half –
but more than double the voltage

Divide and conquer

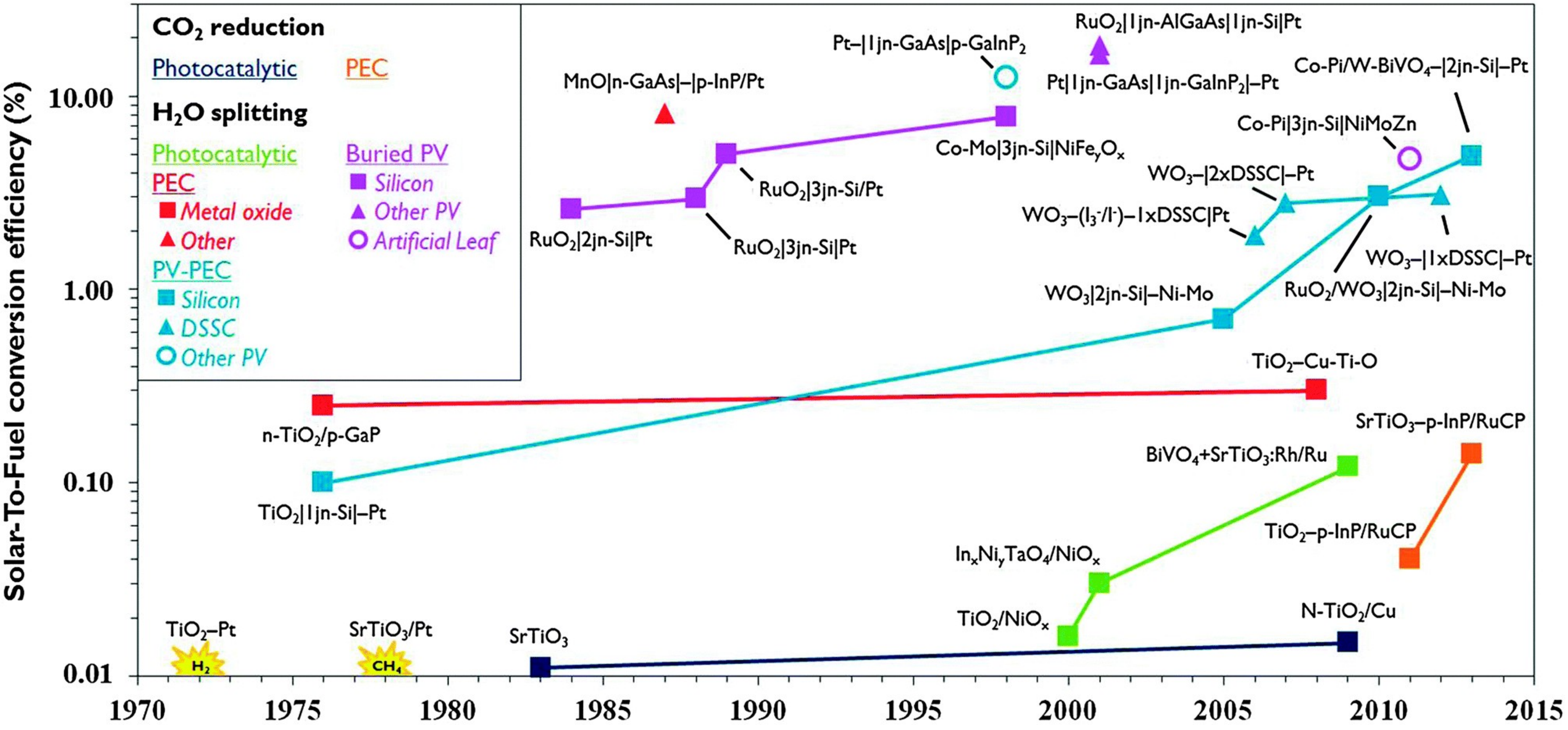






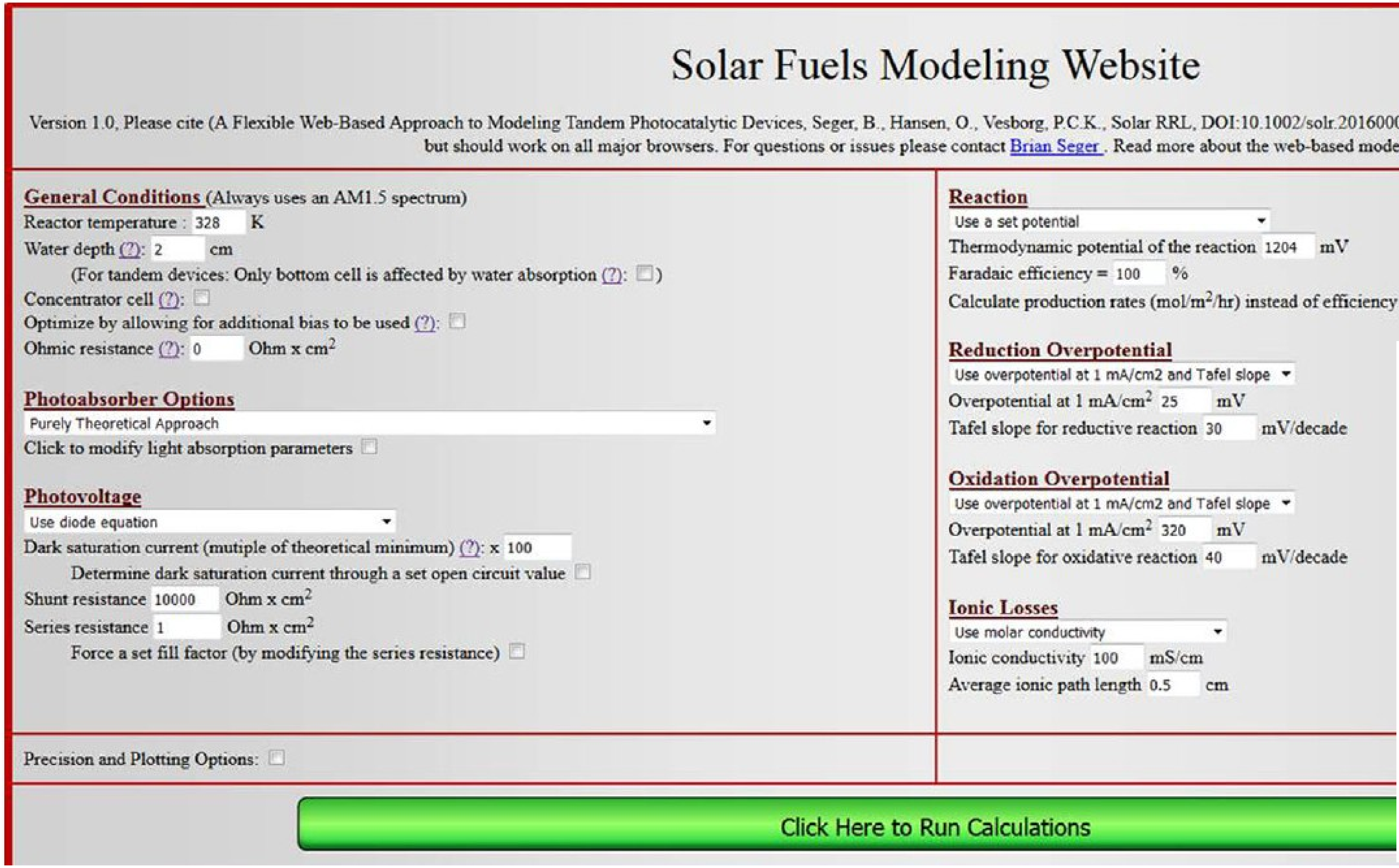
Seger, B. et al., *JACS*, 135, 1057, **2013**

Seger, B, et al., *Sol. RRL*, 1, 1600013, **2017**



Rongé, J. et al.,
Chem. Soc. Rev. , 43, 7963, **2014**

Online modeling tool



Solar Fuels Modeling Website

Version 1.0, Please cite (A Flexible Web-Based Approach to Modeling Tandem Photocatalytic Devices, Seger, B., Hansen, O., Vesborg, P.C.K., Solar RRL, DOI:10.1002/solr.201600013) when using this mode. Program optimized for Firefox, but should work on all major browsers. For questions or issues please contact Brian Seger . Read more about the web-based model here.

General Conditions (Always uses an AM1.5 spectrum)
Reactor temperature : 328 K
Water depth (?): 2 cm
(For tandem devices: Only bottom cell is affected by water absorption (?):)
Concentrator cell (?):
Optimize by allowing for additional bias to be used (?):
Ohmic resistance (?): 0 Ohm x cm^2

Photoabsorber Options
Purely Theoretical Approach
Click to modify light absorption parameters

Photovoltage
Use diode equation
Dark saturation current (mutiple of theoretical minimum) (?): x 100
Determine dark saturation current through a set open circuit value
Shunt resistance 10000 Ohm x cm^2
Series resistance 1 Ohm x cm^2
Force a set fill factor (by modifying the series resistance)

Reaction
Use a set potential
Thermodynamic potential of the reaction 1204 mV
Faradaic efficiency = 100 %
Calculate production rates (mol/m^2/hr) instead of efficiency

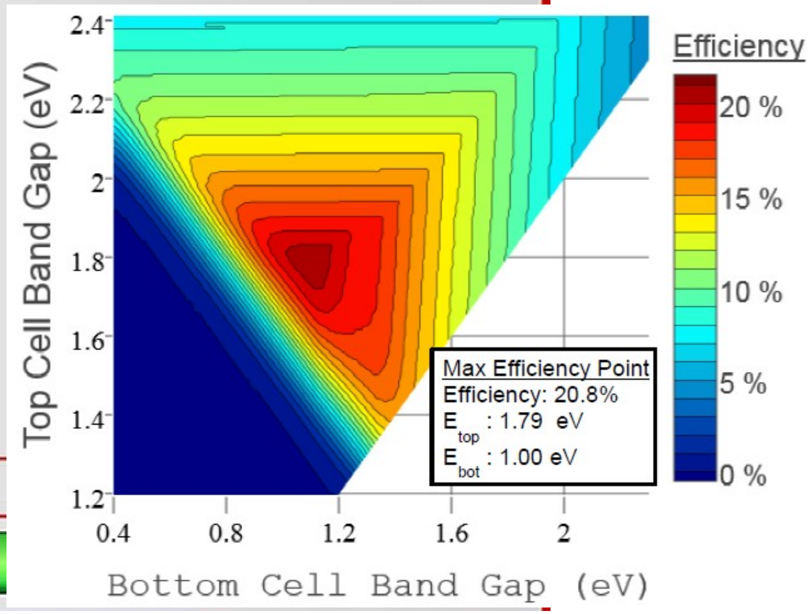
Reduction Overpotential
Use overpotential at 1 mA/cm2 and Tafel slope
Overpotential at 1 mA/cm^2 25 mV
Tafel slope for reductive reaction 30 mV/decade

Oxidation Overpotential
Use overpotential at 1 mA/cm2 and Tafel slope
Overpotential at 1 mA/cm^2 320 mV
Tafel slope for oxidative reaction 40 mV/decade

Ionic Losses
Use molar conductivity
Ionic conductivity 100 mS/cm
Average ionic path length 0.5 cm

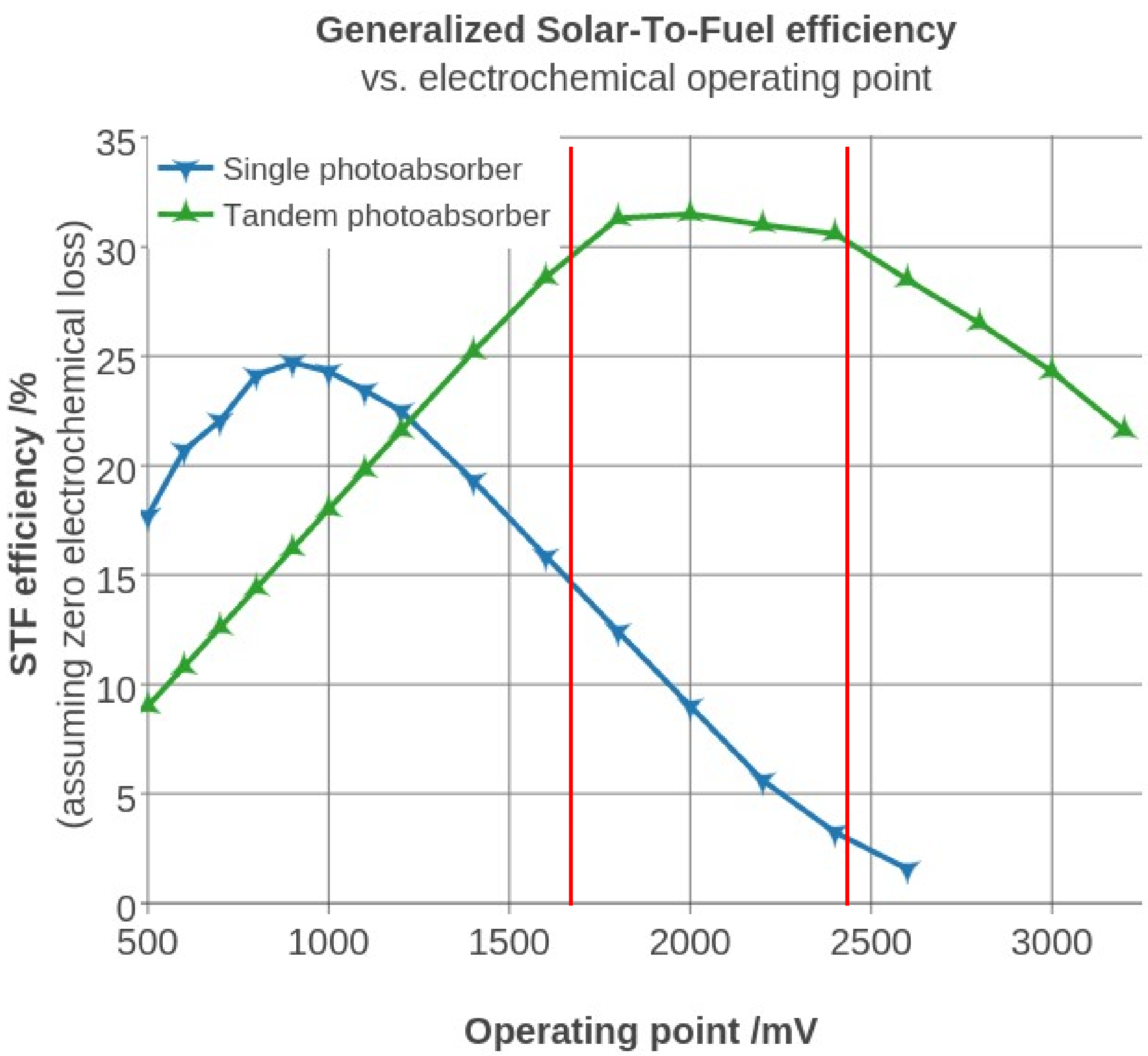
Precision and Plotting Options:

Click Here to Run Calculations



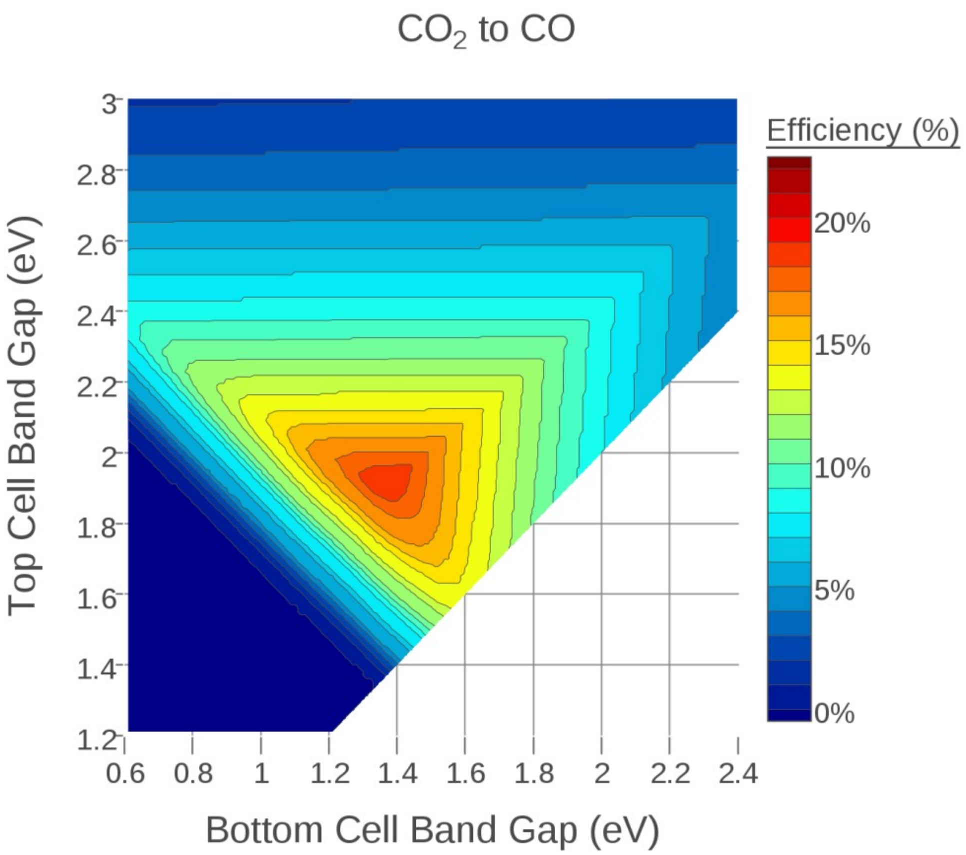
Seger, Hansen, Vesborg,
Sol. RRL, 1, 1600013, **2017**

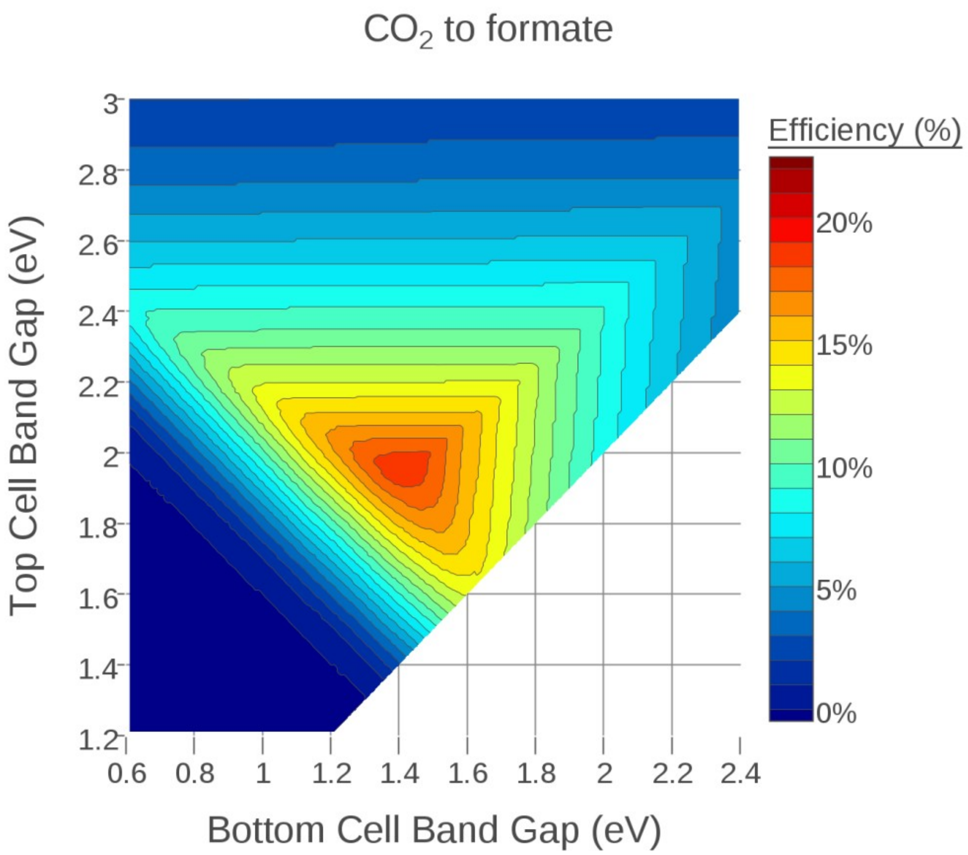
Generalized efficiencies – beyond water splitting



Vesborg, D.C.K & Seger, B., *Chem. Mater.*, 28, 8844, **2016**

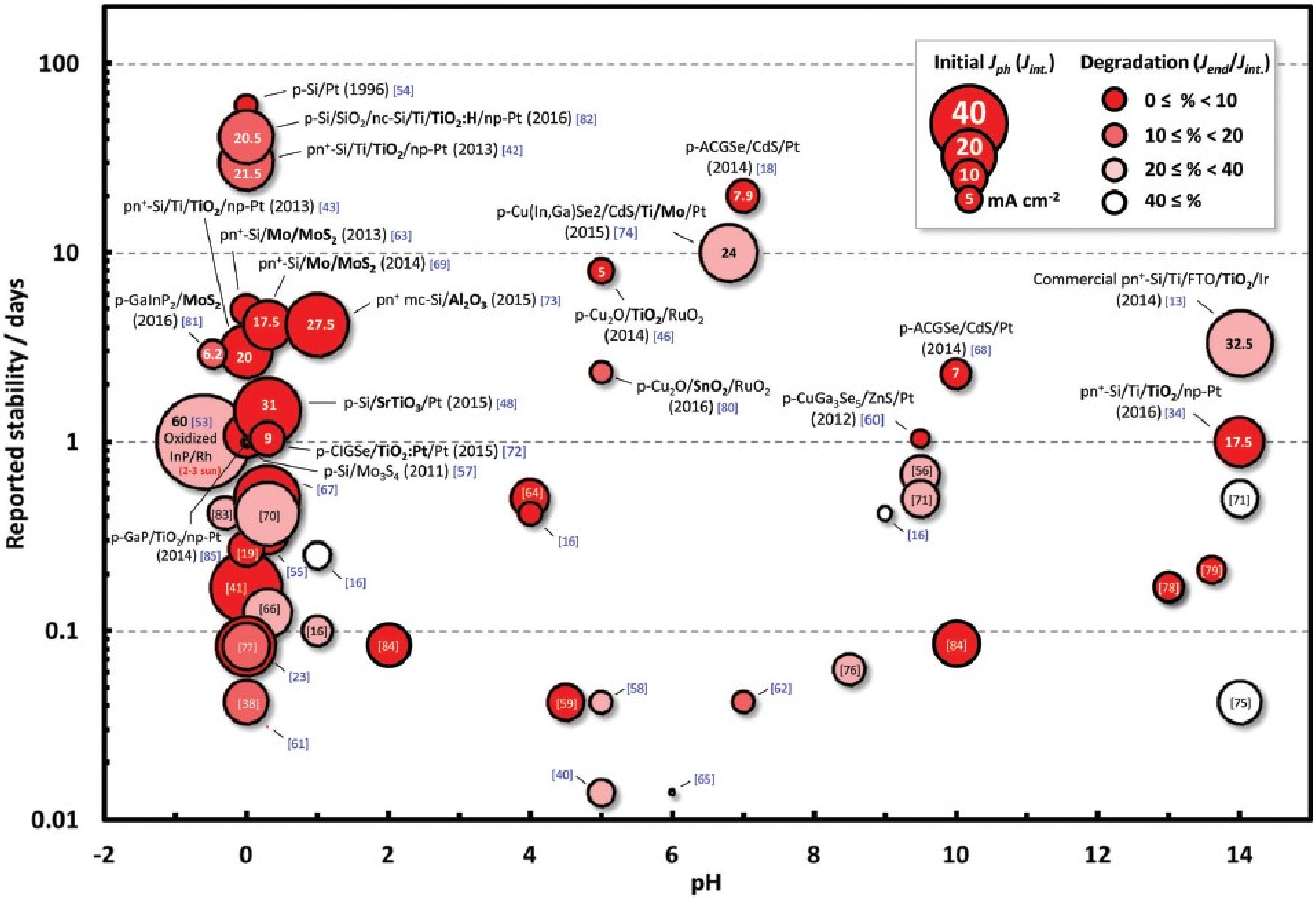
Direct CO_2 reduction





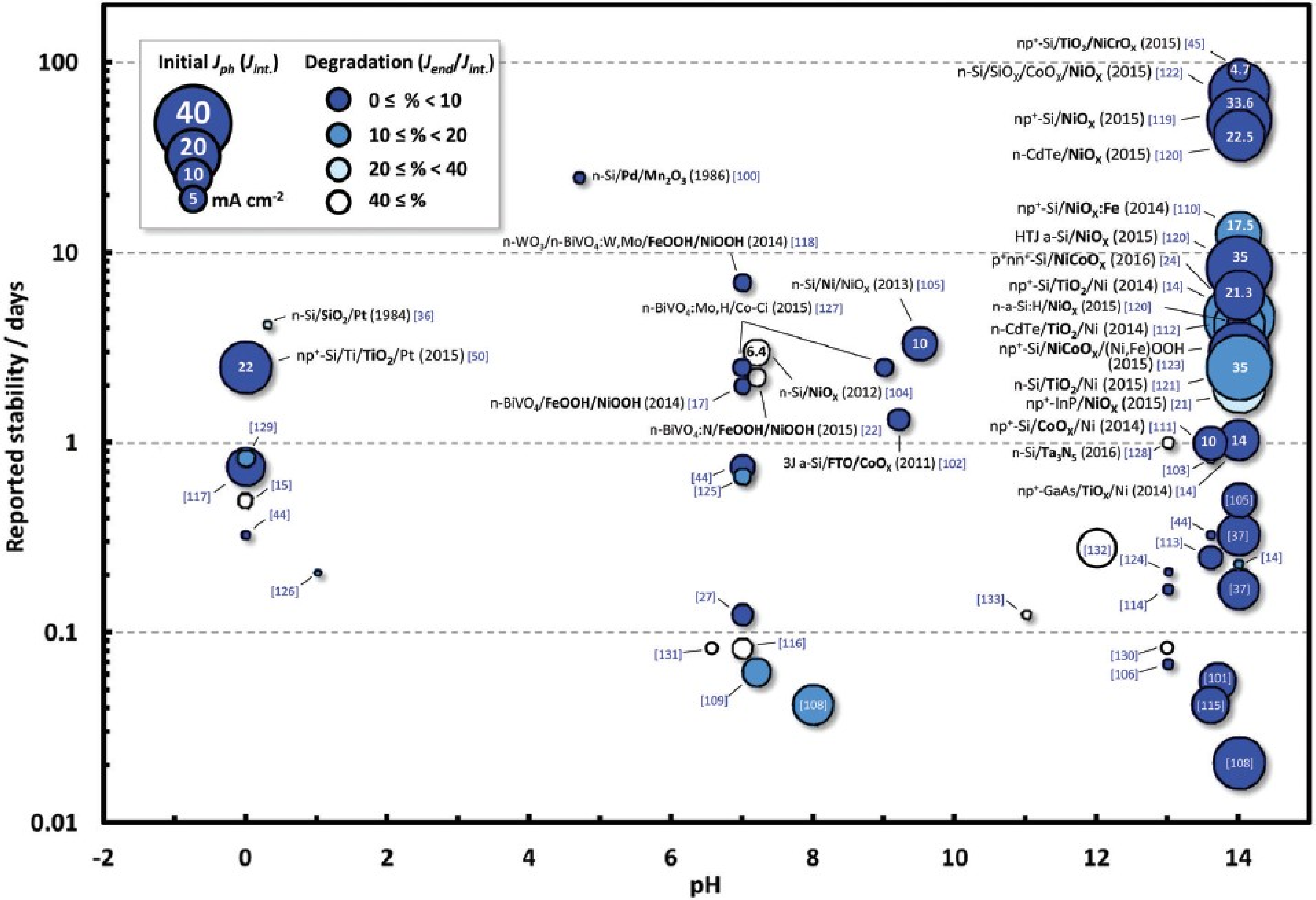
2-electron products look most promising due to efficiency and *selectivity*

Vesborg, D.C.K & Seger, B.,
Chem. Mater., 28, 8844, **2016**



H_2 evolution

Bae, D. et al., *Chem. Soc. Rev.*, **2017**



O_2 evolution

Bae, D. et al.,
Chem. Soc. Rev., **2017**


To do list

Q1 Explore the PVeducation site

Go to http://www.pveducation.org

Read section 2. At least read from “Basics of light” and to “Air mass”.

At which wavelength does a hot metal filament at T=2500 K (behaves like a black body) have its peak irradiance? What happens it you can somehow increase the temperature to 3000 K?

A piece of steel glows bright orange around 1200 K (see chart). How can this be?
Look up "Kruithof curve".

Read section 4.2. In particular, read about ”short circuit current” and ”open circuit voltage”.

color	approximate temperature		
	°F	°C	K
faint red	930	500	770
blood red	1075	580	855
dark cherry	1175	635	910
medium cherry	1275	0690	0965
cherry	1375	0745	1020
bright cherry	1450	0790	1060
salmon	1550	0845	1115
dark orange	1630	0890	1160
orange	1725	0940	1215
lemon	1830	1000	1270
light yellow	1975	1080	1355
white	2200	1205	1480

Q2 A closer look at sunlight

Look up the standardized solar spectra ASTM-G 173-03
www.nrel.gov/grid/solar-resource/spectra-am1.5.html
(Download the .xls spreadsheet)

Co-plot AM1.5D and AM1.5G in the range 350 nm to 1300 nm

- Plot irradiance as a function of wavelength
- Work out and plot photon flux as a function of wavelength

Why might the photon flux plot more interesting than irradiance to a solar cell designer?

Figure out what the the ”D” and ”G” spectra are. Why are they different?

Which of those spectra is relevant for PhotoVoltaics and which is relevant for ConcentratedSolarPower?

How is the blue/red balance affected as you go from morning conditions to noon conditions (for both ”D” and ”G”)?

Q3 Play with PEC modelling site and tandems

Navigate to http://solarfuelsmodeling.com

Using default parameters for the electrochemistry (parameters on the right-hand side)

- What is the best solar-to-hydrogen efficiency you can hope for using a single bandgap absorber – and what is the optimum bandgap?
- Ditto for a tandem absorber. What is the best efficiency and what are the optimum bandgaps?
- Explain why the tandem is much better.
- Explain why highest of the two bandgaps in the optimum tandem is lower than the bandgap of the optimum single absorber.

Looking at the single absorber, what happens as you change the temperature of the cell? Is it good or bad if the cell heats up in the sun?