Materials challenges for terawatt-scale photovoltaics (PV)

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4TU.HTM Symposium Dutch Materials 2017
Beatrixgebouw, Utrecht
13 October 2017

Content

- Thinking big
- The materials and technologies toolbox
- Towards ultra-high efficiencies and new applications
- Economics and market
- One size (no longer) fits all
- A view on the future

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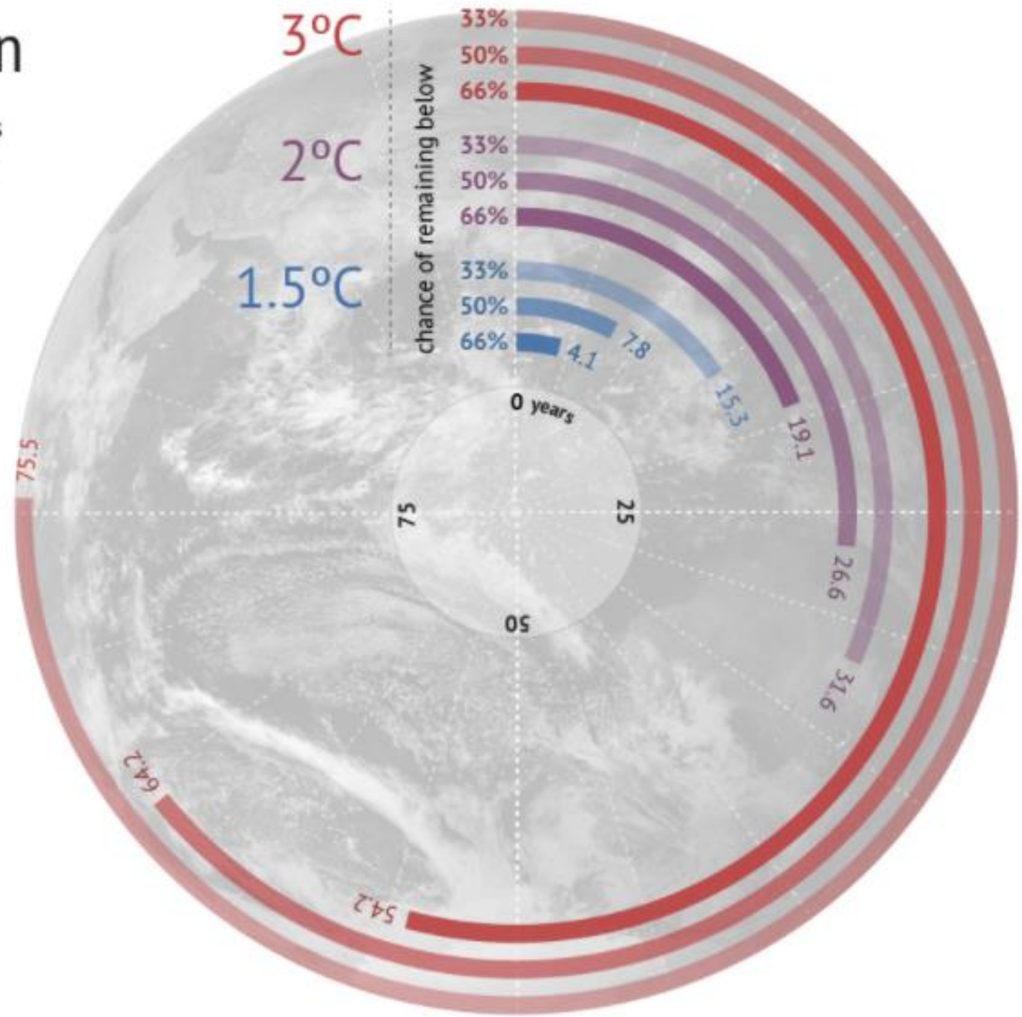
Bold thinking is needed:
multi-terawatts a.s.a.p.

ECN

Carbon Countdown

As of the start of 2017, how many years of current emissions would use up the IPCC's carbon budgets for different levels of warming?



CarbonBrief
CLEAR ON CLIMATE

Photo: NASA Goddard Space Flight Center
Stopwatch icon: T-Kot/Shutterstock.com

What is needed for impact?

- World primary/final energy consumption (rounded): 19/12 TW
- PV power expressed as power @ 1 sun (= 1000 W/m^2)
  e.g. at 25% module efficiency: 250 Wp/m^2
- Typical ratio average/peak power (= capacity factor)
  of PV systems (globally): 0.2

  PV "24/7" power: 50 W/m^2

→ **Covering 1% of current global energy requires ≈5000 km^2 module area**
(including conversion and storage losses)

Multi-terawatt deployment needed and possible

Terawatt-scale photovoltaics: Trajectories and challenges

Coordinating technology, policy, and business innovations

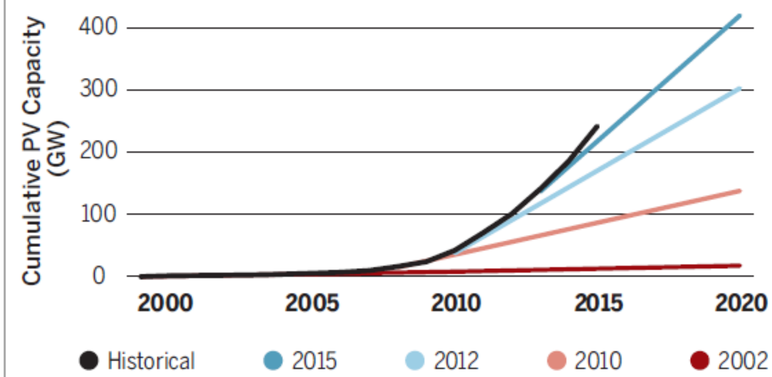
By **Nancy M. Haegel, Robert Margolis, Tonio Buonassisi, David Feldman, Armin Froitzheim, Raffi Garabedian, Martin Green, Stefan Glunz, Hans-Martin Henning, Burkhard Holder, Izumi Kaizuka, Benjamin Kroposki, Koji Matsubara, Shigeru Niki, Keiichiro Sakurai, Roland A. Schindler, William Tumas, Eicke R. Weber, Gregory Wilson, Michael Woodhouse, Sarah Kurtz**

NREL (US), FhG-ISE (DE) & AIST (JP)

Science, Vol. 356, Issue 6334, 141-143 (2017)

Cumulative PV installations

Projected (labeled by year of IEA publication) versus actual (labeled as "historical"). See supplementary materials for data sources and discussion.



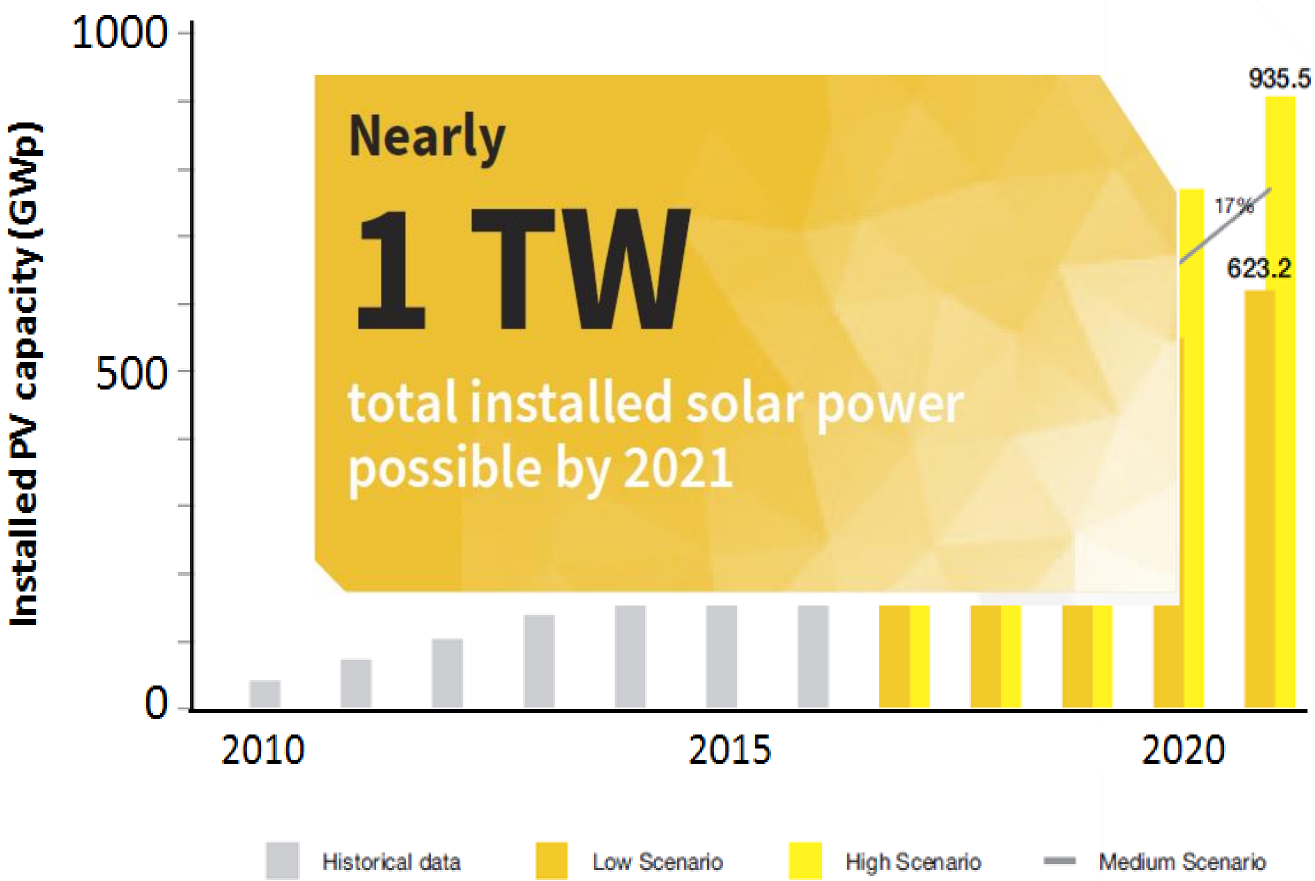
Estimated compound annual growth rate (CAGR) required to reach TW-scale deployment in 2030

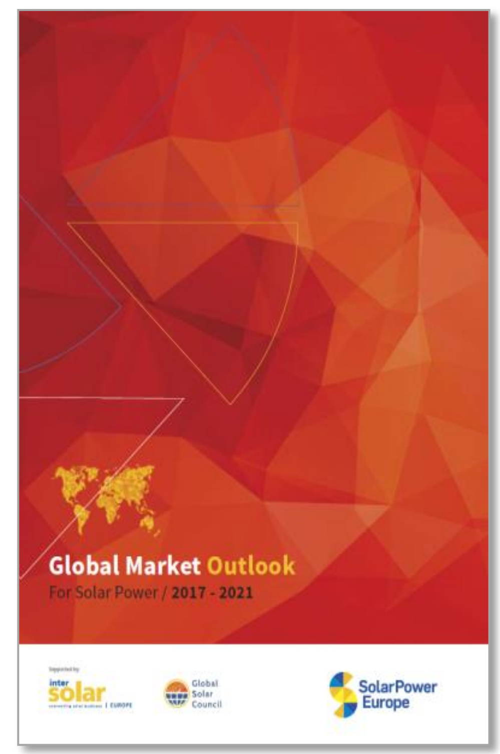
Analysis includes annual loss fractions per year of 0.02 (past capacity) and 0.04 (newly installed capacity). See supplementary materials for model details.

2030 TARGET (TW)	CAGR (%)	ESTIMATED TOTAL INSTALLED ANNUAL PRODUCTION CAPACITY IN 2030 (TW/YEAR)
3	15	0.5
5	21	1
8	27	1.9
10	29	2.5

The first terawatt is in sight now

- Projected growth in installed PV capacity





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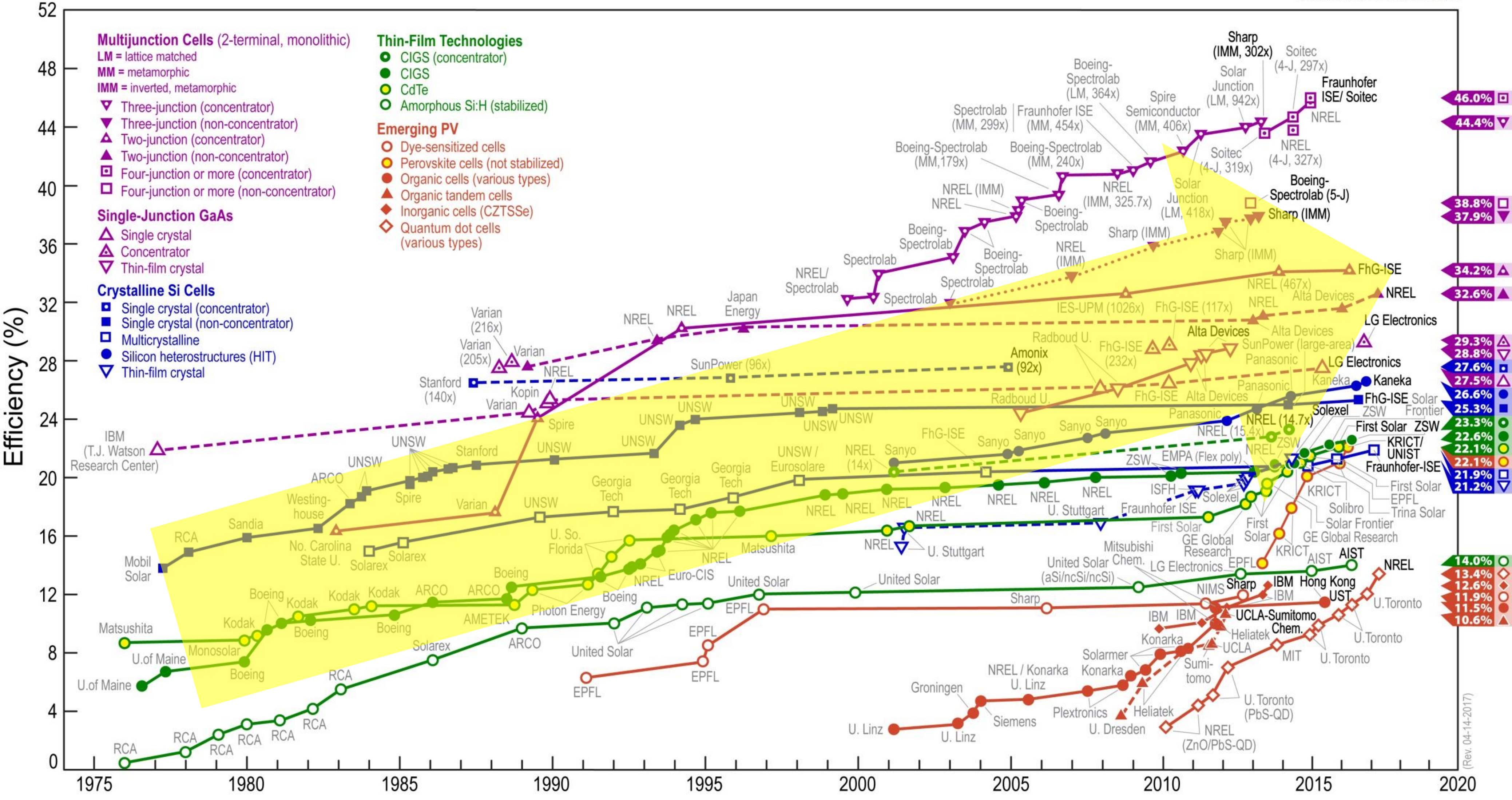
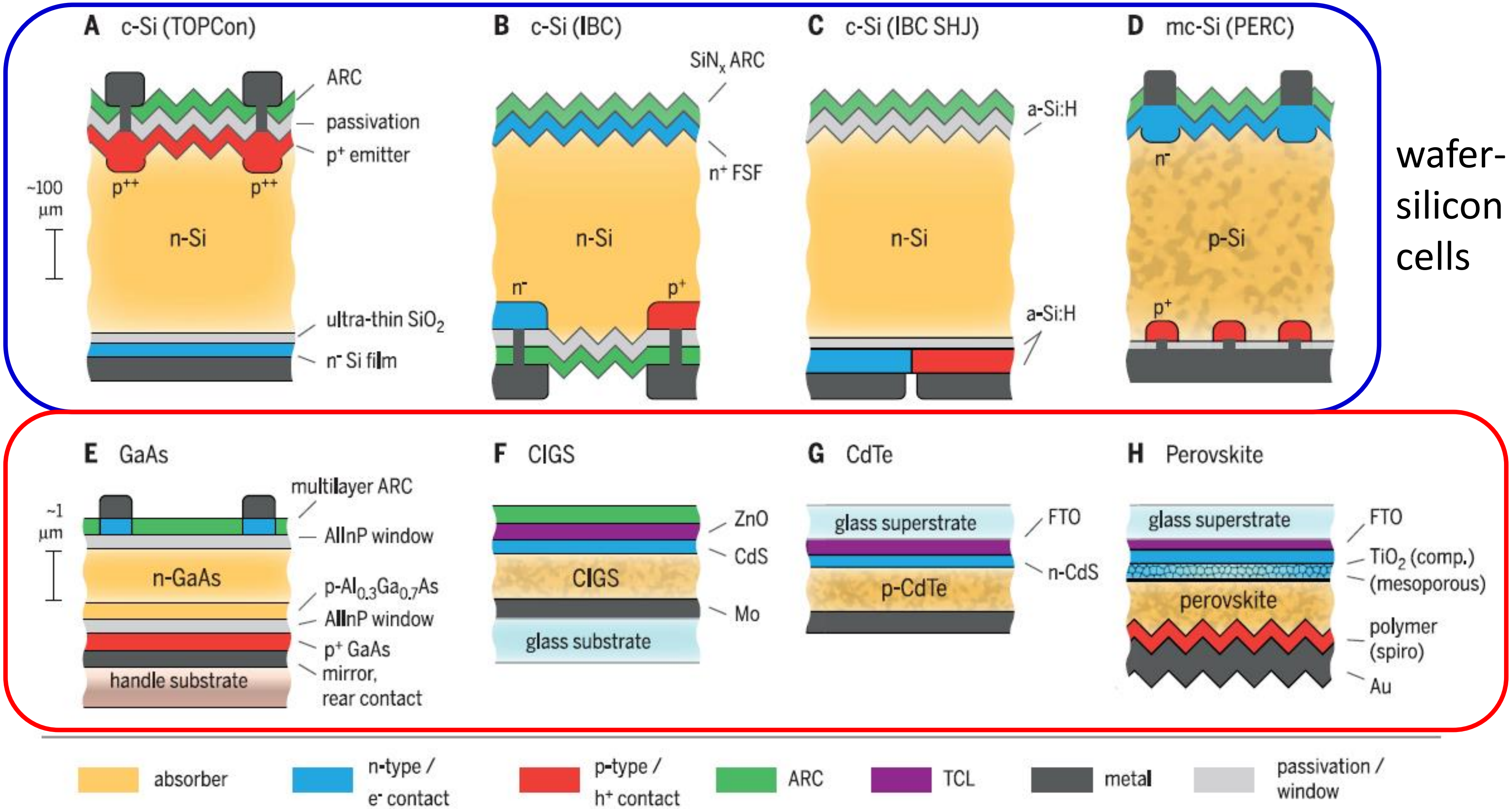
Best research-cell efficiencies: the foundation of module efficiency improvement



www.nrel.gov/ncpv/images/efficiency_chart.jpg

Interactive version on: http://spectrum.ieee.org/static/interactive-record-breaking-pv-cells

Maximizing efficiency
Selected record cell architectures

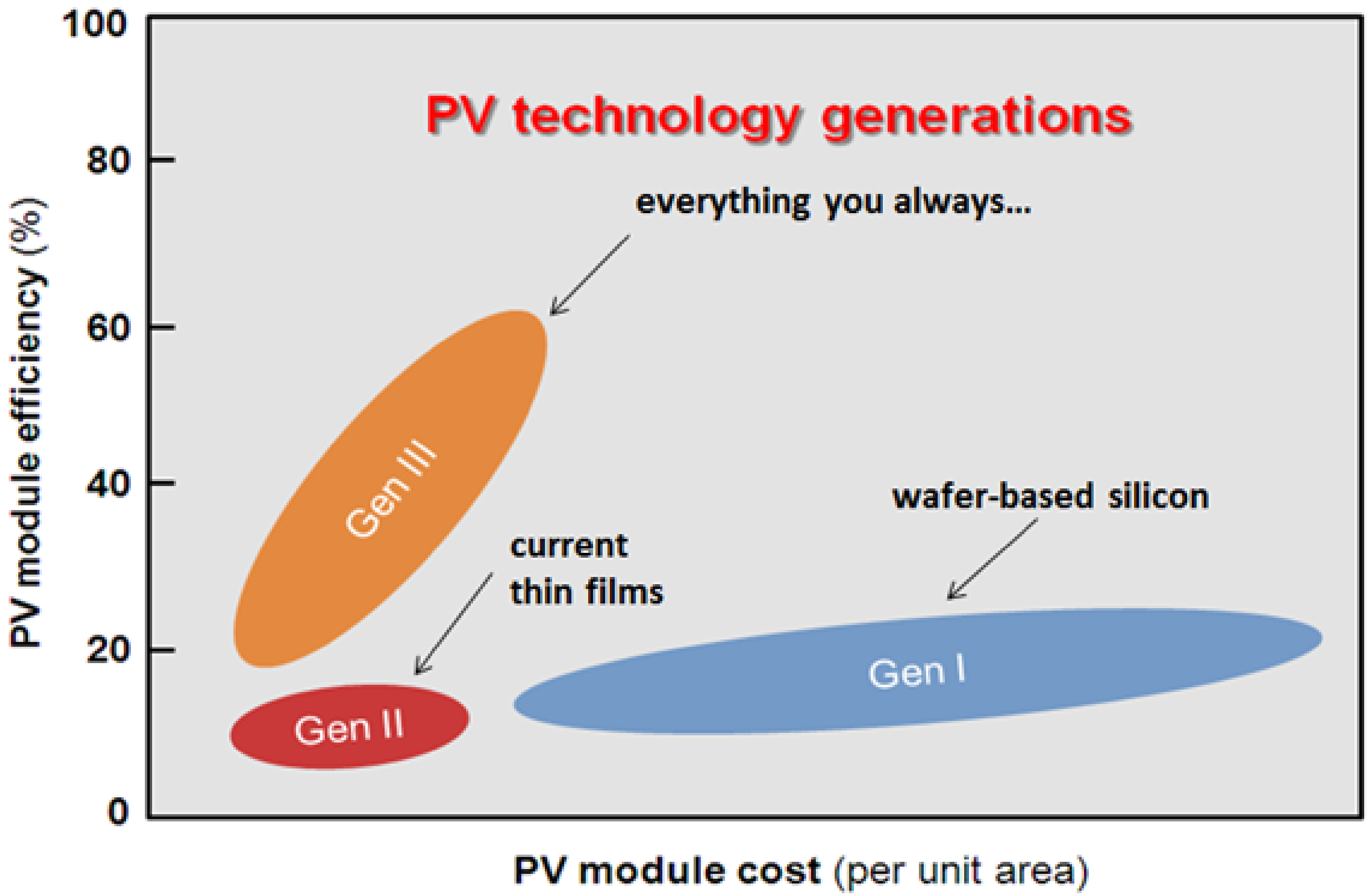


wafer-silicon cells

thin-film cells

Albert Polman, Mark Knight, Erik C. Garnett, Bruno Ehrler, Wim C. Sinke, *Science* 15 Apr 2016: Vol. 352, Issue 6283, DOI: 10.1126/science.aad4424

Commercial PV technologies
The common view



(2010)

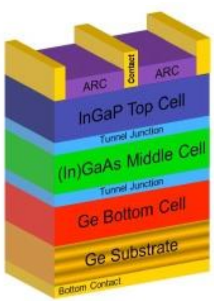
Commercial PV technologies
Current situation

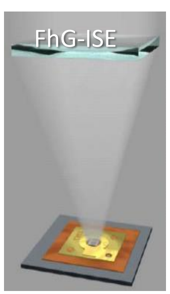
Standard ("flat plate") use:
wafer-based crystalline silicon

Module efficiencies 16 ~ 22%

Standard ("flat plate") use:
thin films (CdTe, CIGS, Si)

Module efficiencies 8 ~ 17%

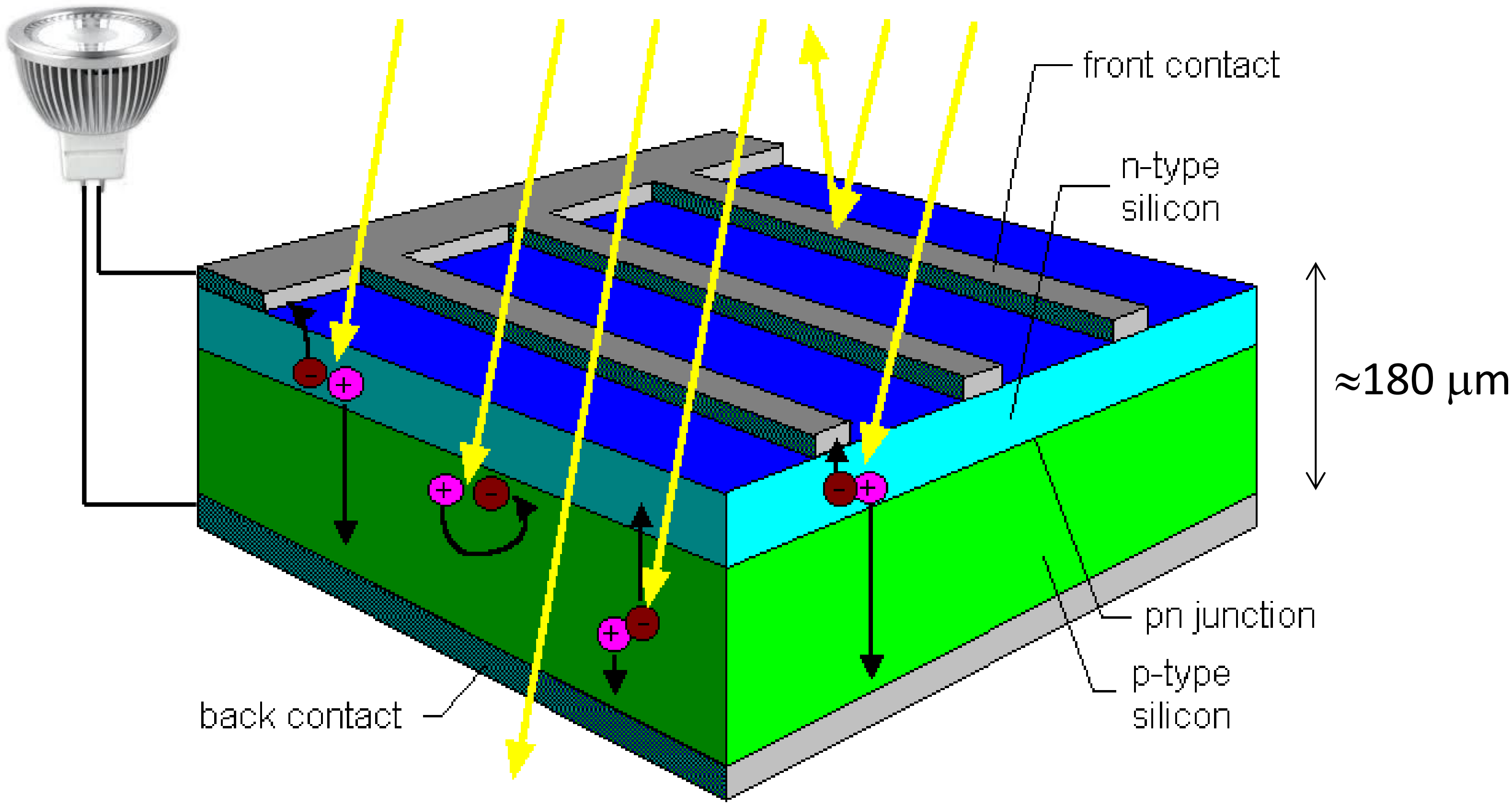




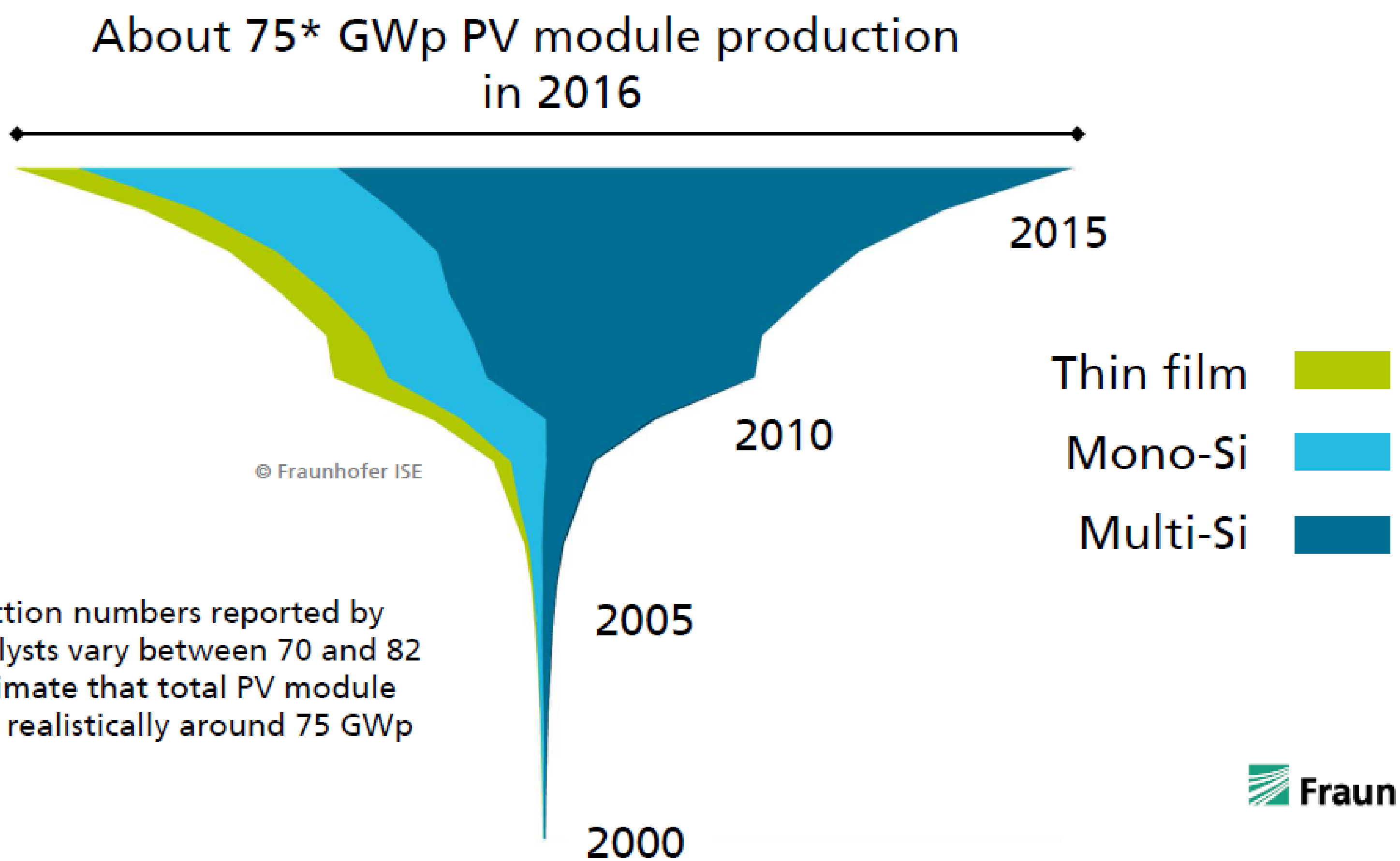
Concentrator use (sun tracking):
III-V tandems and Si

Module efficiencies 25 ~ 35%

Today's commercial workhorse
Simplicity is difficult to beat in cost



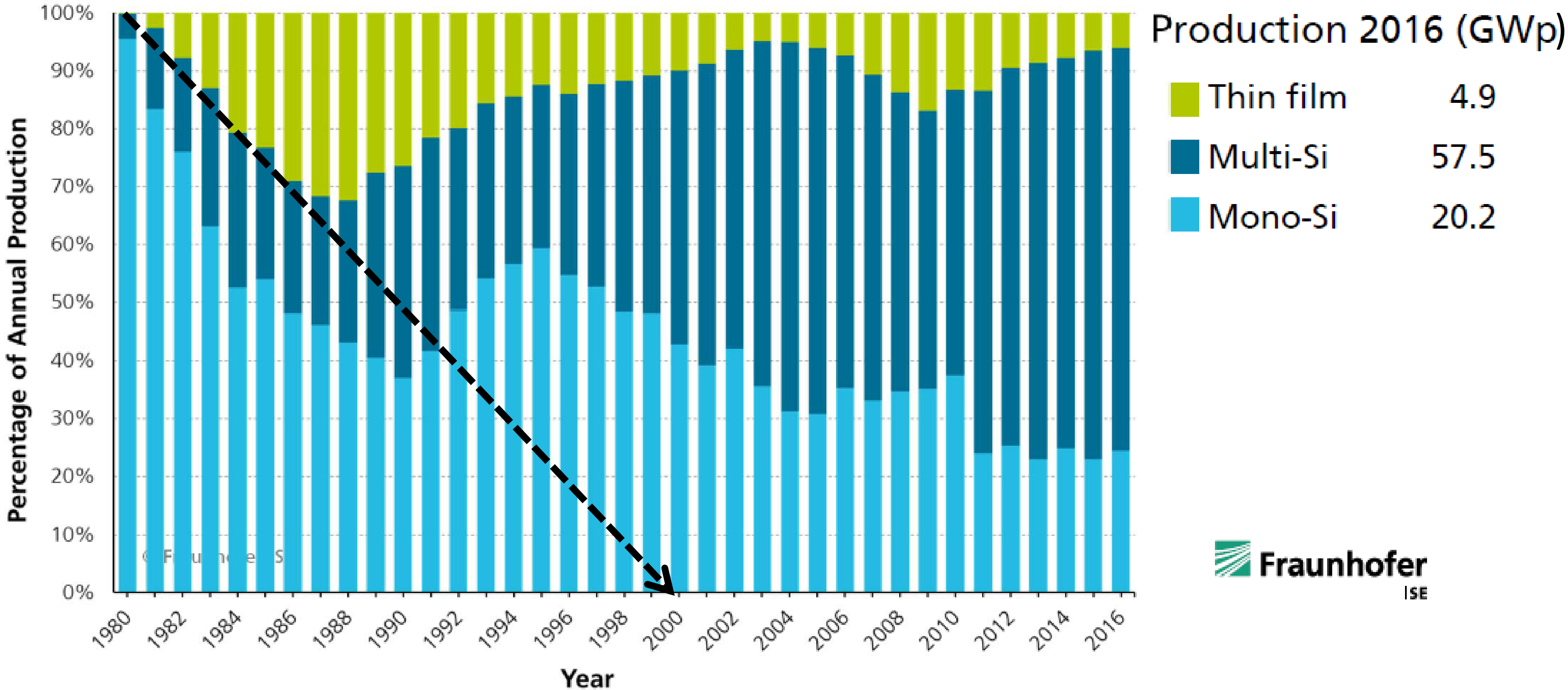
PV technology market shares



*2016 production numbers reported by different analysts vary between 70 and 82 GWp. We estimate that total PV module production is realistically around 75 GWp for 2016.

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE AG 2017

PV technology market shares



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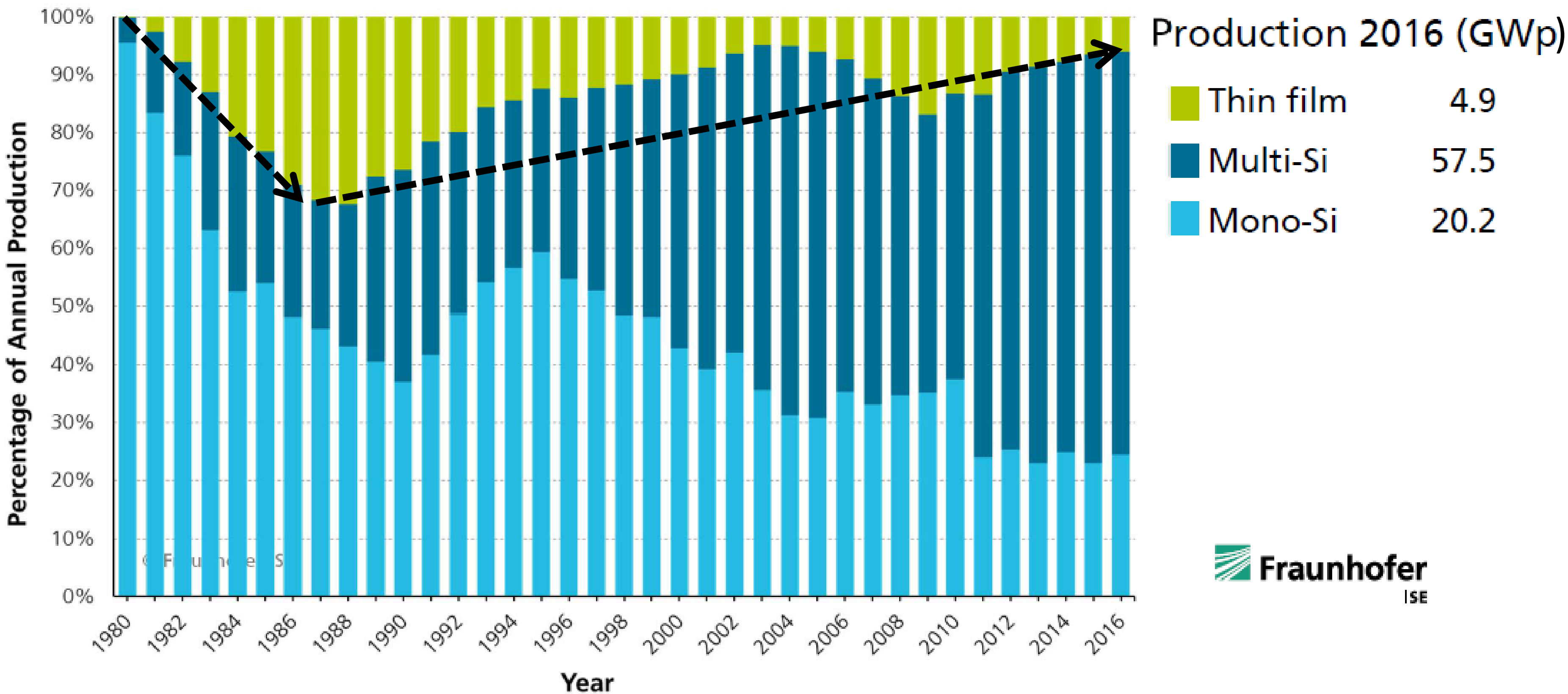
PV technology market shares



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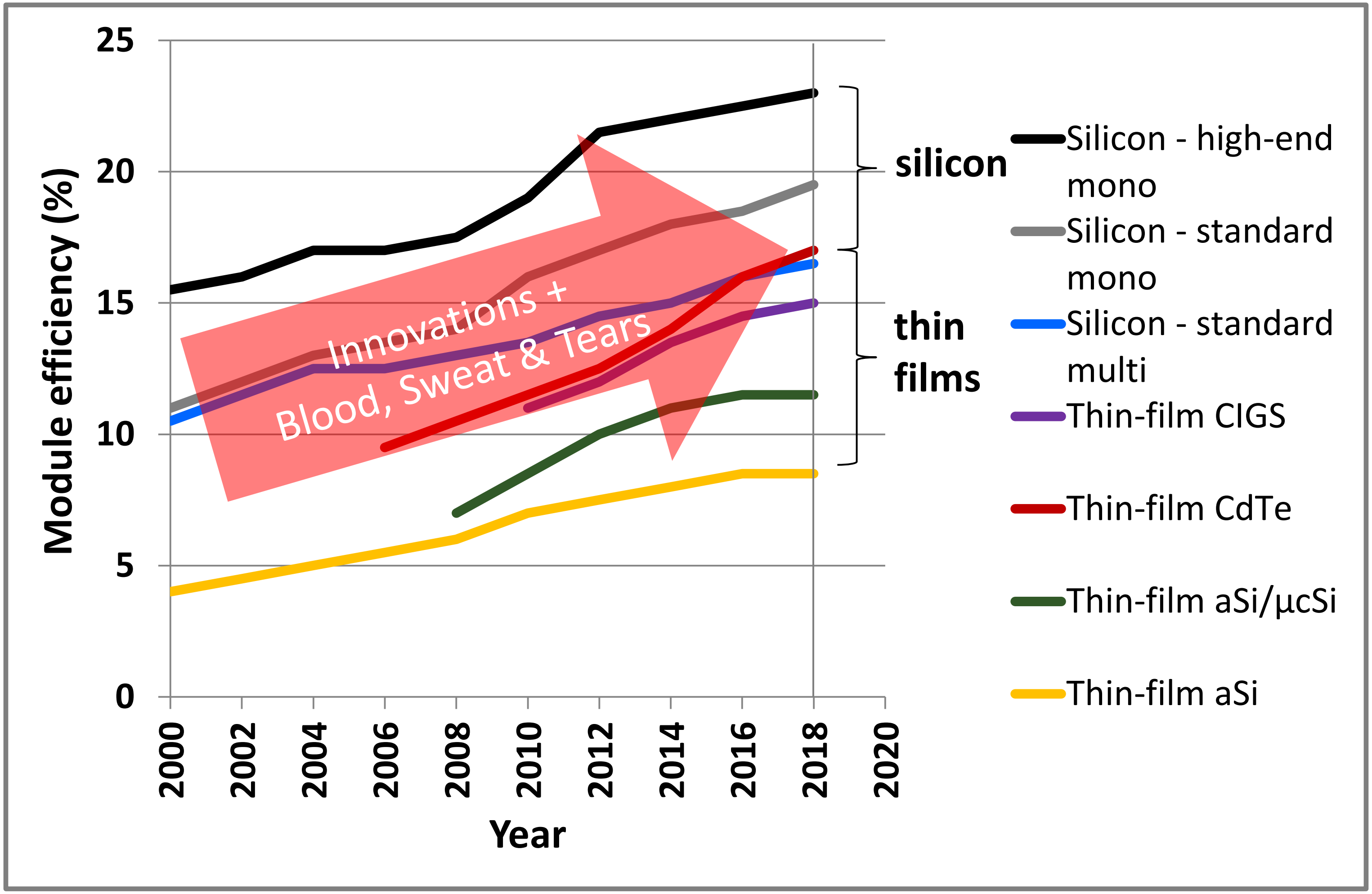
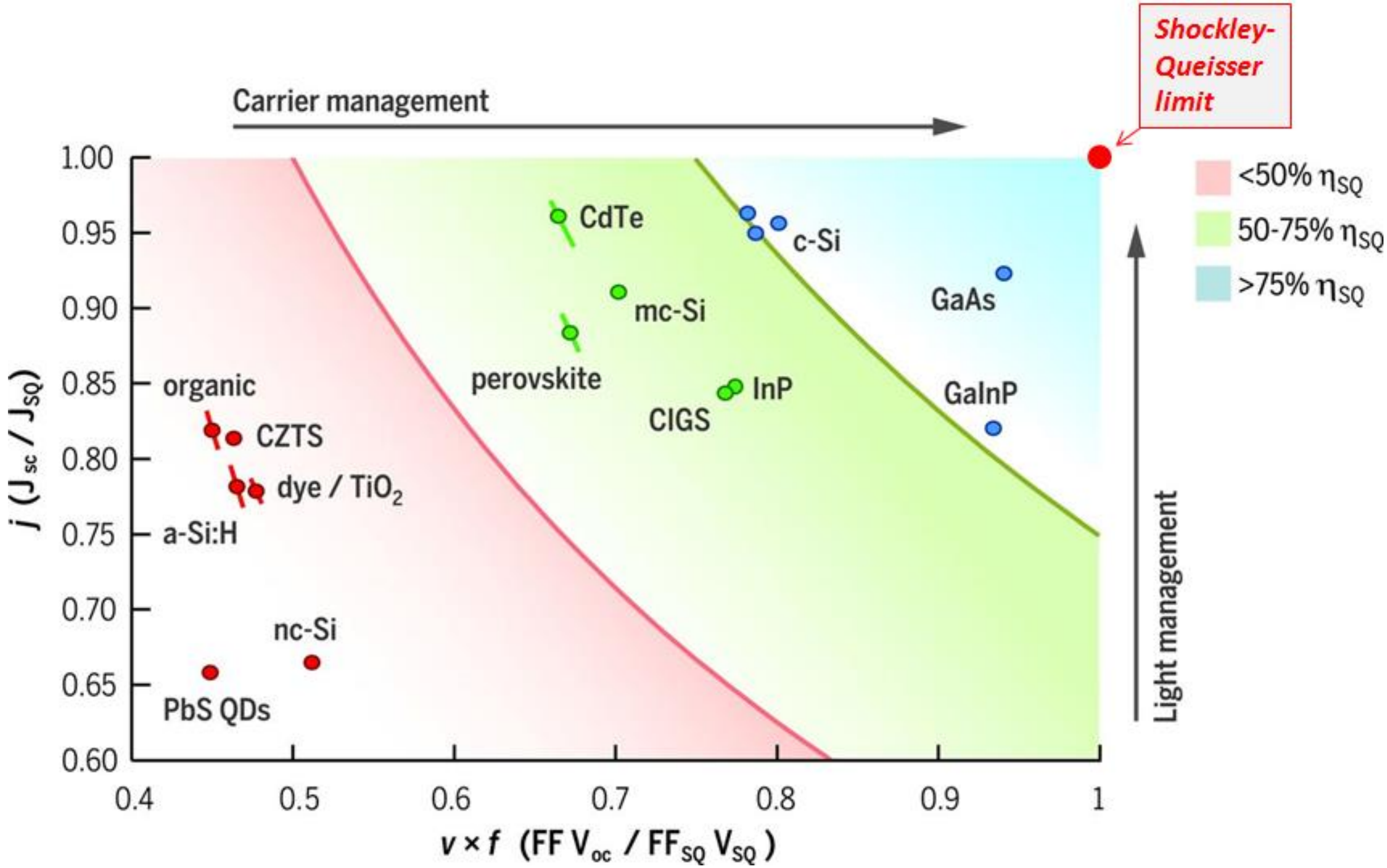
Commercial module efficiencies
Gradual but robust increase



Striving for perfection
Record cells compared



Albert Polman, Mark Knight, Erik C. Garnett, Bruno Ehrler, Wim C. Sinke
Science 15 Apr 2016: Vol. 352, Issue 6283, DOI: 10.1126/science.aad4424

http://subsites.amolf.nl/lmpv/shockley-queisser/

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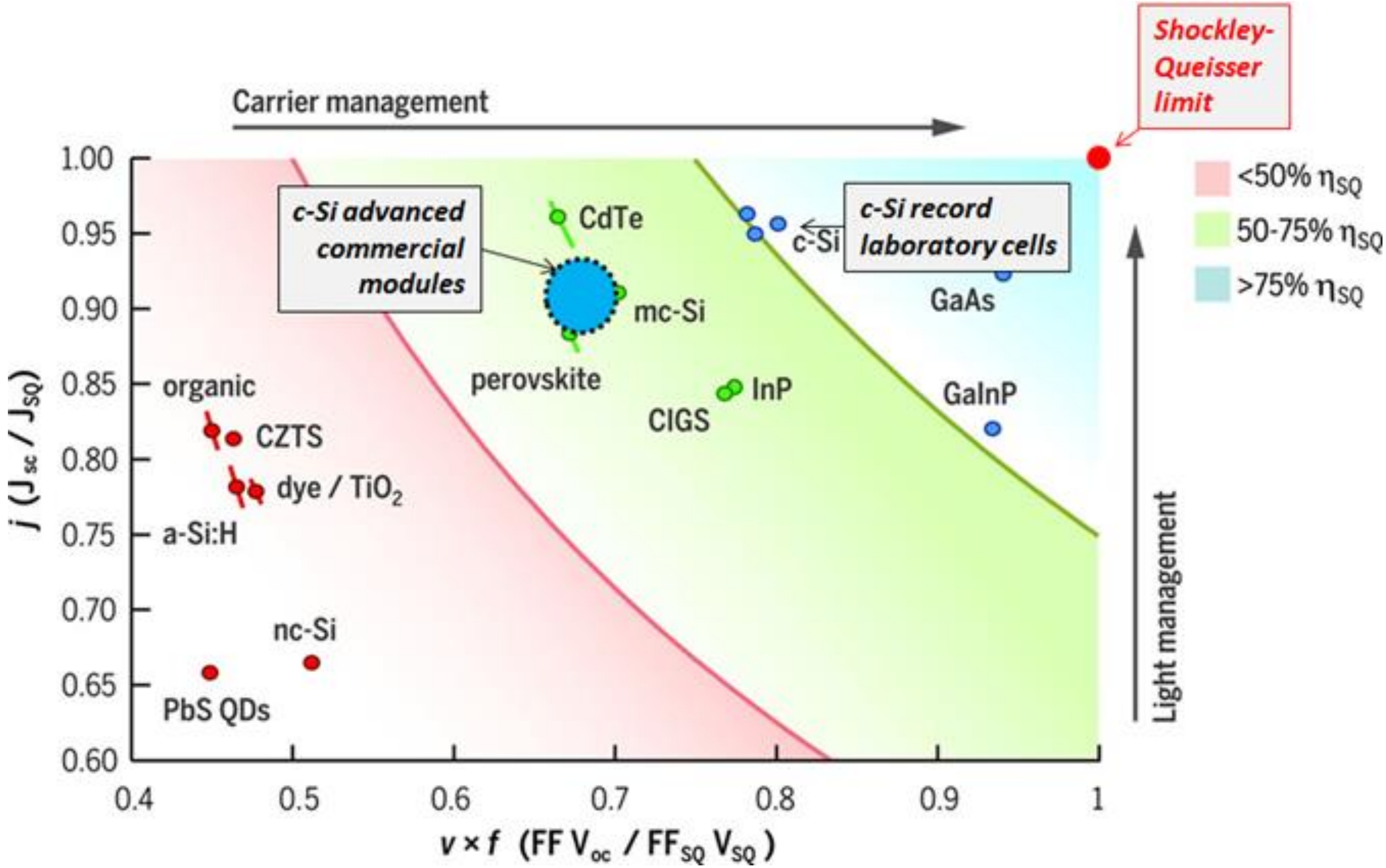

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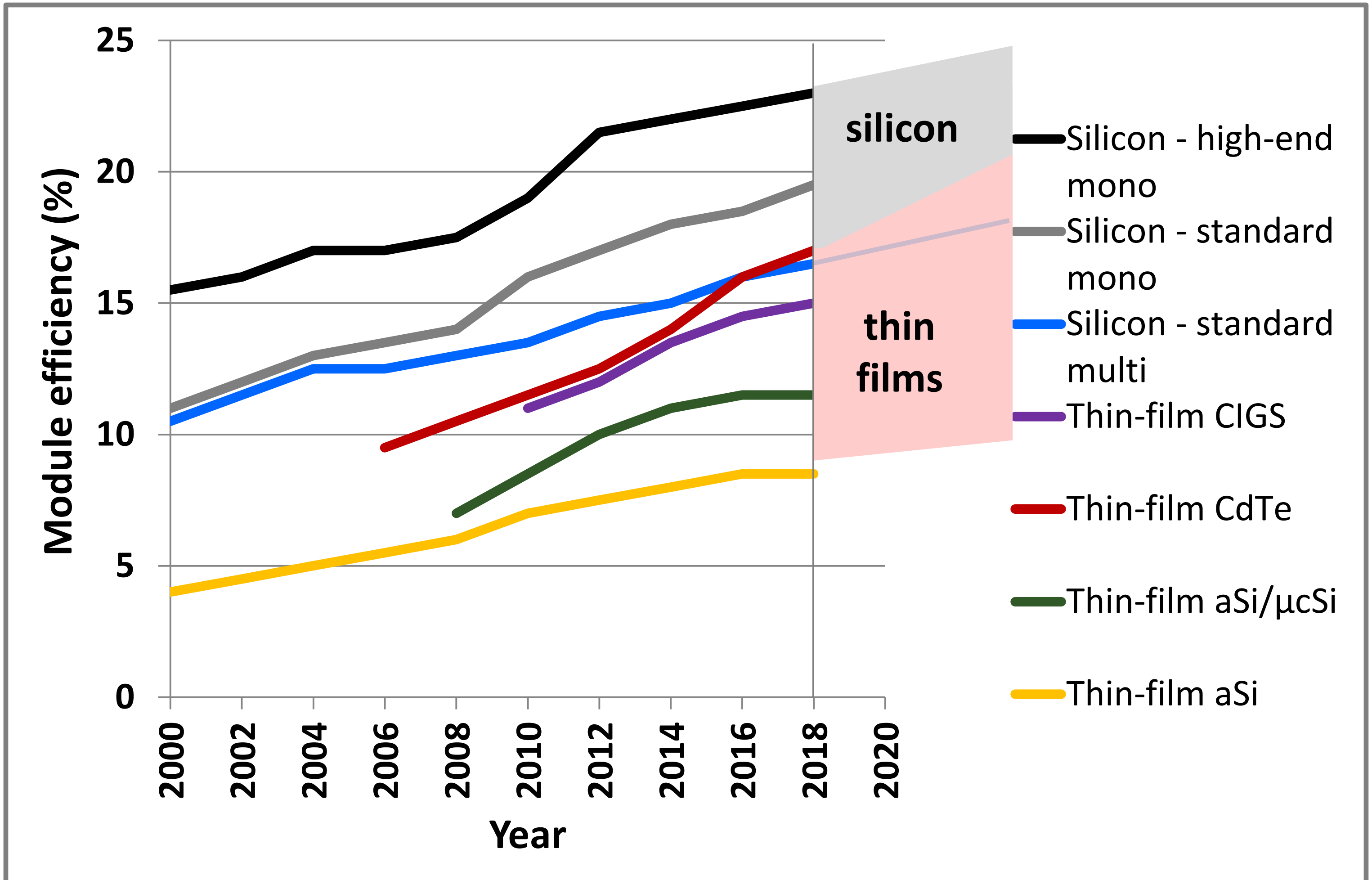
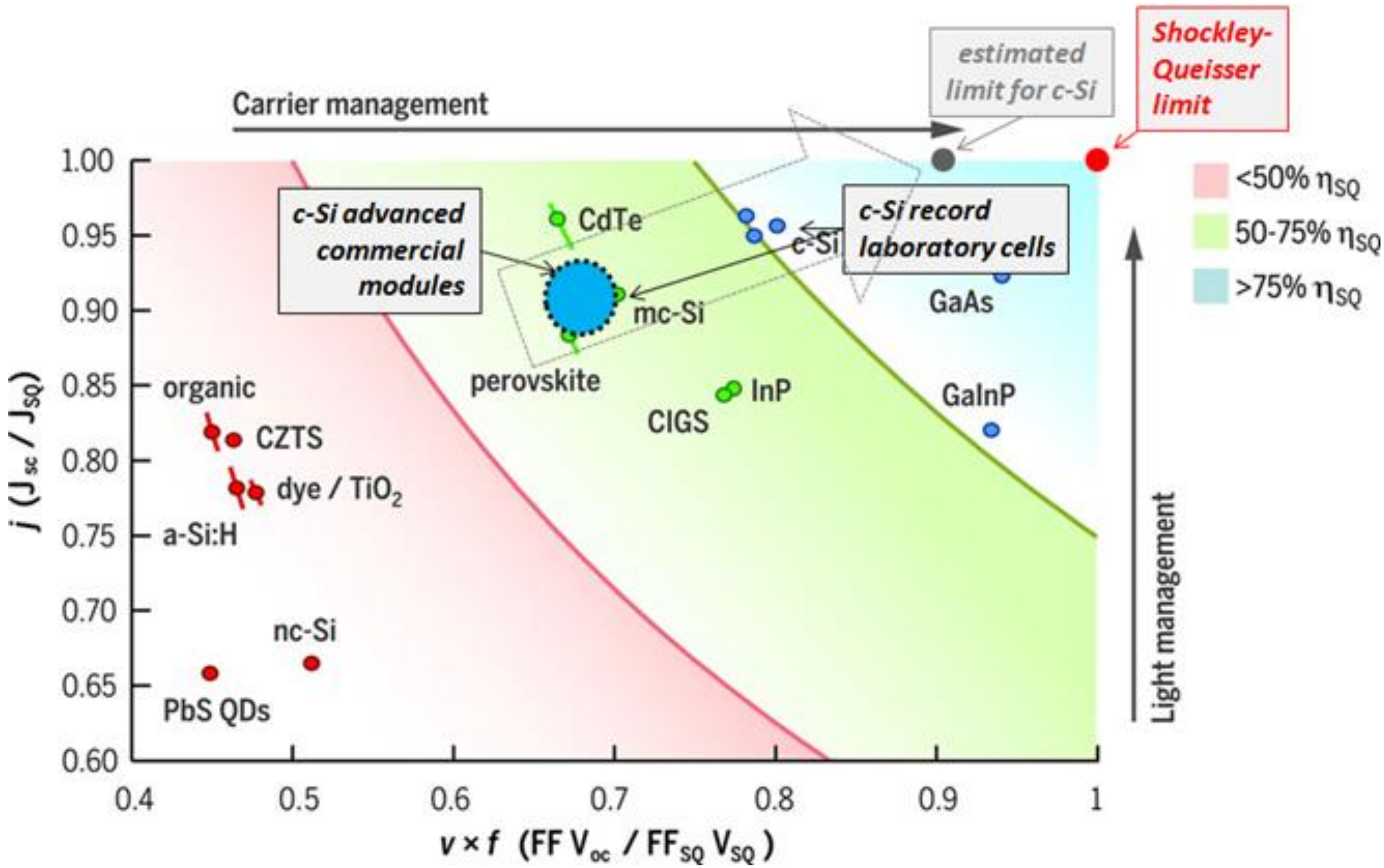
Towards high module efficiencies

The first step: closing the lab/fab gap



Striving for perfection
Record cells compared



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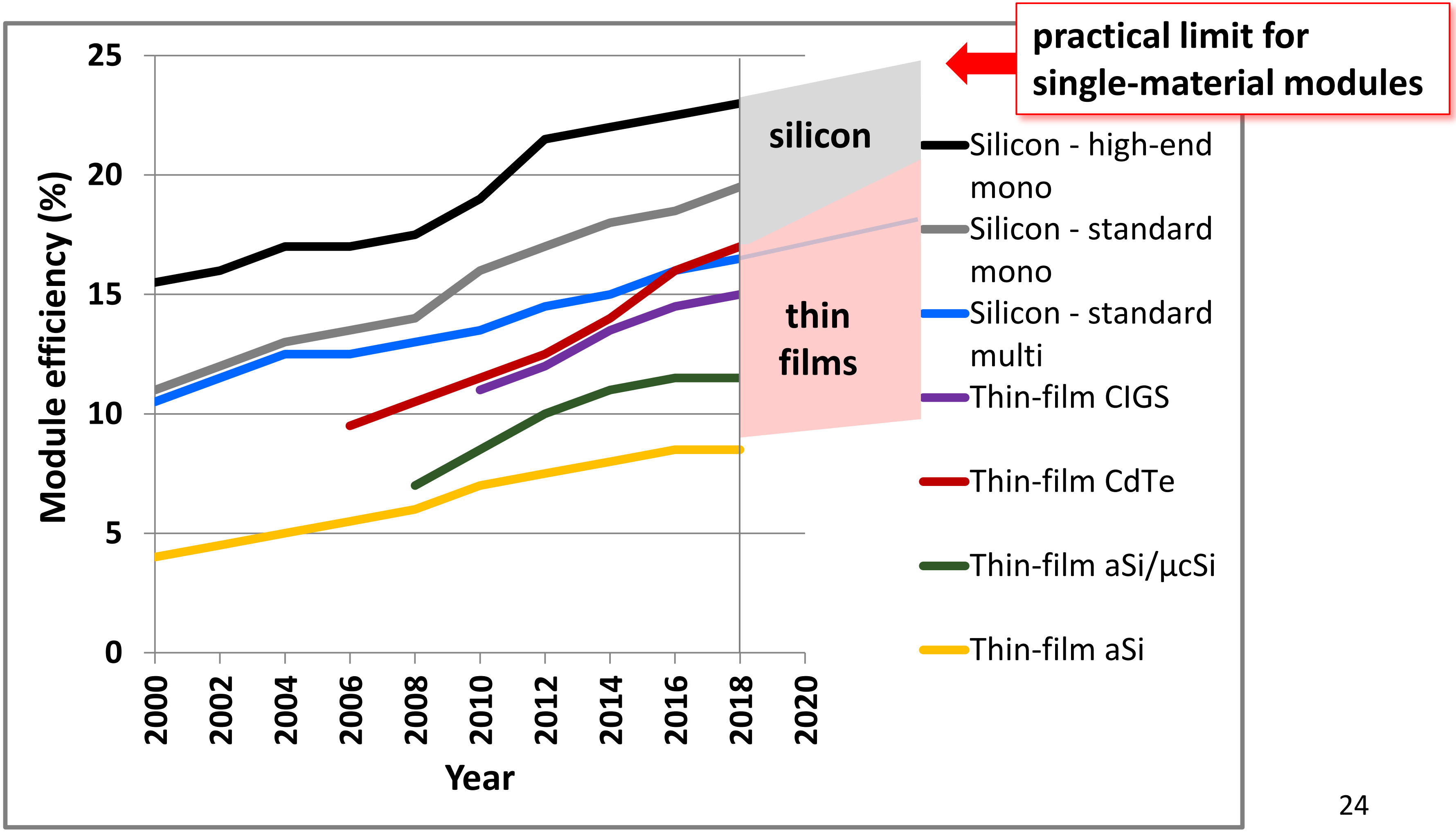
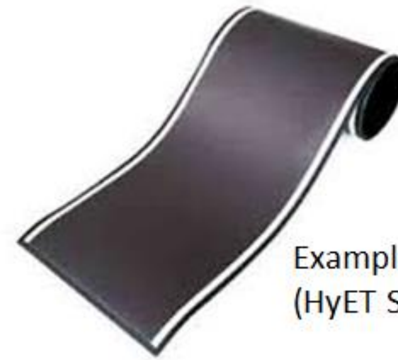


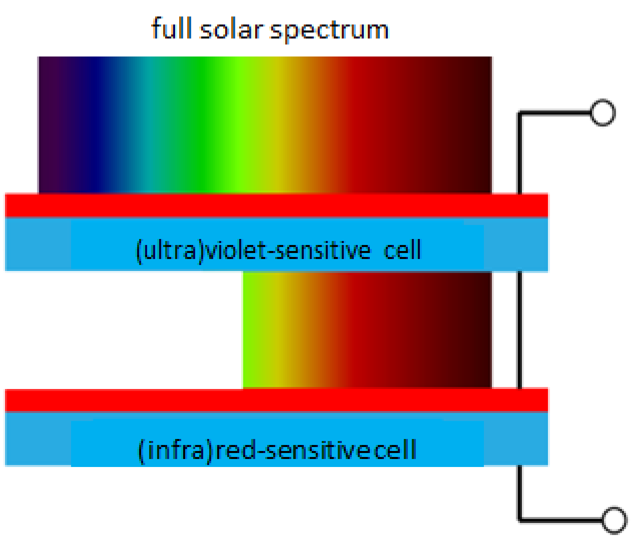
Developments in the lab

- Very-high efficiency concepts
- Very low-cost concepts
  & and technologies for new applications

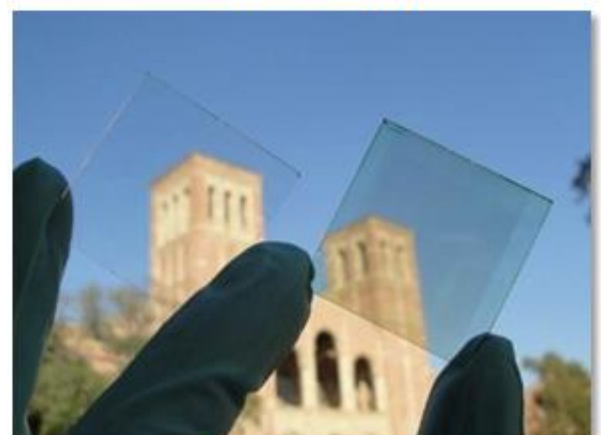


Example: solar foil
(HyET Solar; NL)

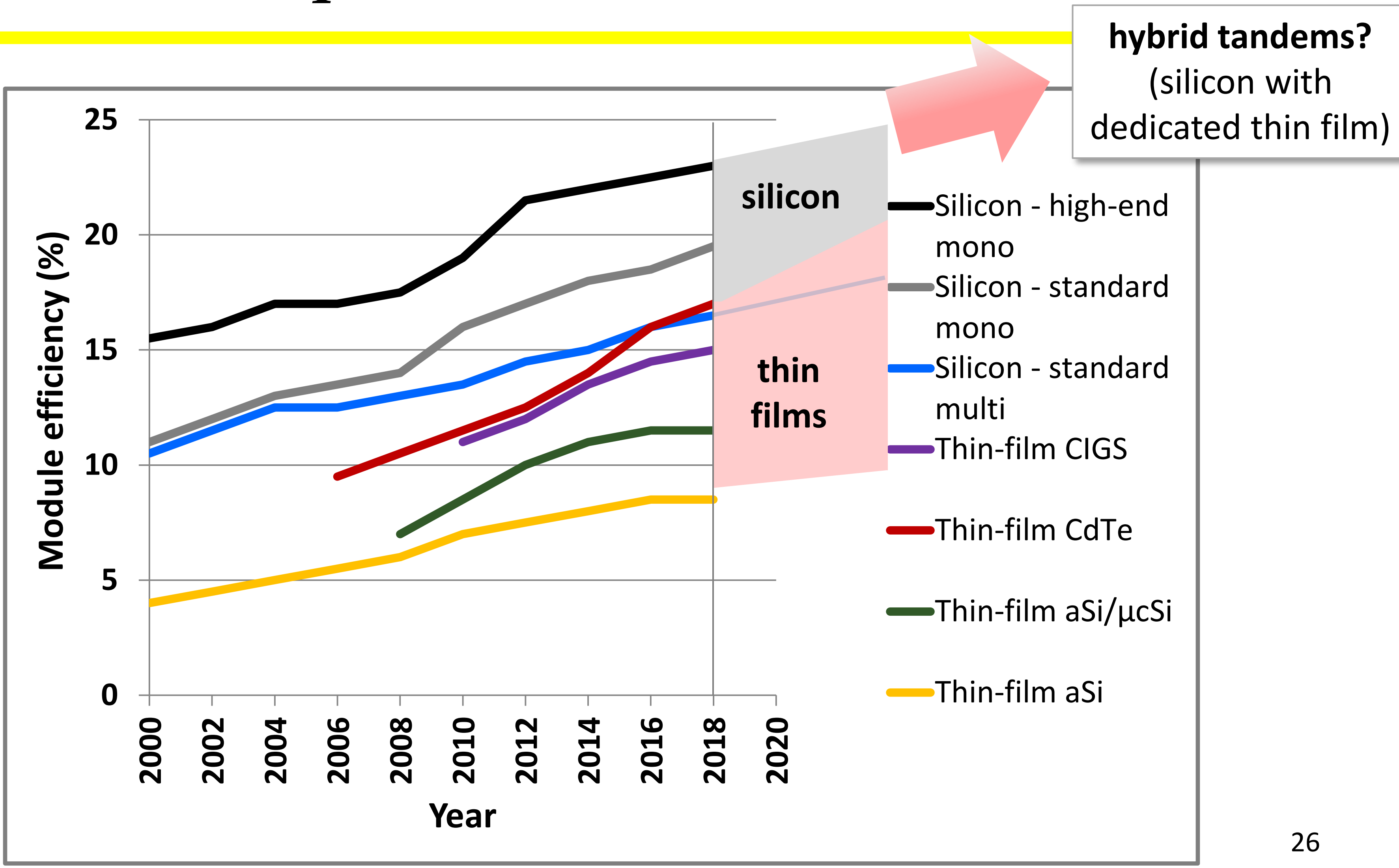
Example: tandem solar cell



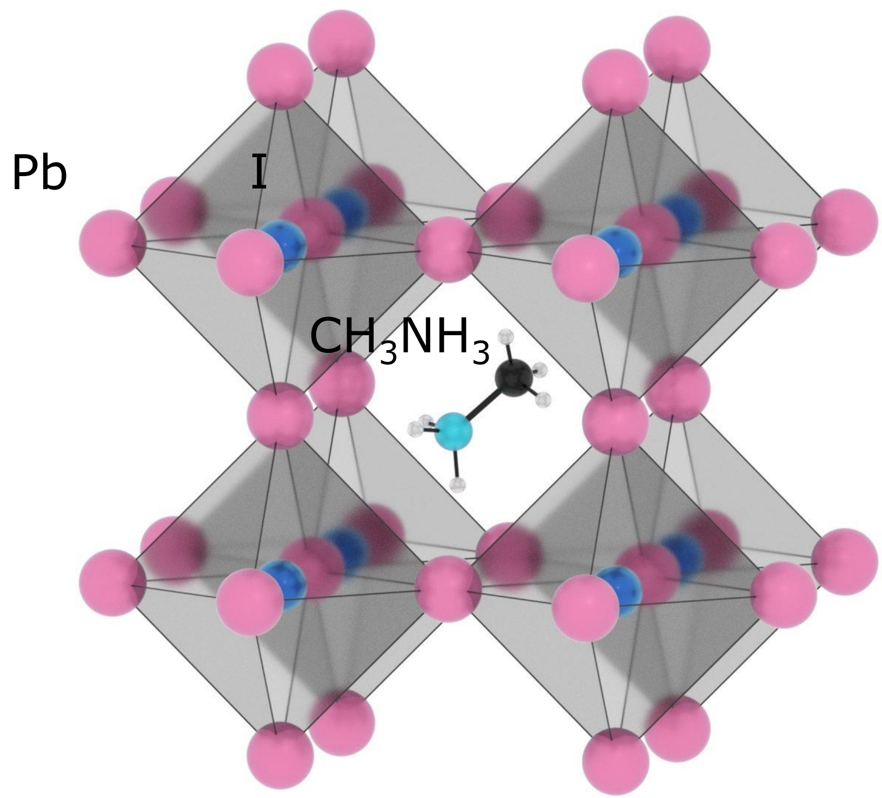
Example: PV window
(UCLA; USA)



Towards high module efficiencies
The next step: tandems?



Top cell candidate: methyl ammonium lead halide perovskite



$CH_3NH_3PbI_3$

Silicon technology generations

- **Gen1**
  - Limited by (a.o.) extrinsic Si material quality:
    - Multi → mono, HP multi; p → n

  today

- **Gen2**
  - Limited by surface & interface quality:
    - Advanced surface passivation; passivating contacts; heterojunctions

  today

- **Gen3**
  - Limited by intrinsic Si material quality:
    - Thin wafers + light trapping (to SQ)

- **Gen4**
  - Limited by Si bandgap
    - Tandems (beyond SQ)

Silicon technology generations

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today

- **Gen2**
  - Limited by surface & interface quality:
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today

- **Gen3**
  - Limited by intrinsic Si material quality:
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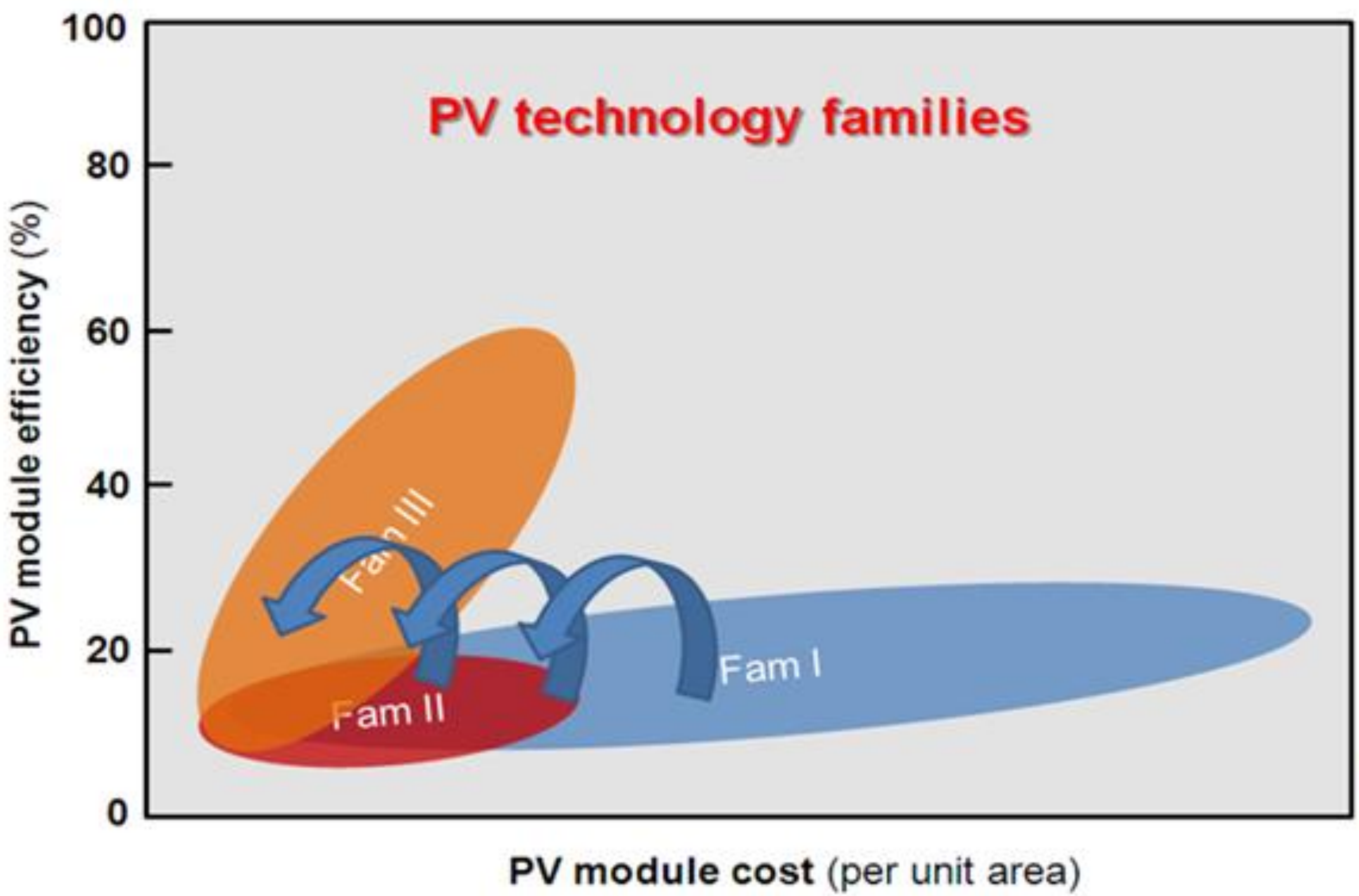
- **Gen3?**
  - Limited by Si bandgap
    - Tandems (beyond SQ)

Commercial PV technologies: *an alternative view*



(2010)

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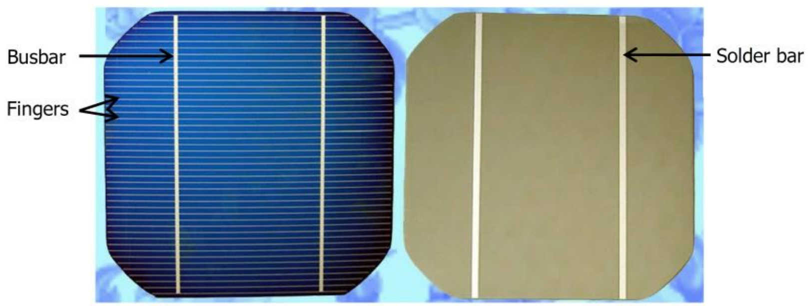
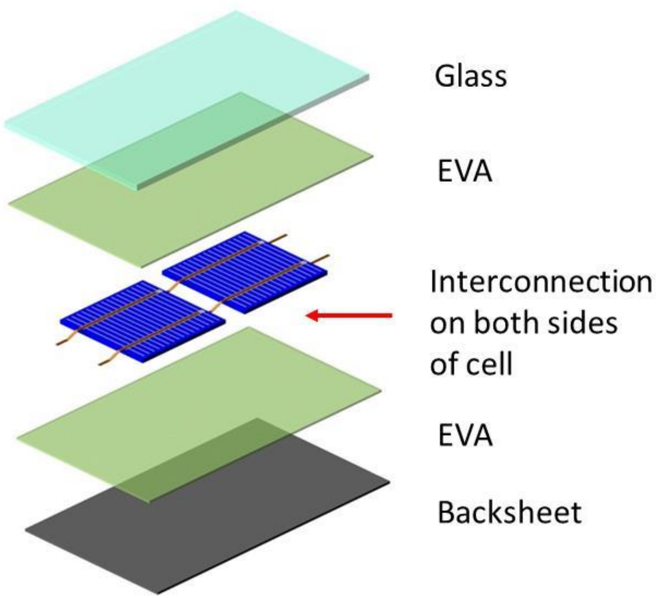
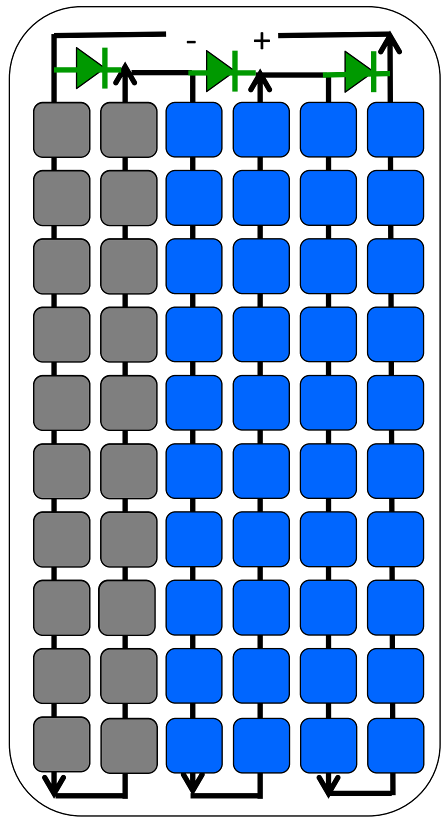
From cell to module: current approach

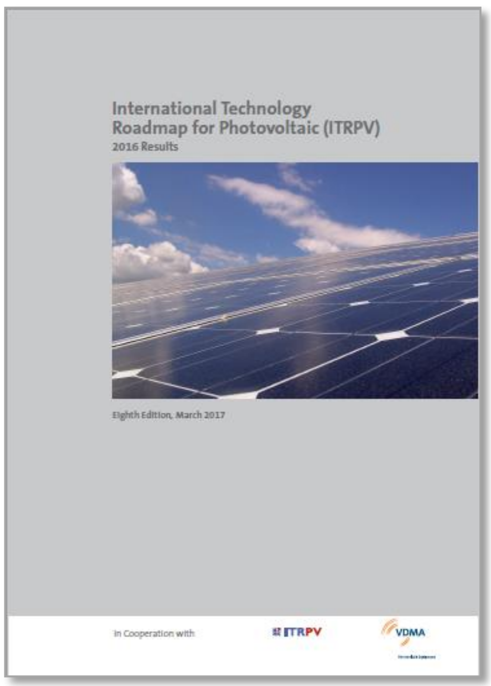


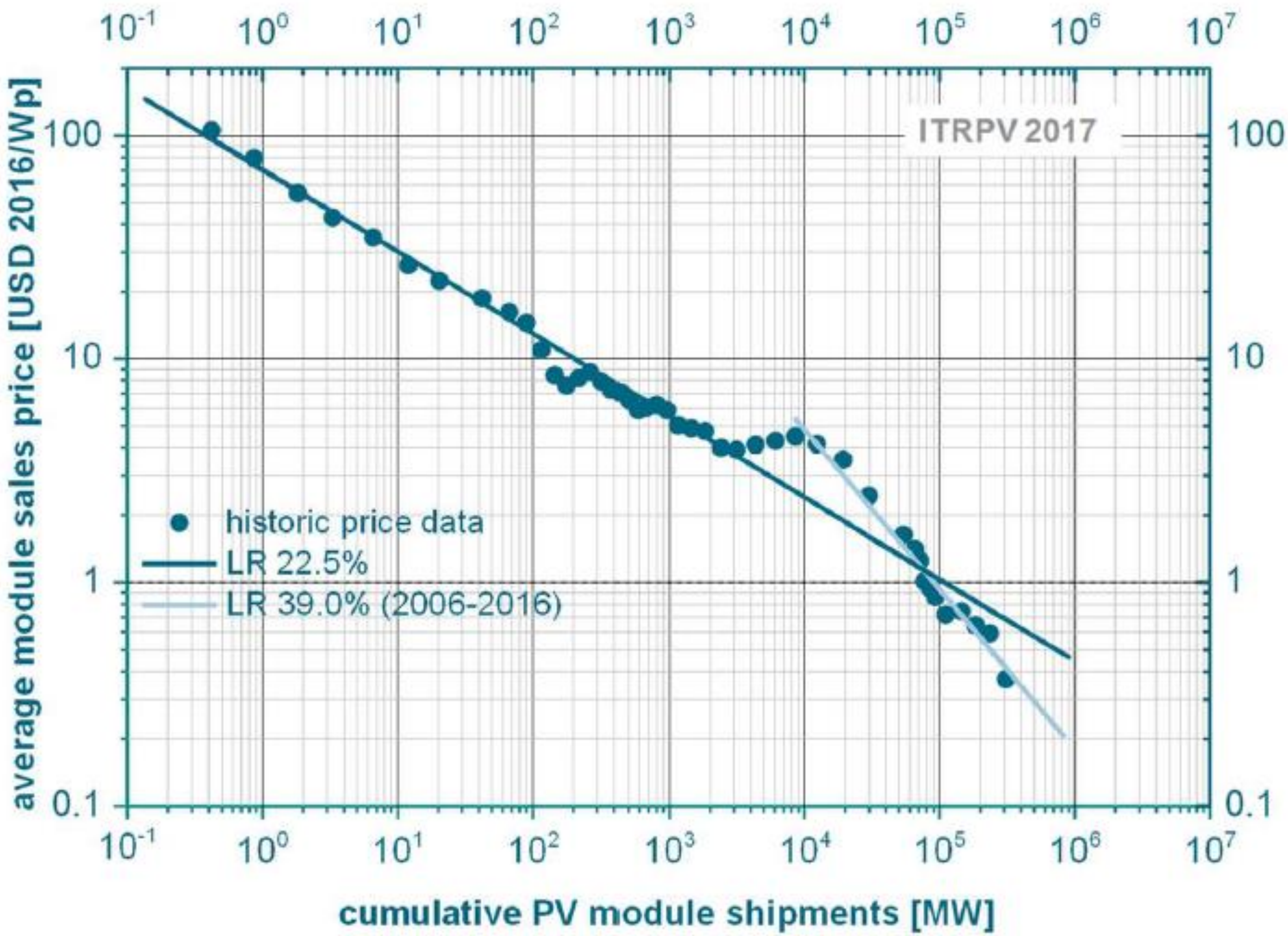




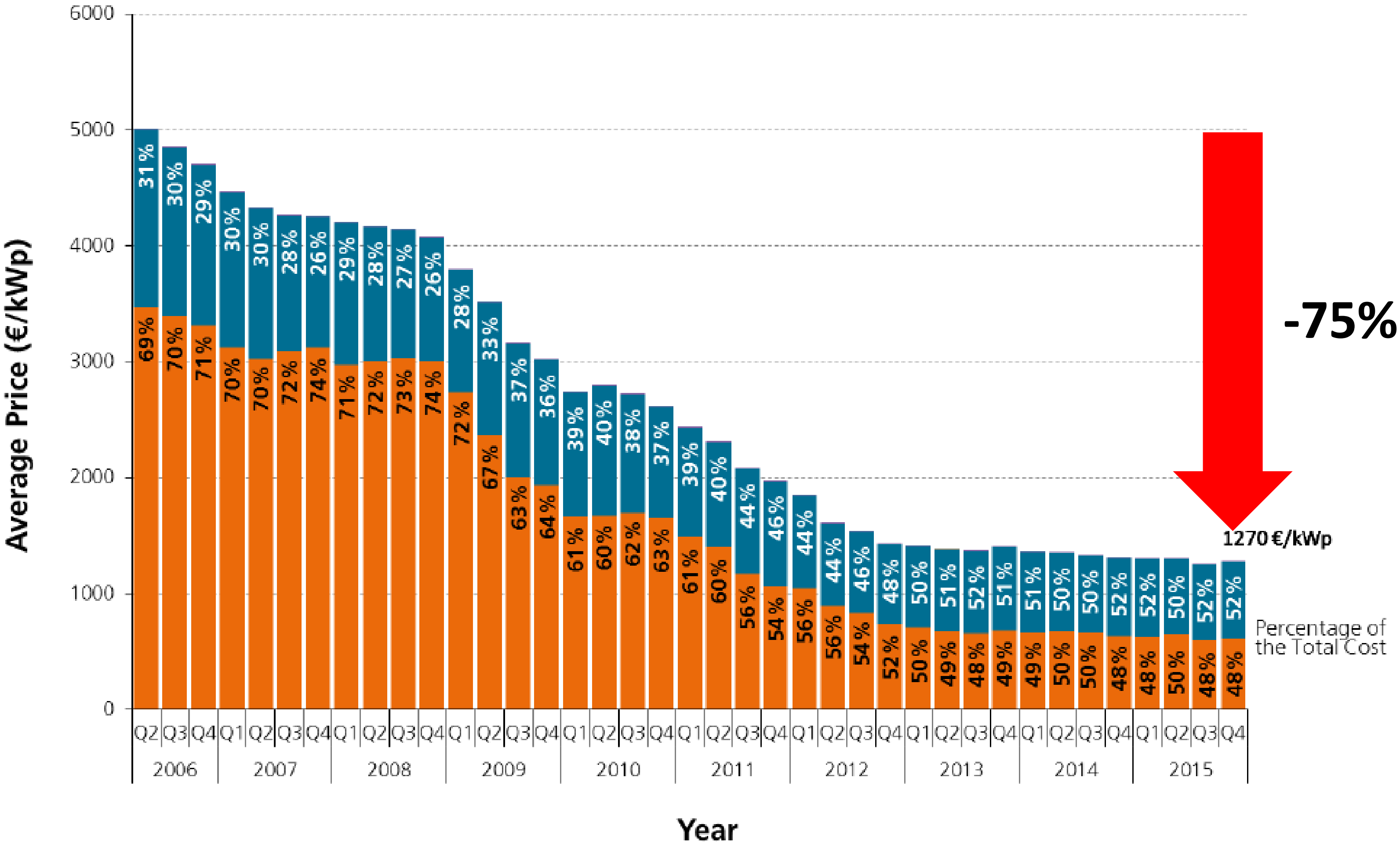
≈300 watt-peak (Wp)

Price-experience curve PV modules
Combined effects of volume and innovation





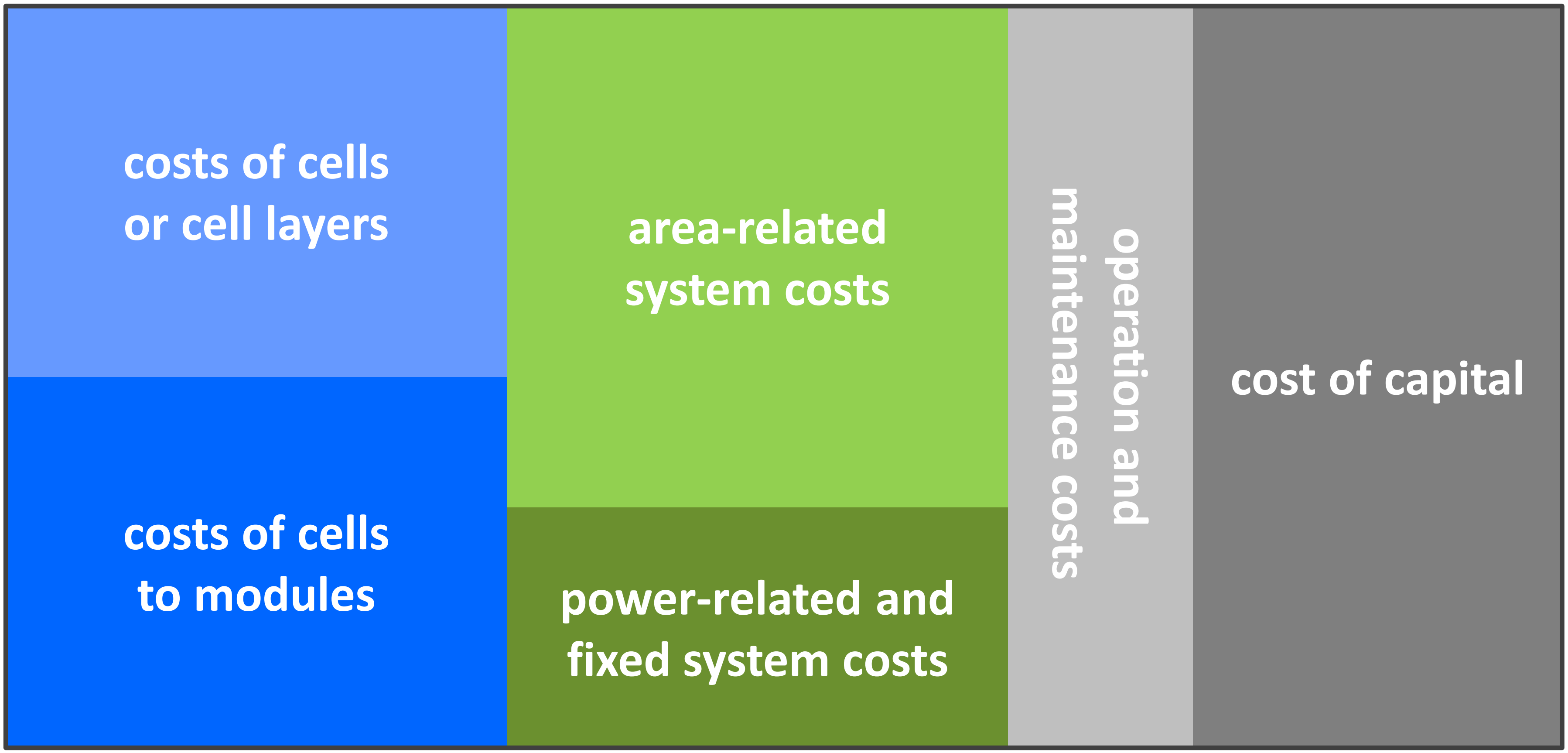
Price of roof systems (Germany)



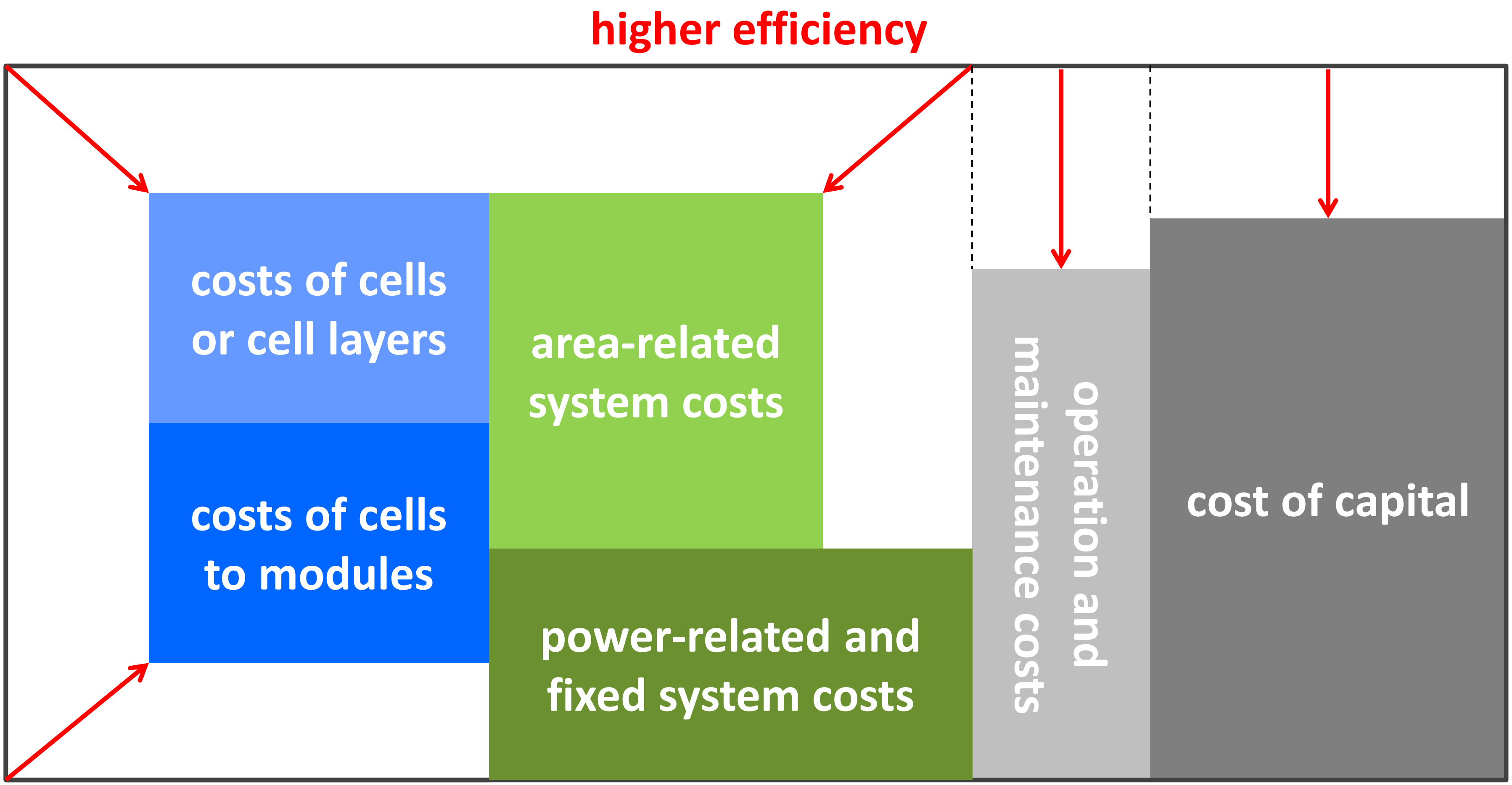
Data: BSW-Solar. Graph: PSE AG 2016

(Bron: Fraunhofer ISE)

Efficiency matters
Cost structure electricity generation



Efficiency matters
Cost structure electricity generation



Spectacular development in generation cost


Bloomberg Markets Tech Pursuits Politics Opinion Businessweek Sign In Subscribe

Solar Could Beat Coal to Become the Cheapest Power on Earth

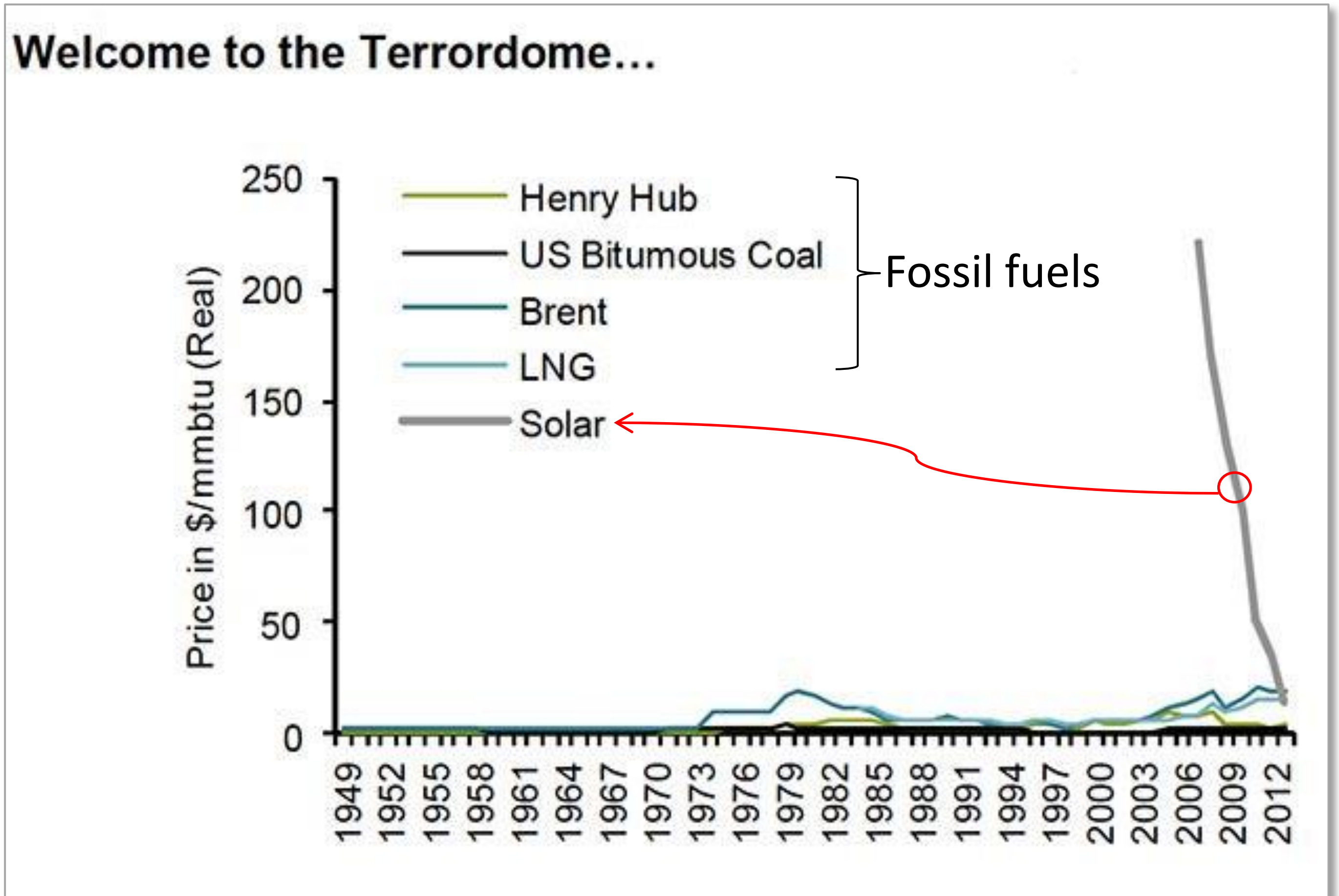
by **Jessica Shankleman** and **Chris Martin**

January 3, 2017, 1:00 AM GMT+1 *Updated on* January 3, 2017, 1:16 PM GMT+1

- Global average solar cost may fall below coal within 10 years
- Countries from Saudi Arabia to Mexico planning auctions

ECN

Game-changing price reduction of solar energy



www.bloomberg.com/news (29 October 2014)

Power Purchasing Agreement (PPA) price offers

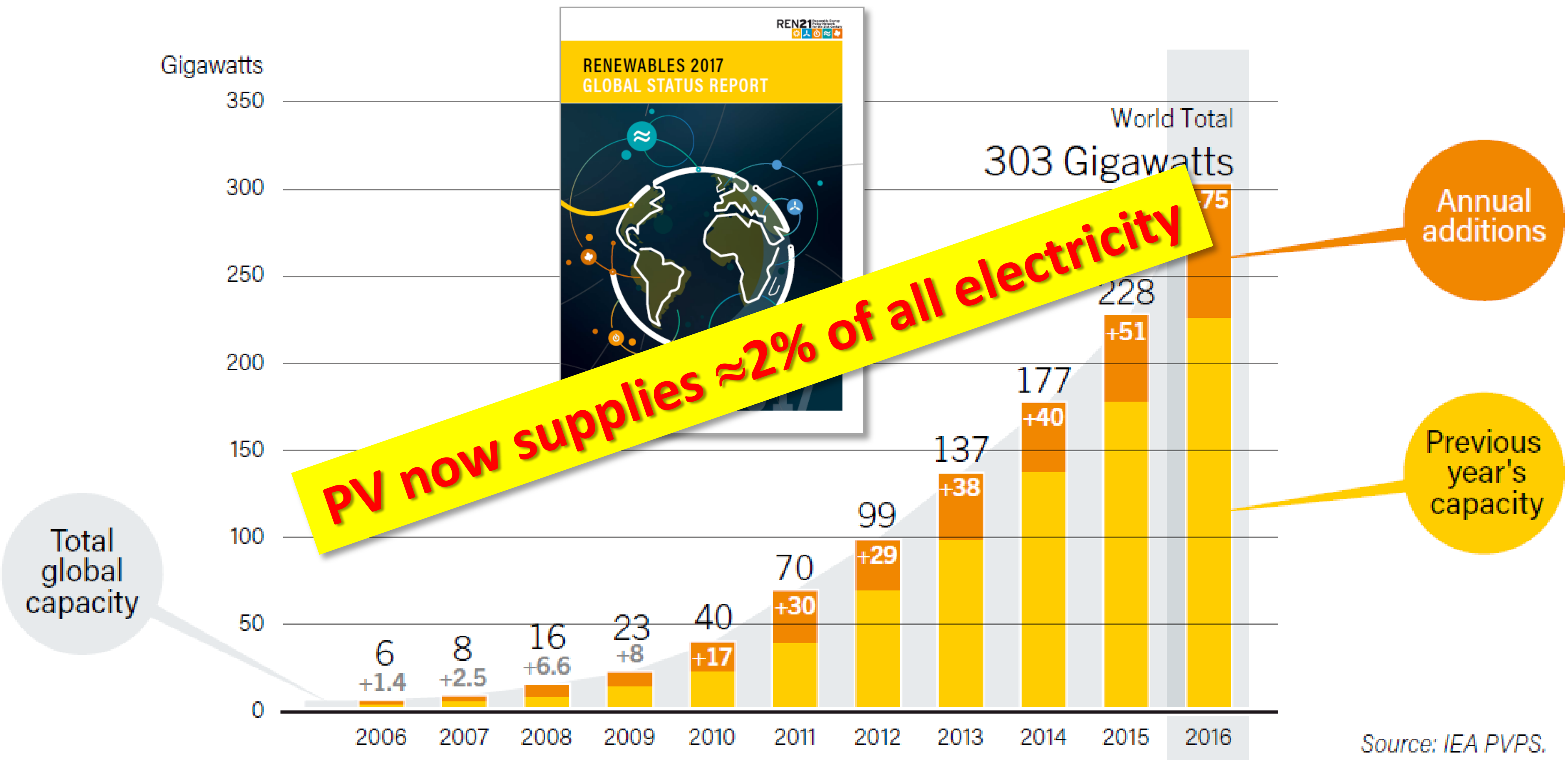
ECN

Lowest ever solar bids submitted in Abu Dhabi

By Tom Kenning | Sep 20, 2016 11:43 AM BST | 0

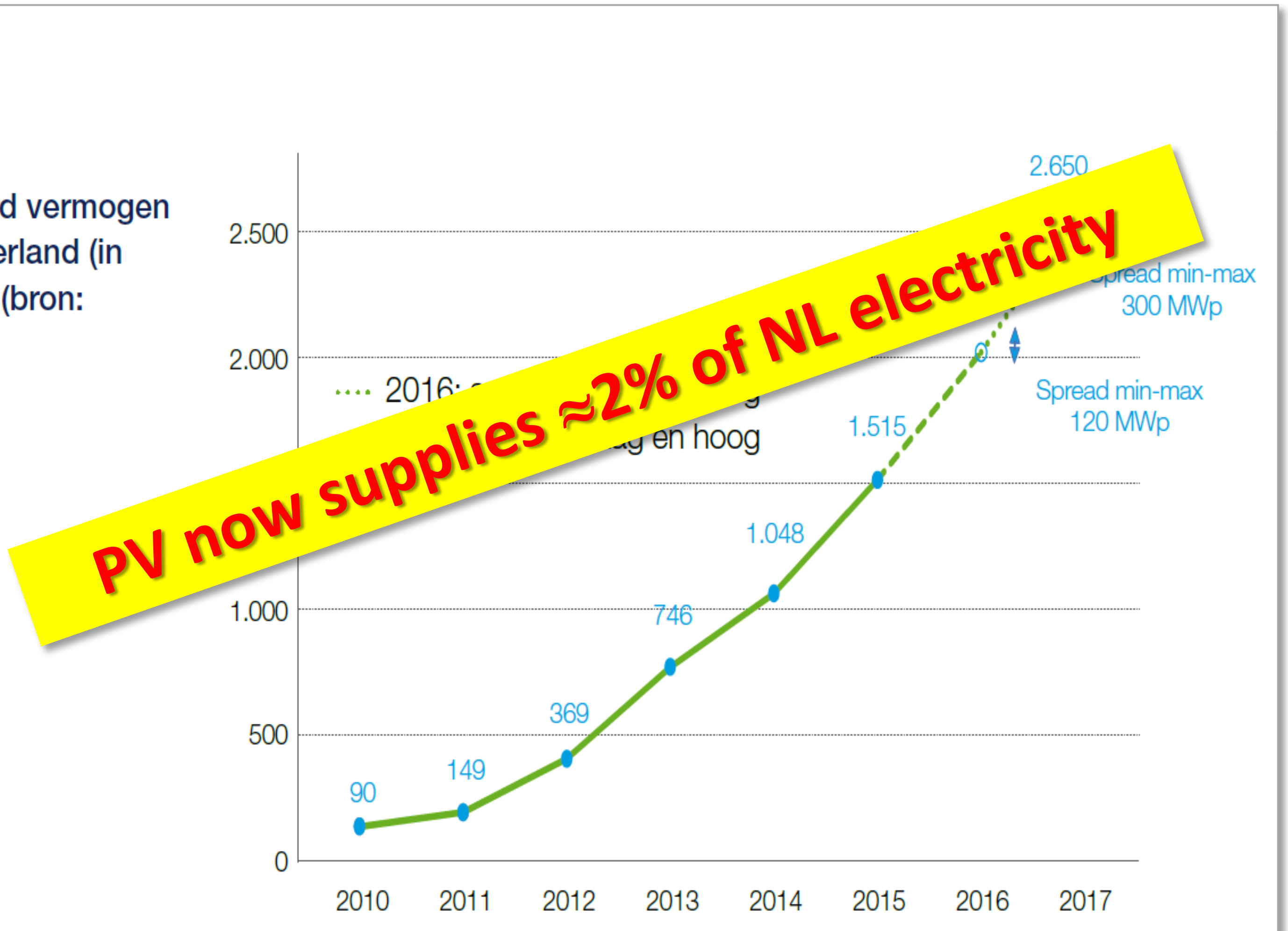
Share

Global cumulative capacity (in GWp)

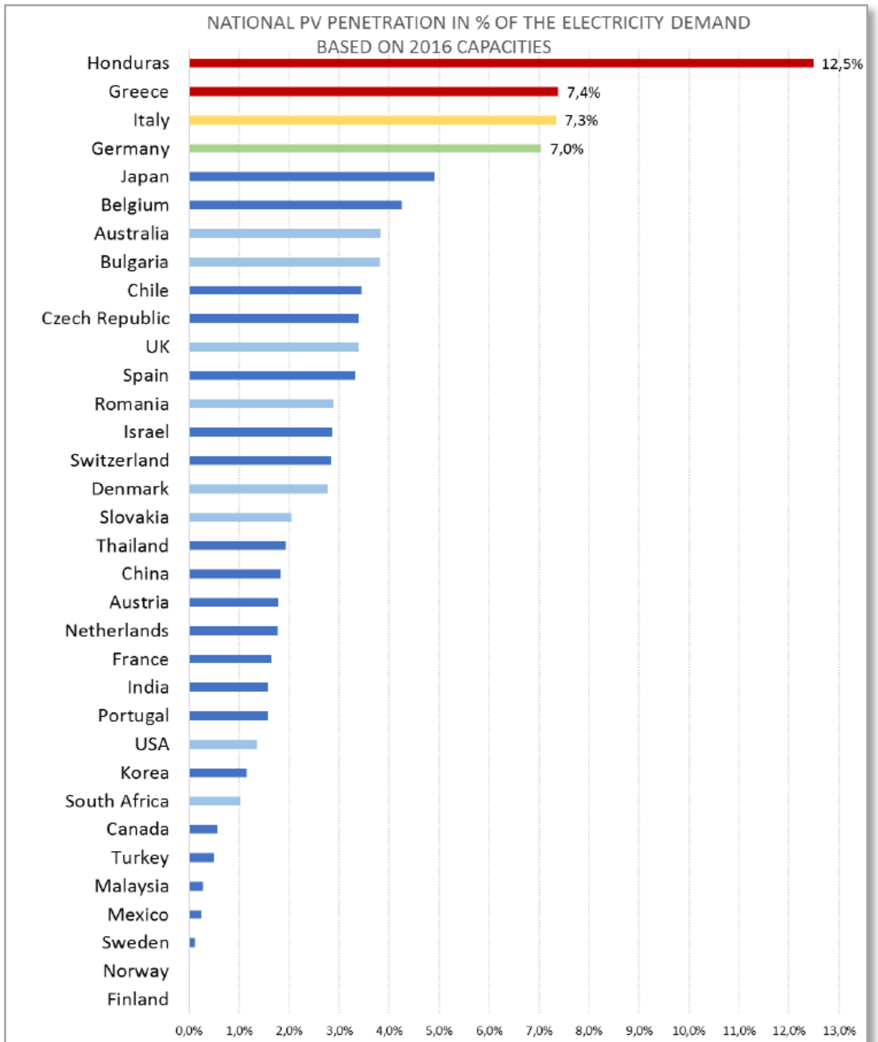


Source: IEA PVPS.

Installed capacity NL (in MWp)



Contribution of PV to electricity use per country



Source: IEA PVPS (2017)

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Volume by and with diversity

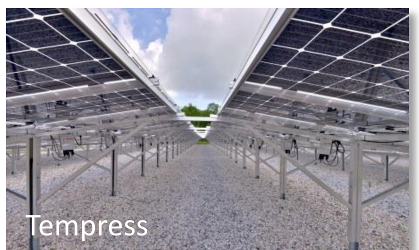
Lightyear


Exasun


ZigZagSolar


Twente Zon


Heijmans/AERspire


Tempress


Artist impression A37
(Studio Marco Vermeulen)


W.J. van Graven, Lisse


Solar Park Ameland


Amsterdam, Sunfloat,
Tempress en ECN

Freedom of shape

Julianadorp, NL
Photo Paul Pex

http://energieanders.nl/trienergia-driehoek-paneel-100wp-detail

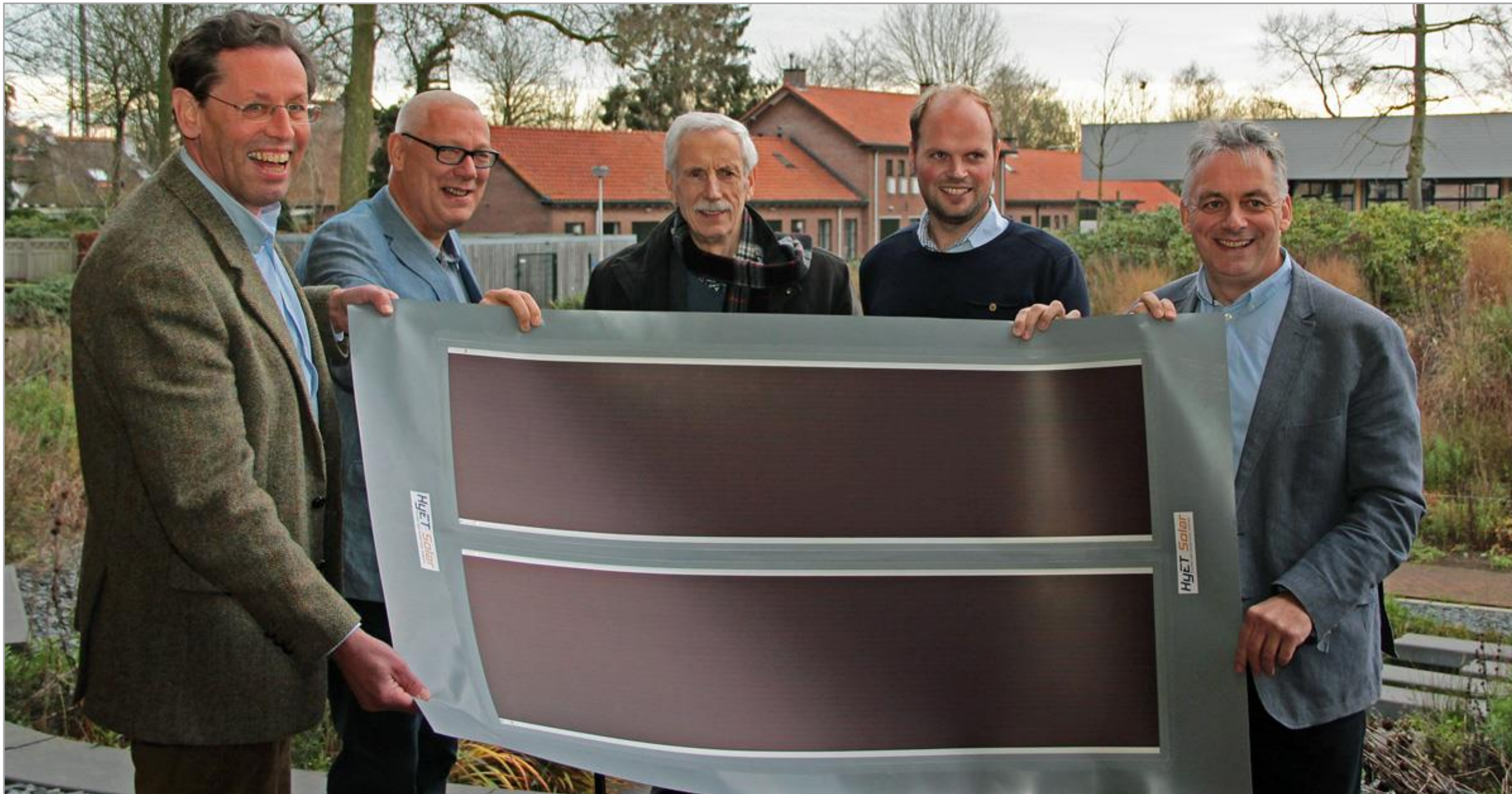
Aesthetic quality

ZEP BV

Exasun

Heijmans/AERspire

Flexibility & light weight



HyET Solar (NL) / BrummenEnergie

Solar energy meets Dutch Design
Solar modules made to your liking

ECN

ECN, UNStudio, TS Visuals, Aldowa, Design Innovation Group and Hogeschool van Amsterdam; project *Dutch Solar Design.*

Solar energy meets Dutch Design
Solar modules made to your liking

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Solar energy meets Dutch Design
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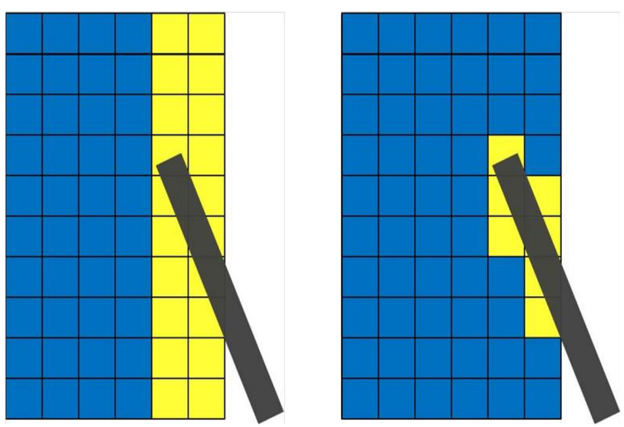
Solutions for ‘B’ and ‘C’ locations
Shade-linear modules



Prototype of shade-linear module (ECN)

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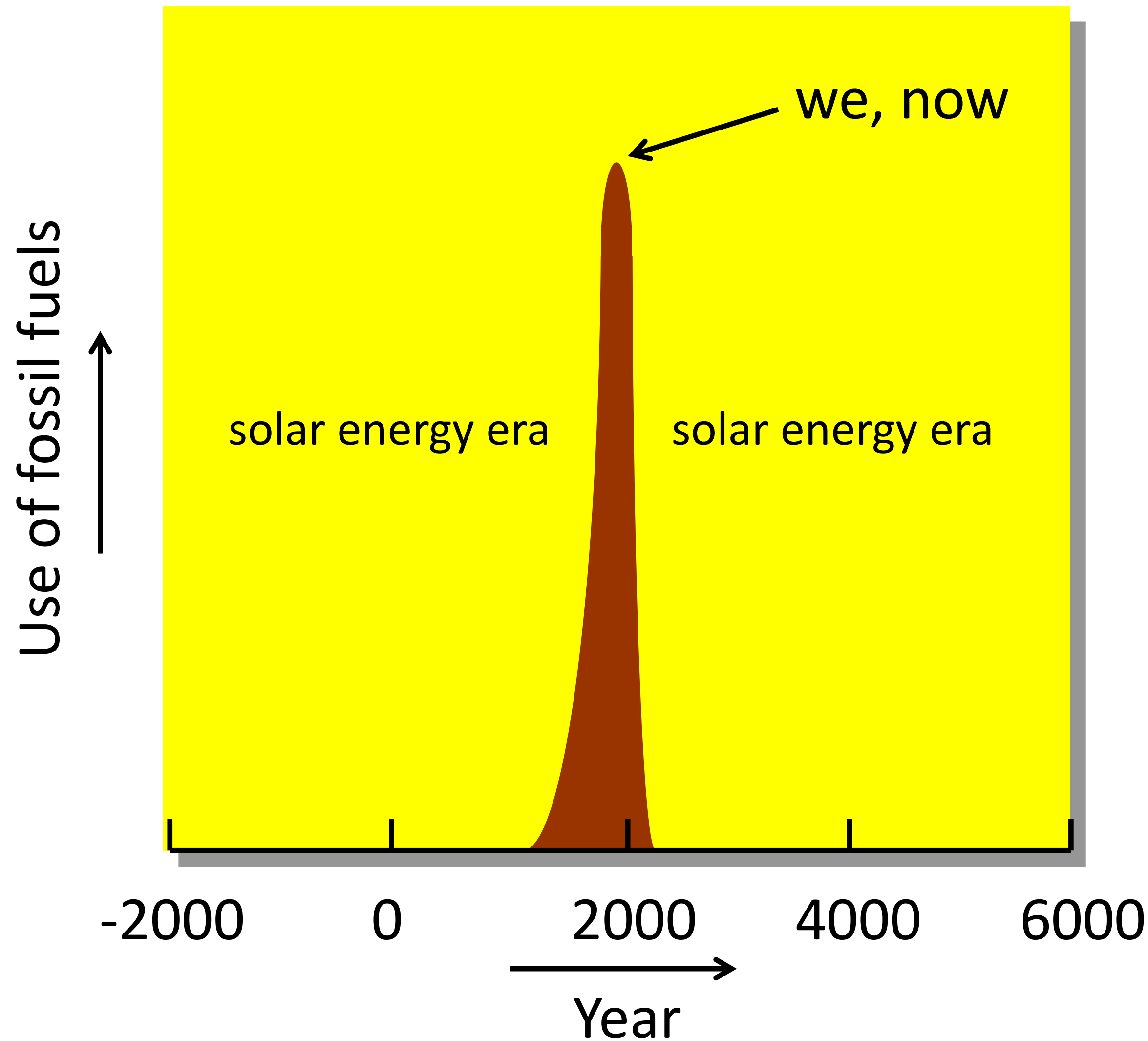
Selected challenges in materials research for terawatt-scale photovoltaics

Stable, high-quality, low-cost, sustainable:

- Wide (& narrow) bandgap absorbers for tandem PV
- Selective IR and UV absorbers for PV windows
- Transparent and non-metal conductors and carrier-selective contacts
- Low-dimensional materials for new optoelectronic properties
- Encapsulants, anti-soiling coatings, support structures

+ closing materials cycles (design for sustainability)

The (solar) energy transformation



http://www.fototavling.nu/ExternaSkript/bidrag/kontraster/large/large_catch-the-sun-4311.jpg