OXFORD PV™

The Perovskite Company

The case for solar?

Christopher Case

1767
World's first solar collector built

1839
Photovoltaic effect discovered

1873
Photoconductivity reported in solid selenium

1905

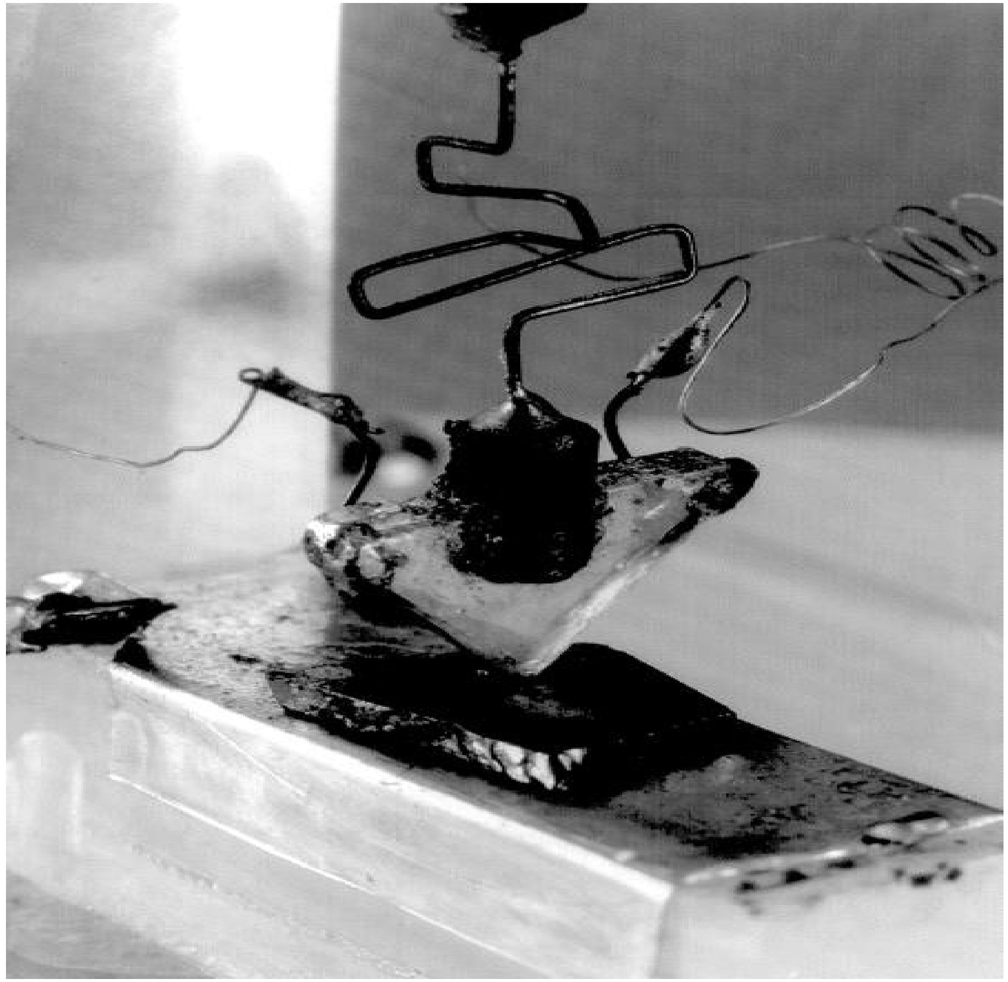
Albert Einstein publishes paper on photoelectric effect

9. *Ueber die lichtelektrische Wirkung;* *von P. Lenard.*

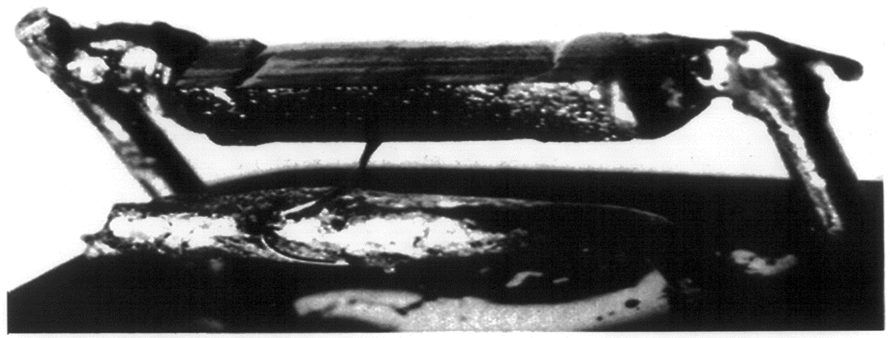
(Hierzu Taf. I, Figg. 1 u. 2.)

In einer früheren Mitteilung habe ich gezeigt, dass ultraviolettes Licht, das auf Körper trifft, Kathodenstrahlung aus denselben veranlassen kann.[1]) Diese Erzeugung von Kathodenstrahlen erwies sich unabhängig vom Vorhandensein eines Gases; sie ging, im Gegensatz zur früher allein bekannten Erzeugungsart in Entladungsröhren, auch im äussersten Vacuum vor sich.[2]) Charakteristisch war es, wie im Vacuum gefunden wurde, dass elektrische Kräfte diese Erzeugung nicht beeinflussten; ein Ansteigen der Kraft an der negativ ge-

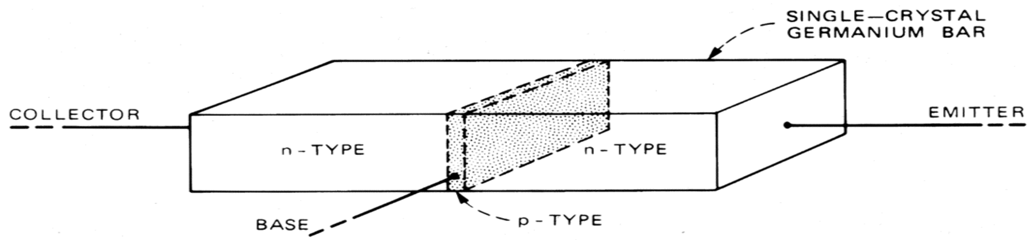
The first transistor - 1947



The positive negative rectifier



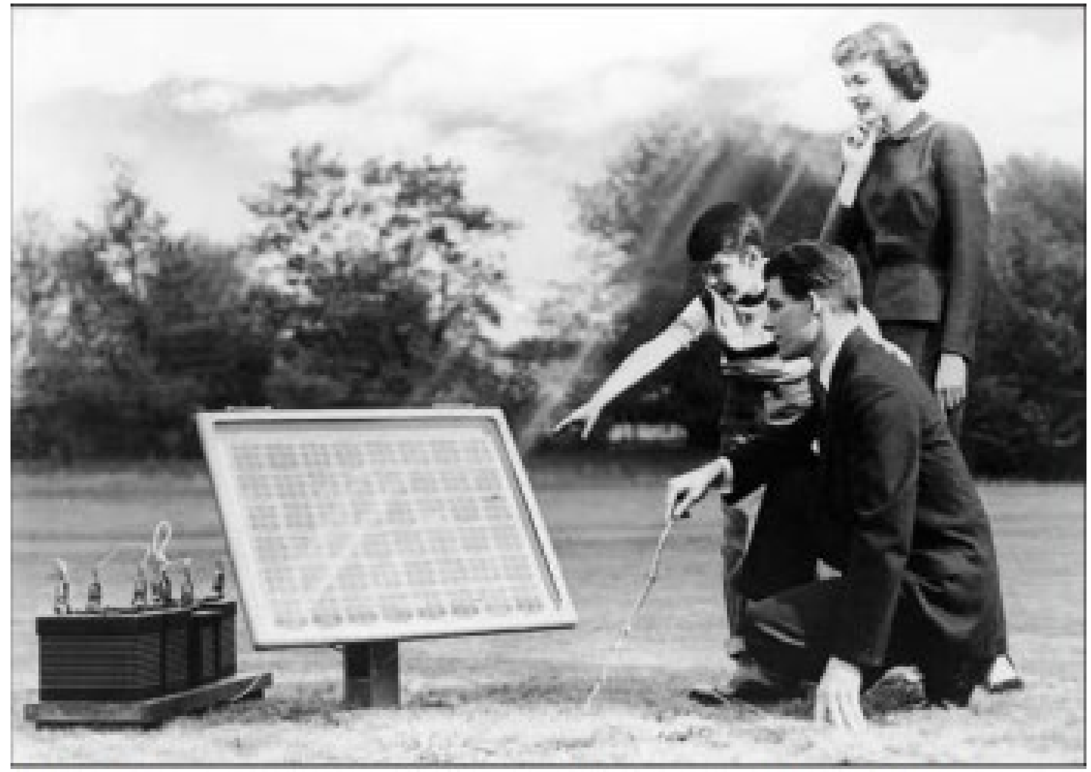
(a)



(b)

The inventors Pearson, Chapin and Fuller: Solar Battery

Gerald Pearson, Daryl Chapin and Calvin Fuller



Advertisement photos, such as this one that appeared in the 1956 issue of Look Magazine, show off the "Bell Solar Battery" to the American public.

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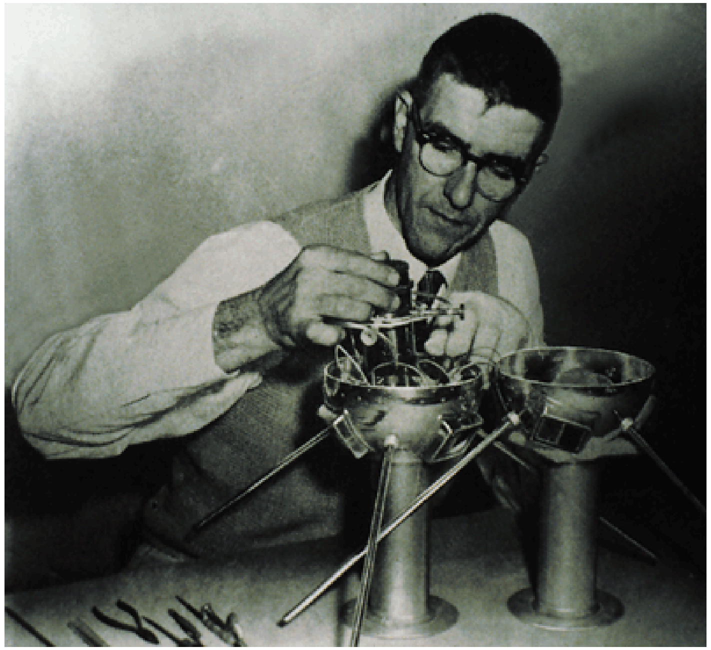
The first solar powered satellite, Vanguard I

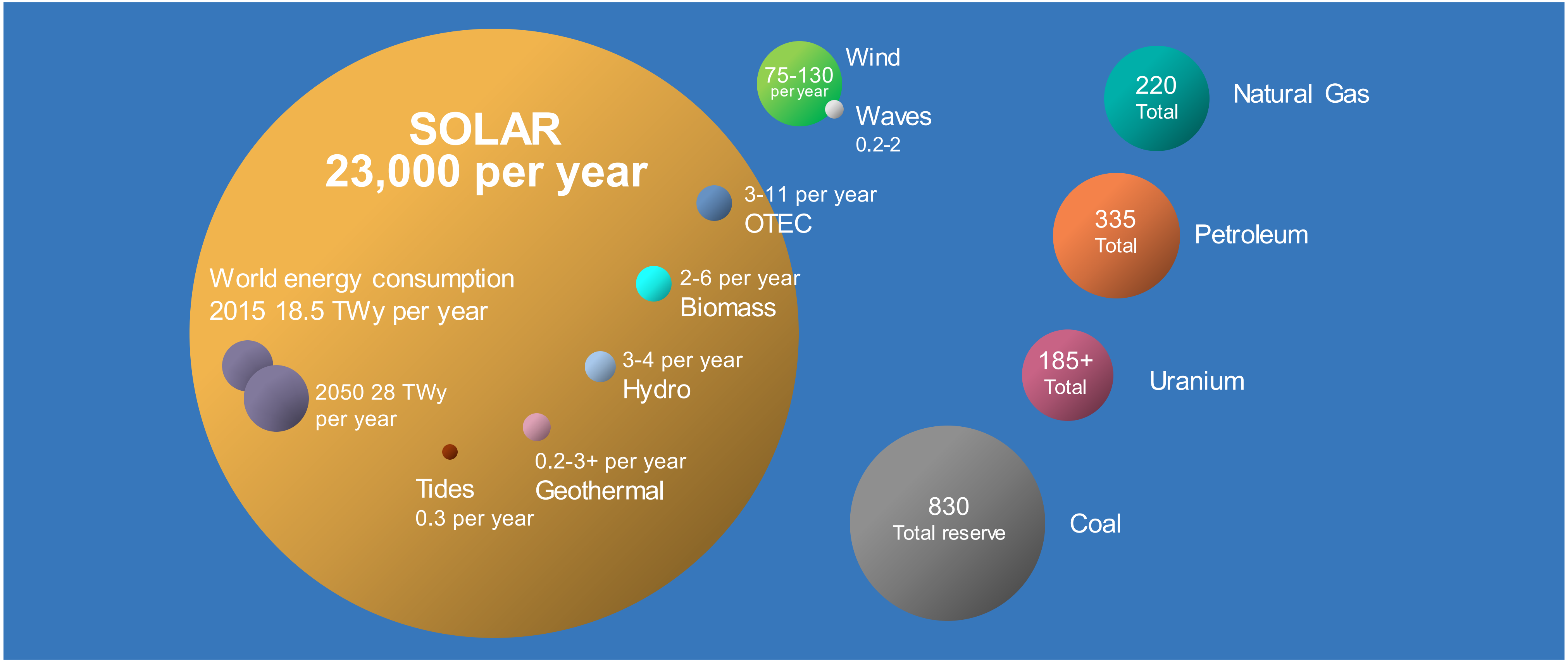
The Vanguard I is launched from Cape Canaveral, March 17, 1958.



The first solar powered satellite, Vanguard I, was launched with the first solar cells providing 0.01W of power on March 17, 1958. It broadcast for six years.

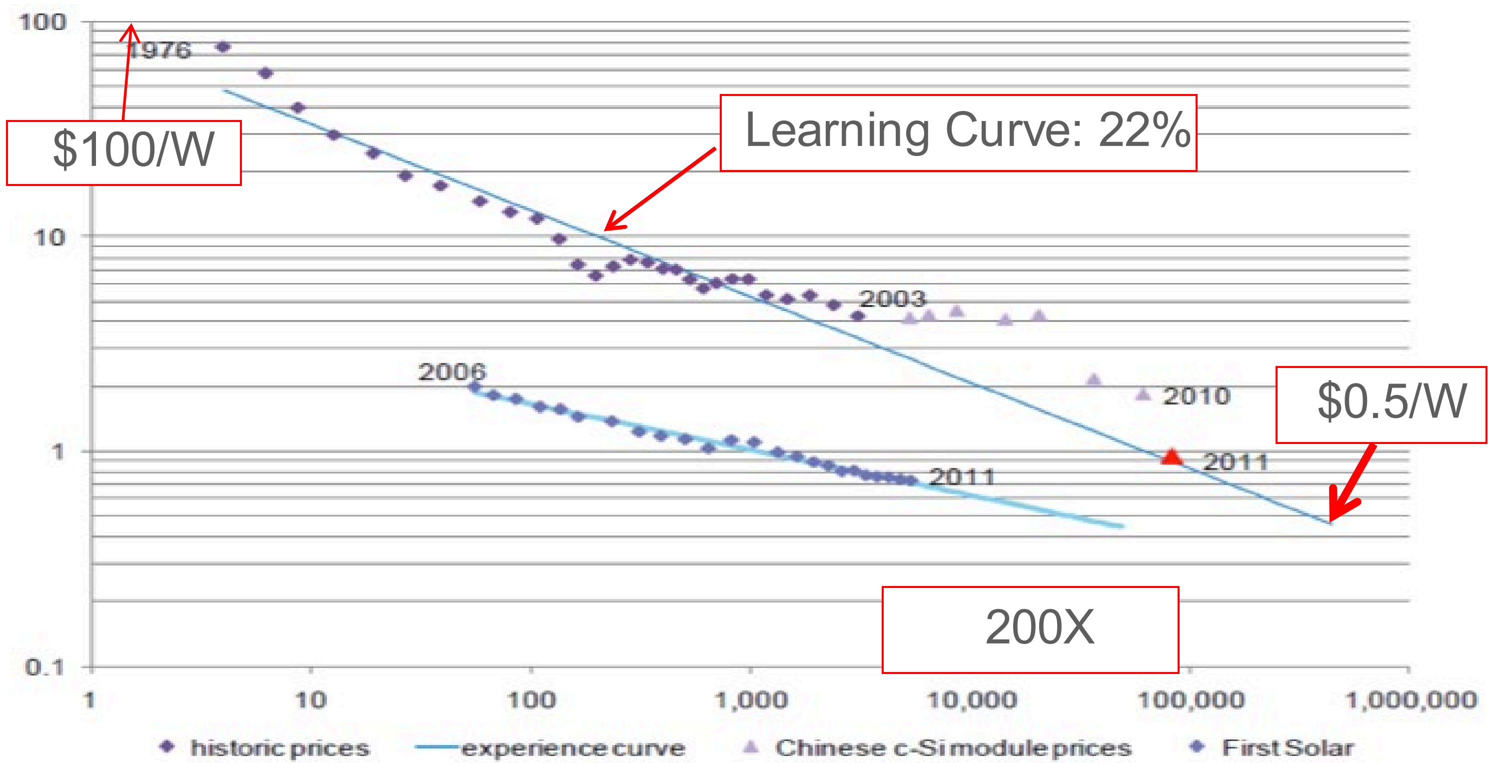
The challenge

To capture and convert the sun's energy cost effectively



© R. Perez shc solar update November 2015

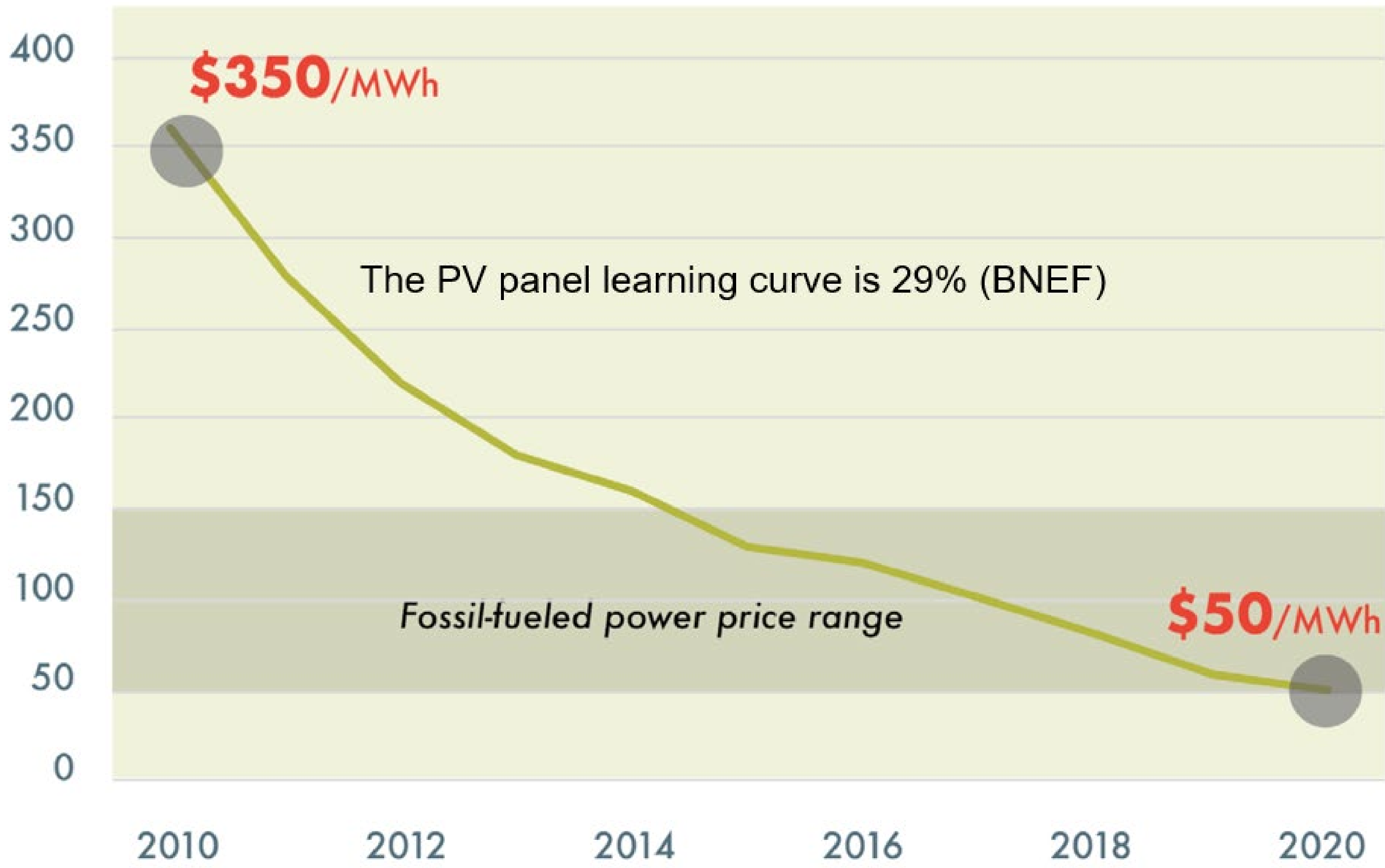
Solar PV costs drop by 200X



Source: BNEF – Economics of PV Power

Global average PV cost fallen 77% since 2010

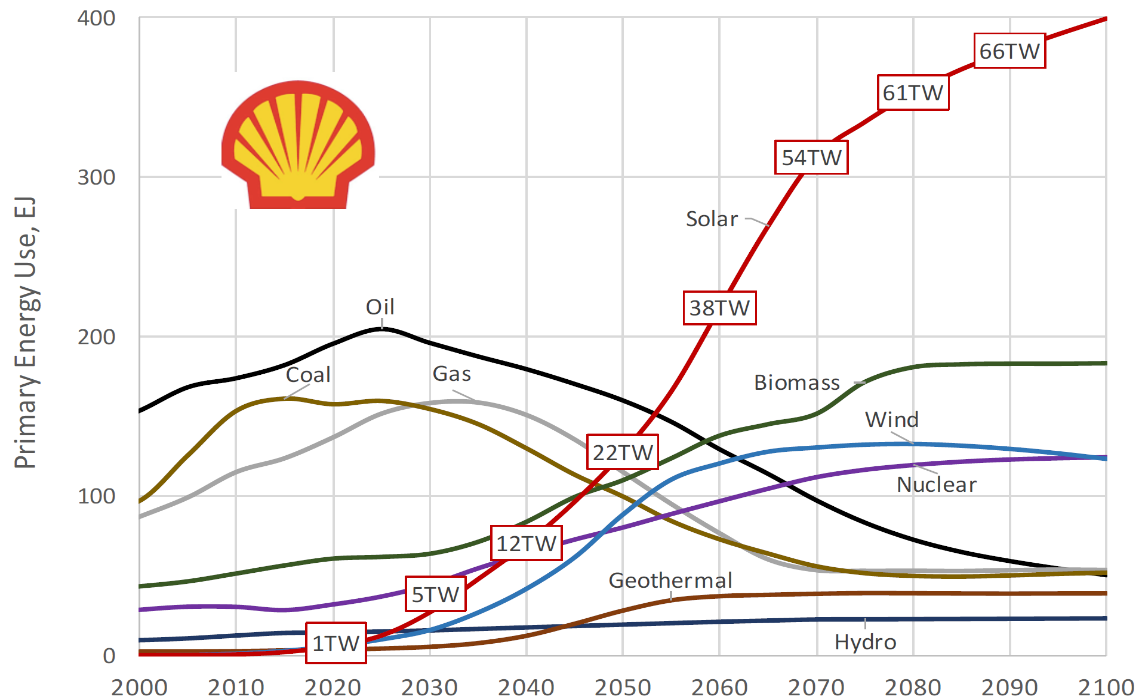
To $80/MWh, 11 September 2018



Source: IRENA, Carbon Tracker

The electricity mix shifts to solar

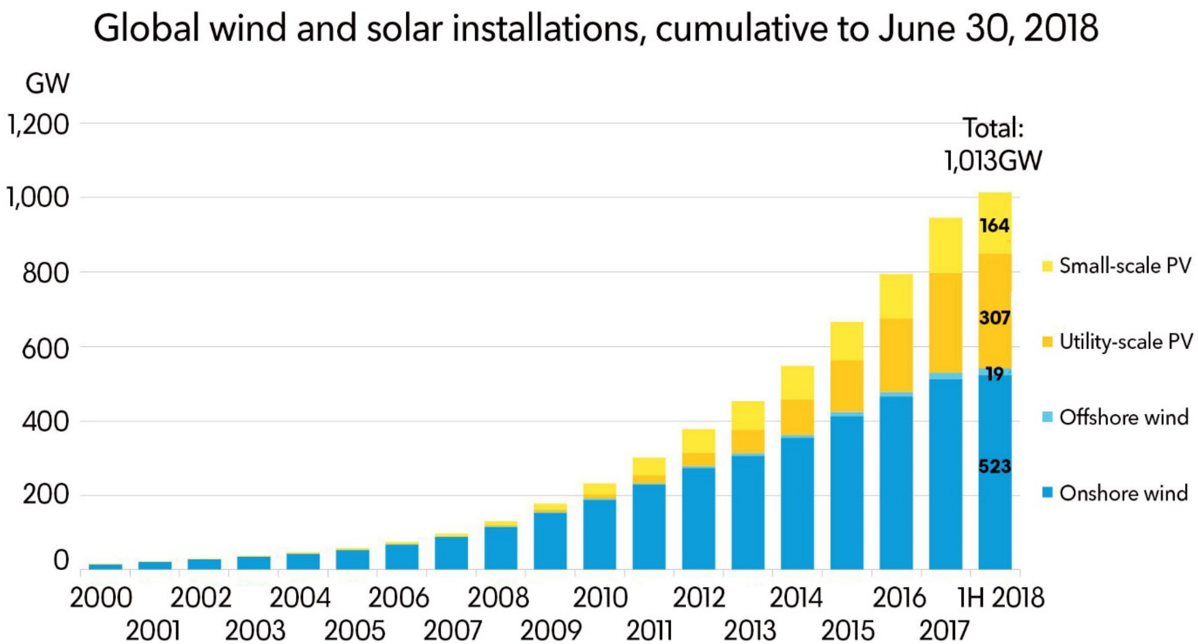
Not fast enough to limit 2°C temperature increase



Sources: Primary energy use in Shell's "Sky scenarios" (2018)

World passes 1,000 GW of wind and solar

2 August 2018

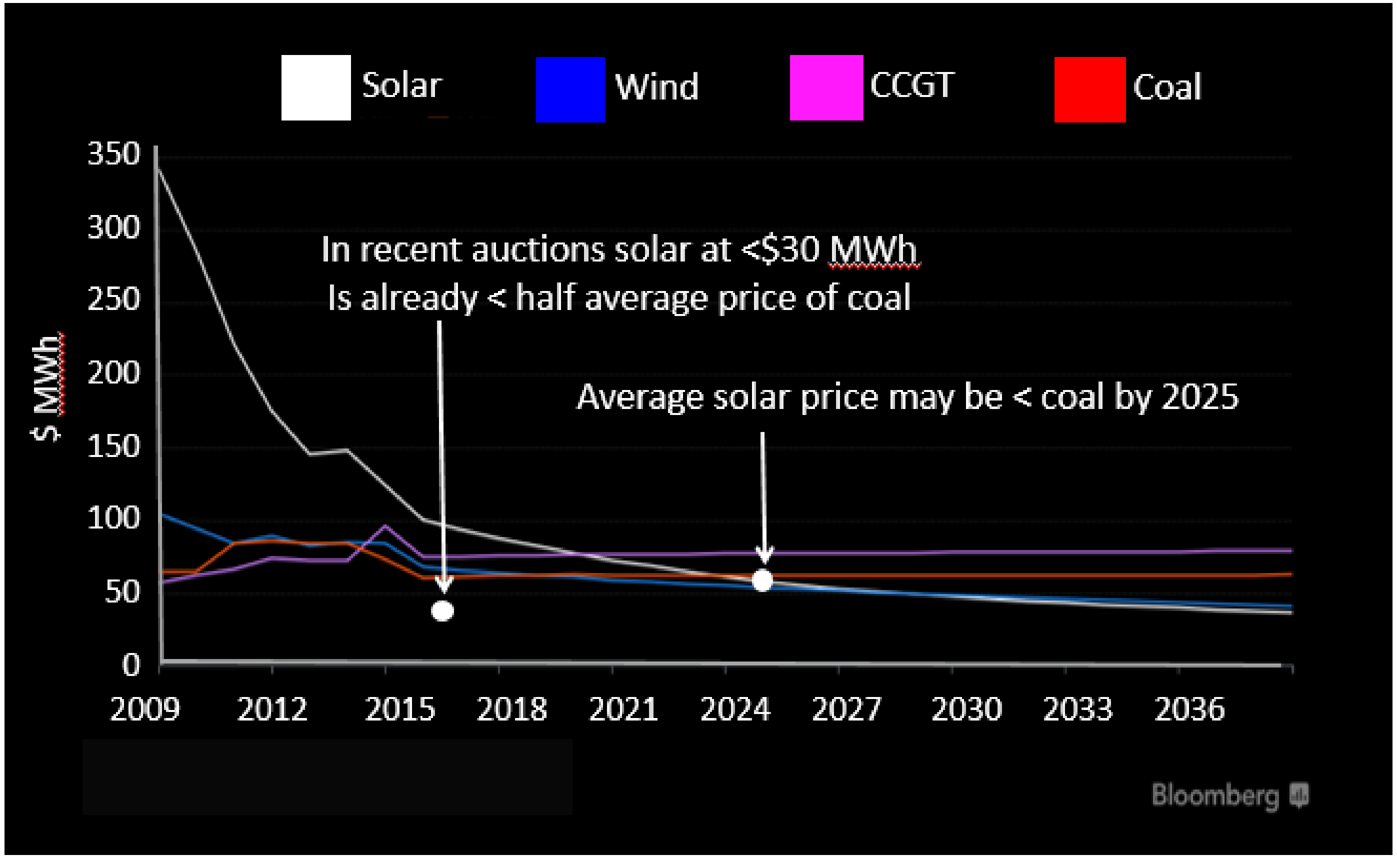


Source: Bloomberg NEF. Note: 1H 2018 figures for onshore wind are based on a conservative estimate; the true figure will be higher. BNEF typipcally does not publish mid-year installation numbers.

- Record on a rising exponential curve, in the last days of June
- BNEF estimates the second TW will arrive by mid-2023, costing 46% less than the c.$1.3 tn required for the first, 54% wind, 46% solar.

“Solar could become the cheapest power on earth”

2017

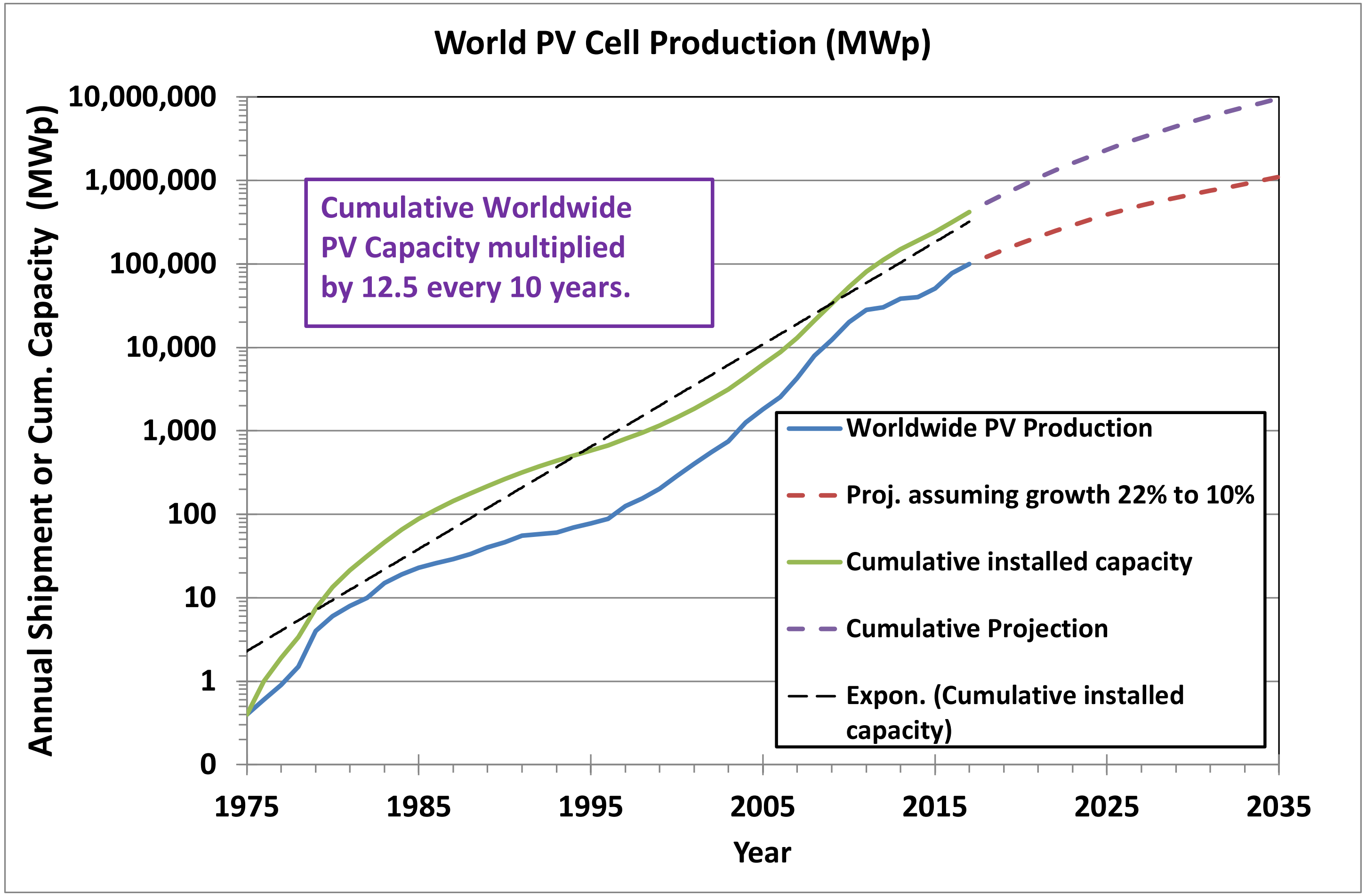


Bloomberg

Source: Bloomberg New Energy Finance

Where is solar today?

Only ~2% of global electricity generation



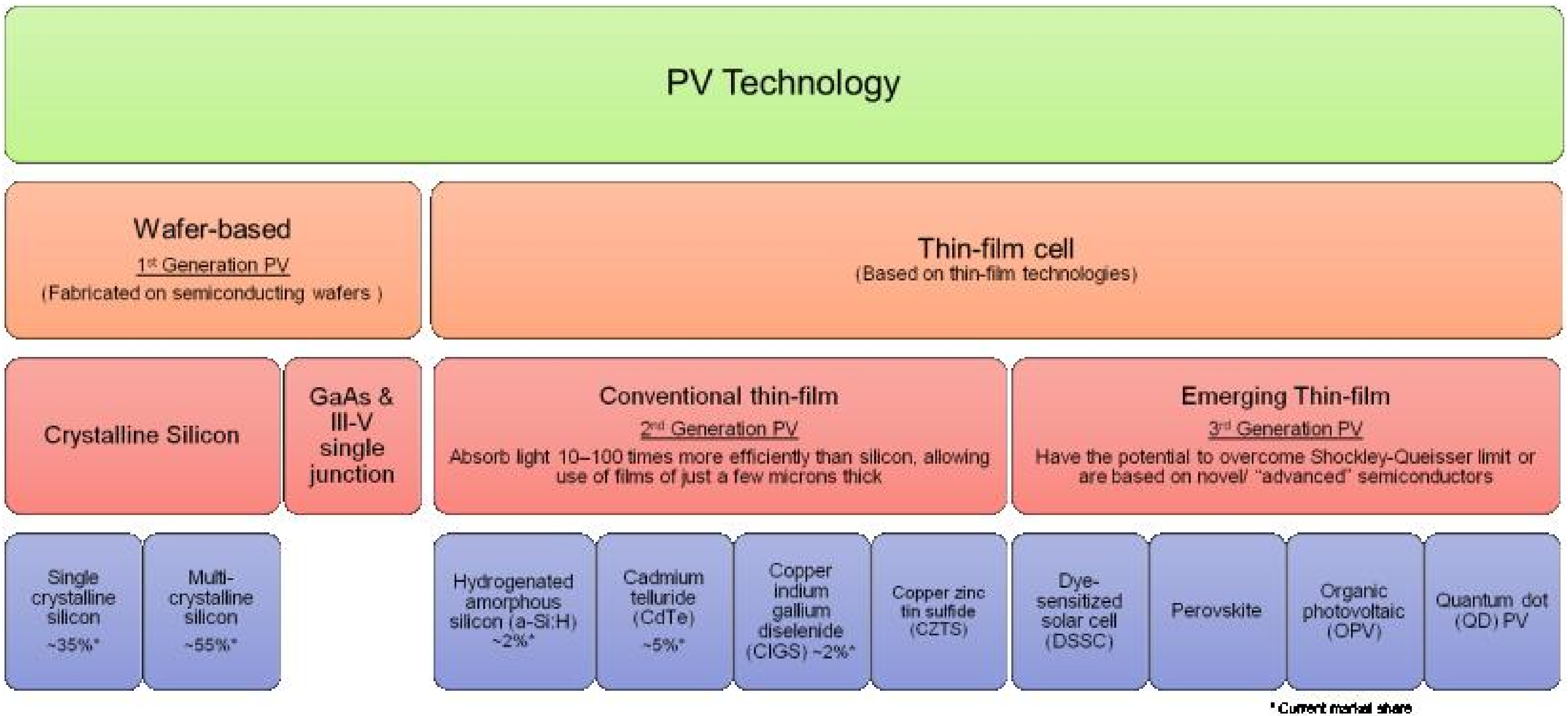
- We need to add 100 GW of production capacity within three years
- We need to add 300 GW of production capacity in six years

The future is all electric

Mainstream solar is reaching its practical and economic efficiency limit

The opportunity for perovskite

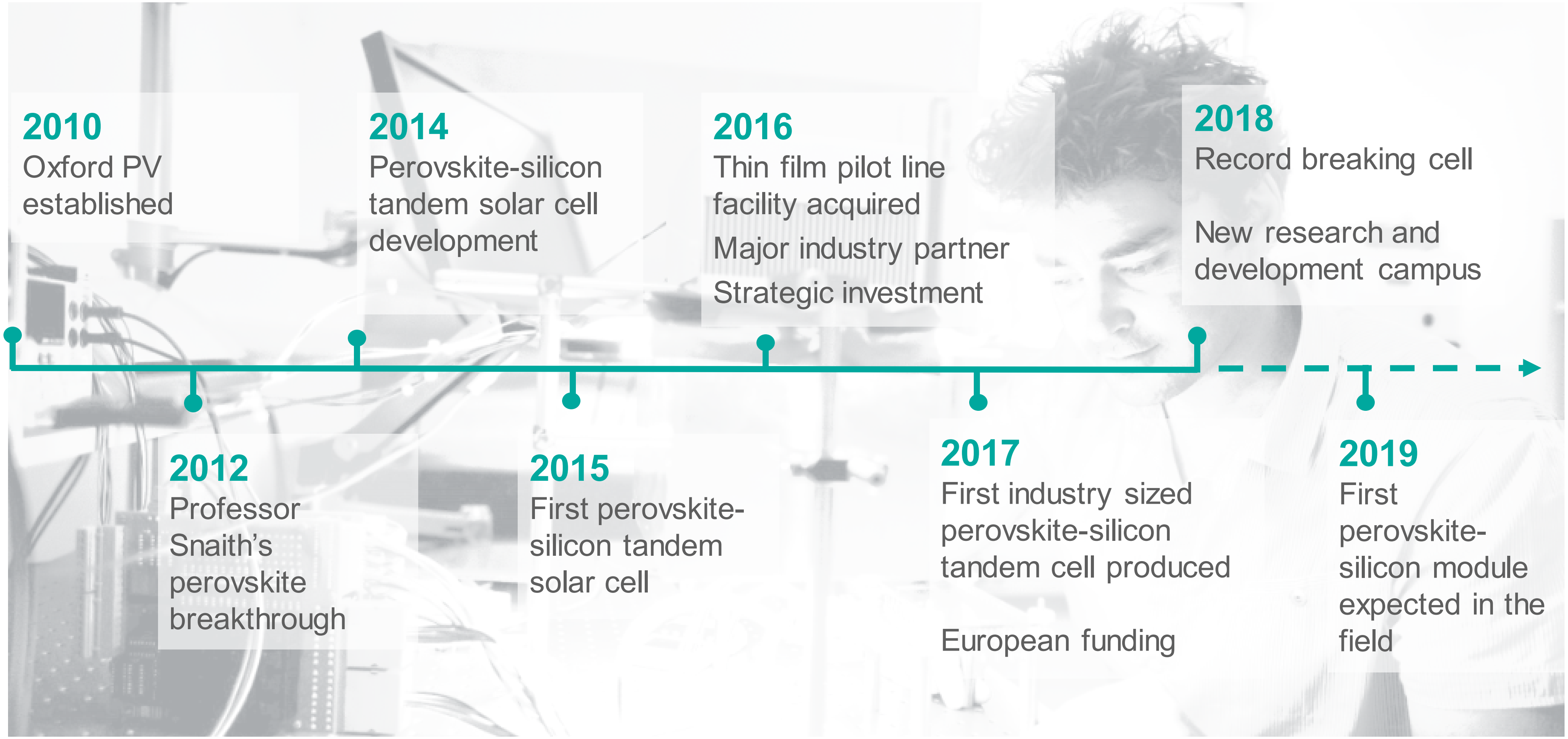
Solar cell technologies



http://www.idtechex.com/research/reports/perovskite-photovoltaics-2015-2025-technologies-markets-players-000442.asp

Journey to perovskite solar cell technology leader

From Professor Henry Snaith's Oxford University lab



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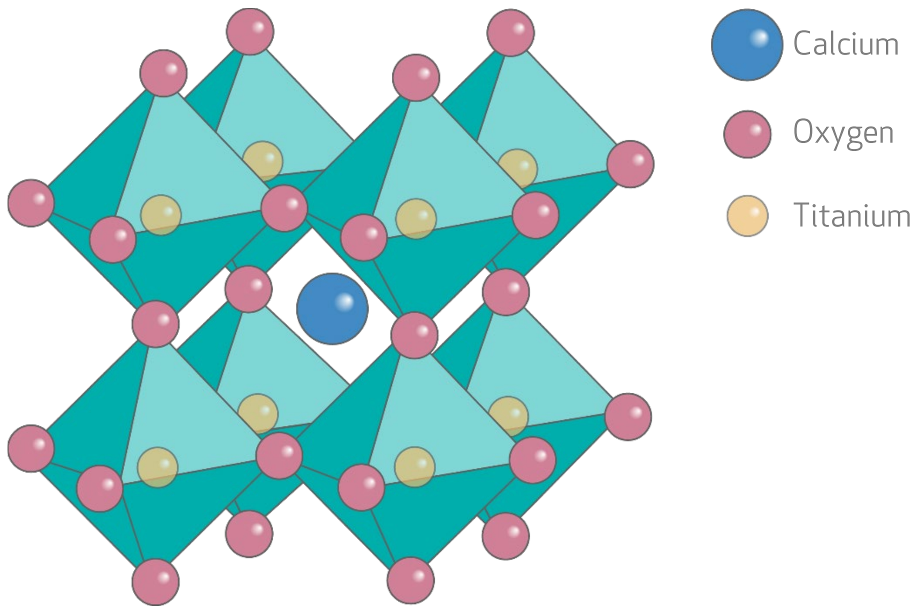
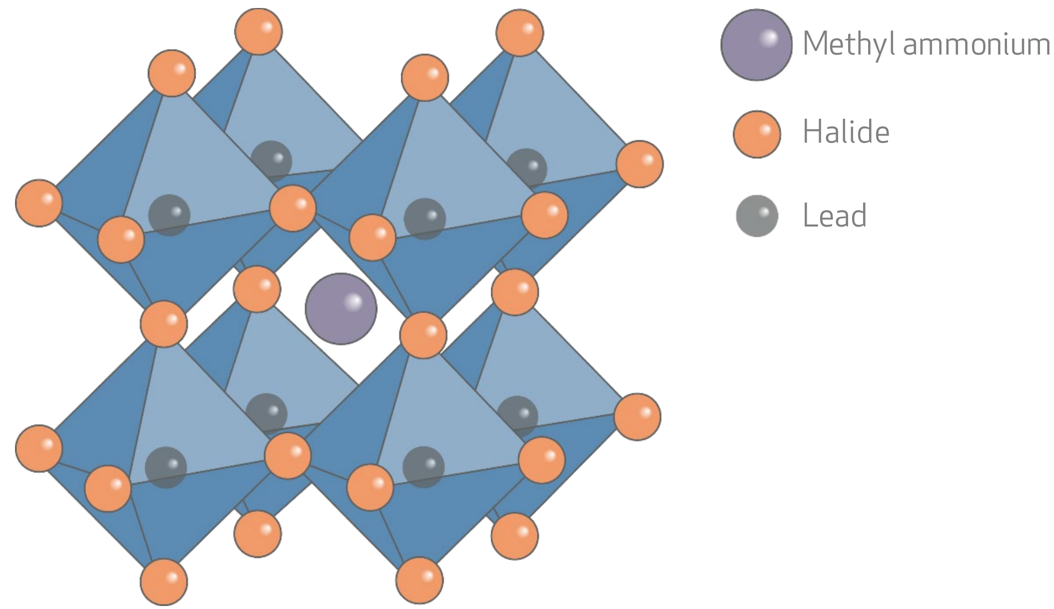
What is a perovskite based solar material?

ABX3 - $CaTiO_3$

The mineral perovskite



Typical perovskite solar absorber



1892: 1st paper on lead halide perovskites

Über die Cäsium- und Kalium-Bleihalogenide.

Von

H. L. Wells.[1]

Als Fortsetzung der in diesem Laboratorium[2] begonnenen Arbeit über Doppelhalogenide ist von den Herren G. F. Campbell, P. T. Walden und A. P. Wheeler eine Untersuchung über die Cäsium-Bleisalze unternommen worden. Diese Herren haben die Untersuchung mit vielem Eifer und Geschick durchgeführt, und es macht mir Freude, ihnen meinen Dank auszusprechen. Sie haben die Existenz folgender Salze konstatiert:

Cs_4PbCl_6	Cs_4PbBr_6	—
$CsPbCl_3$	$CsPbBr_3$ [3]	$CsPbJ_3$
$CsPb_2Cl_5$	$CsPb_2Br_5$	—

Sheffield Scientific School, New Haven, Conn., Oktober 1892.

Structure deduced 1959:

Kongelige Danske Videnskabernes Selskab, Matematisk-Fysike Meddelelser (1959) 32, p1-p17

Author: **Moller, C.K.**

Title: The structure of cesium plumbo iodide Cs Pb I3

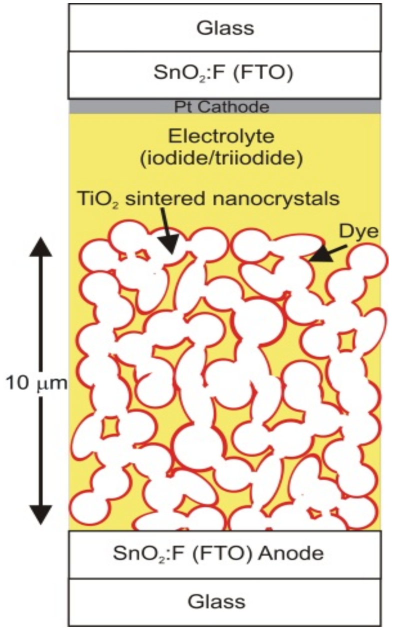
First published perovskite PV cells

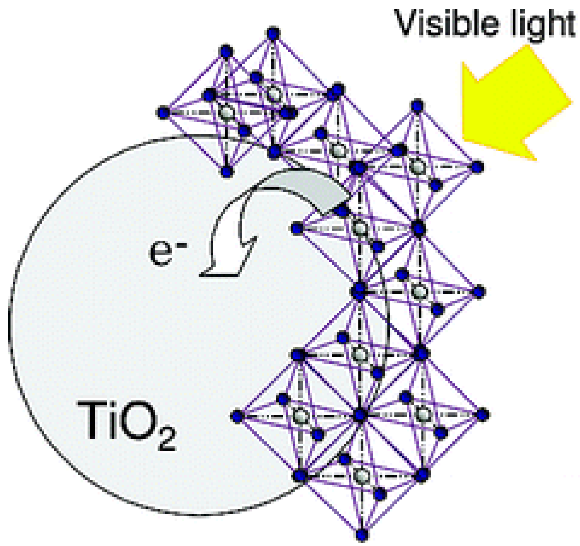
Dye sensitized

Organometal Halide Perovskites as Visible-Light Sensitizers for Photovoltaic Cells

Akihiro Kojima,† Kenjiro Teshima,‡ Yasuo Shirai,§ and Tsutomu Miyasaka*,†,‡,||

J. AM. CHEM. SOC. 2009, *131*, 6050–6051





Perovskite nanocrystalline sensitizers

Miyasaka *et al.* JACS 2009, 131, 6050-6051
Park *et al. Nanoscale*, 2011,**3**, 4088-4093

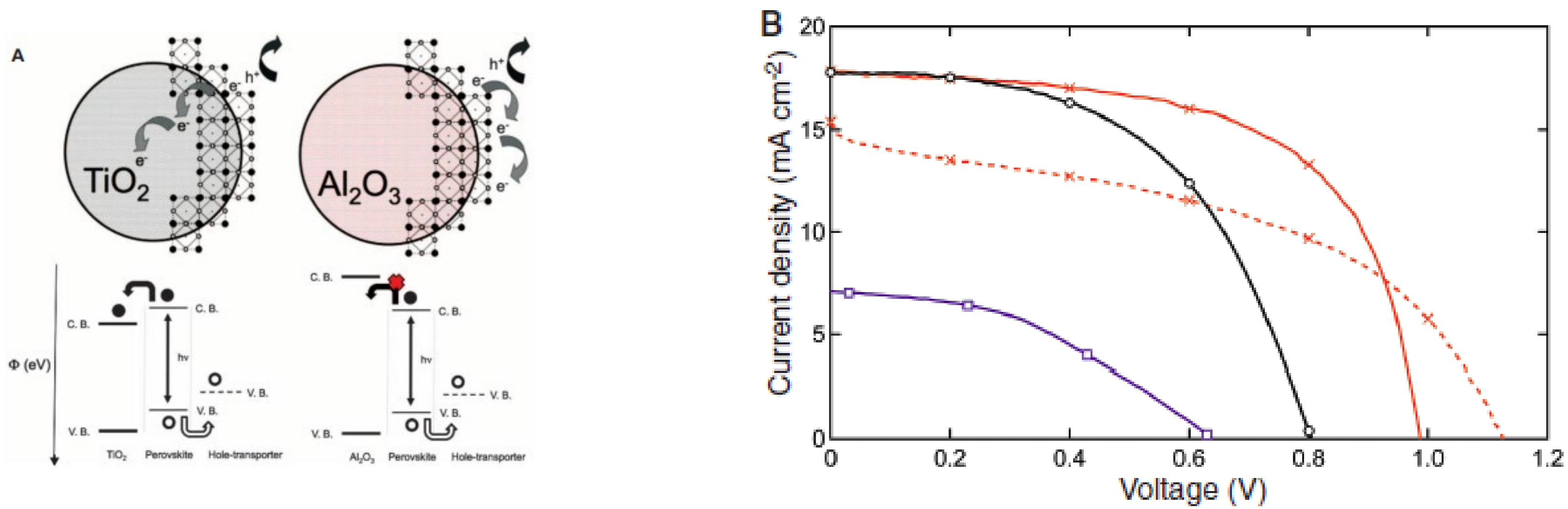
The paper in *Science* 2012 that prompted all the fuss

10,000 publications later

Efficient Hybrid Solar Cells Based on Meso-Superstructured Organometal Halide Perovskites

Michael M. Lee,[1] Joël Teuscher,[1] Tsutomu Miyasaka,[2] Takurou N. Murakami,[2,3] Henry J. Snaith[1*]

SCIENCE VOL 338 2 NOVEMBER 2012 **643**



Generic p-i-n “heterojunction” cell

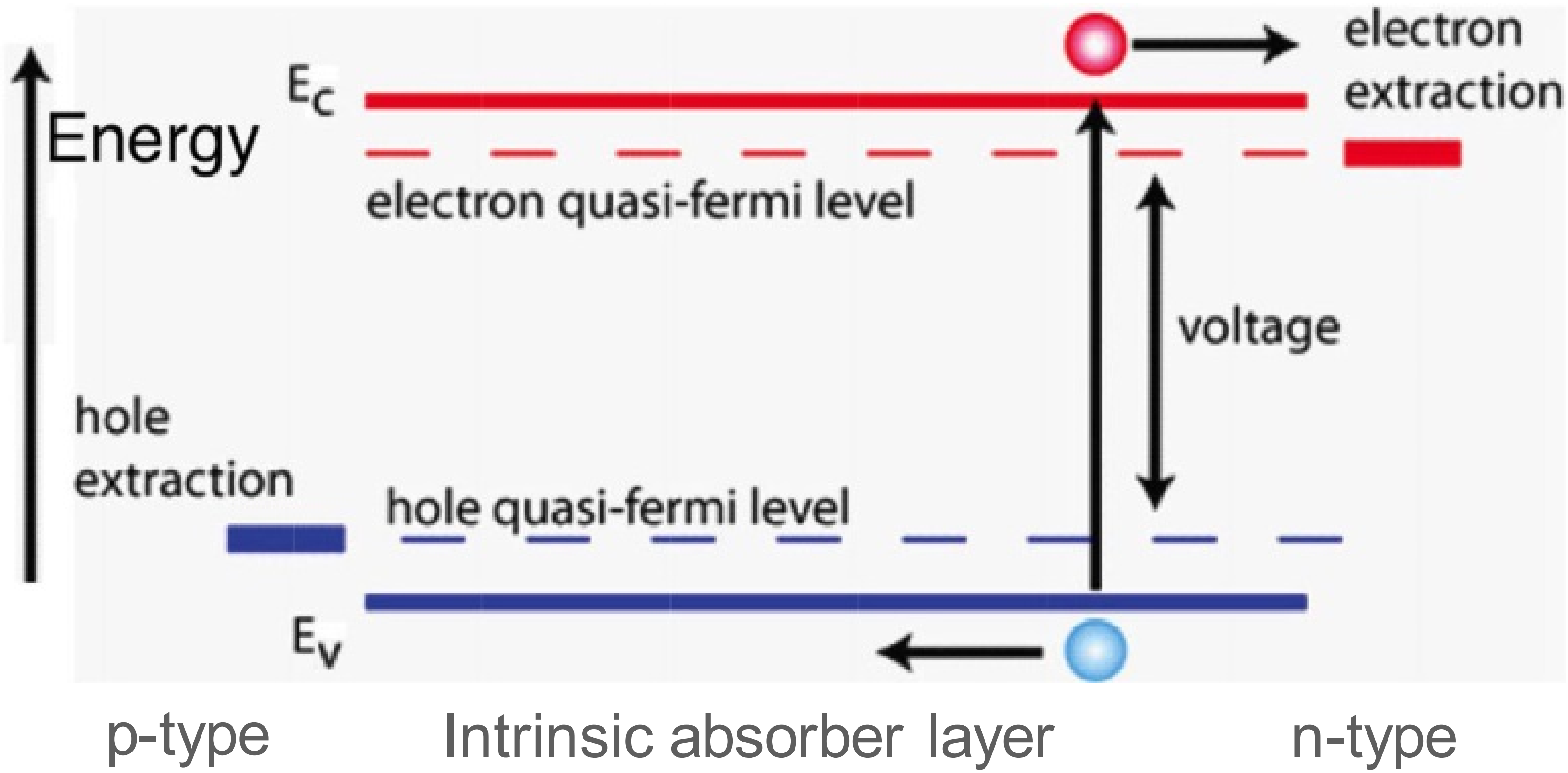
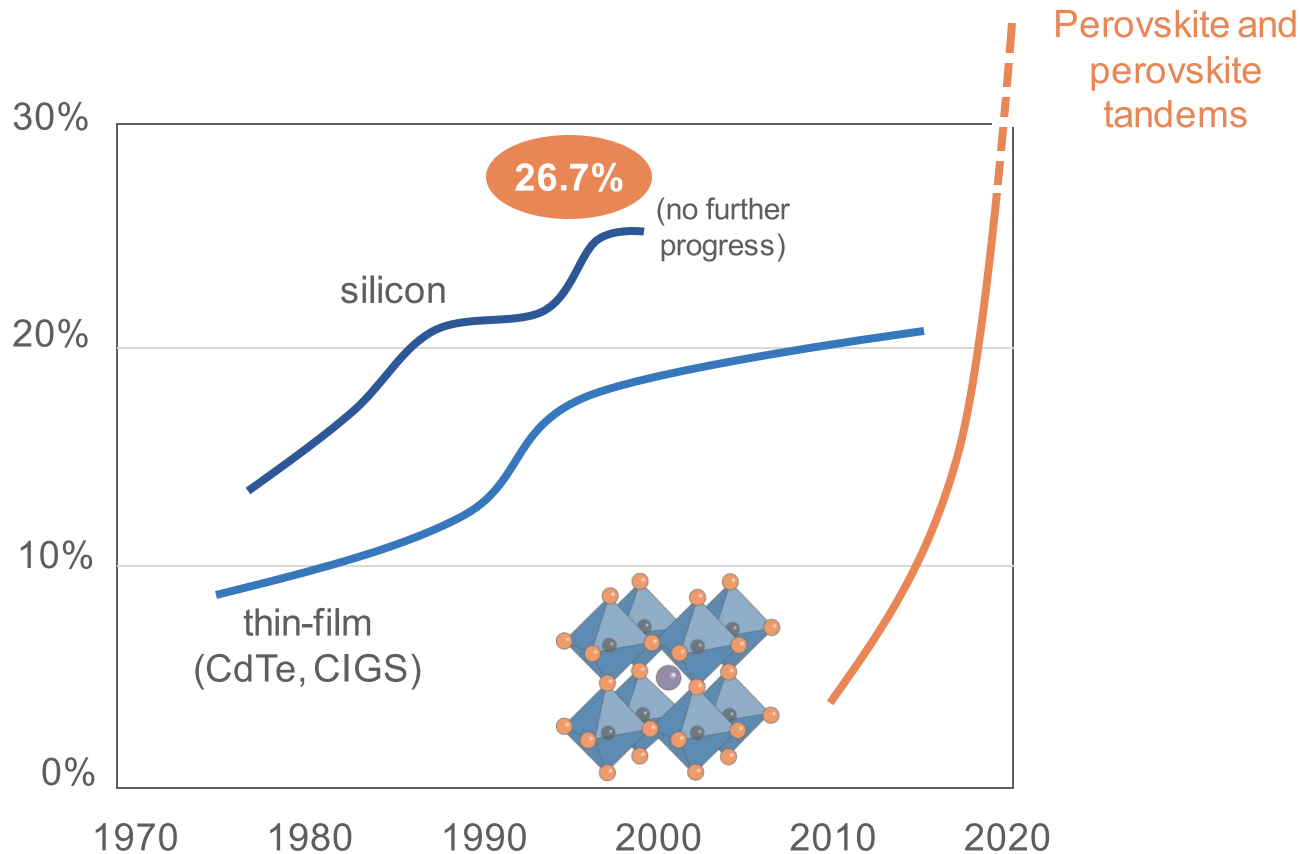


Diagram adapted from SPIE Newsroom 2013 10.1117/2.1201307.004681

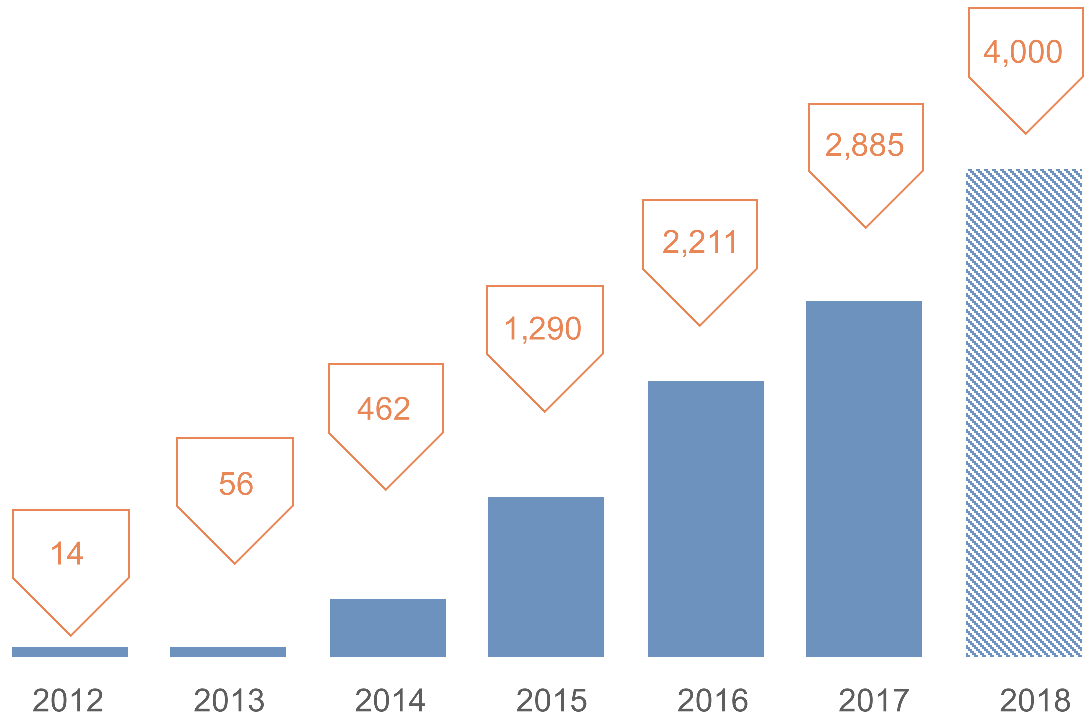
The fast improving photovoltaics material ever seen

Low cost and high performance



Explosion in activity globally

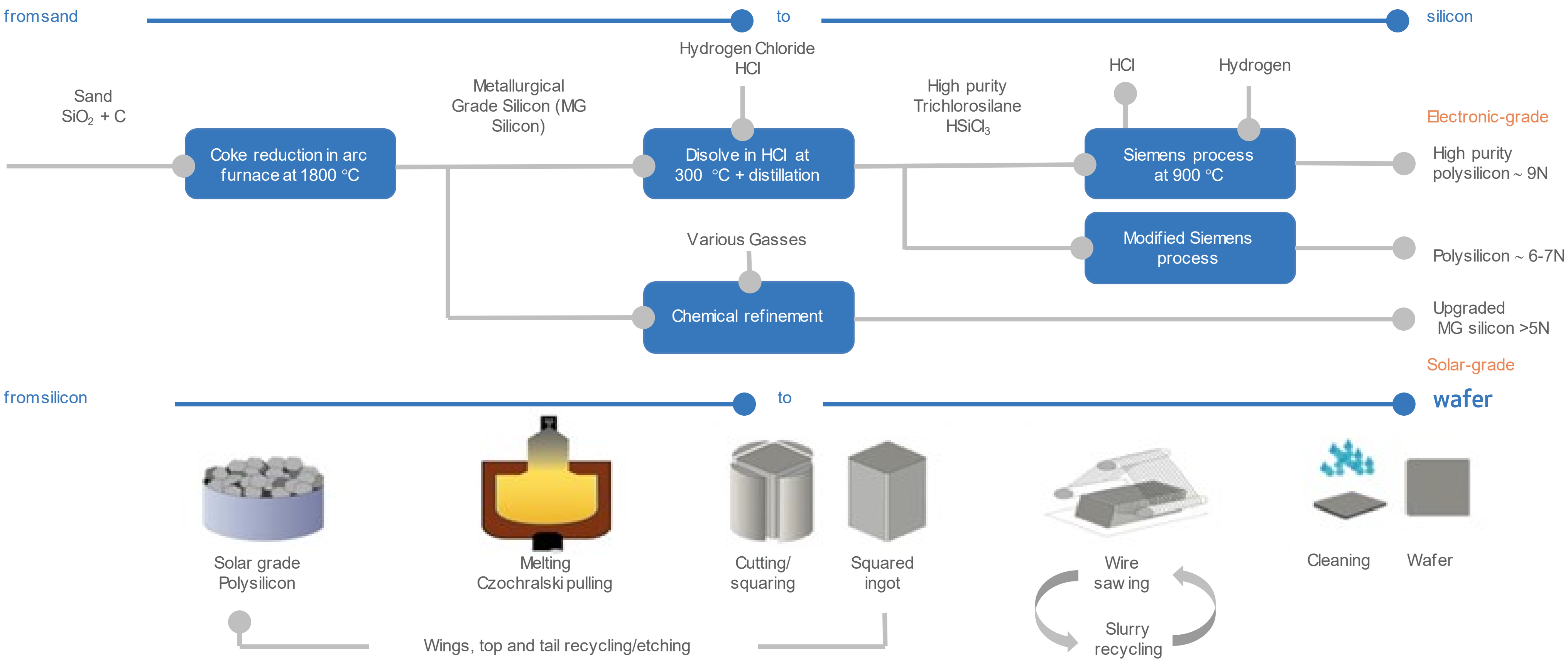
Over 10,000 academic publications



Source: Academic publications in Web of Science

Silicon production is expensive and wasteful

Expensive, high-energy process generating high levels of waste material



Steep cost reduction curve is saturating: after streamlining, the silicon PV industry will be limited to incremental cost reductions in the future

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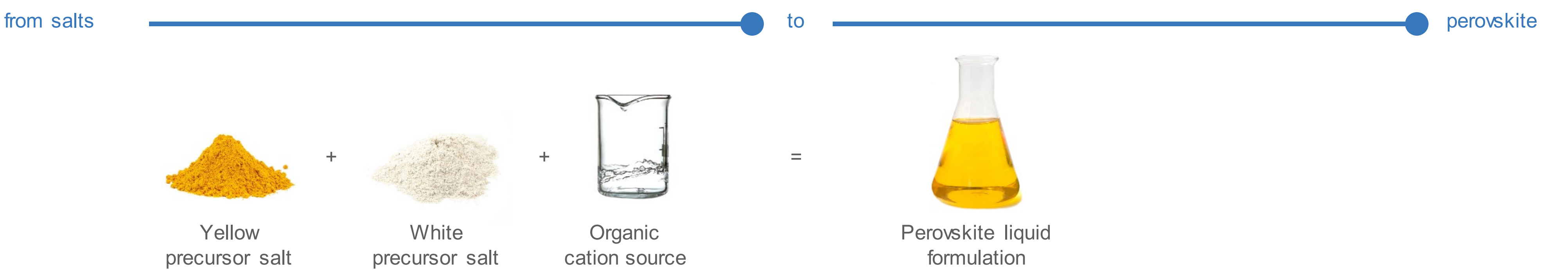
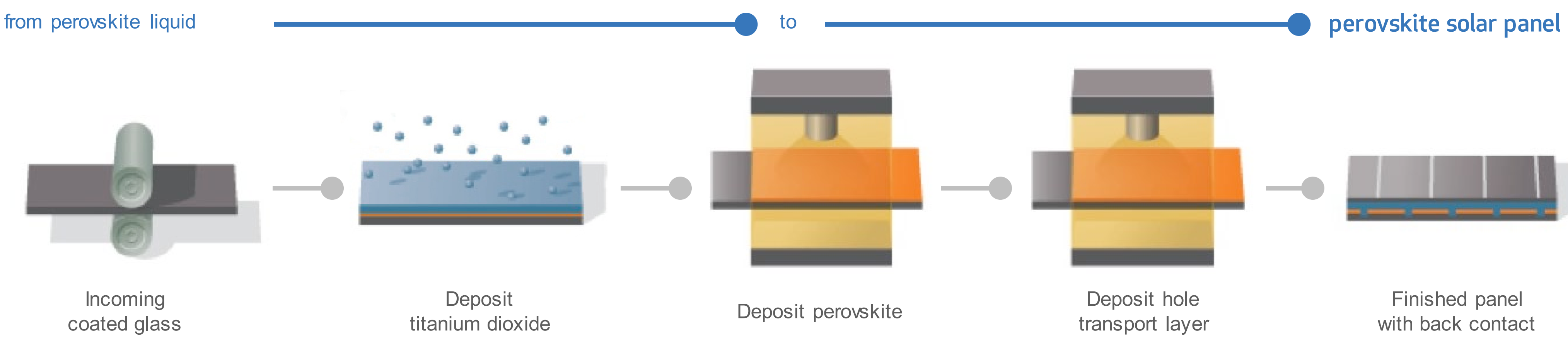
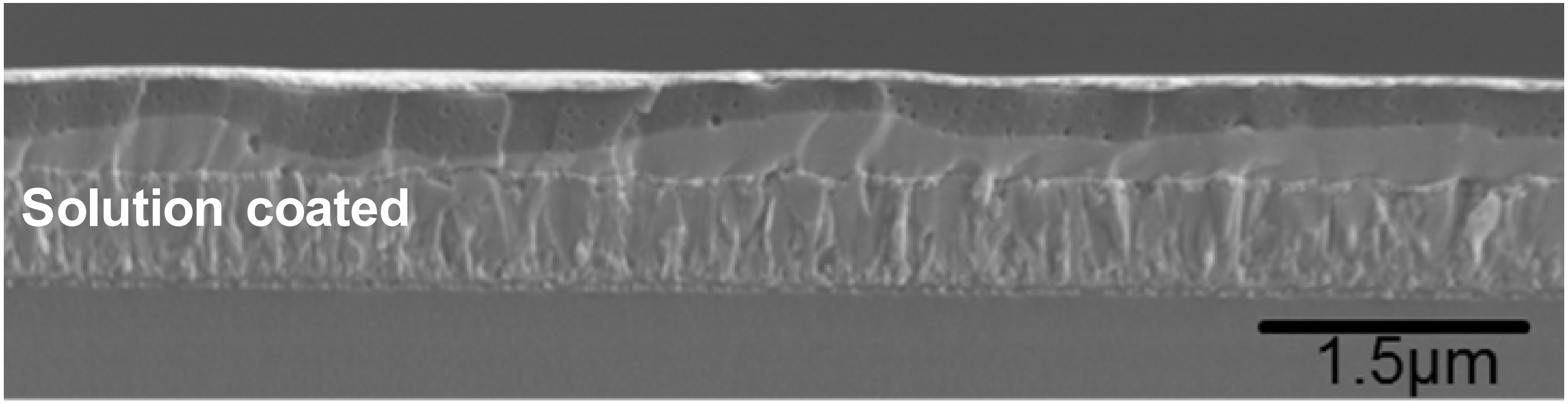
Production of perovskite cell

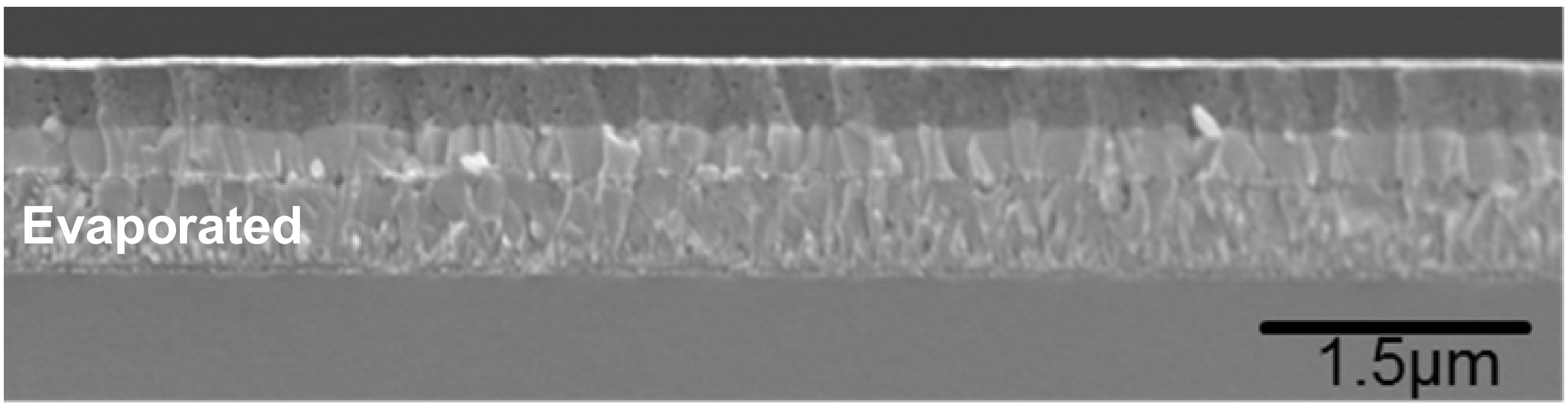
Simpler, lower cost, lower energy payback, reduced environmental impact, lowest LCOE





Cross section of films and devices

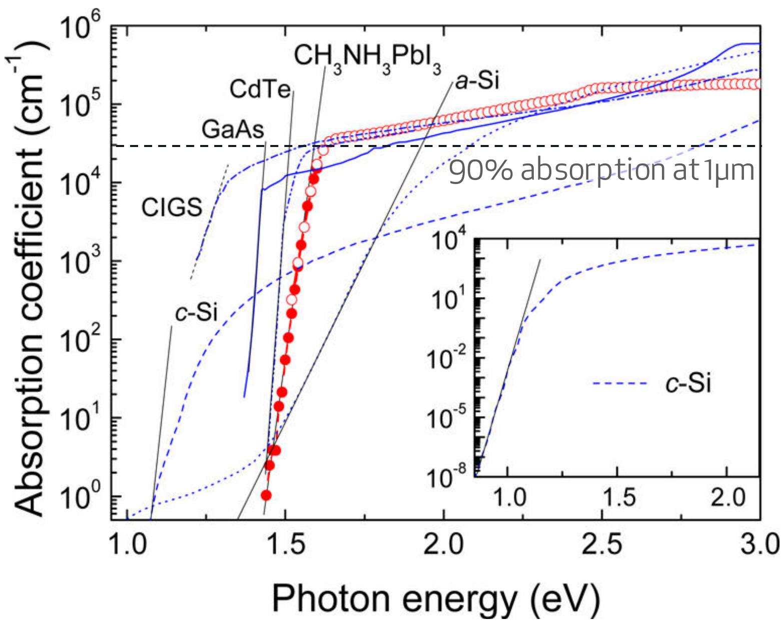




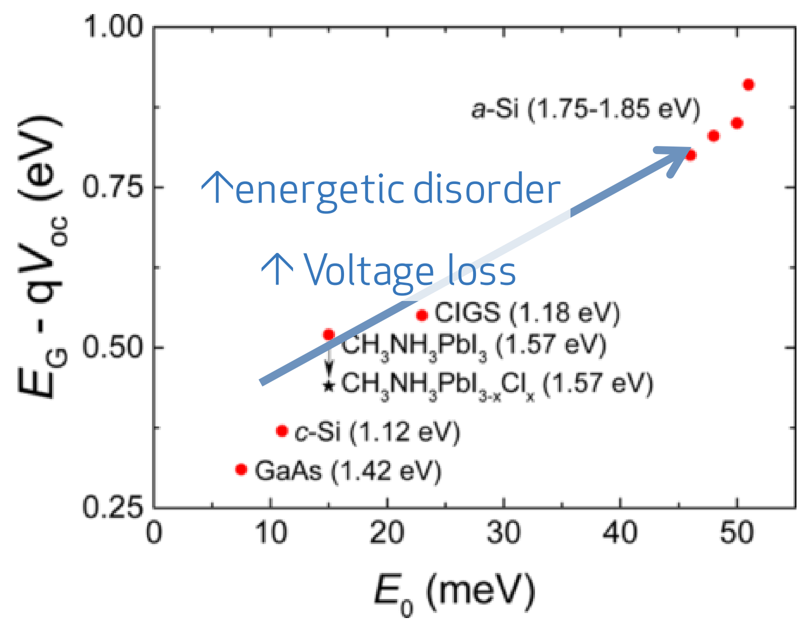
Perovskites are very strong absorbers with low energetic disorder High Voc

Direct bandgap, strong absorption: thin film (c. 1µm) required

Sharp absorption onset (low Urbach energy – 15meV): low energetic disorder in bandgap



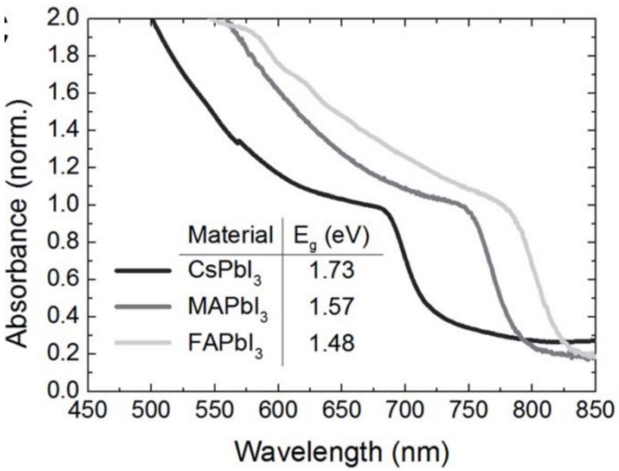
Low energetic disorder enables high voltage operation (relative to bandgap)

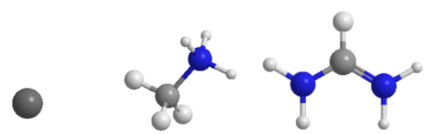


Source: De Wolf, S. *et al. J. Phys. Chem. Lett.* **5,** 1035–1039 (2014)

Band gap tuneable by composition ABX3

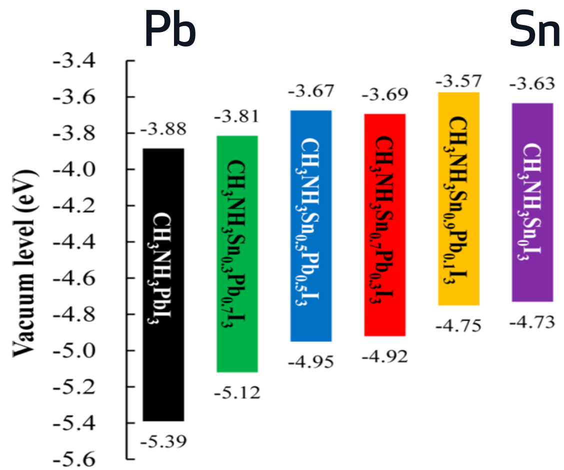
A cation substitution

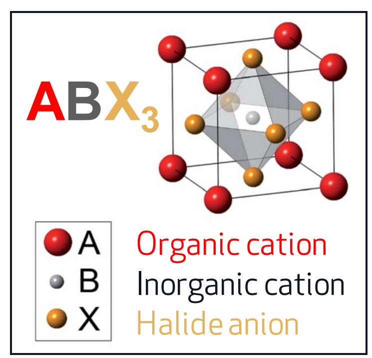




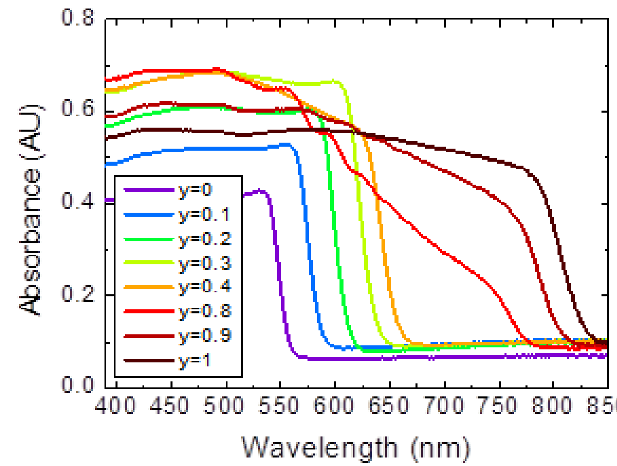
Caesium Methylammonium Formamidinium

B: Metal substitution





X: Halide substitution



2.23 eV 1.48 eV

Br_3 I_3

28% efficiency

World record efficiency for a perovskite solar cell and roadmap to >30% efficiency. Record efficiency of single junction silicon is 26.7%.

~20% saving on system costs

From increased cell efficiency and lower balance of system costs per watt.

No.1 IP portfolio

>100 filed or granted patents. Our perovskite patent portfolio is recognised globally as the largest for our technology.

~80 scientists and engineers

in Oxford, UK and Brandenburg an der Havel, Germany.

$40 billion

addressable market.

Nearly a decade

of research and product development since inception.

Why perovskite?

A technology that is:

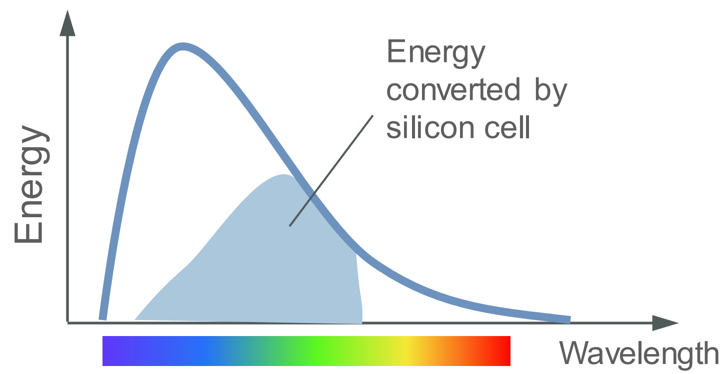
- Higher efficiency than conventional technologies
- Demonstrated long term reliability
- Can capture different areas of the solar spectrum (tuning of bandgap)
- Low cost material
- As a thin film technology, it is not constrained to specific form factors

In tandem with an existing silicon PV cell,
the **highest efficiency level commercially feasible today** can be achieved

Oxford PV's perovskite-on-silicon tandem solution

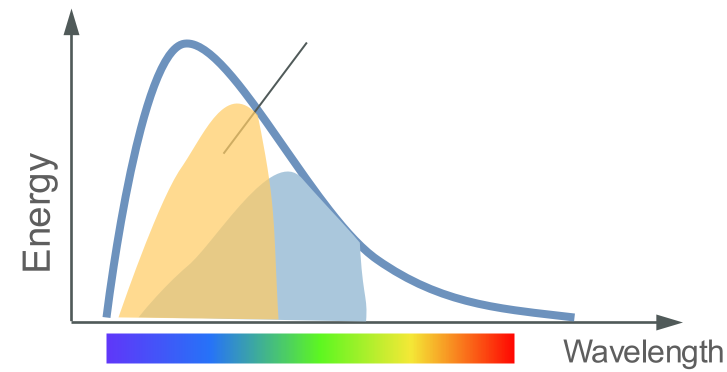
Captures a larger amount of the solar spectrum and converts it into electricity

Efficiency limited to ~25%



Silicon cell **(22%)**

Efficiency >30% possible



Perovskite layer
Silicon layer

Tandem cell (27%+)

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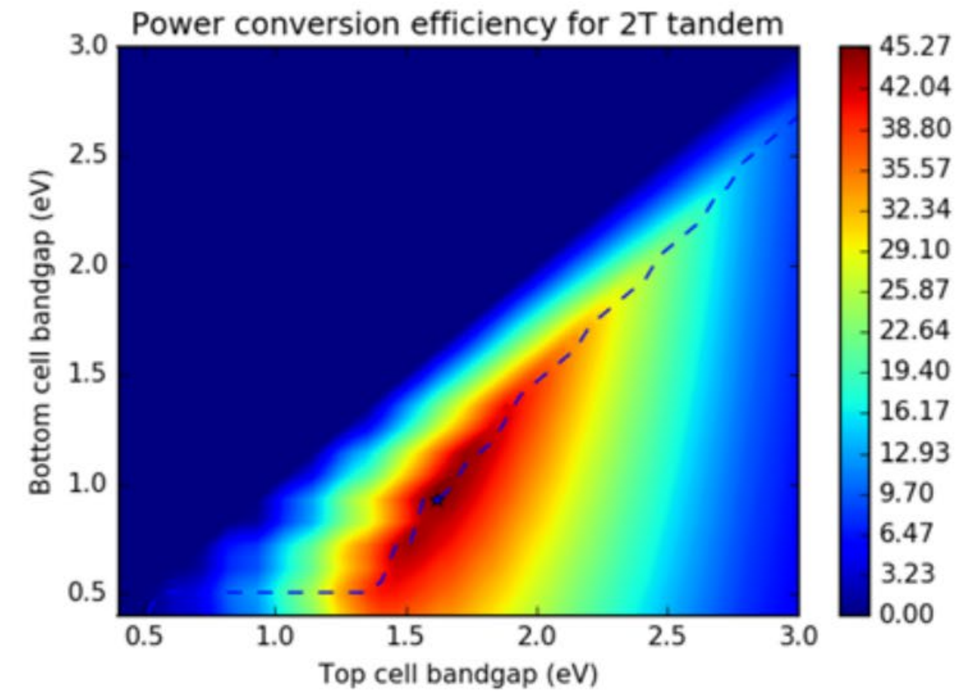
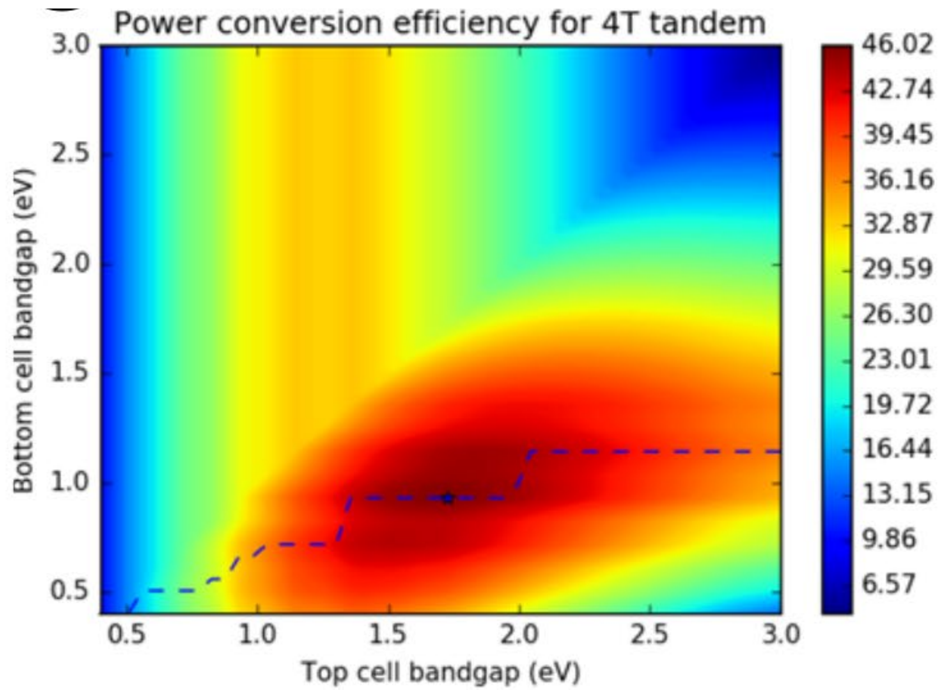
Perovskites in tandem solar cells

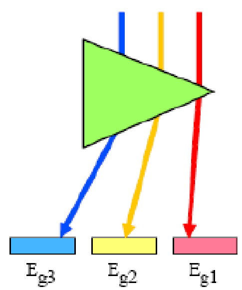




Two cells in one

Possible tandem integration schemes

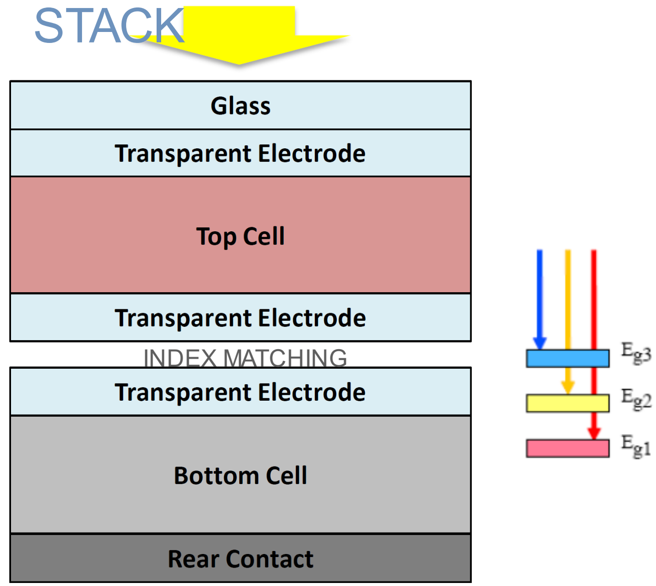
NO INTEGRATION



Spectral splitting of incident illumination

- Demonstration vehicle
- Not an obvious product

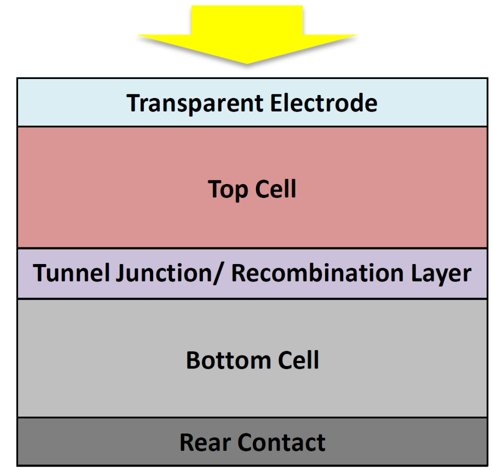
MECHANICAL STACK



4-terminal (mechanical stacking)

- Development time is probably shorter
- Optical loss of extra electrode layers
- More electrical components required

MONOLITHIC STACK

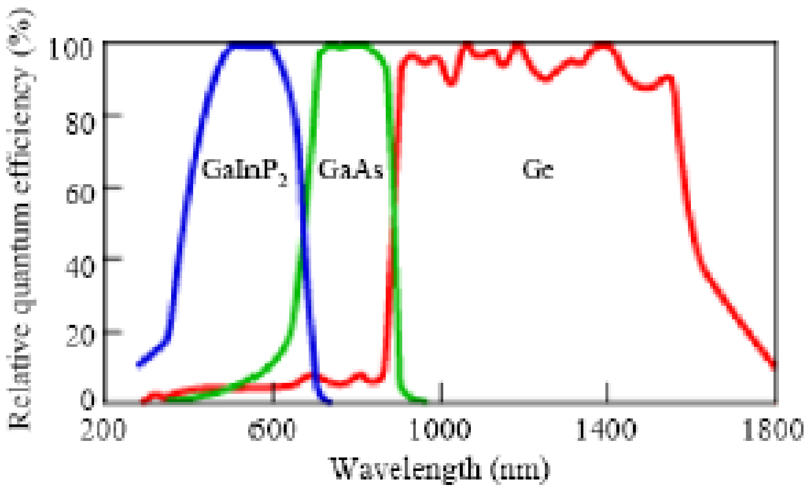


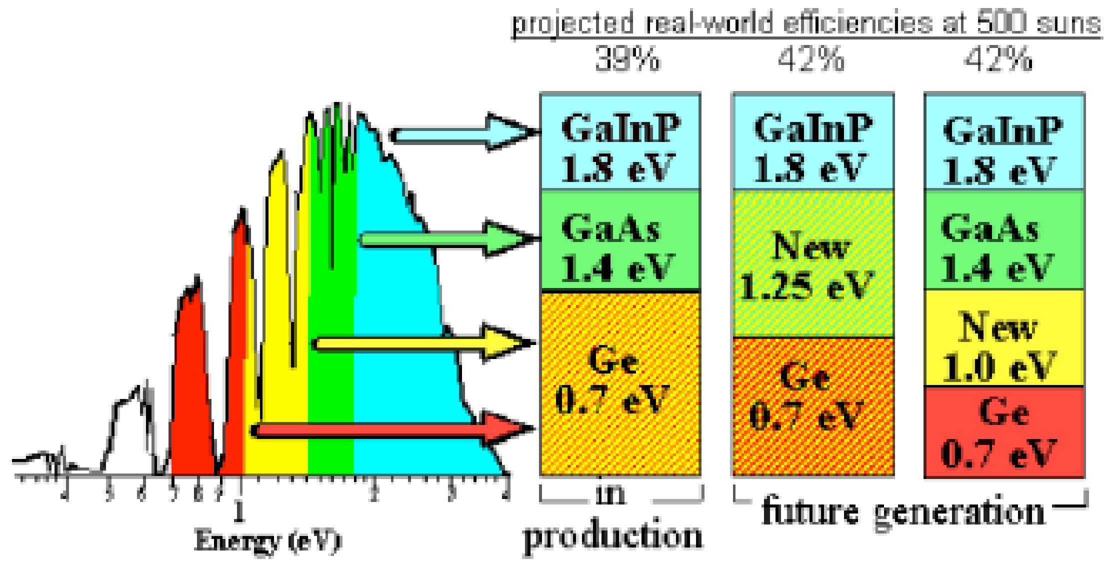
2-terminal (monolithic)

- Module fabrication easier
- Standard electrical connections
- Tunnel junction and current matching required

Predicted max efficiency is similar between both architectures

More than two sub-cells possible



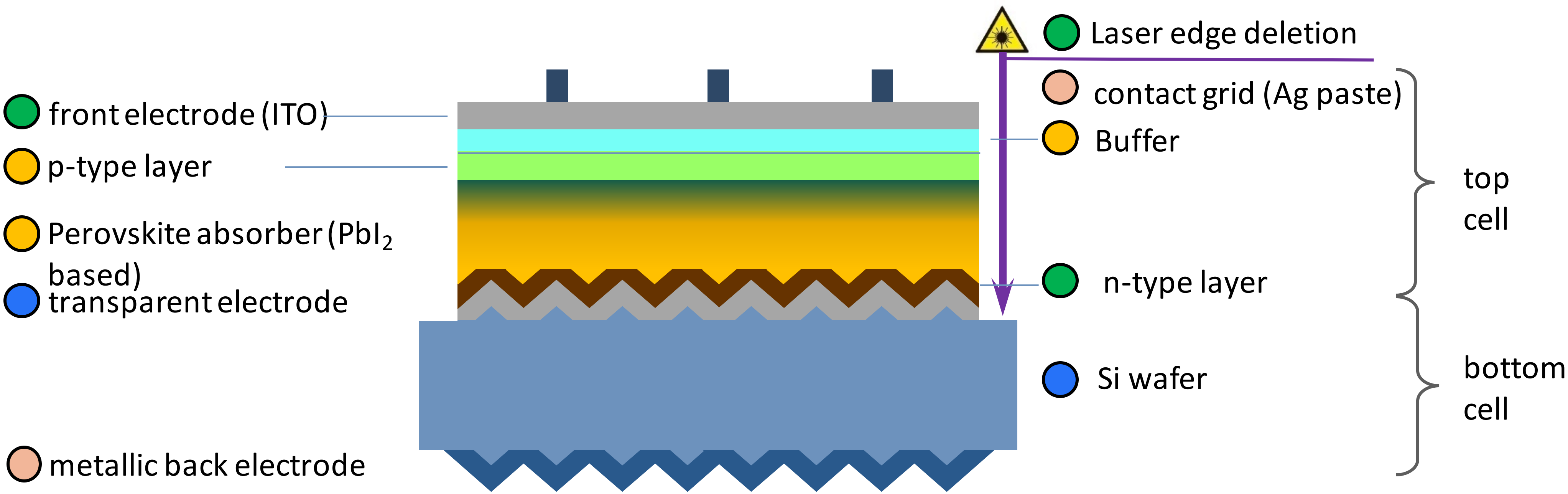


Oxford PV's perovskite-on-silicon tandem solar cell

- Conventional 156 mm x 156 mm silicon bottom cell
  20-22% typical efficiency
- Oxford PV perovskite top cell
  Built on top to extend the bandgap
- Resulting 156 mm x 156 mm perovskite-silicon tandem solar cell
  Could exceed 30% efficiency

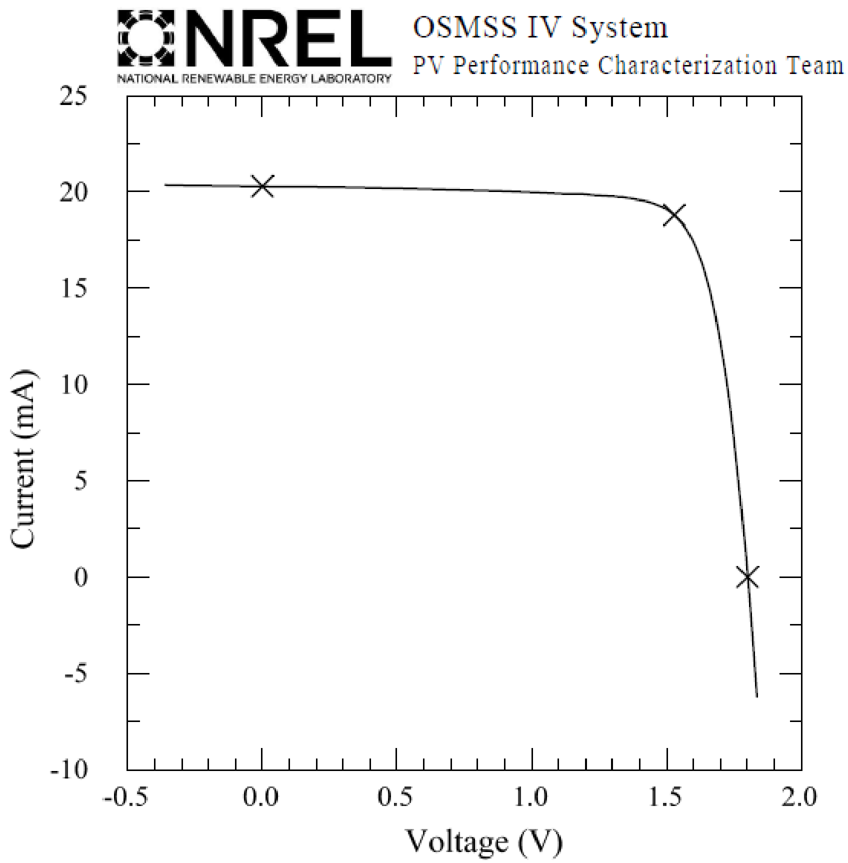
Tandem cell architecture – 2T

Commercial deposition tools



Progress - 28% certified 1 cm^2 monolithic tandem

December 2018



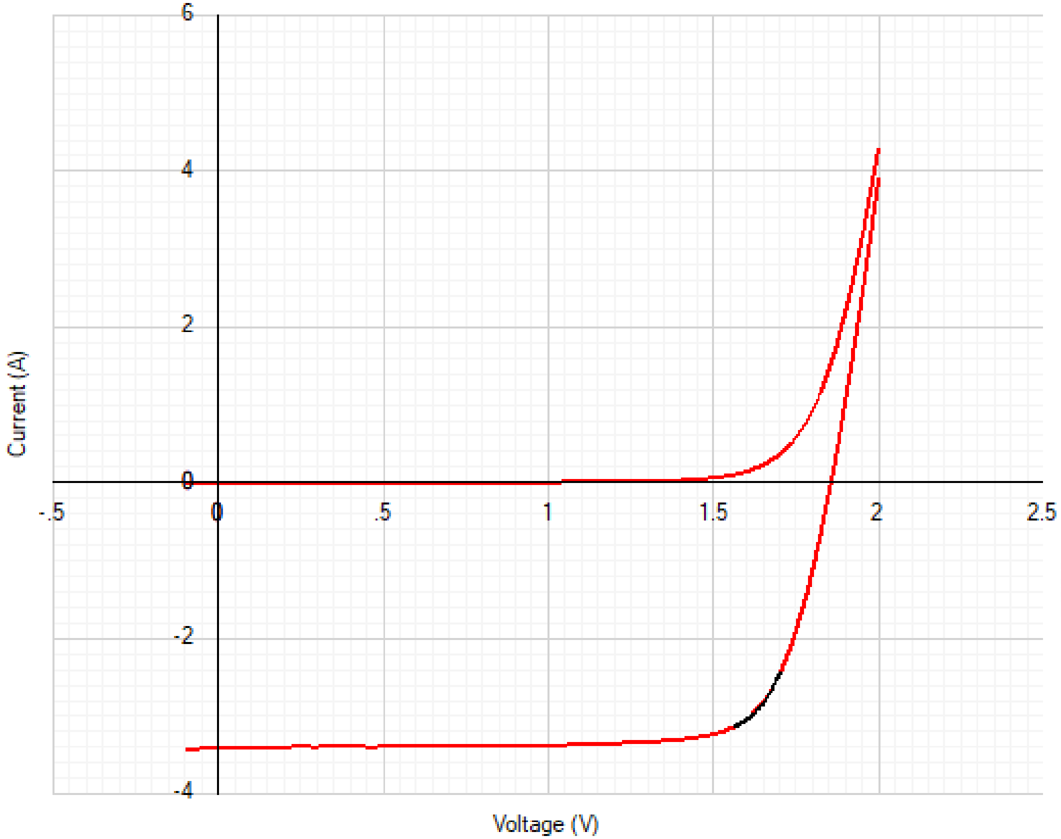
V_{oc} = 1.8009 V ± 1.7%	I_{max} = 18.794 mA ± 1.3%
I_{sc} = 20.287 mA ± 1.3%	V_{max} = 1.5292 V ± 1.7%
J_{sc} = 19.767 mA/cm^2 ± 1.3%	P_{max} = 28.740 mW ± 2.0%
Fill Factor = 78.7 ± 0.7%	Efficiency = 28.00 ± 0.7%

Oxford PV industrial site

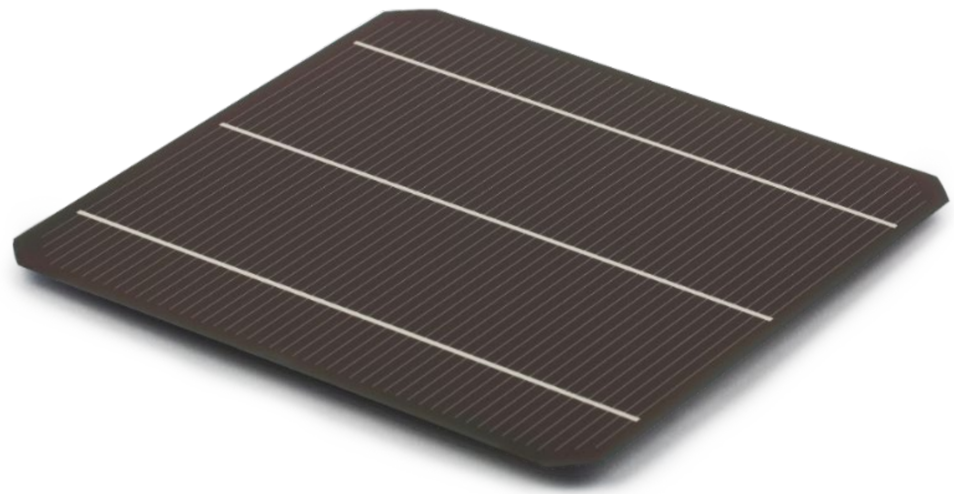
Pilot line in Brandenburg, Germany - 17,000 m^2

Full size M2 perovskite- silicon 2T tandem - ID2905

Summary IV and MPP performance



	ID 2905
V_{oc} (V)	1.85
FF (%)	77.8
I_{SC} (A)	3.41



Costs - LCOE

Efficiency increase drives higher power output

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FOR DEMONSTRATION PURPOSES ONLY

Oxford PV does not intend to mass produce PV modules.
This datasheet illustrates the concept of a PV module fabricated with Oxford PV's perovskite-silicon tandem solar cells at market entry (2019).
Oxford PV's product roadmap is to 400+ Watts power output.

PEROVSKITE-Si®
MODULE

PEROVSI-360

FEATURES

60 cells
6 inch, perovskite-silicon tandem solar cells

360 Watts
Power output range

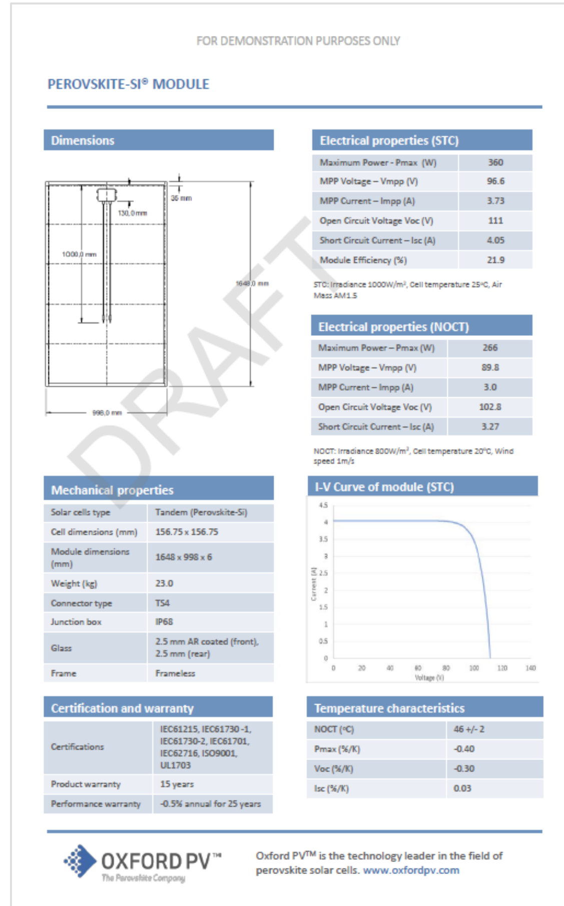
0/+5W
Power tolerance

Certified
Full IEC certification

25 year
Performance warranty

The Perovskite-Si ® is the first of its kind heterojunction, double glass solar module featuring Oxford PV's proprietary perovskite tandem solar cell technology, significantly improving the power output, making it one of the most powerful modules in the market.

DRAFT



FOR DEMONSTRATION PURPOSES ONLY

PEROVSKITE-SI® MODULE

Dimensions

Electrical properties (STC)

Maximum Power - Pmax (W)	360
MPP Voltage – Vmpp (V)	96.6
MPP Current – Impp (A)	3.73
Open Circuit Voltage Voc (V)	111
Short Circuit Current – Isc (A)	4.05
Module Efficiency (%)	21.9

STC: Irradiance 1000W/m², Cell temperature 25°C, Air Mass AM1.5

Electrical properties (NOCT)

Maximum Power – Pmax (W)	266
MPP Voltage – Vmpp (V)	89.8
MPP Current – Impp (A)	3.0
Open Circuit Voltage Voc (V)	102.8
Short Circuit Current – Isc (A)	3.27

NOCT: Irradiance 800W/m², Cell temperature 20°C, Wind speed 1m/s

Mechanical properties

Solar cells type	Tandem (Perovskite-Si)
Cell dimensions (mm)	156.75 x 156.75
Module dimensions (mm)	1648 x 998 x 6
Weight (kg)	23.0
Connector type	TS4
Junction box	IP68
Glass	2.5 mm AR coated (front), 2.5 mm (rear)
Frame	Frameless

I-V Curve of module (STC)

Certification and warranty

Certifications	IEC61215, IEC61730 -1, IEC61730-2, IEC61701, IEC62716, ISO9001, UL1703
Product warranty	15 years
Performance warranty	-0.5% annual for 25 years

Temperature characteristics

NOCT (°C)	46 +/- 2
Pmax (%/K)	-0.40
Voc (%/K)	-0.30
Isc (%/K)	0.03

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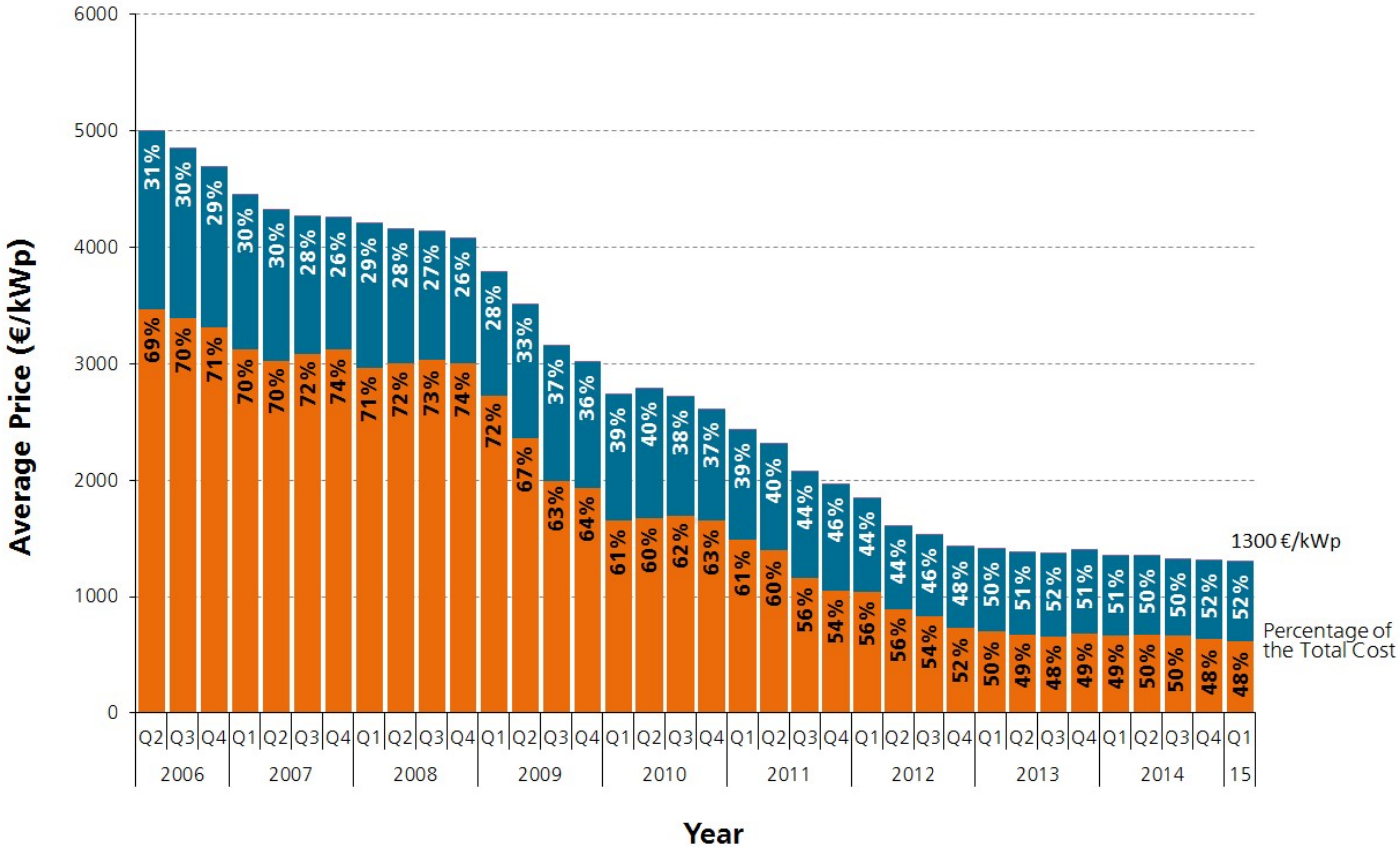
Oxford PV™ is the technology leader in the field of perovskite solar cells. www.oxfordpv.com

DRAFT

Balance of System (BOS) is >50% - higher efficiency is the lever

Average Price for PV Rooftop Systems in Germany (10kWp - 100kWp)



Data: BSW-Solar. Graph: PSE AG 2015

Reduced cost per watt

Efficiency benefit outweighs extra cost

		Base cell		Upgraded cell
Cell output	*watts*	4.5	+20% cell efficiency →	5.4
Cost per watt	$/w	**0.33***		**0.32**
Total cost of 1 cell	$	1.49		1.71
			Extra production cost to upgrade cell →	0.22**

4.5 x $0.33

$1.71 ÷ 5.4

$1.49 + $0.22

** U.S. average 2015, source: GTM Research*

***verified in a 3rd party manufacturing cost model; detail in appendices*

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Bankability

Large scale solar is primarily a financial instrument

Project or proposal with sufficient collateral, future cashflow, and high probability of success to be acceptable to institutional lenders for financing

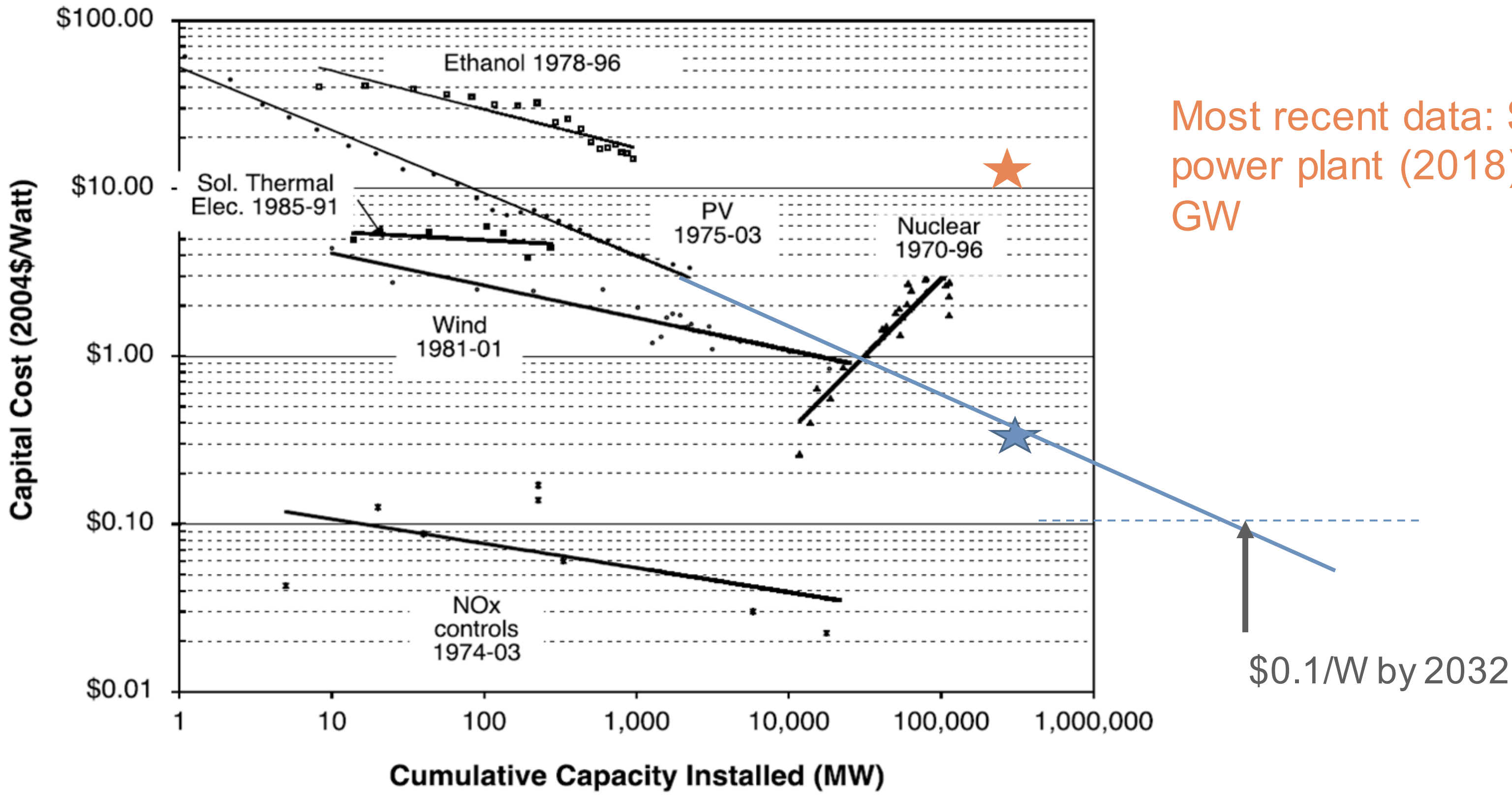
Bank

Certified labs

Insurance

Early adopters

Examples of experience curves



Most recent data: $11/W for a nuclear power plant (2018) Cum. Capacity: 393 GW

Source: http://www.theenergycollective.com/noah-deich/2171221/problems-17t-save-planet-headlines

Levelised cost of electricity (LCOE)

Calculates the "net present value" of the unit-cost of electricity over the system lifetime

$$LCOE = \frac{\sum costs}{\sum energy\,produced} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

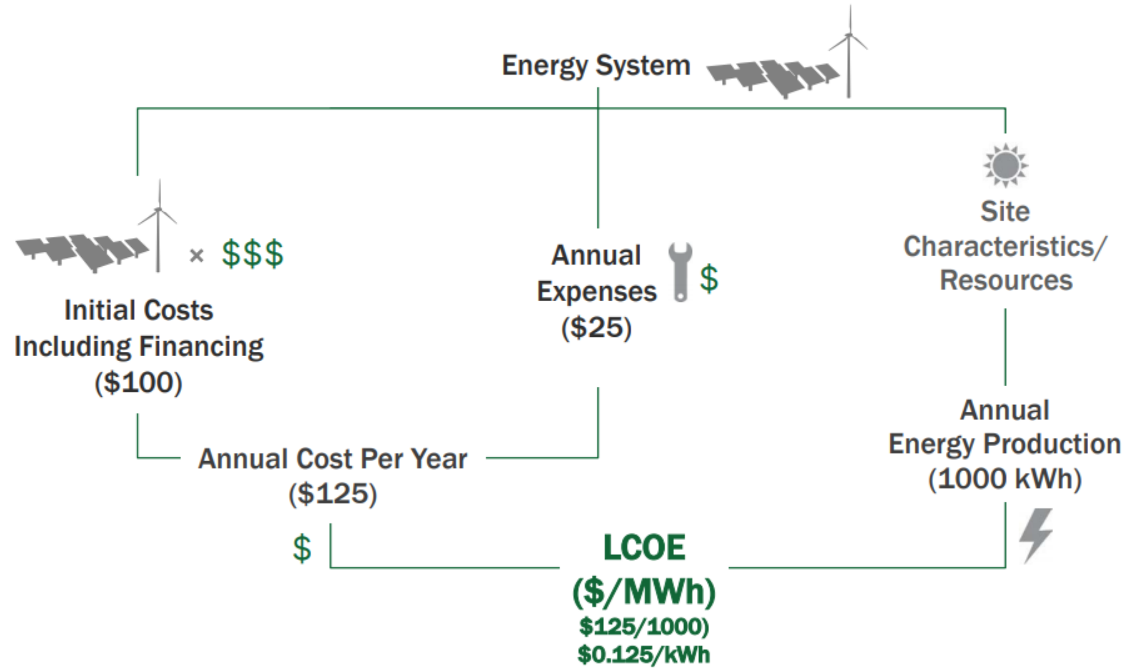
I_t investment expenditure (year t)

M_t operation and maintenance (year t)

E_t energy generated (year t)

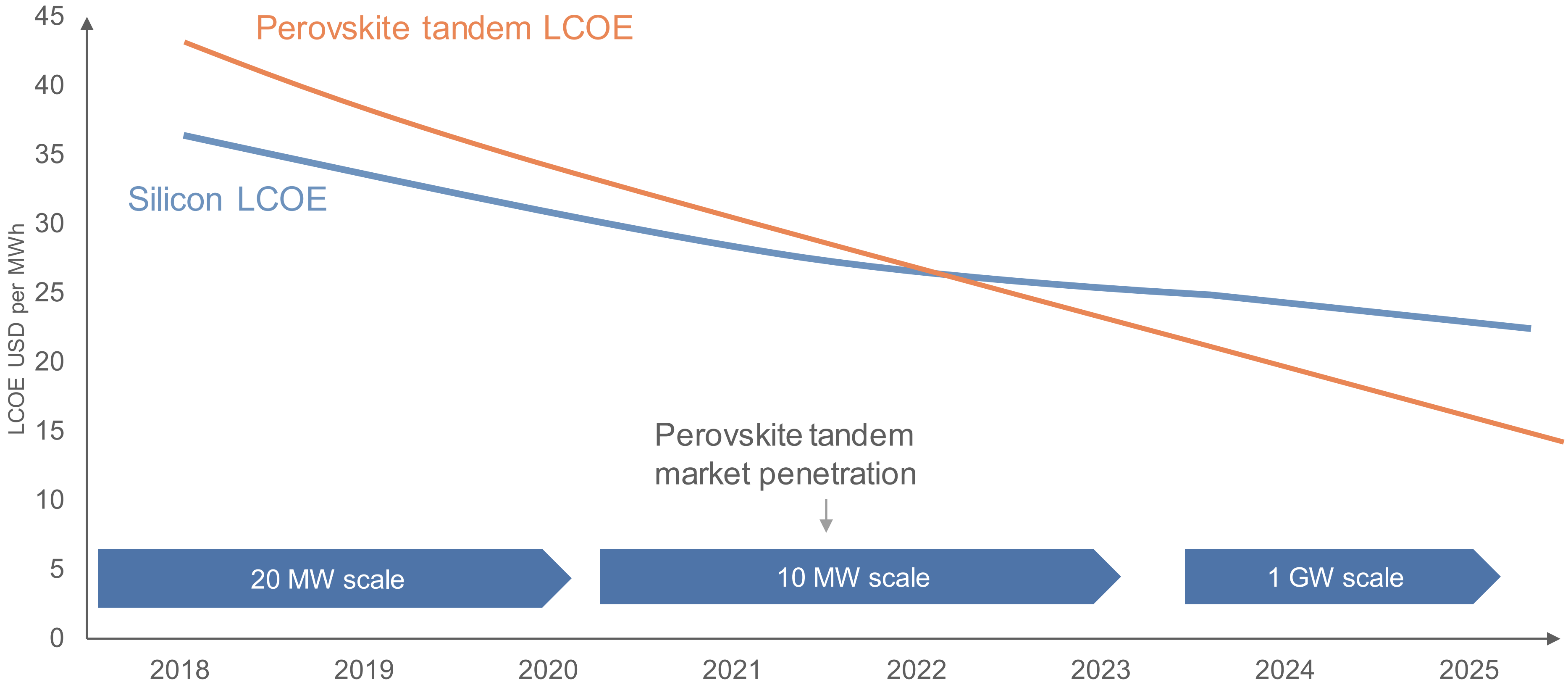
r discount rate

n expected system lifetime



Adapted from European Wind Energy Association, "Economics of Wind Energy,"

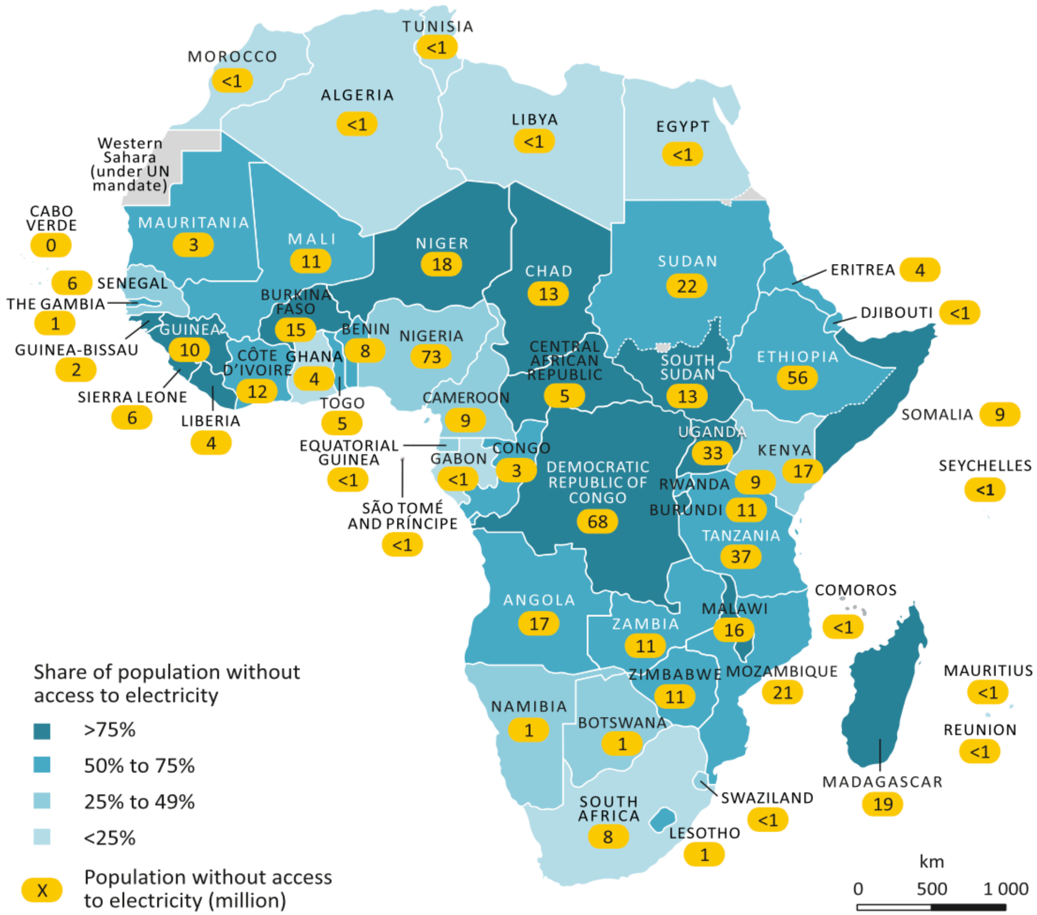
Transforming solar economics



Source: GTM Research, ITRPV 9th Edition, Oxford PV

Future – 2% - 20% - 100%

1,060 million people have no electricity access in 2017



…588 million (48%) in Africa

Source: IEA Energy Access Outlook 2017

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Thank you