Solar PV energy becomes mainstream but what are the opportunities for future developments?

Professor Stuart Irvine
Emeritus professor
Materials Science and Engineering
Swansea University

Plan of talk

- Climate change and progress since 2012
- Large scale generation of PV electricity
- Silicon still dominates PV panel production
- Thin film PV
- What are the practical limits to PV module efficiency
- What is the true energy generation of PV?
- Space Based Solar Power to increase load factor
- Opportunities for novel thin film PV materials

Update on climate change from COP27

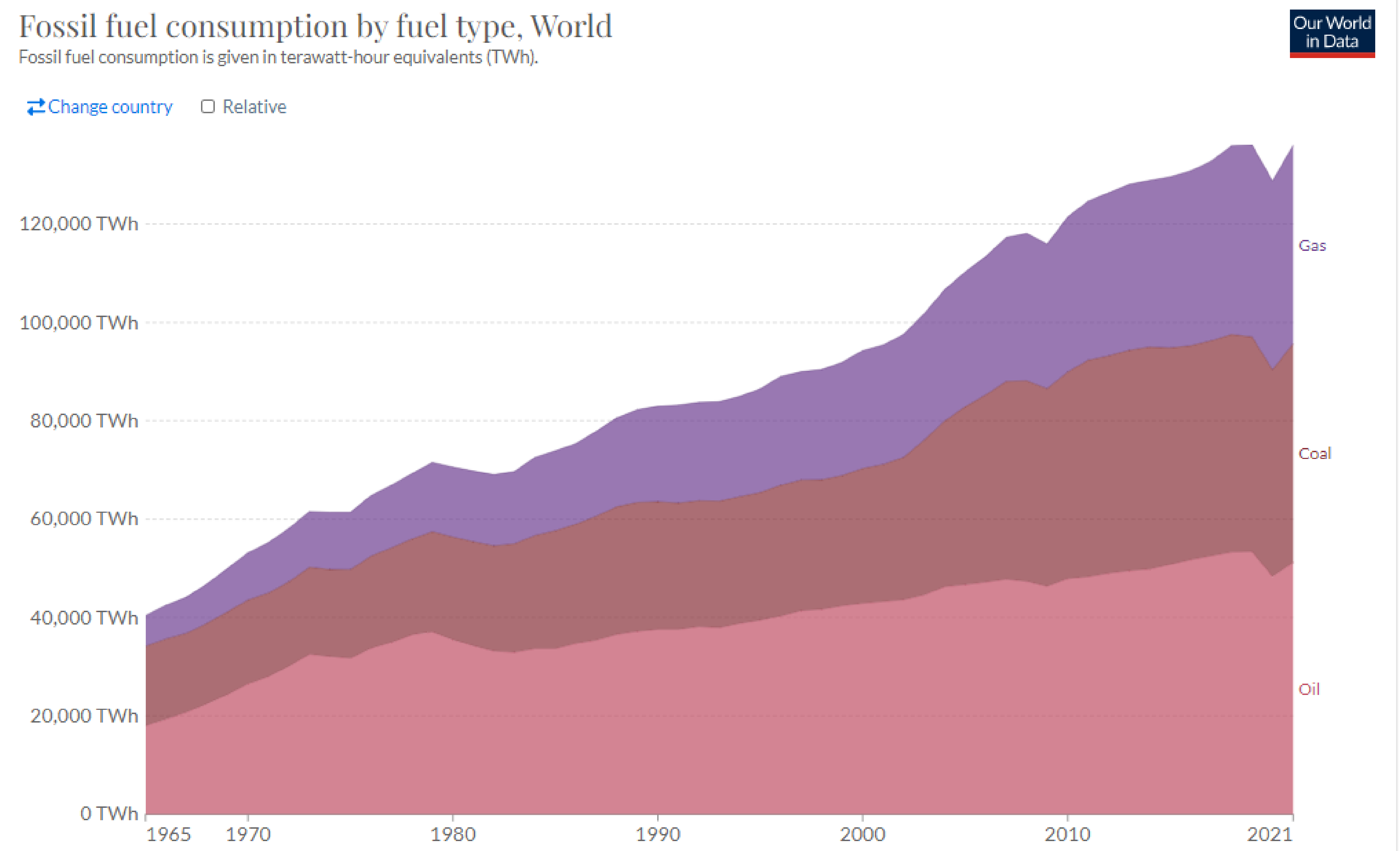
The Big 3

Carbon dioxide (CO_2) is the most important greenhouse gas, and its atmospheric concentration is measured by parts per million (ppm). **Methane (CH_4)** and **nitrous oxide (N_2O)** are also extraordinarily important for the global climate and are measured by parts per billion (ppb). In 2021...

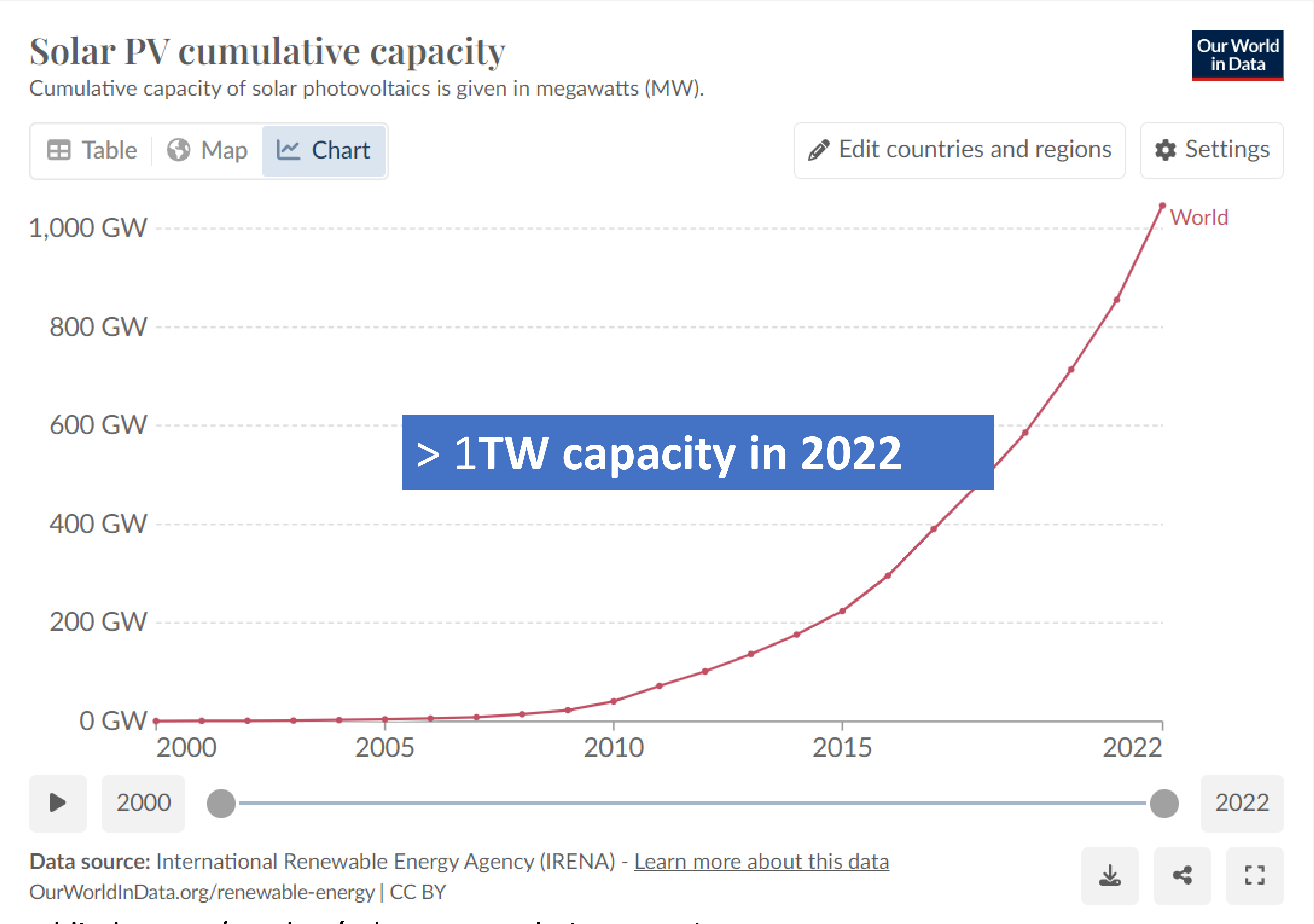
Carbon dioxide: 415.7ppm ± 0.2 = **149% of pre-industrial levels.**
Methane: 1908±2 ppb = **262% of pre-industrial levels.**
Nitrous oxide: 334.5±0.1 ppb = **124% of pre-industrial levels.**

Fossil fuel consumption by fuel type, World

Fossil fuel consumption is given in terawatt-hour equivalents (TWh).

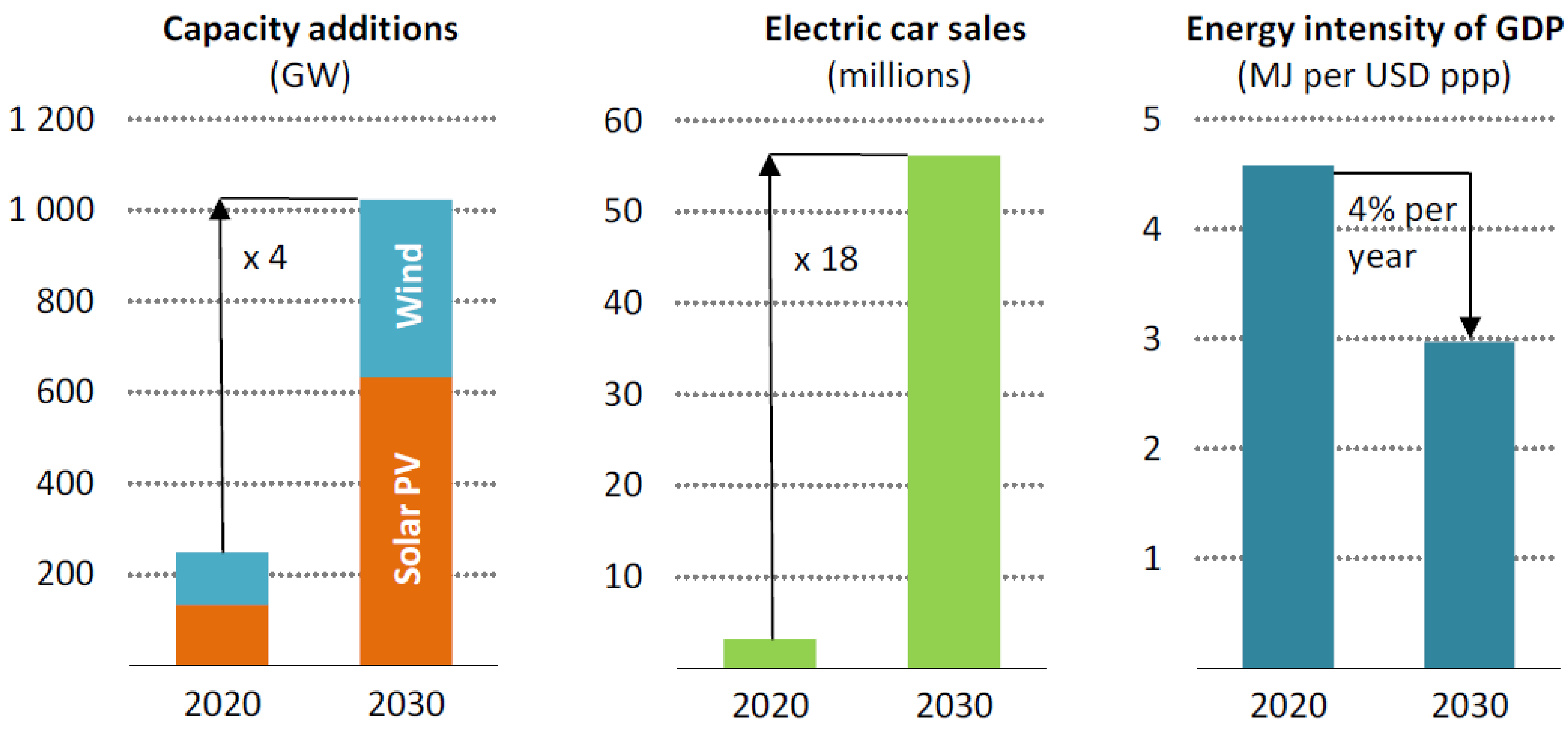


Source: BP Statistical Review of Global Energy



https://ourworldindata.org/grapher/solar-pv-cumulative-capacity

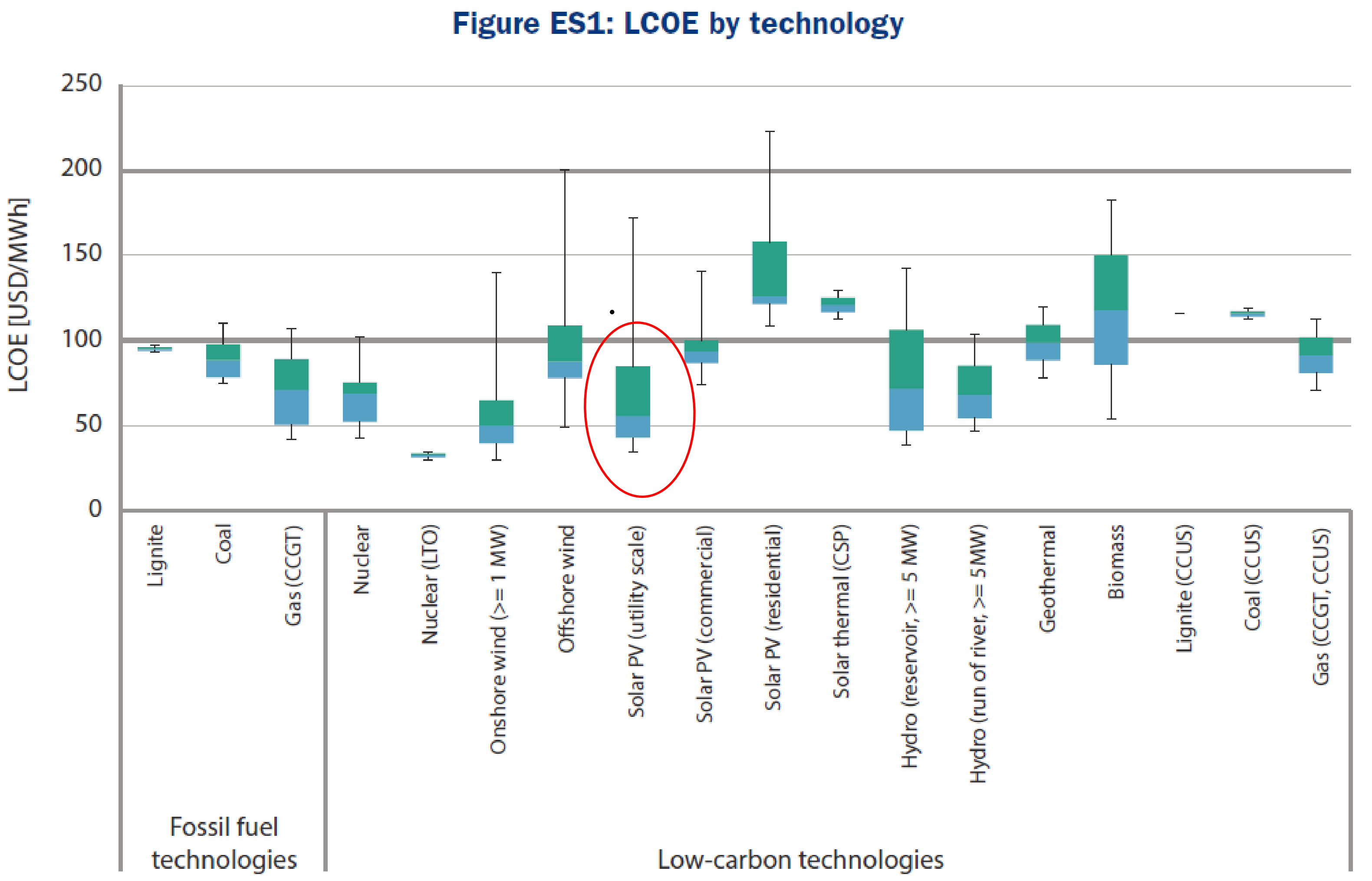
Key clean technologies ramp up by 2030 in the net zero pathway



Note: MJ = megajoules; GDP = gross domestic product in purchasing power parity.

IEA Report – Net zero by 2050 – A Roadmap for the Global Energy Sector

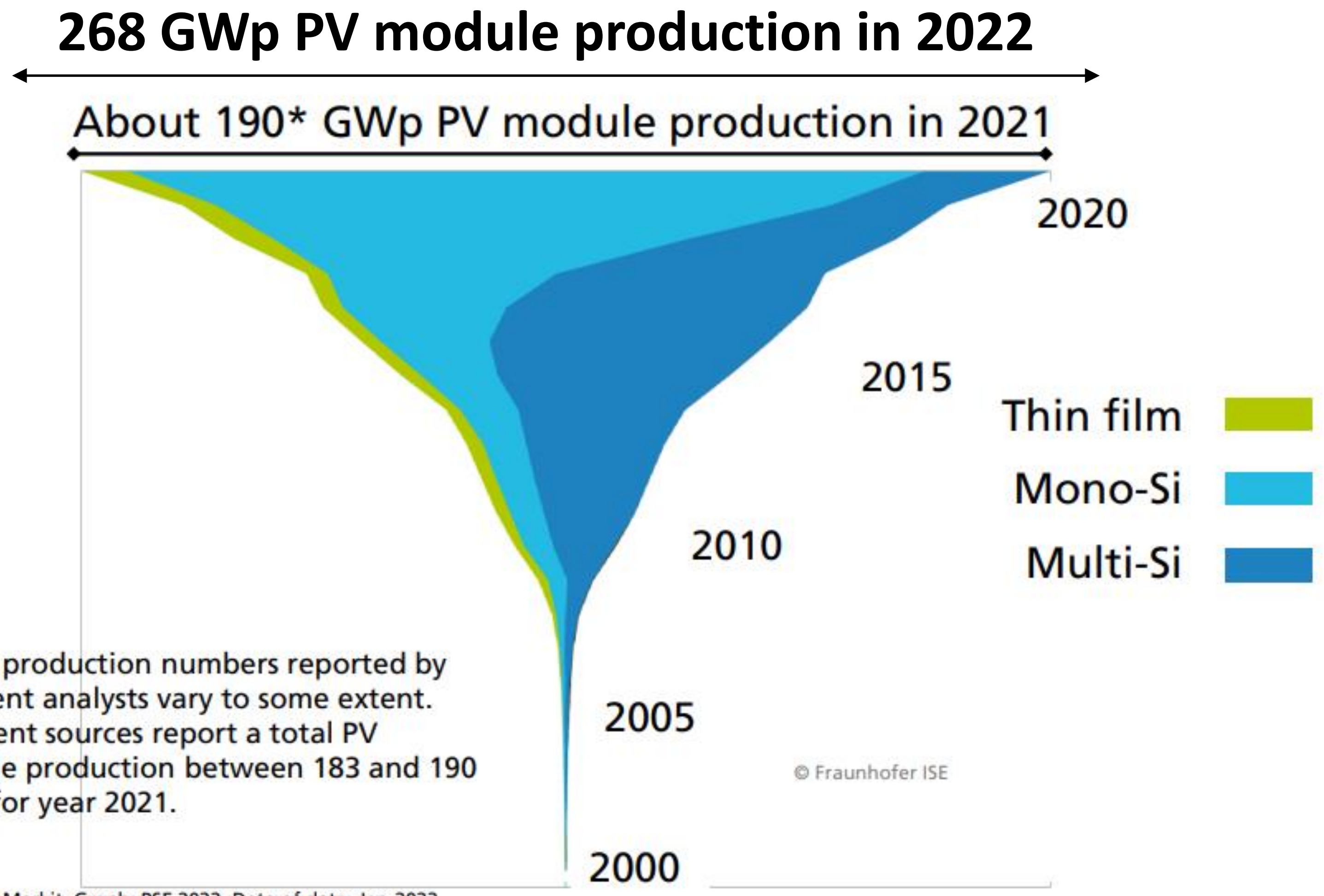
IEA Projected Costs of Generating Electricity – report 2020



Note: Values at 7% discount rate. Box plots indicate maximum, median and minimum values. The boxes indicate the central 50% of values, i.e. the second and the third quartile.

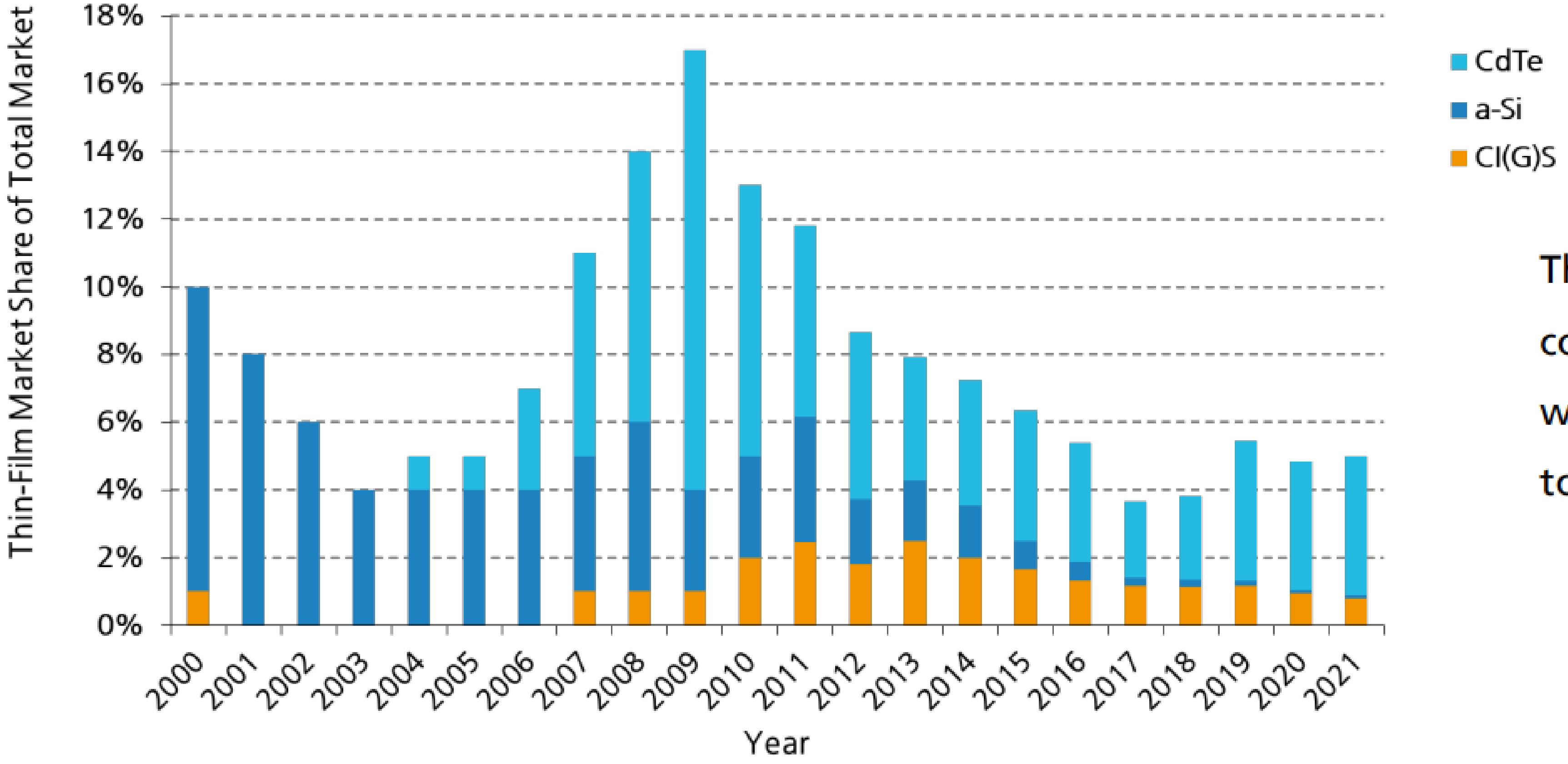
Utility scale PV is now one of the lowest cost sources of electricity

Annual PV Production by Technology
Worldwide (in GWp)



Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE 2022. Date of data: Jan-2022

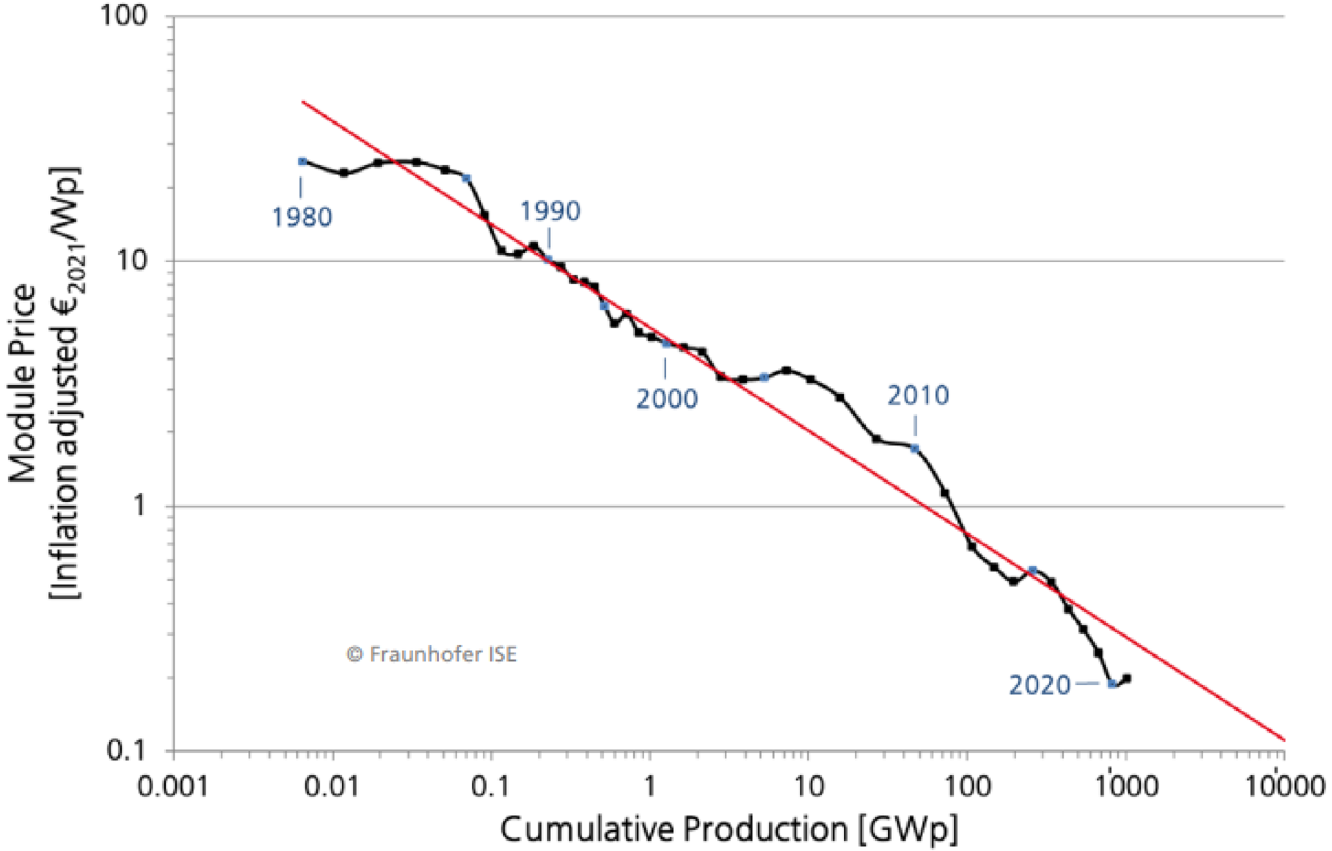
Market Share of Thin-Film Technologies
Percentage of Total Global PV Production



Thin-Film technology contributed in year 2021 with about 5% to the total PV-market.

Data: from 2000 to 2009: Navigant; from 2010 to 2021 IHS Markit; from 2022 IEA. Graph: PSE 2022 . Date of data: July 2022

Price Learning Curve
Includes all Commercially Available PV Technologies



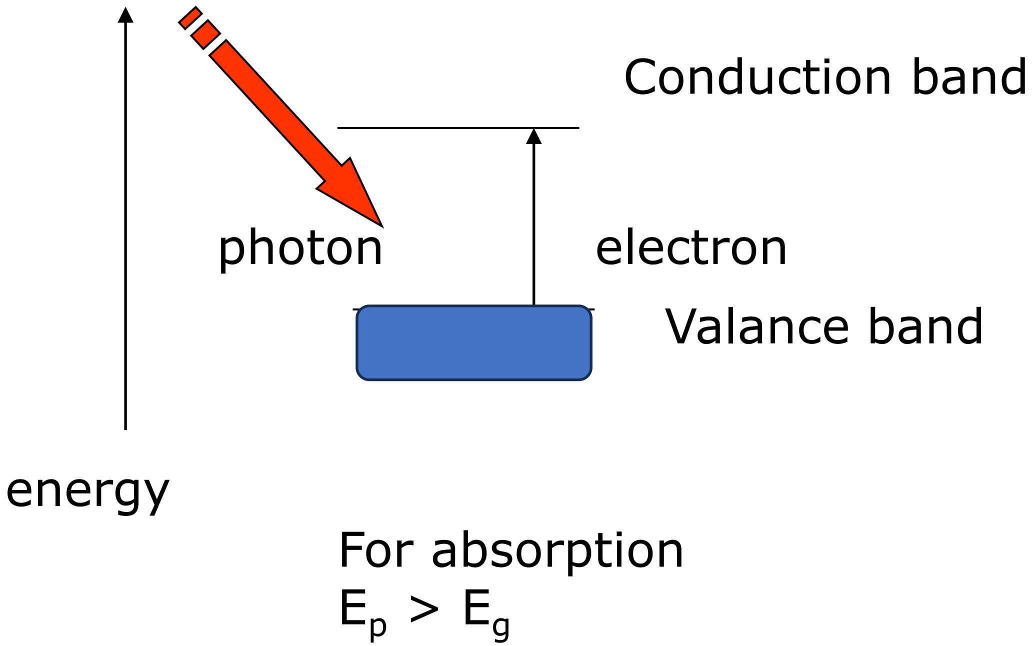
Learning Rate:
Each time the cumulative PV module production doubled the price went down by about 25% for the last 41 years.

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit; Graph: PSE 2022

Fraunhofer ISE

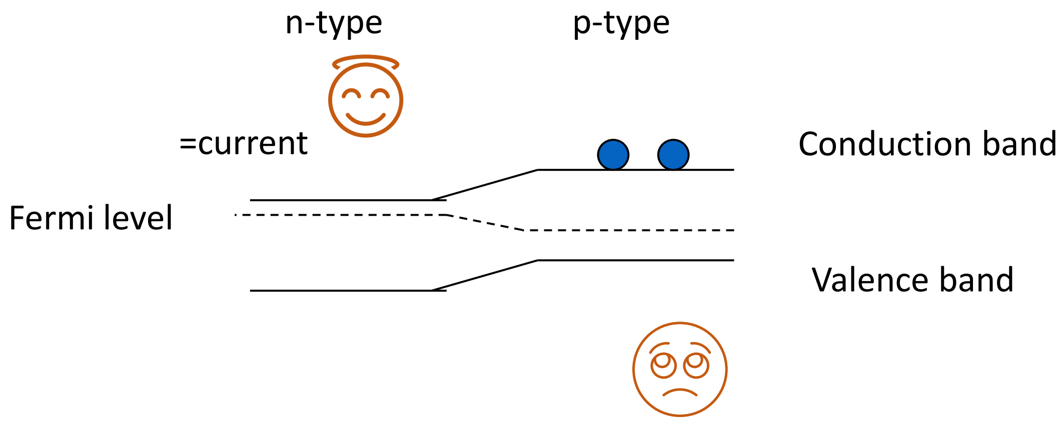
How is solar energy converted into electricity? Stage 1 – absorb solar radiation

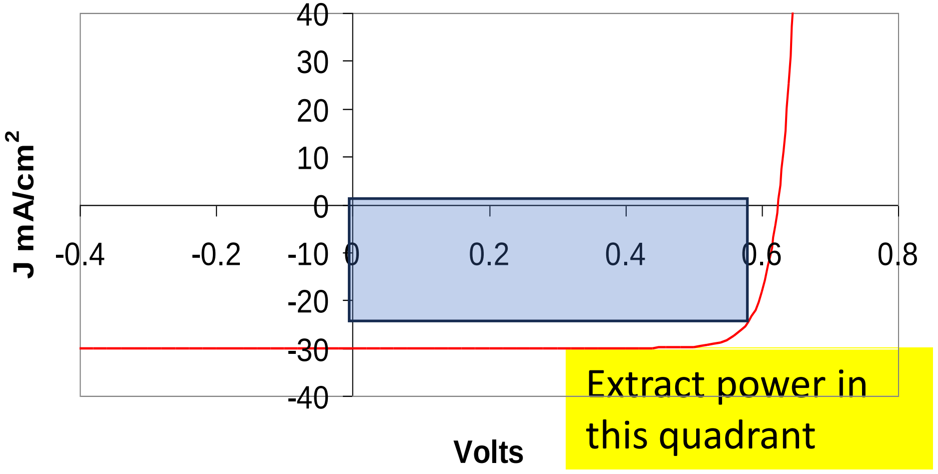
- Solar energy is absorbed in a semiconductor by exciting an electron from the valence band to the conduction band
- For photon energy less than the band gap (long wavelength) the photon is transmitted without transferring any energy



Stage 2 – extraction of electrical power

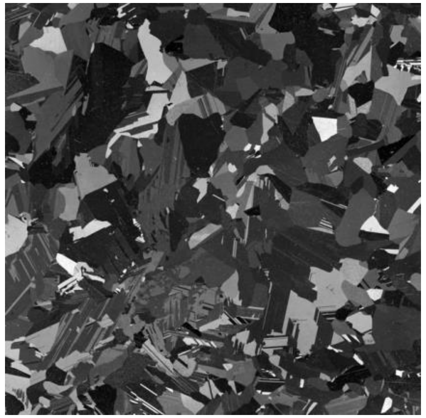
- Photon absorption creates an electron-hole pair in the absorber (n-type) layer.
- The electron is a minority charge in this layer and is unstable.
- Transition back to the valence band will not contribute to external power.
- The minority charge has to diffuse to the junction where it is swept across by the internal field and becomes a majority charge that can be conducted to an external circuit.





P= J x V

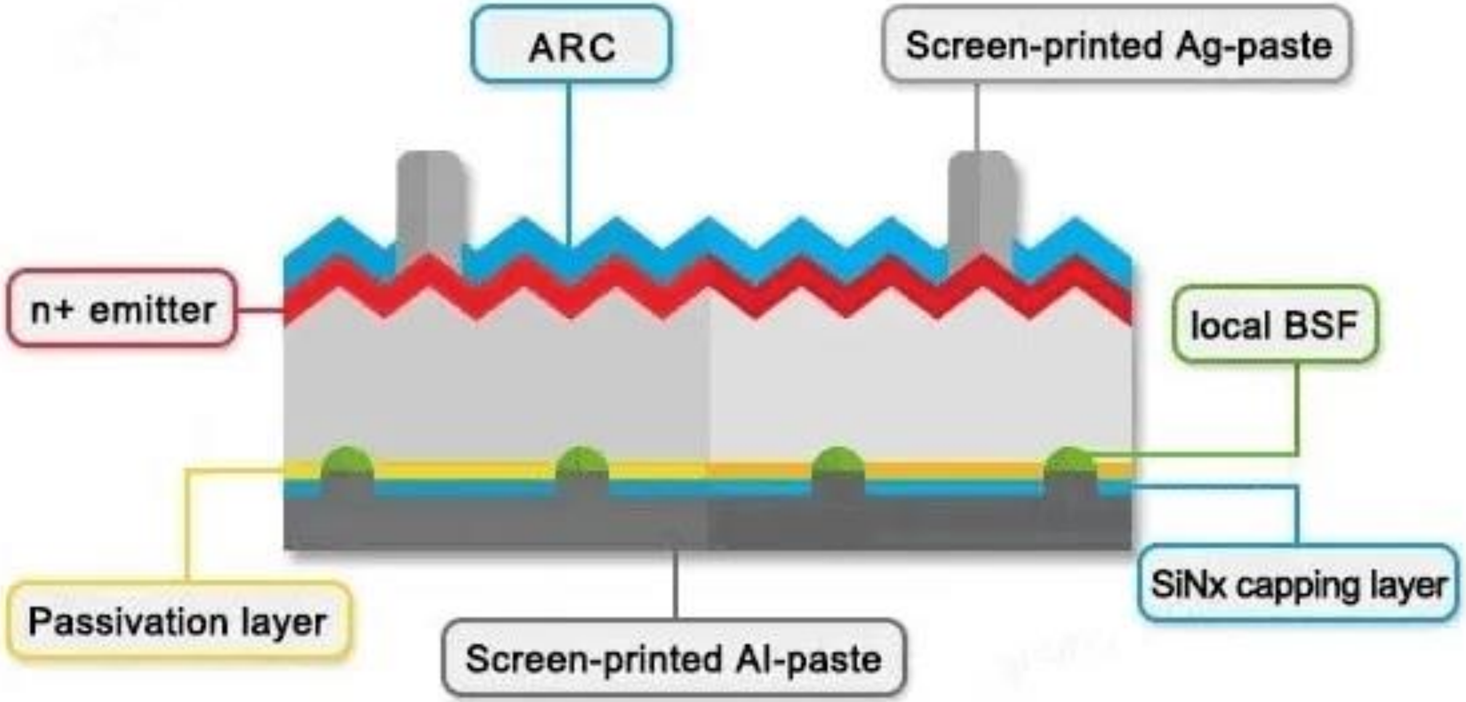
multi-crystalline mono- or silicon?



Lower cost
Grain boundaries
Lower performance

higher cost
Single crystal
Higher performance

Passivated Emitter and Rear Contact (PERC) solar technology now dominating global industry



Enabled PV module efficiency to exceed 20%

Source: The Physics of Solar Power from Colorado College

Top 10 Module Suppliers in 2022
(by shipment volume)

Rank	Module Supplier	Change (Y/Y)
1	LONGi Green Energy	–
2	JinkoSolar	↑
3	Trina Solar	↓
4	JA Solar	↓
5	CSI Solar (Canadian Solar)	–
6	Risen Energy	–
7	Astronergy (Chint)	↑
8	First Solar	↓
9	Q CELLS (Hanwha Solutions)	–
10	DMEGC Solar (Hengdian Group)	↑

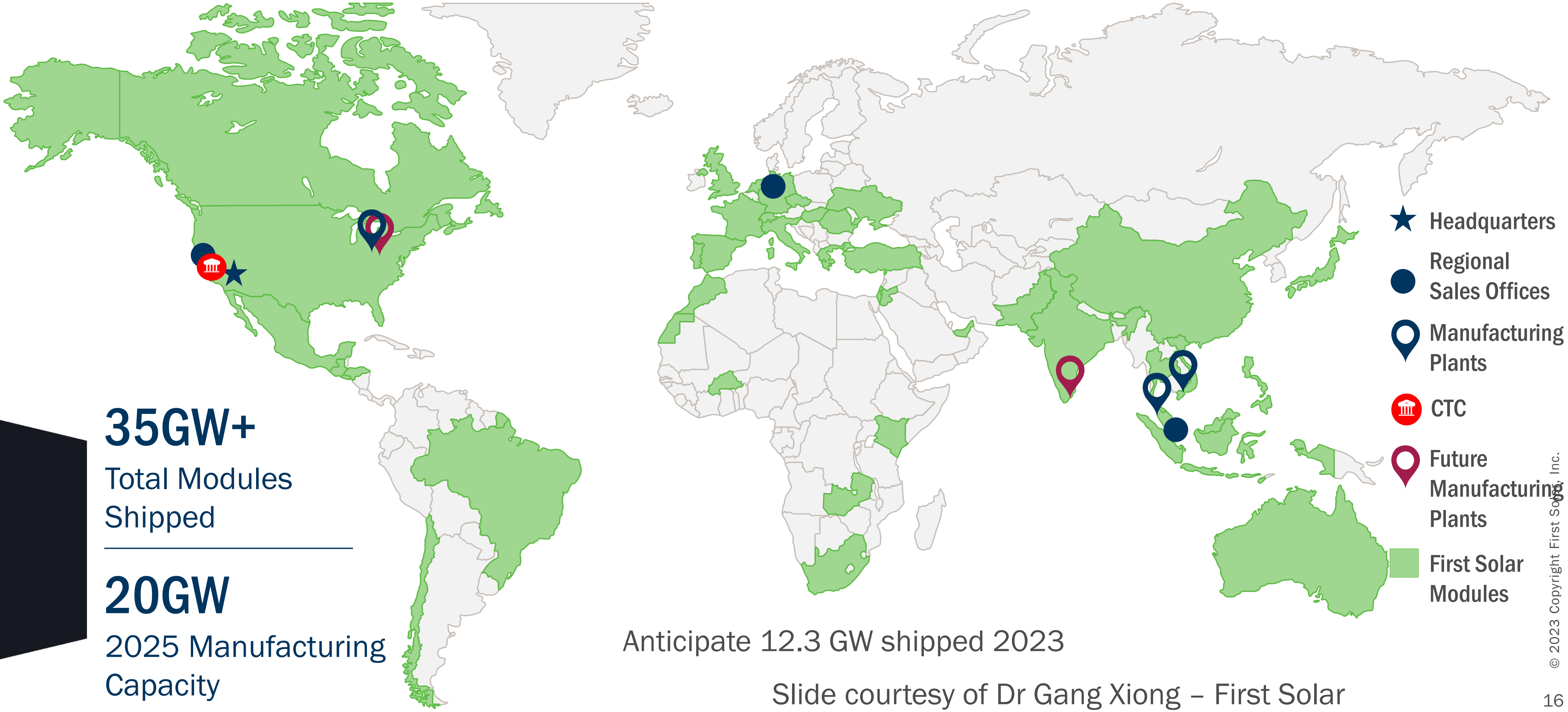
Source: *PV Manufacturing & Technology Quarterly* report, Feb. 2022 release.

PVTECH RESEARCH

245 GW shipped in 2022 by top 10

Only thin film PV in top 10

First Solar – leading thin film PV manufacturer

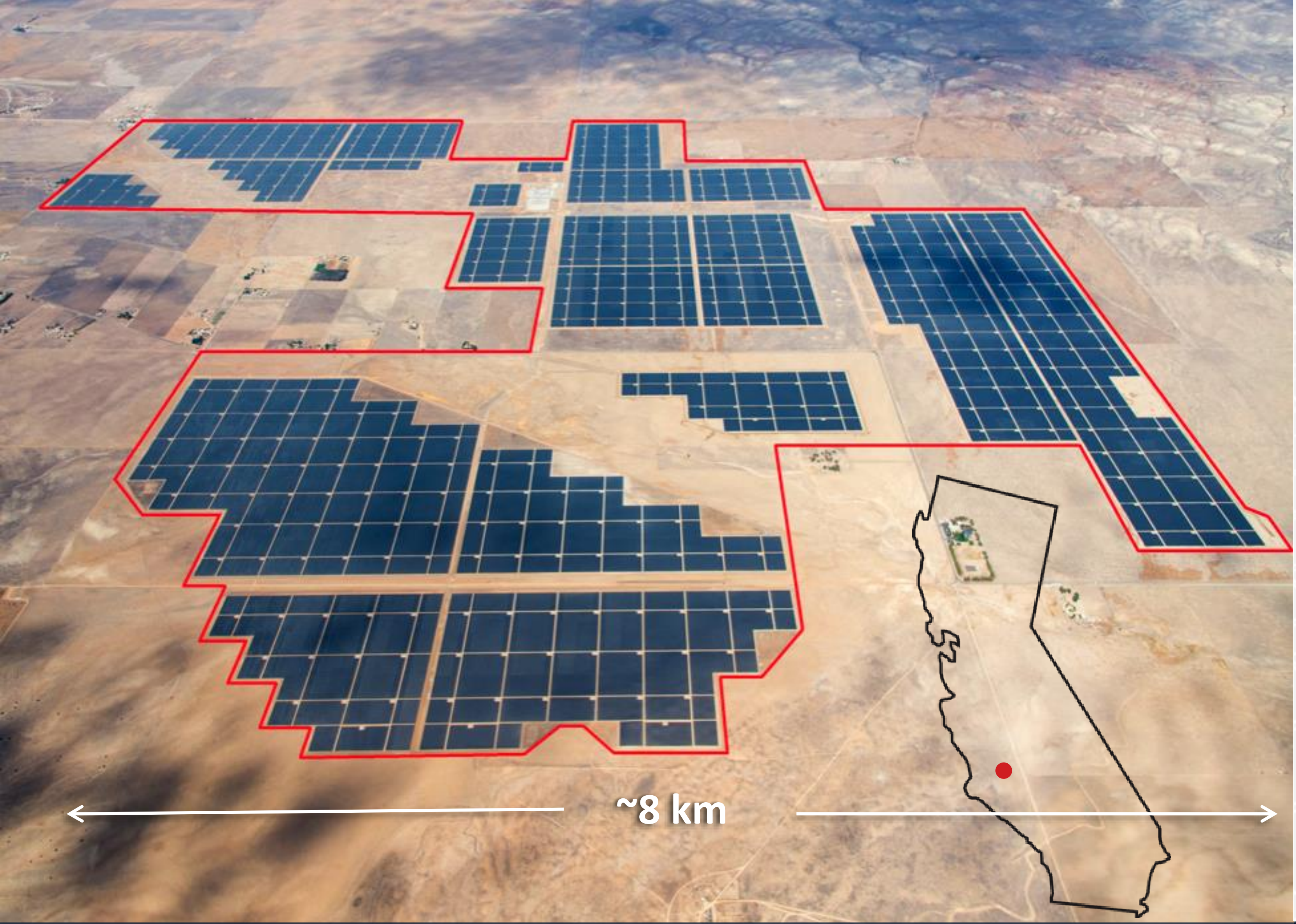


35GW+
Total Modules Shipped

20GW
2025 Manufacturing Capacity

Anticipate 12.3 GW shipped 2023

Slide courtesy of Dr Gang Xiong – First Solar



San Luis Obispo County, California

Customer: **MidAmerican**

Size: **550MW (AC)**

Construction Time: **2011–2015**

Hectares: **~3,100 site**

Modules: **~9 million**

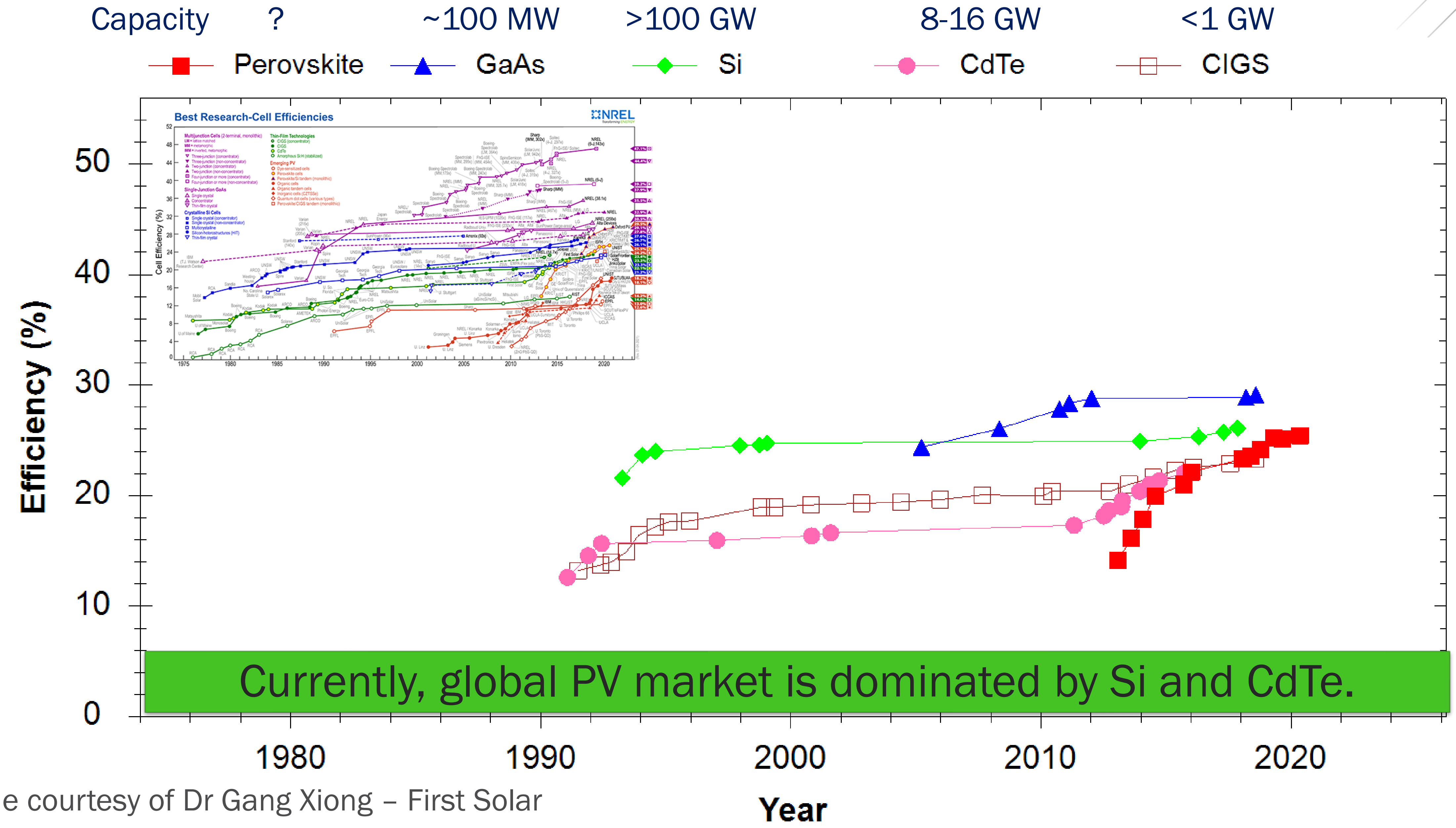
Equivalent to:

Cars Removed:
73,000

Tons CO_2 Displaced Annually:
377,000

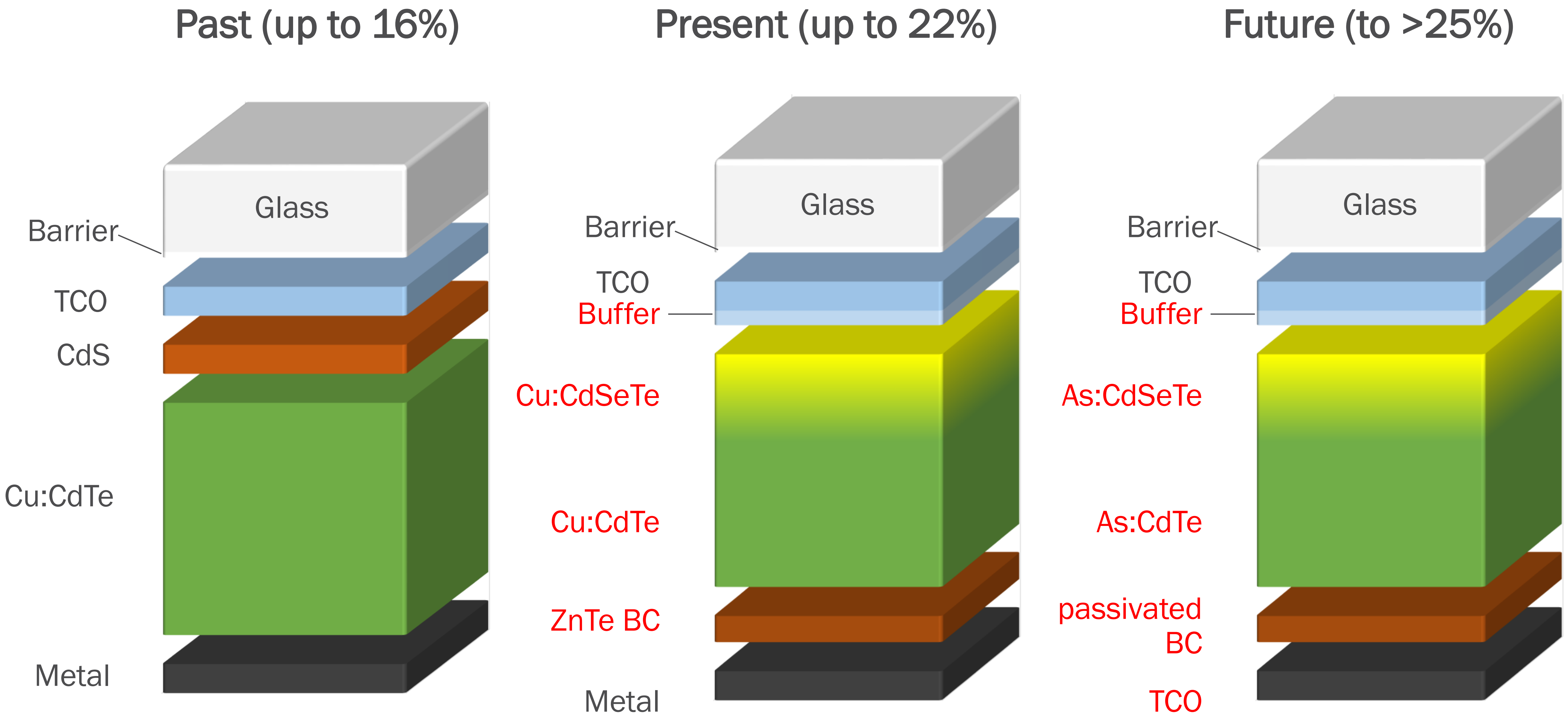
TOPAZ SOLAR FARM

High efficiency has to be transitioned to large scale production for low cost PV
It is not just about record cell efficiency but long term stability and energy yield



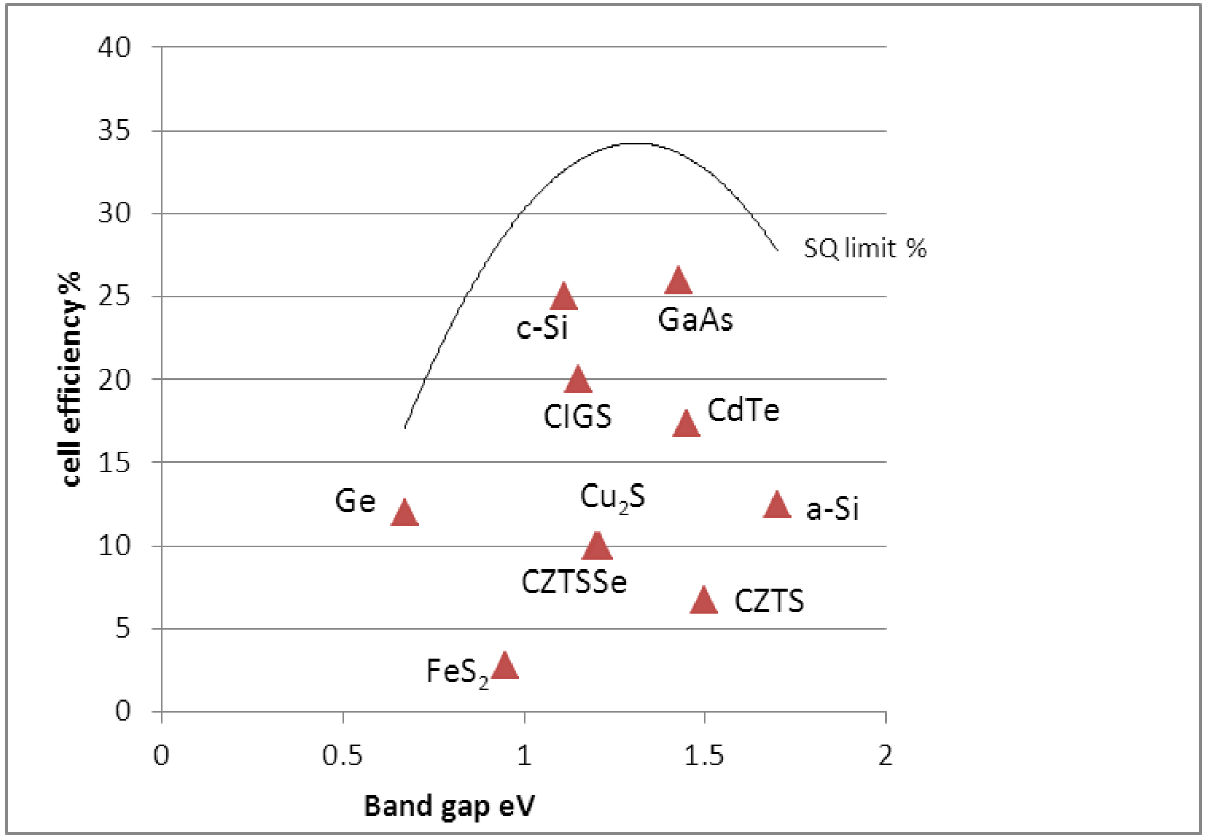
Slide courtesy of Dr Gang Xiong – First Solar

CdTe Solar Cells have Evolved



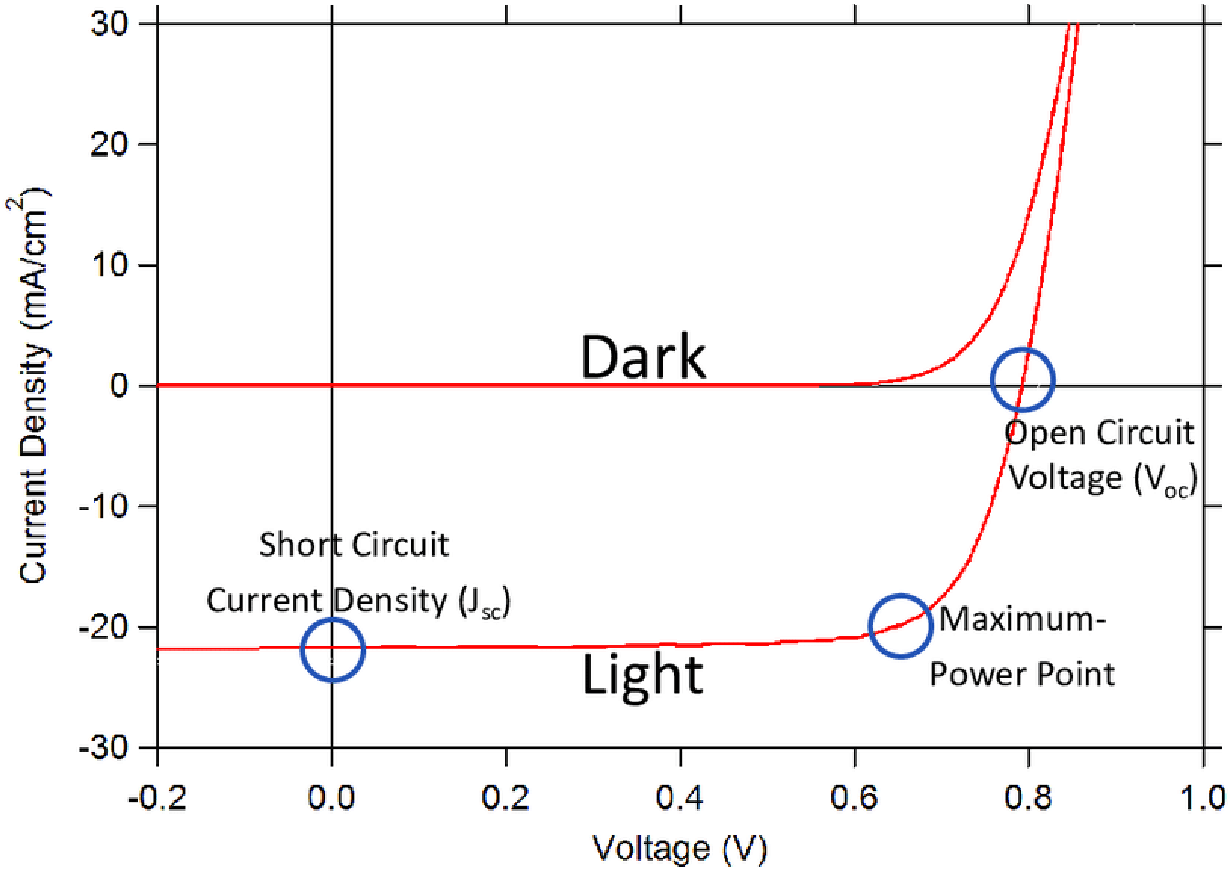
Slide courtesy of Dr Gang Xiong – First Solar

Single junction solar cells are limited in efficiency (Shockley Quiesser limit)



The S-Q limit can be exceeded using multi-junction solar cells to capture different parts of the solar spectrum more efficiently

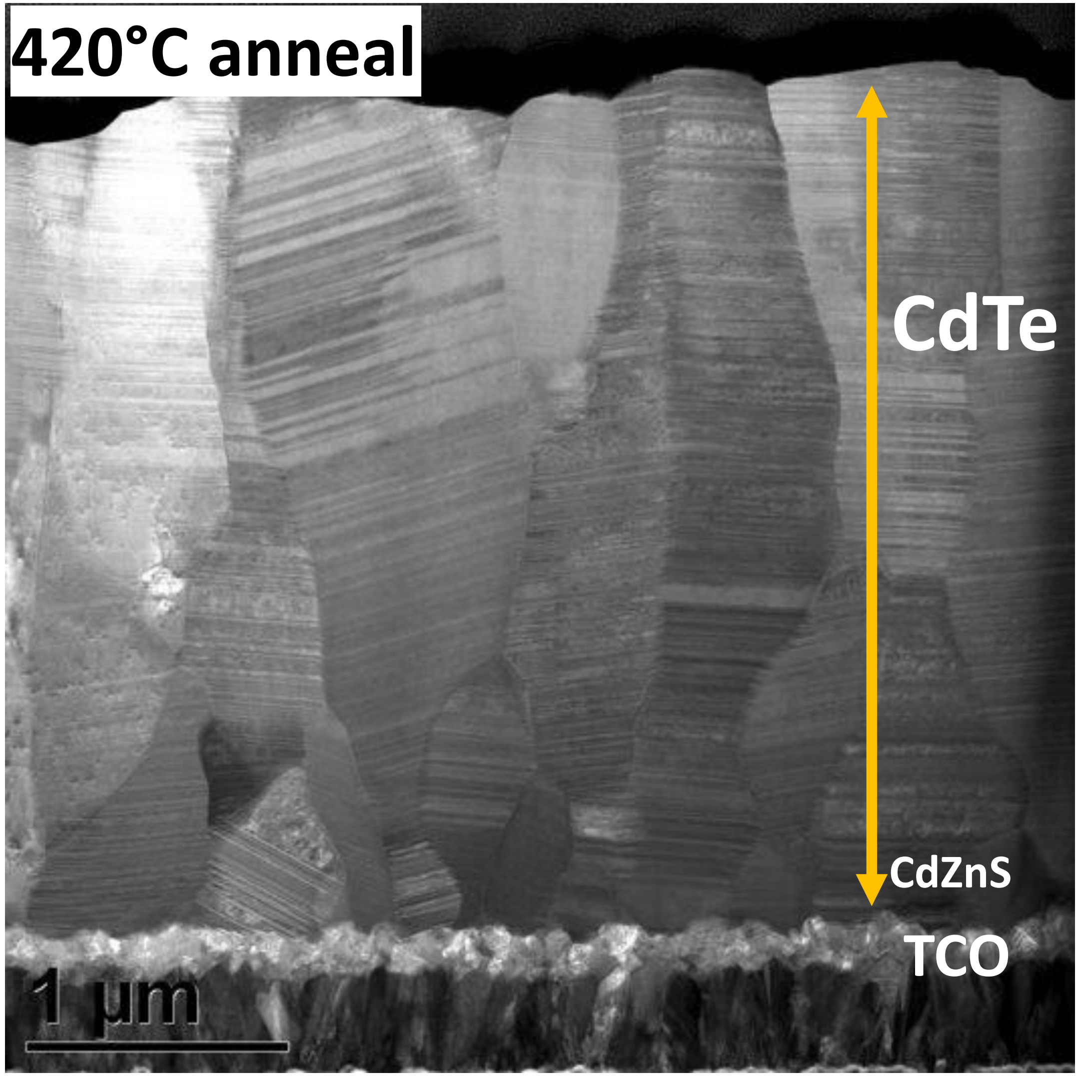
Higher CdTe cell efficiency will require higher voltage cells – how do we get there?

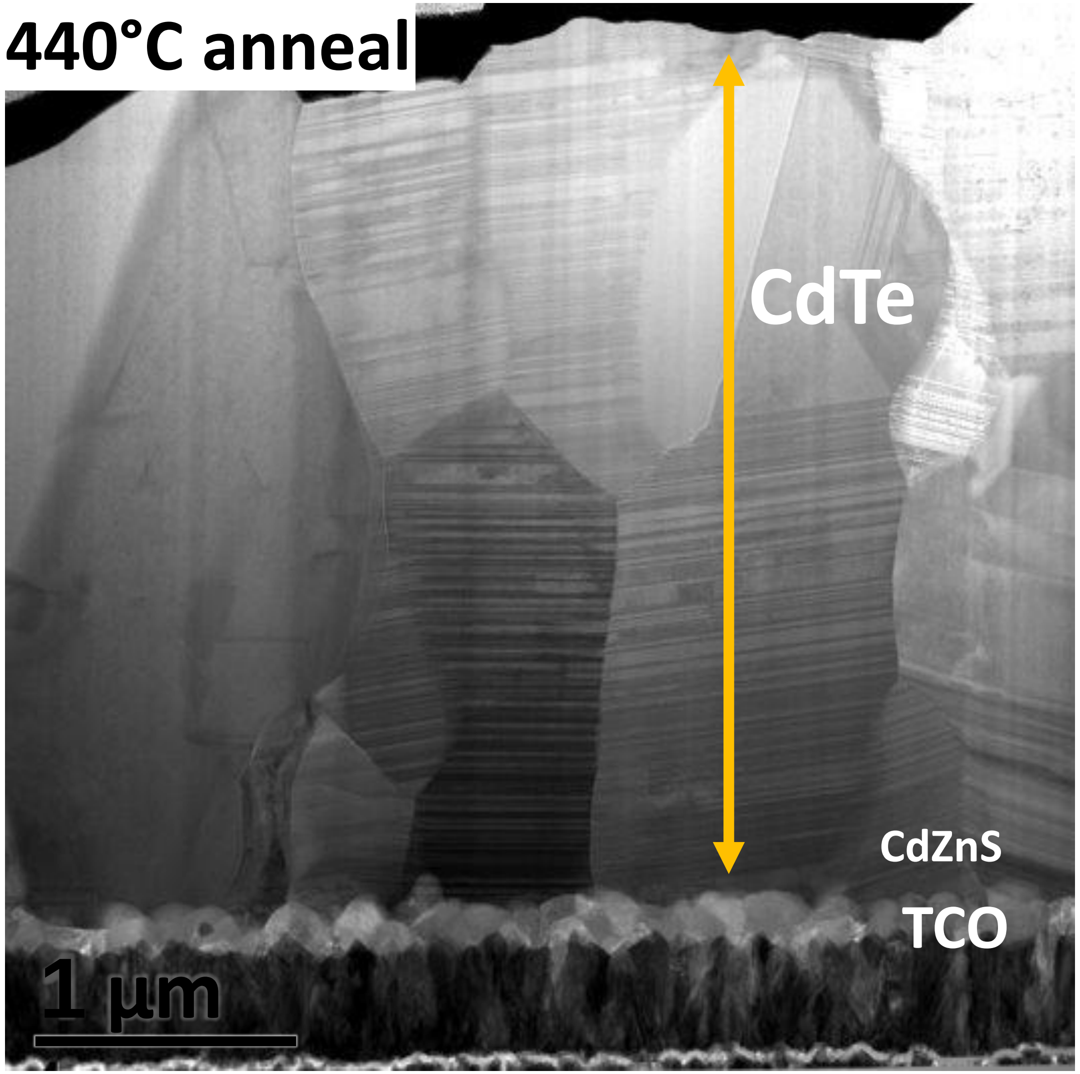


Parameter	Cell parameters	% of S-Q max
V_{oc}	0.8759 V	73
J_{sc}	30.25 mA/cm^2	99
FF	79%	88
$Efficiency$	21.0	65

Largest deficit in V_{oc}

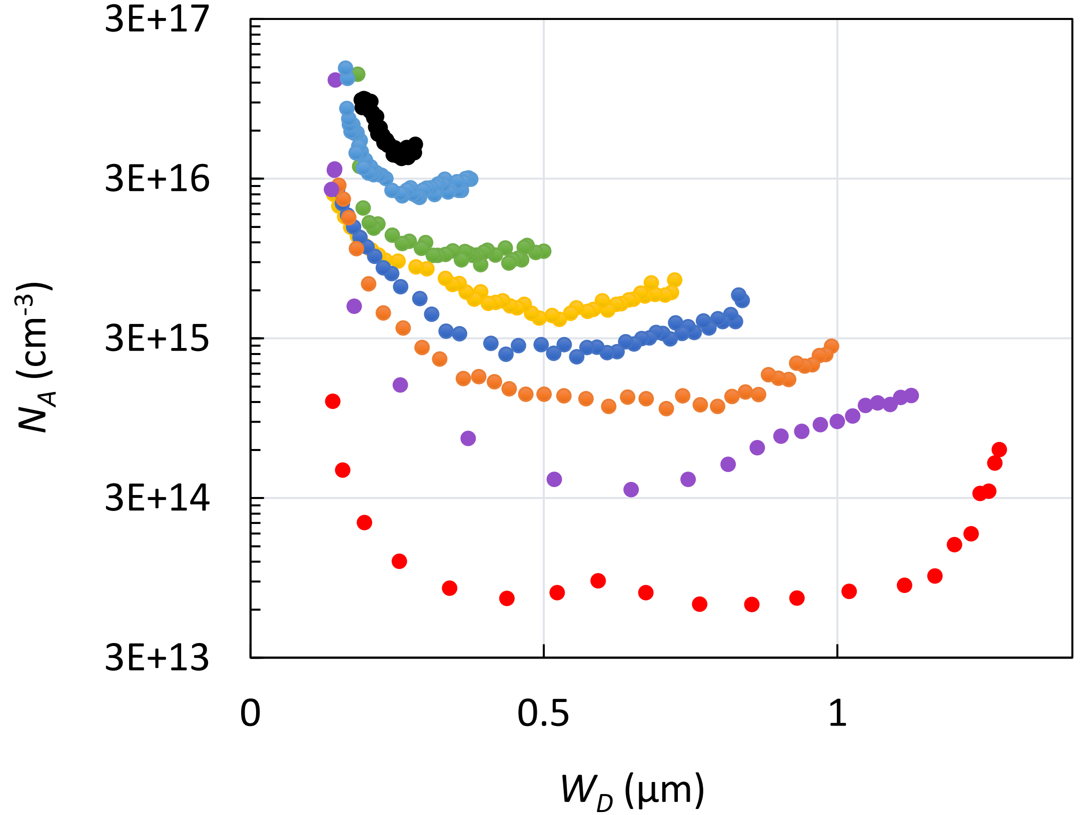
Micro-structure – STEM (TCO/CdZnS/CdTe:As Cd-saturated) – (Swansea/Loughborough/First Solar)

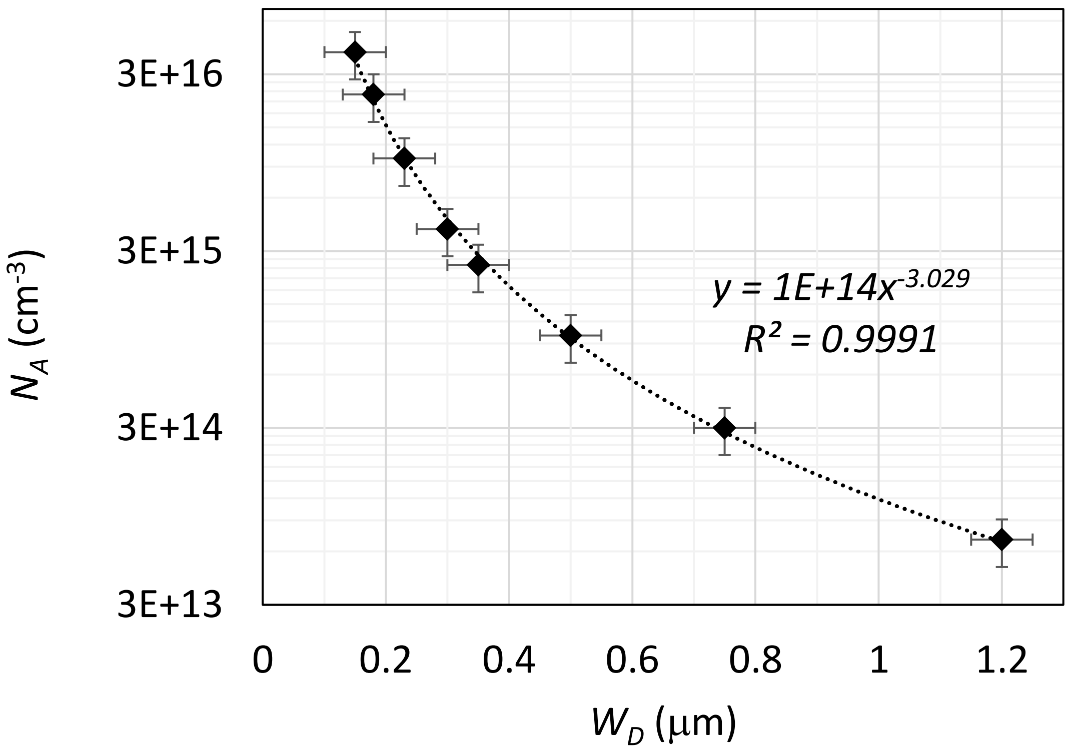




CHT at elevated temperature (440°C) increased grain sizes and reduced density of stacking faults

Efficiency >25% will require high N_a for the CdSeTe – arsenic doping





High N_d doping of the transparent emitter becomes increasingly important to avoid recombination

>1E16 cm^{-3} N_a but depletion width decreases, pushing junction back into high defect region near emitter

G. Kartopu et al., Solar Energy Materials and Solar Cells, (2019) ***194,*** *259-267*

Multi-junction solar cells can exceed S-Q limit
Example: Perovskite thin film top cell on silicon

OXFORD PV™
The Perovskite Company

https://www.oxfordpv.com/

- Conventional 156 mm x 156 mm silicon bottom cell
- 20-22% typical efficiency
- Oxford PV perovskite top cell
- Resulting 156 mm x 156 mm perovskite-silicon tandem solar cell
- > 30% efficiency
- Current world record 28.6% (May 2023)

Solar Energy 227 (2021) 292–302

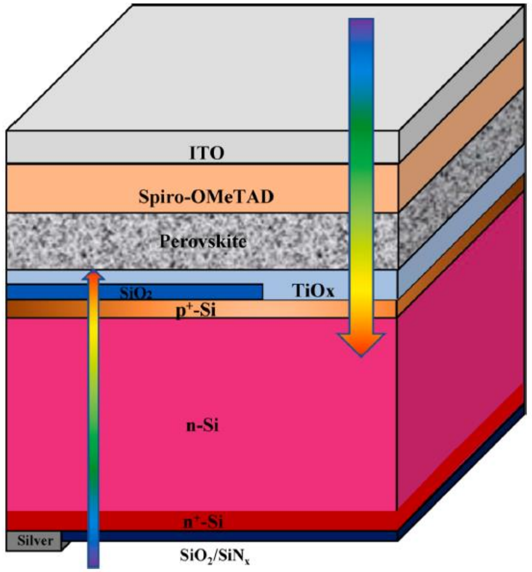


Fig. 1. Three-dimensional (3D) schematic of a bifacial perovskite/silicon tandem cell modeled in this work. The diagram is not drawn to scale.

P. Li et al. *Solar Energy 227 (2021) 292–302*

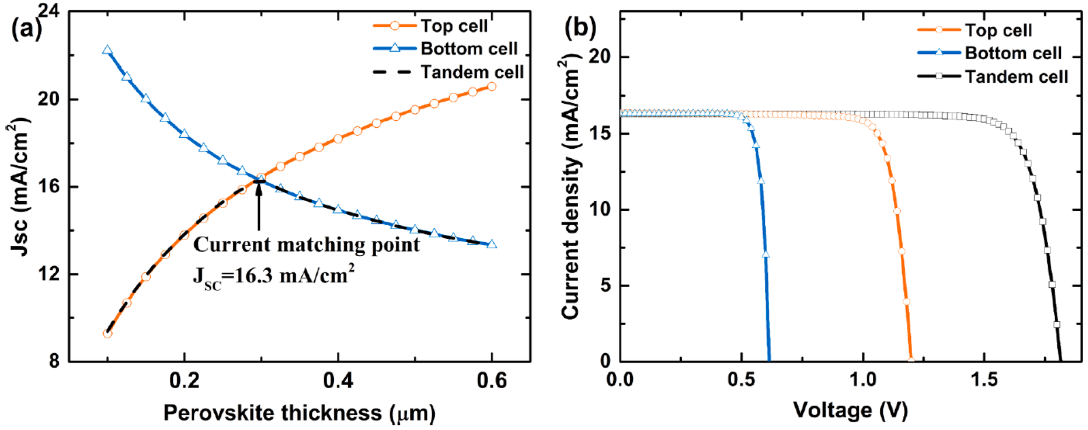
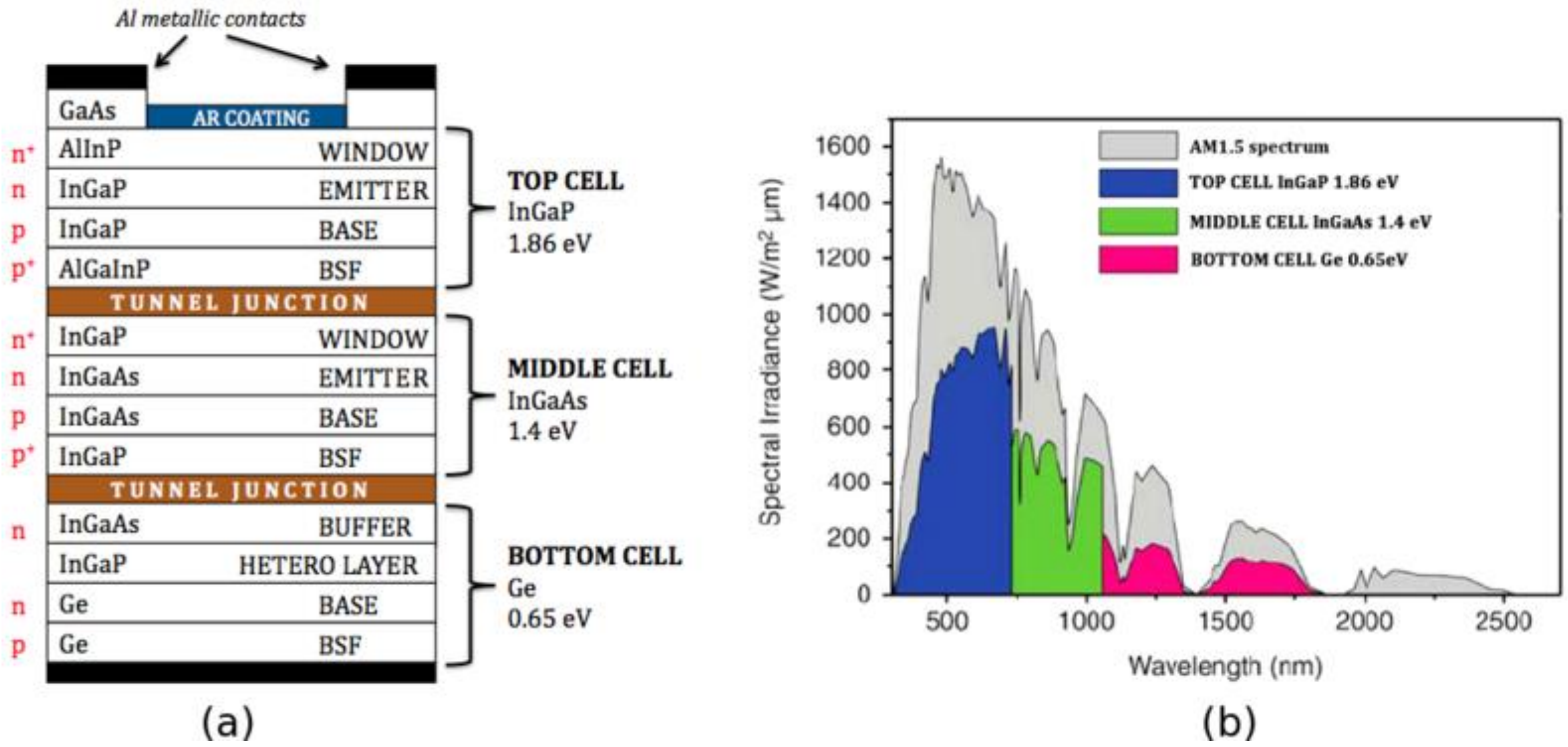


Fig. 5. (a) Jsc of the top and bottom cell as a function of the t_{pvk} in a perovskite/flat-surface-Si tandem solar cell and (b) *J–V* characteristics for the top, bottom and tandem cell under current-matching condition.

Ping Li et al, Modeling and simulation of bifacial perovskite/PERT silicon tandem solar cells, Solar Energy 227 (2021) 292-302

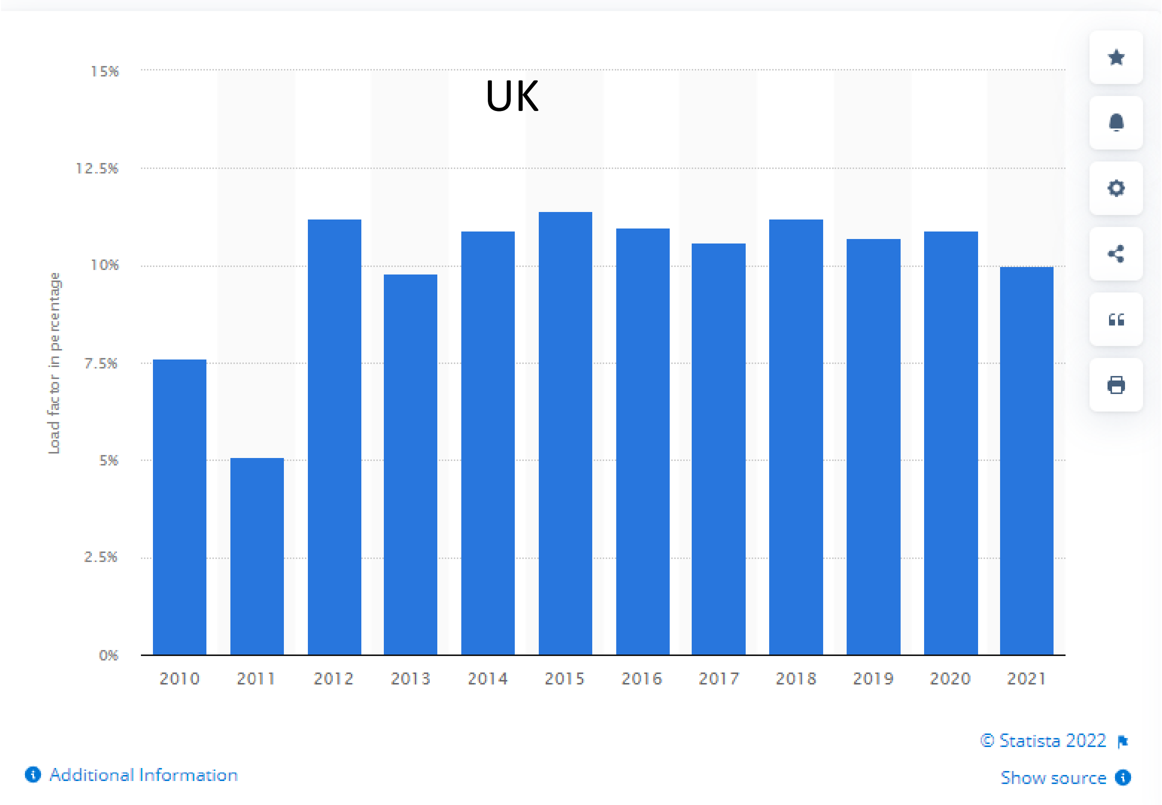
Multi-junction III-V solar cells powering satellites

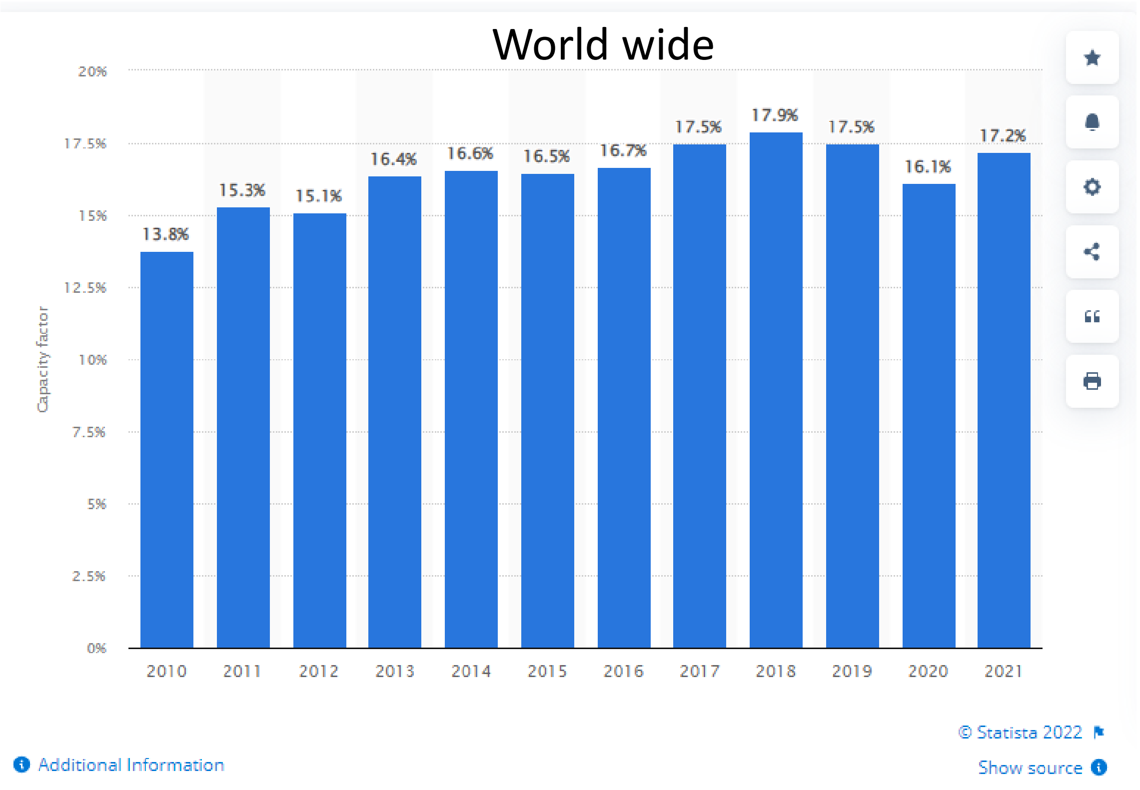
High efficiency but high cost



Energy yield of PV modules – kWh is more important than W(peak)

- PV panels are rated with solar radiation of 1,000 W/m^2 (only achieved in UK at midday in Southern England on a clear day)
- 100% load factor for 1kW installation equivalent to 8,760 kWh per year
- In the UK expect ~10% load factor – 876 kWh over the year
- California expect ~28% load factor





Space Based Solar Power

https://spaceenergyinitiative.org.uk/space-based-solar-power/

Energy Generation

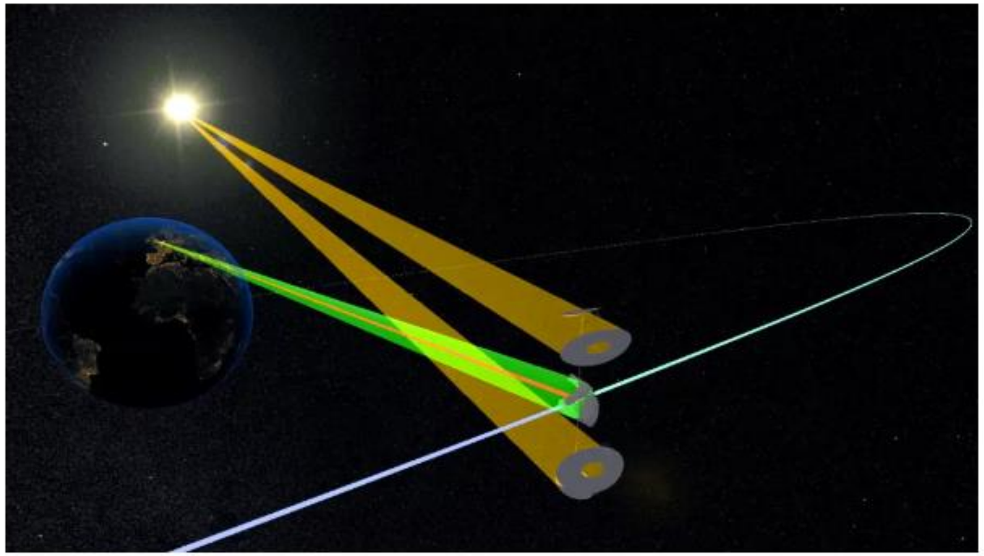
- Continuous power generation, 24/7, 365 days/year
- Gigawatt levels of base-load energy generation
- Could be a source of green hydrogen generation for the transport sector

- Delivering Net Zero
- Roadmap for orbital demonstrator by 2030
- Operational system could be developed by 2040
- Scalable to provide substantial proportion of energy

A solar power plant in space? The UK wants to build one by 2035.

By Tereza Pultarova published May 11, 2022

The U.K. is getting serious about beaming solar power.



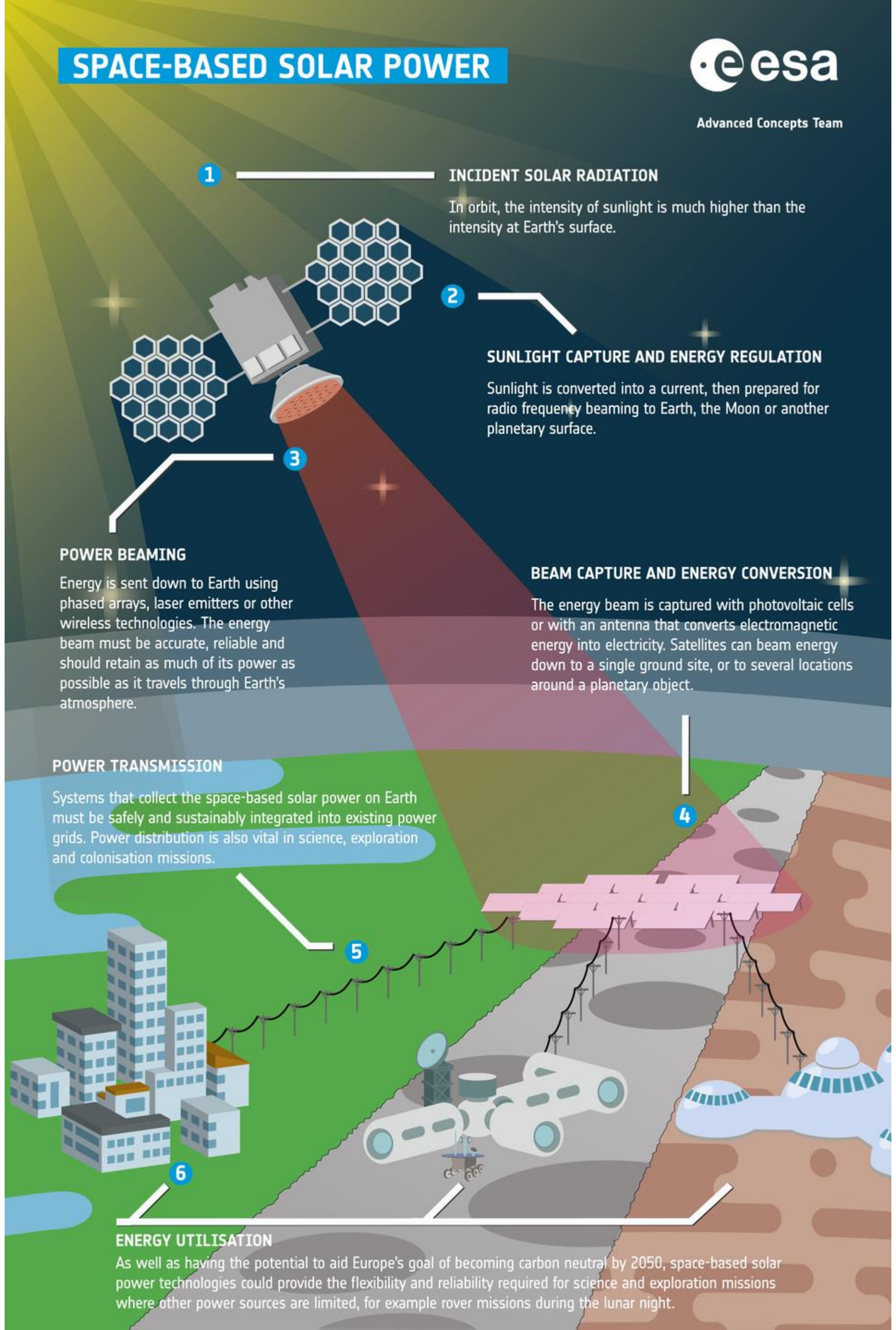
The U.K, might have a space-based solar power station in orbit by 2035. (Image credit: Space Energy Initiative)

The United Kingdom is getting serious about beaming solar power from space

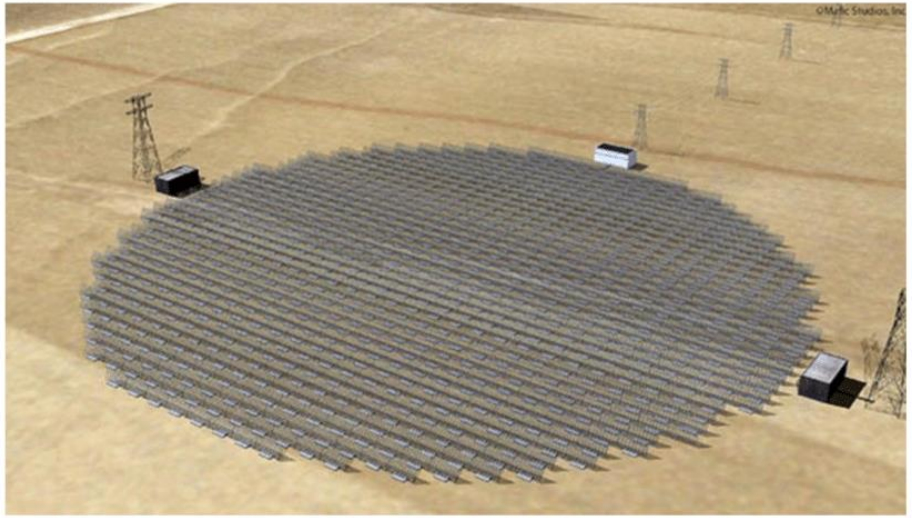
Space Energy Initiative

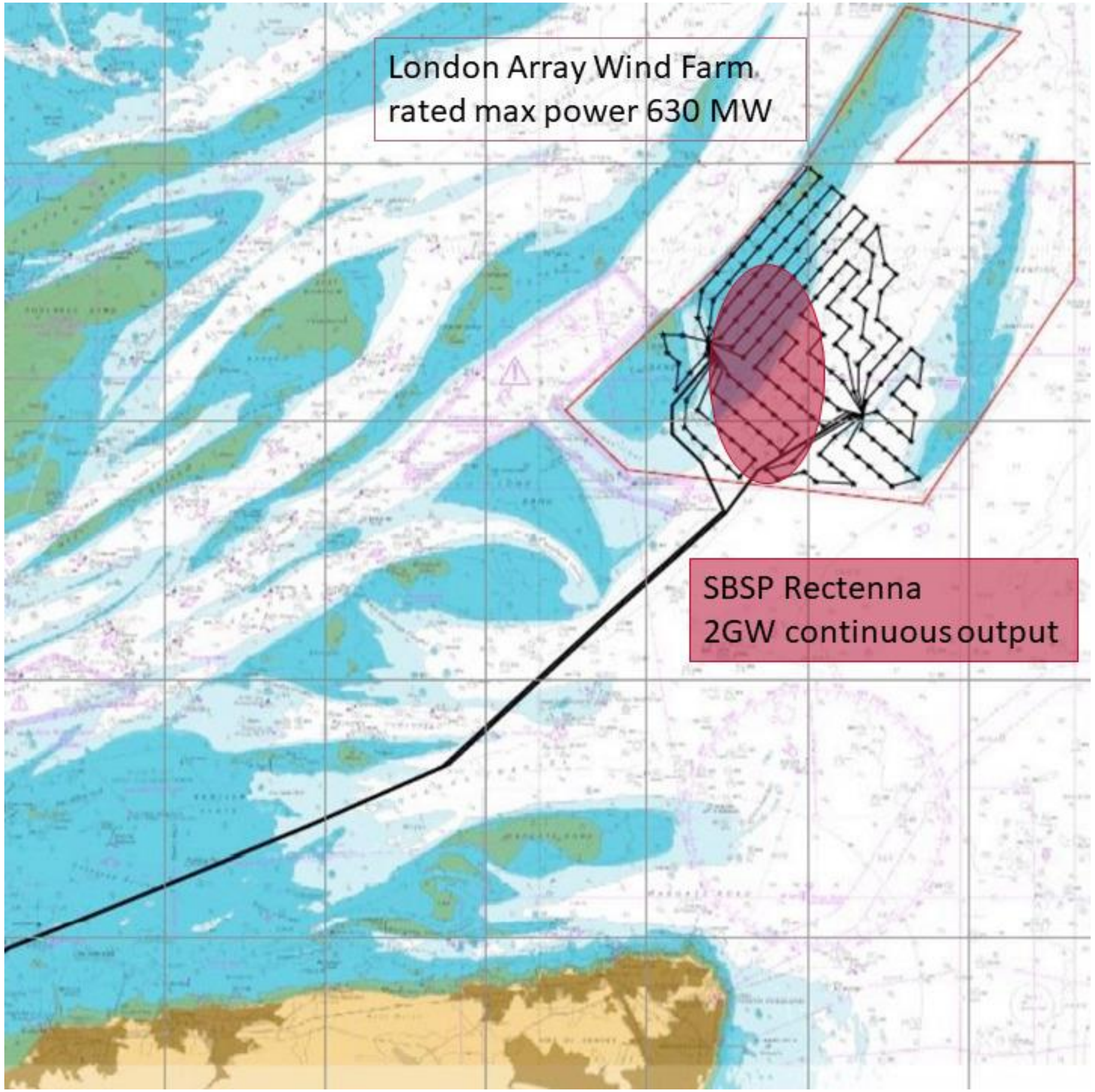
- A typical system comprises a constellation of massive, kilometre scale satellites in GEO.
- Each has very lightweight solar panels and a system of mirrors to concentrate sunlight onto the panels, generating around 3.4 GW of electricity on the satellite.
- This is converted into RF microwave radiation, with an efficiency of 85%. The microwave frequency proposed is typically 2.45GHz to be transparent to the atmosphere and moisture, and a net 2.9 GW of power is beamed to a receiving antenna at a fixed point on the ground below.

- A secure pilot beam is transmitted from the ground to the satellite to allow the microwave beam to lock onto the correct point.
- The ground rectifying antenna or ‘rectenna’ converts the electromagnetic energy into direct current electricity and then through an inverter which delivers a net 2 GW of AC power into the grid.



SBSP – efficient use of land area for receiver station



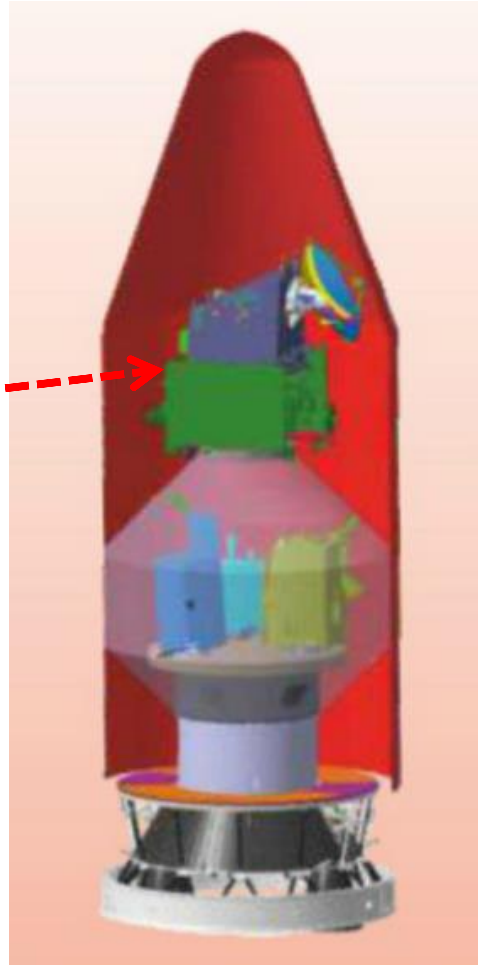


A new generation of solar cells will be needed for SBSP

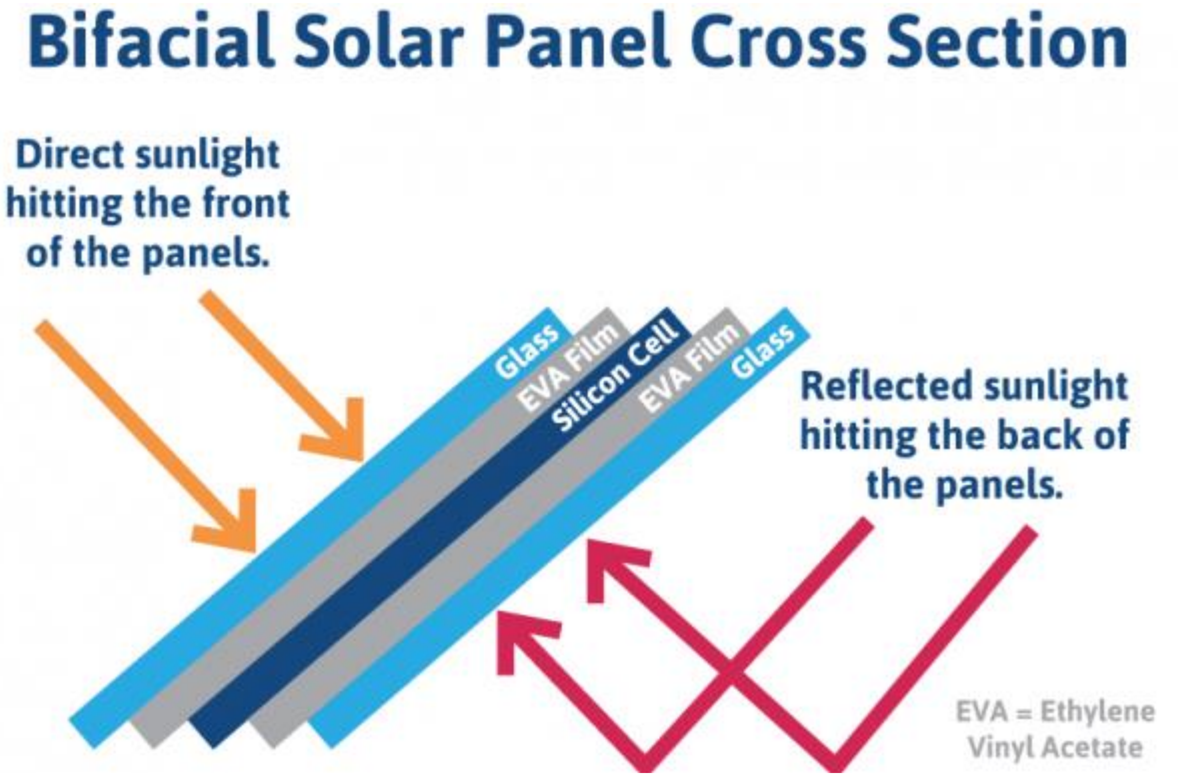
- Very light weight (high specific power) to minimise launch cost
- Light-weight deployment structures
- Radiation resilient
- Capable of large-scale manufacture at low cost
- Possible candidates: CdTe, CIGS, GaAs, perovskites

AlSat-Nano first successful demonstration of TF CdTe cells in space

- AlSat Nano ready to be shipped
- The Polar Satellite Launch Vehicle EM to be provided then 3 FM's
- Satish Dhawan Space Centre
- Sept 26th 2016 Launch
- 2022 still working and sending data back



Bifacial solar PV – enhance energy yield by up to 25%



Courtesy Regen Power

BiPVco
The Building Integrated Photovoltaic Company

Innovative Building Integrated PV products

Our Vision
To turn buildings into power stations, from consumer of energy to a generator and exporter of energy,
from a carbon liability to an asset, affordably and without compromises on its aesthetics.

Challenge for greater adoption of BIPV
- Light weight
- Aesthetically blending-in with the building structure
- Durable
- Shade tolerance
- Fewer materials and less energy in manufacture

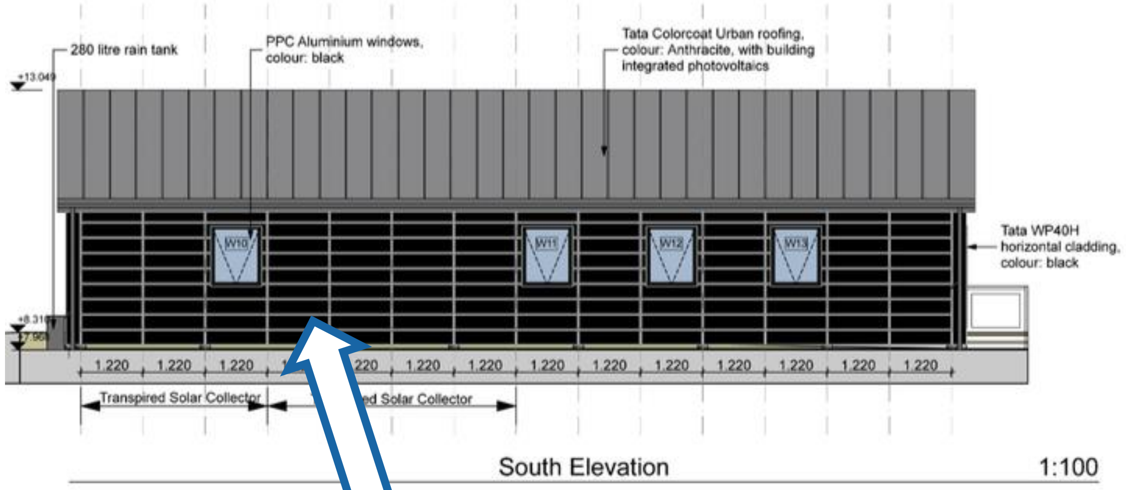
BiPVco
The Building Integrated Photovoltaic Company

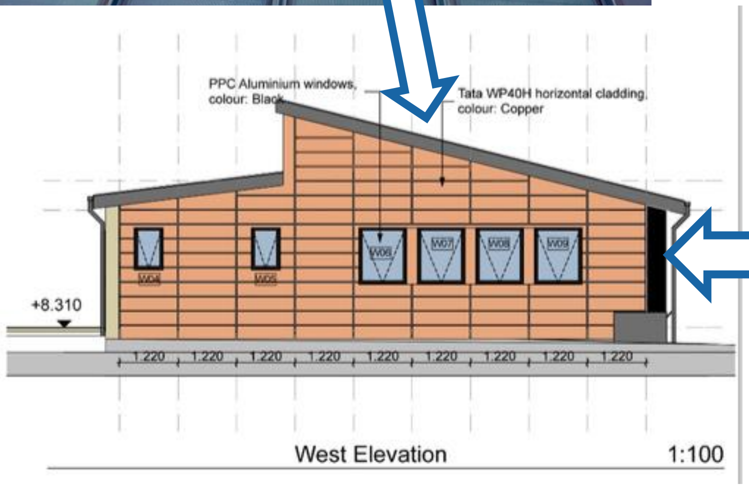
House featuring in Grand Designs

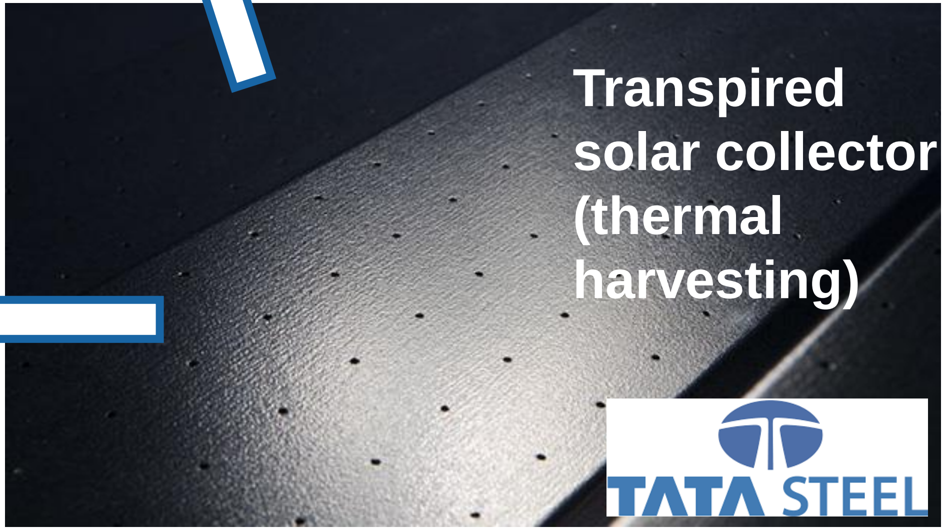
Denmark Hill Station – Europe's first zero carbon station

Energy Positive Buildings – SPECIFIC project

17 kWp integrated roof panels (CIGS)







Energy Positive Homes……

100
1920~2020

Swansea University
Prifysgol Abertawe

pentan architects

Auxilium
ENGINEERING SERVICES

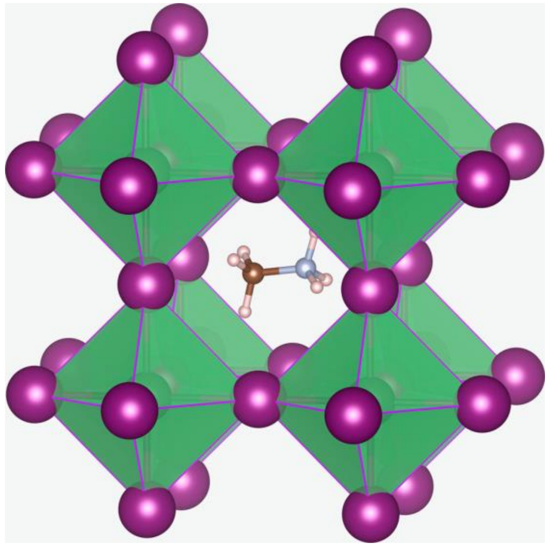
BiPVco
The Building Integrated Photovoltaic Company

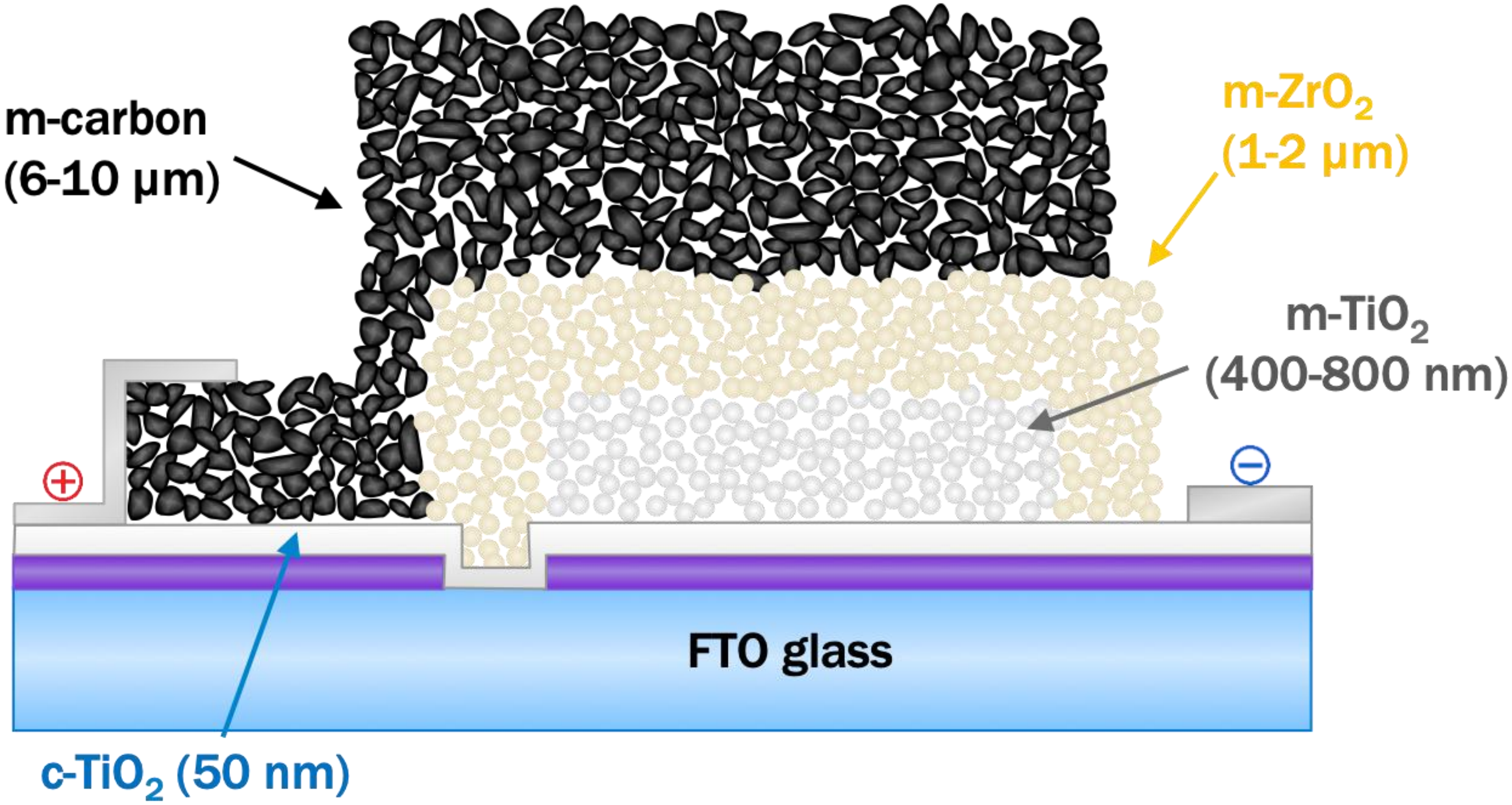
pobl
people making a difference

Neath Port Talbot County Borough
Bwrdeistref Sirol Castell-nedd Port Talbot

ERBROWN

Printing photovoltaics – a path to very low cost flexible PV with potential for very large scale manufacture





Perovskite = ABX_3 structure

e.g. $CH_3NH_3PbI_3$

e.g. $Cs_x(MA_{0.17}FA_{0.83})_{(100-x)}Pb(I_{0.83}Br_{0.17})_3$

Powering the internet of things (IOT)

- Photovoltaics (PV) is an attractive candidate for powering the rapidly growing market of smart devices in the Internet-of-Things (IoT) such as sensors, actuators, and wearables in 2020, 50 bn devices are already in use.
- Using solar cells and rechargeable batteries to power IoT devices avoids the expensive replacement of disposable batteries and reduces the environmental impact.
- IoT devices are often operated indoors under artificial light, which differs from (outdoor) sunlight as it is a much narrower, mainly visible spectrum with typically a factor of 500–1000 lower intensity.

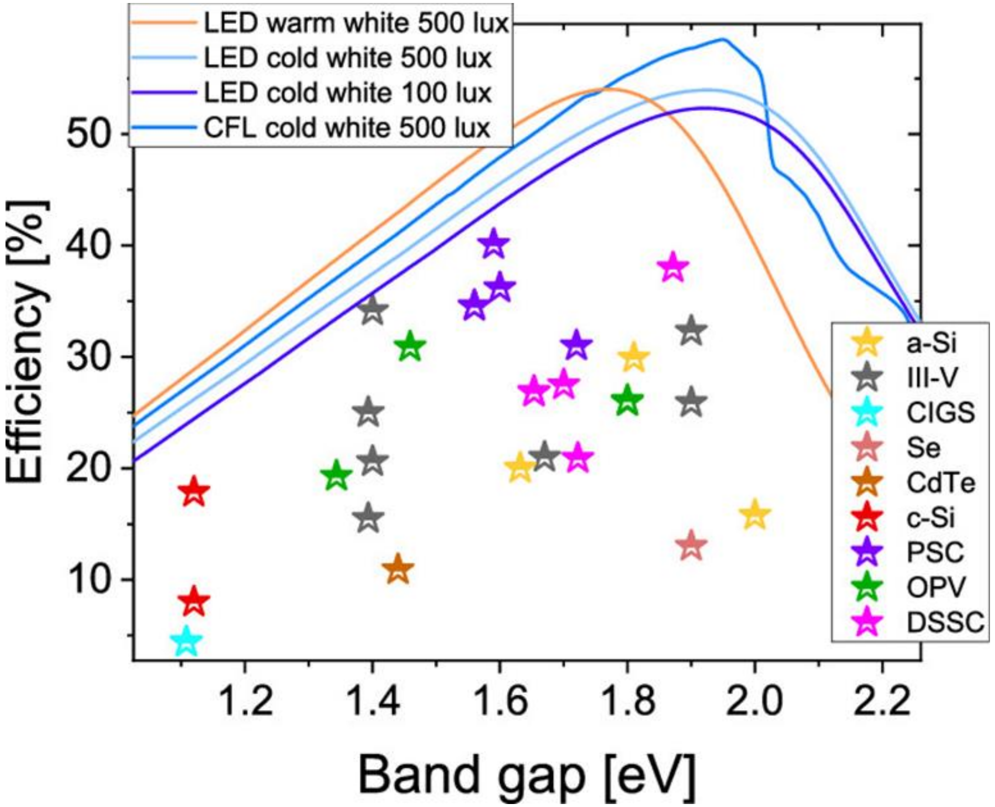
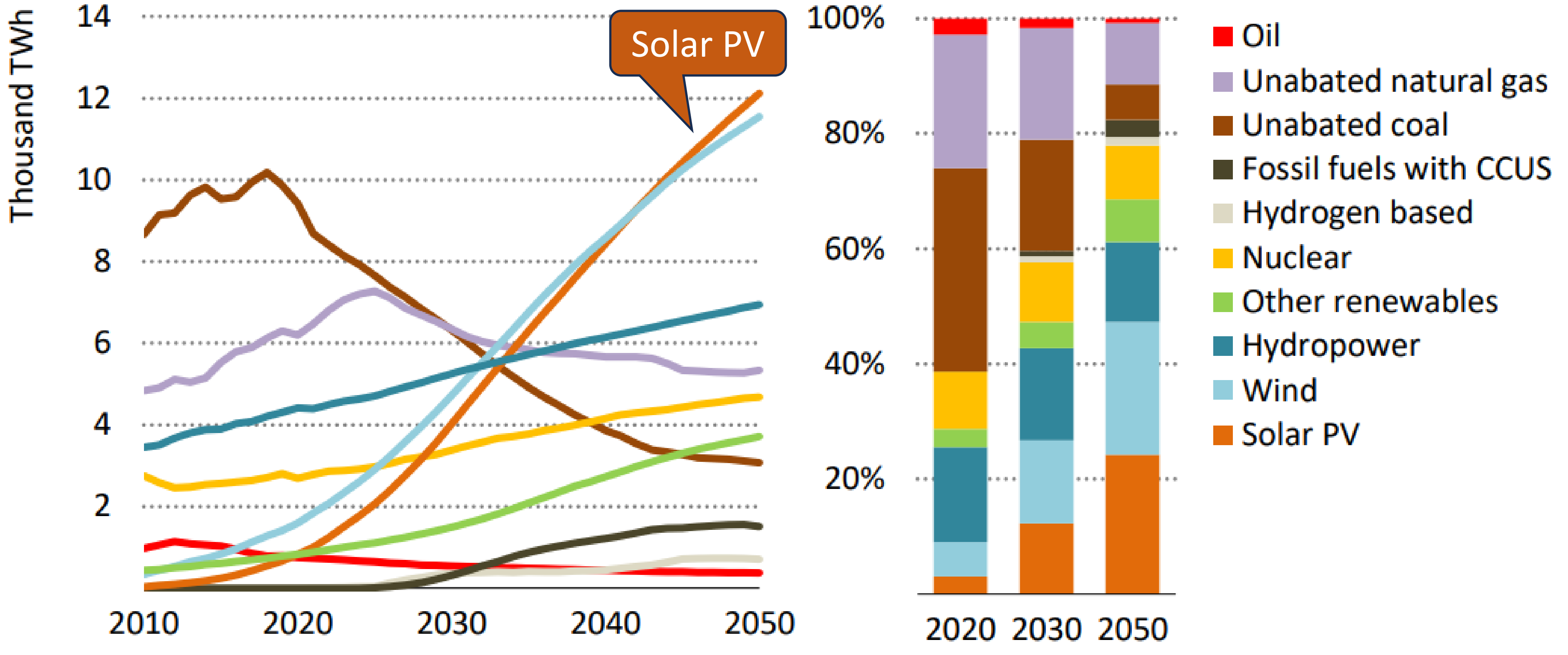


Figure 1. Reported performance as a function of the band gap for several PV technologies measured under artificial indoor light between 50 and 3,000 lx The lines are calculated maximum efficiencies (based on detailed balance analysis) for three different spectra and two different intensities.

David Müller et al., *ACS Appl. Energy Mater.* 2023, 6, 20, 10404−10414

Figure 1.14 ▷ Global electricity generation by source in the APC



Renewables reach new heights in the APC, rising from just under 30% of electricity supply in 2020 to nearly 70% in 2050, while coal-fired generation steadily declines

Note: Other renewables = geothermal, solar thermal and marine.

Conclusions

- PV solar now generates around 5% of world electricity
- Projected to rise to around 30% by 2050
- The secret to success has been lower cost and higher efficiency
- Limits to low-cost module efficiency could be around 25%
- Cadmium telluride modules are leading the charge for thin film PV
- New research will lead to over 25% efficient modules based on As doping
- Energy yield for terrestrial PV is limited by weather and daylight hours
- Space based PV could give 90% energy yield
- Growth of new applications with building integrated PV and opportunity for new materials such as perovskites
- Huge potential for imbedded energy generation with the IoT


Wishing you all a happy
zero-carbon future
powered by the sun!