An aerial photograph of a large-scale solar photovoltaic (PV) farm. The rows of solar panels stretch far into the distance, creating a strong sense of perspective. The sky is a mix of orange and blue, indicating either sunrise or sunset. The overall scene is clean and modern, representing sustainable energy.

# The Astonishing Rise of Solar PV

Dr Chris Jardine

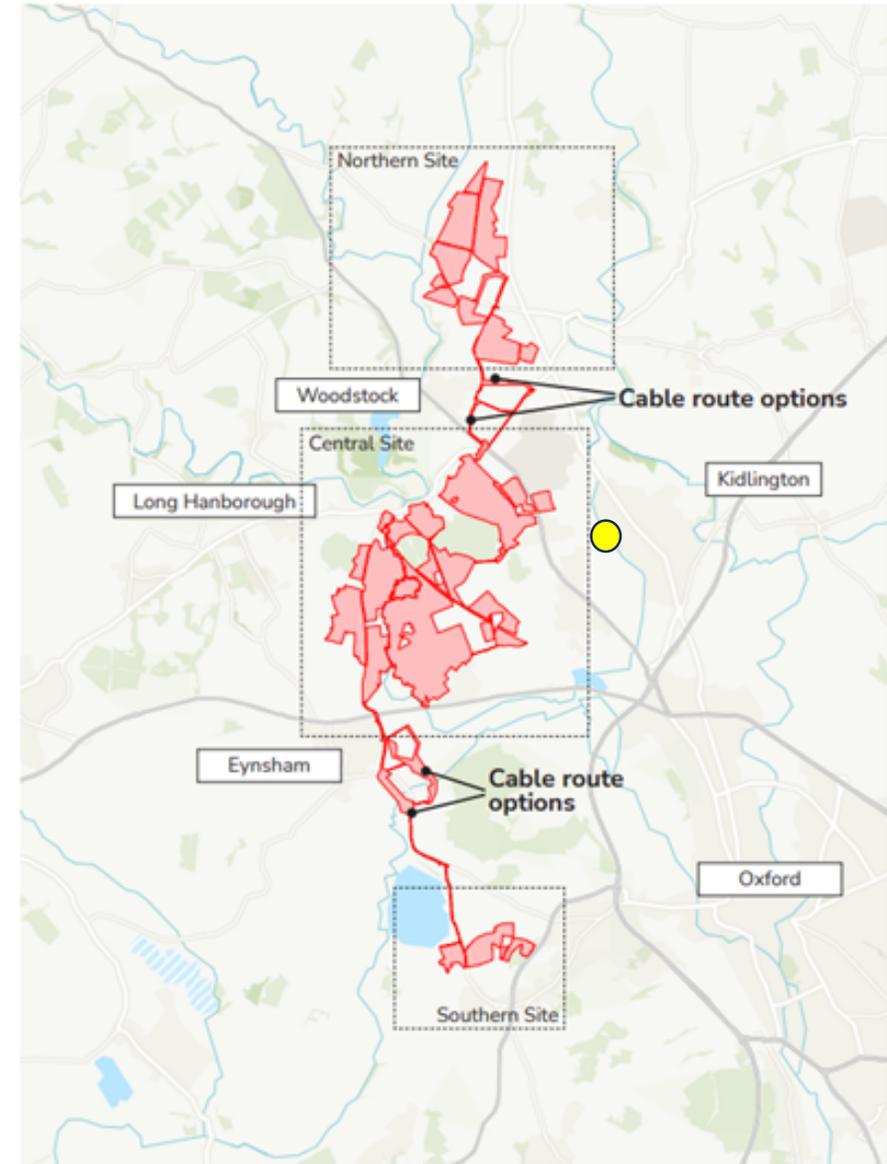
Honorary Research Associate, ECI

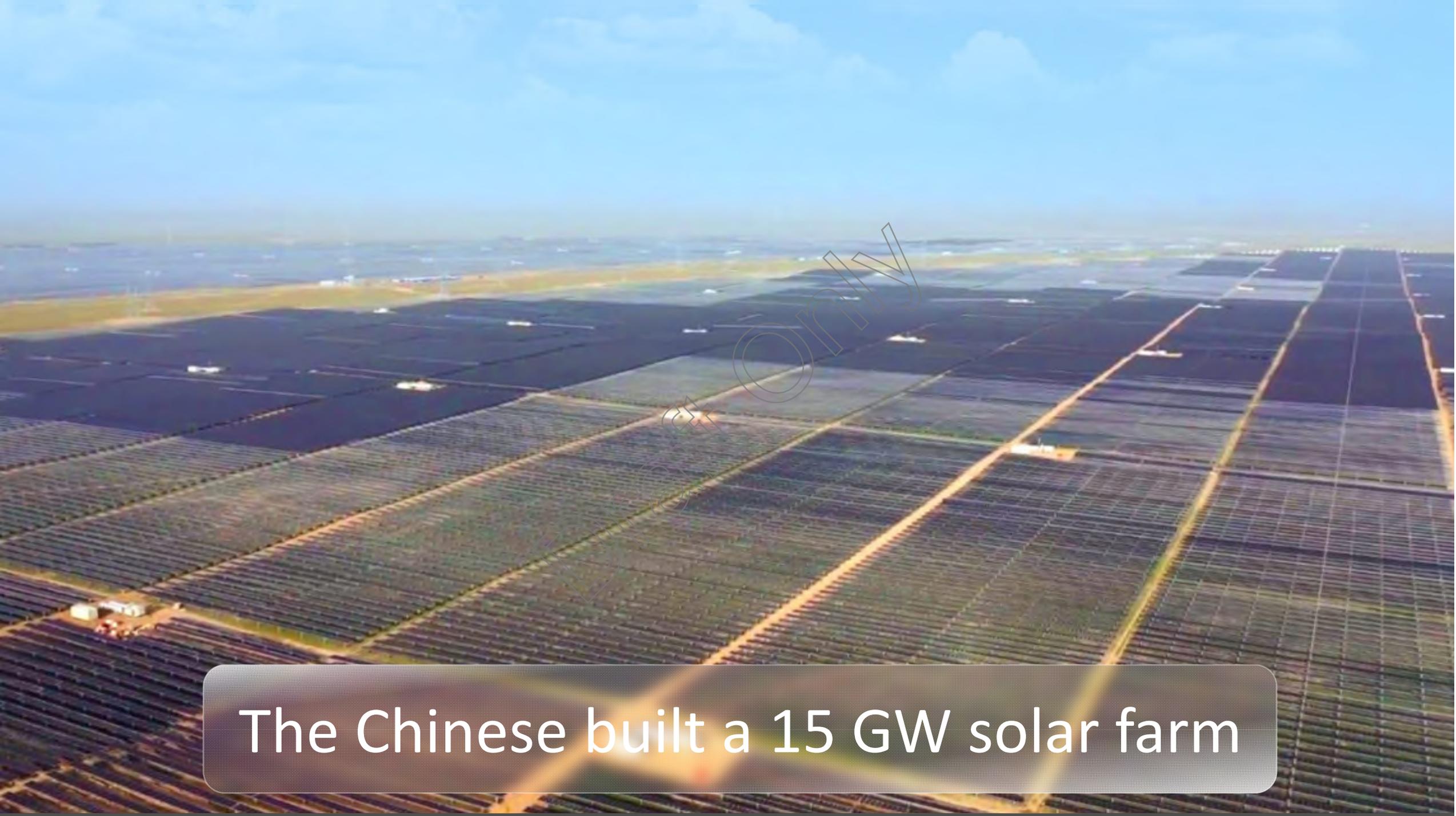


PV Compare: 6kW, 2% of UK capacity

# How it's going ....

- In 2025 proposal for Botley West Solar Farm being considered
- Covering area between Woodstock Kidlington, Long Hanborough and Eynsham
- 860 MW
- This would be ca. 4% of current UK capacity





The Chinese built a 15 GW solar farm



They covered a mountain ...



Draft Only

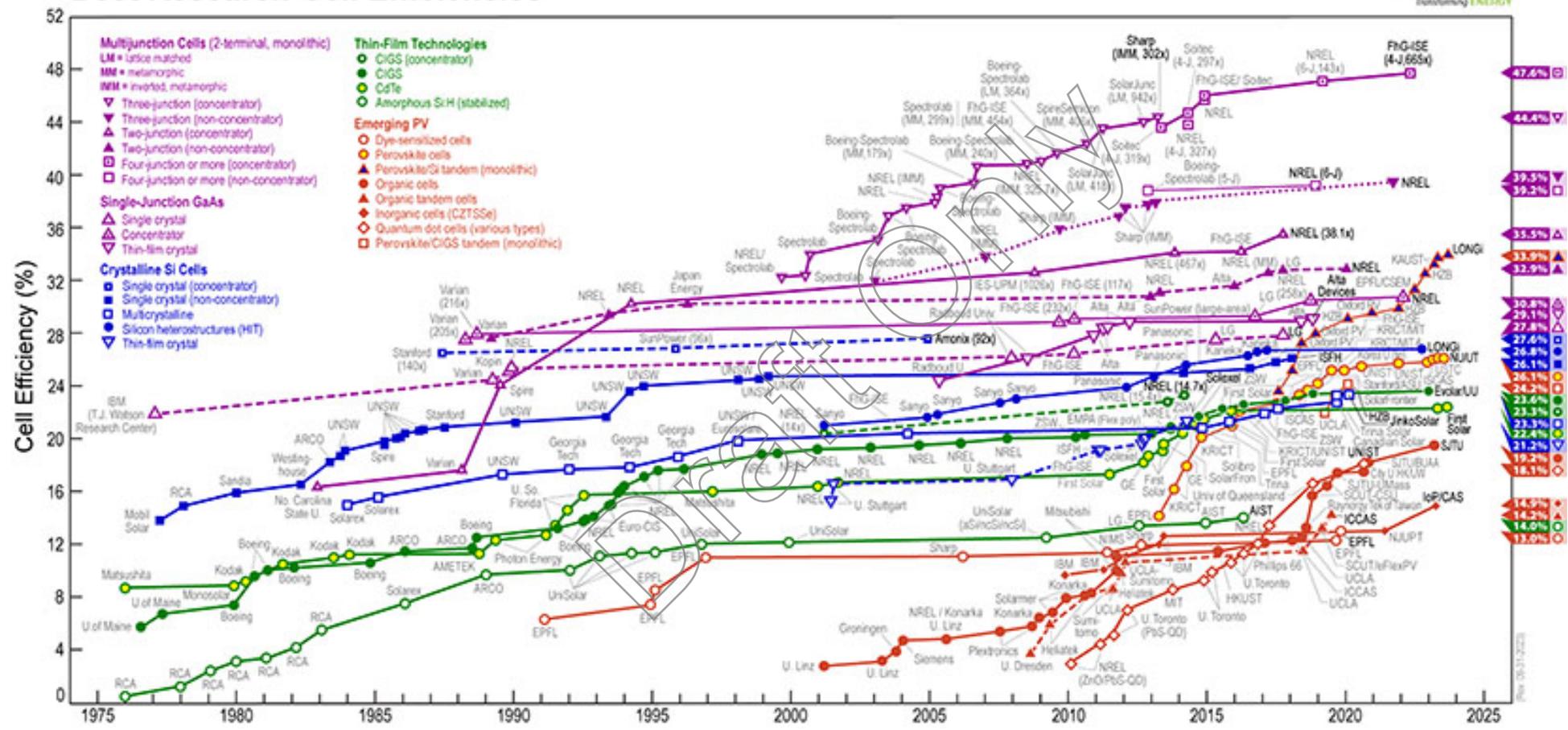
They even built 3GW in the sea!!



# Technology Improvements

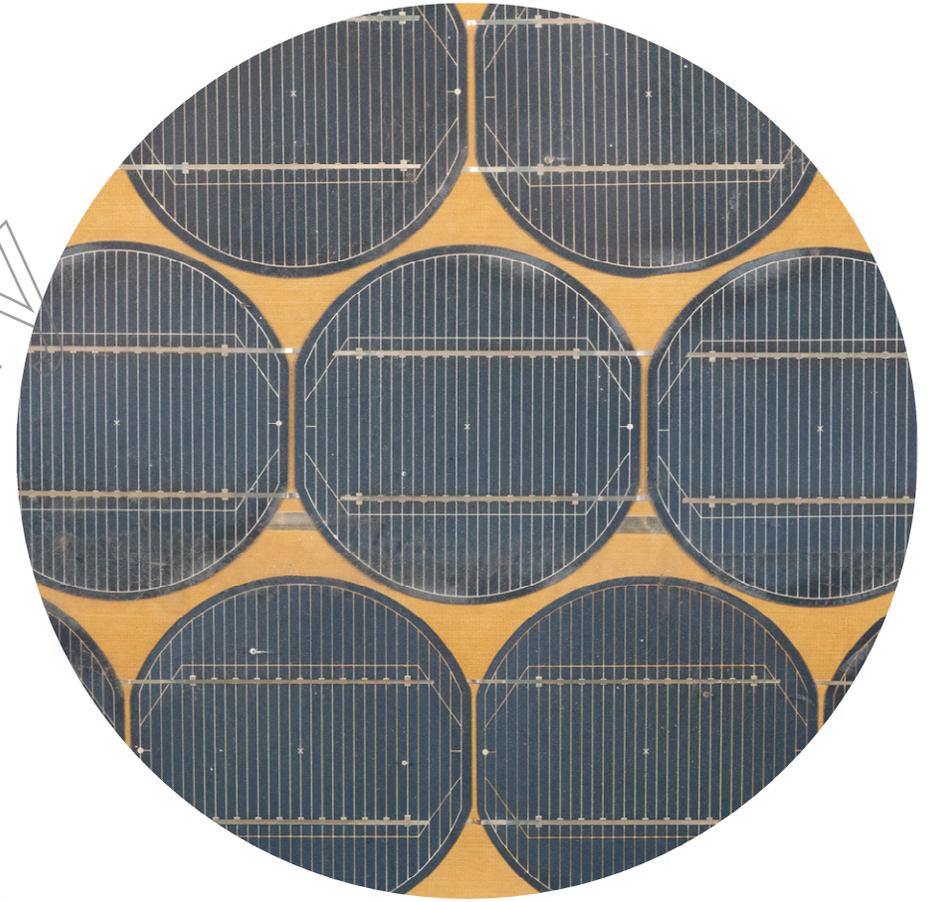
# Efficiency

## Best Research-Cell Efficiencies



# Lifetimes

- Solar panels warrantied for 25 years
- 80% performance guarantee
- Sunpower offering 40 year warranties
- Encapsulation technology improved
- Does the 25-year 'norm' undersell solar?

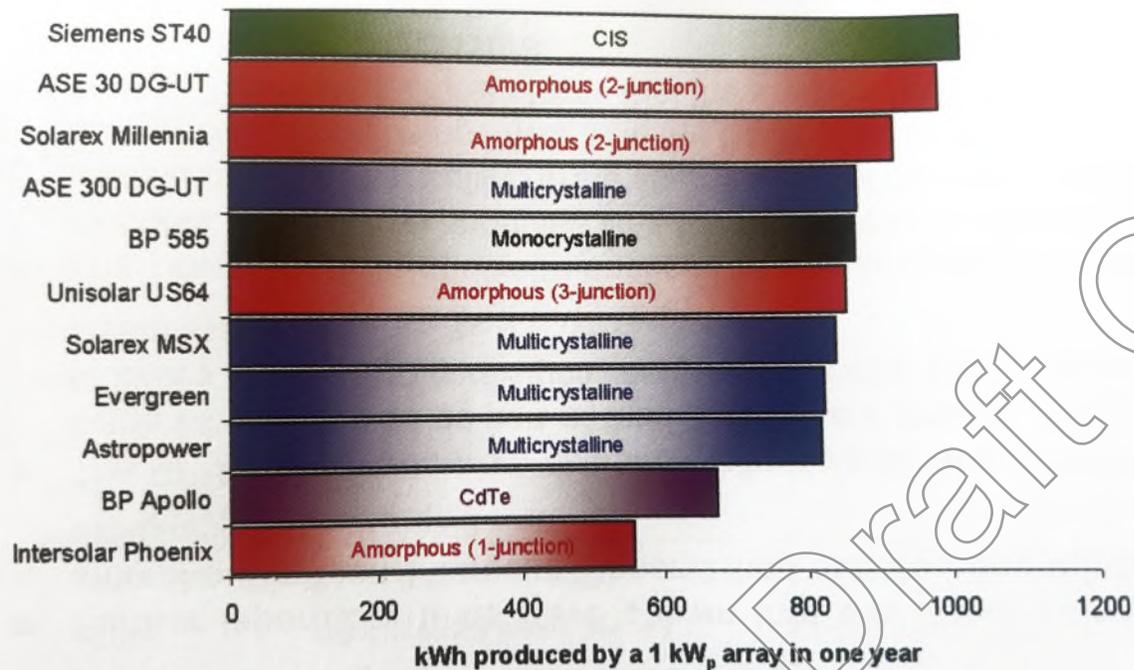


# Toto Forever ...



- In 2009, artist Max Siedentopf installed a solar powered art installation in an undisclosed location in the Namibian desert
- It promises to play 'Africa' by Toto on loop 'for all eternity'

# Improvements in kWh/kWp

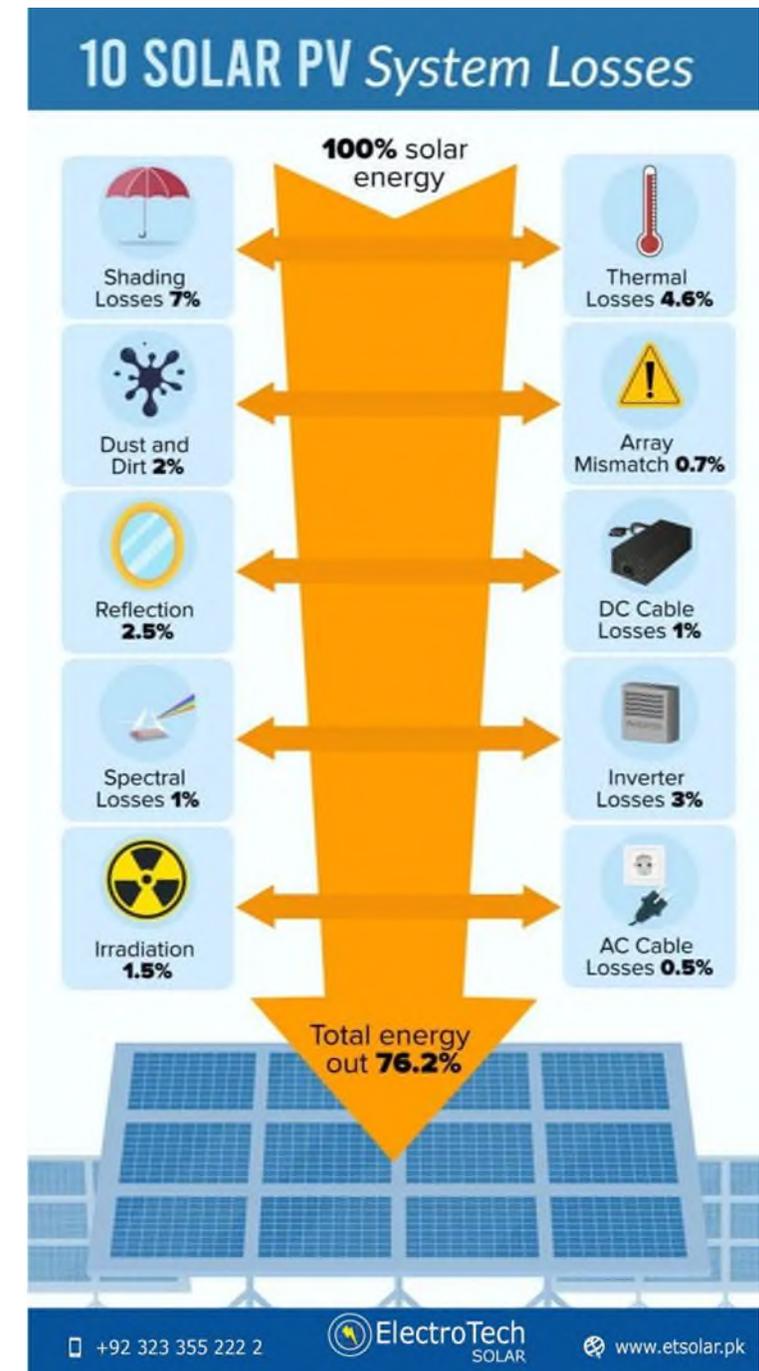


Electricity produced in one year at the UK test site by the different products.

- kWh/kWp is a measure of how much energy is produced compared to lab test conditions
- Light 1000W/m<sup>2</sup>, 25°C, AM1.5 spectrum
- Some improvements increase real-world performance more than lab test performance
- Today you'd quote 913 kWh/kWp for that site

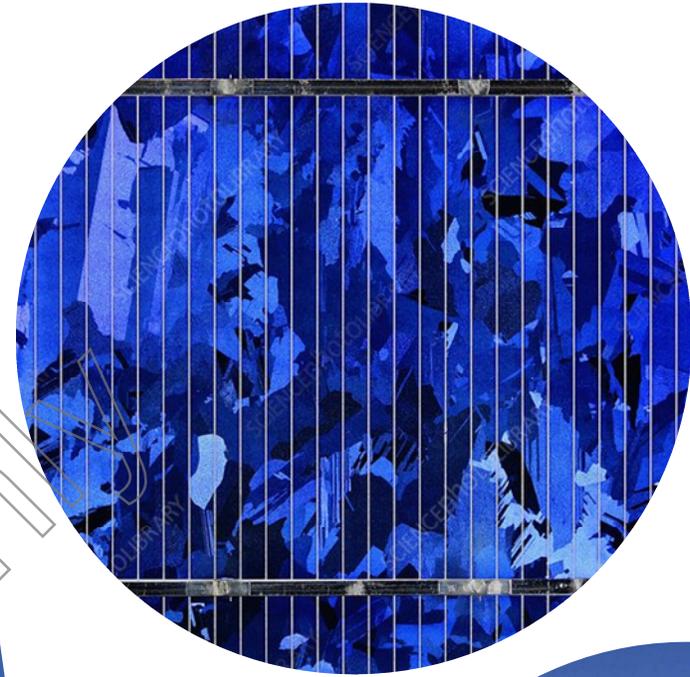
# Improvements in System losses

- Surface coatings to bead up water and dirt better
- Anti-reflective coatings better
- Cells and panels are more uniform – array mismatch reduced
- Inverters are more efficient 98% cf. 93%
- Better knowledge around cable sizing
- And lifetimes longer too



# Anti-reflective coatings

- Multi-crystalline silicon used to be blue and grains were clearly visible
- Intentionally positioned as a high-tech aesthetic
- Now, just a uniform dull blue/black



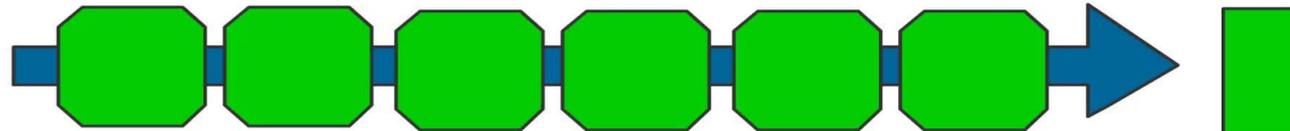
# Coping with dirt

- Solar panels have anti-reflective and surfactant coatings
- Beads up water to help it run away
- Takes dirt with it
  
- Solar panels are considered self-cleaning if pitched  $> 5$  degrees

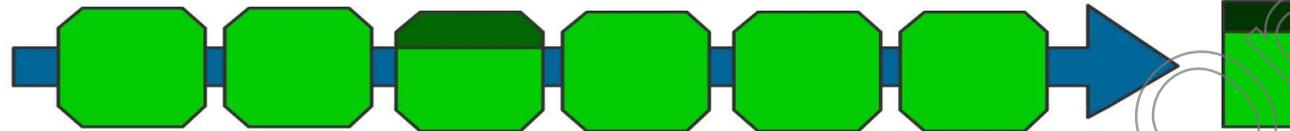


# Cell and Module Mismatch

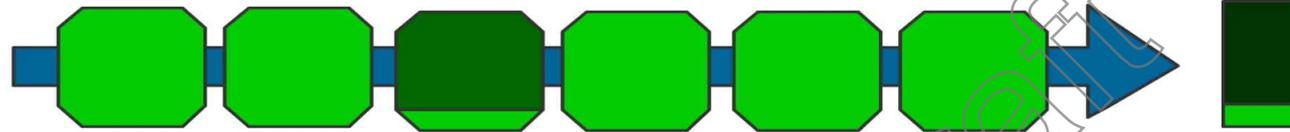
## Effects of Partial Shading of Solar PV Panel



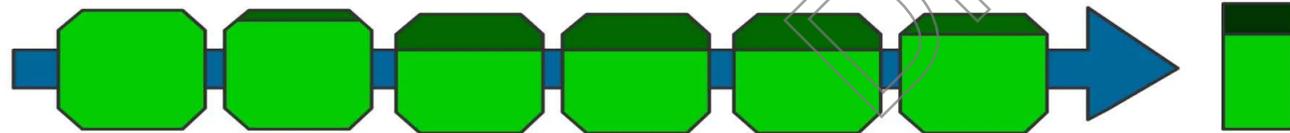
If all cells are unshade - It will produce full power output



If one cells is partially shaded 25% - The current flow reduced 25% and hence reduced in the final power output by 25%



If one cells is partially shaded 75% - The current flow reduced by 75% and hence reduced in the final power output by 75%



If few cells is partially shaded, and the most shaded cell is shaded by 25% - The current flow reduced by ~25% as influenced by the most shaded cell in the series.  
The power output will be lowered > 25% but not as bad as the senario above.

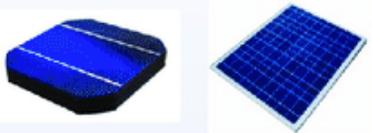
- Kirchoff's Law demands current is equal
- Modules limited by worst cell
- Strings limited by worst module
- More uniform production results in less mismatch

# Generations of PV technologies

## Three generations of PV technologies

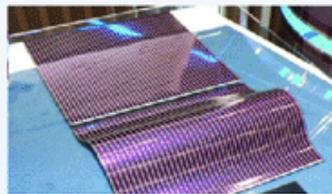
### First generation solar PV cells

*Single-crystal or monocrystalline silicon*  
*Polycrystalline or multicrystalline silicon*



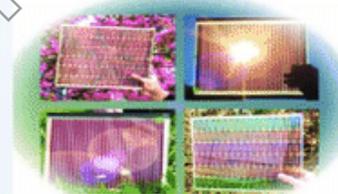
### Second generation solar PV cells

*Amorphous silicon (a-Si)*  
*cadmium telluride (CdTe),*  
*copper indium gallium selenide (CIGS)*



### Third generation solar PV cells

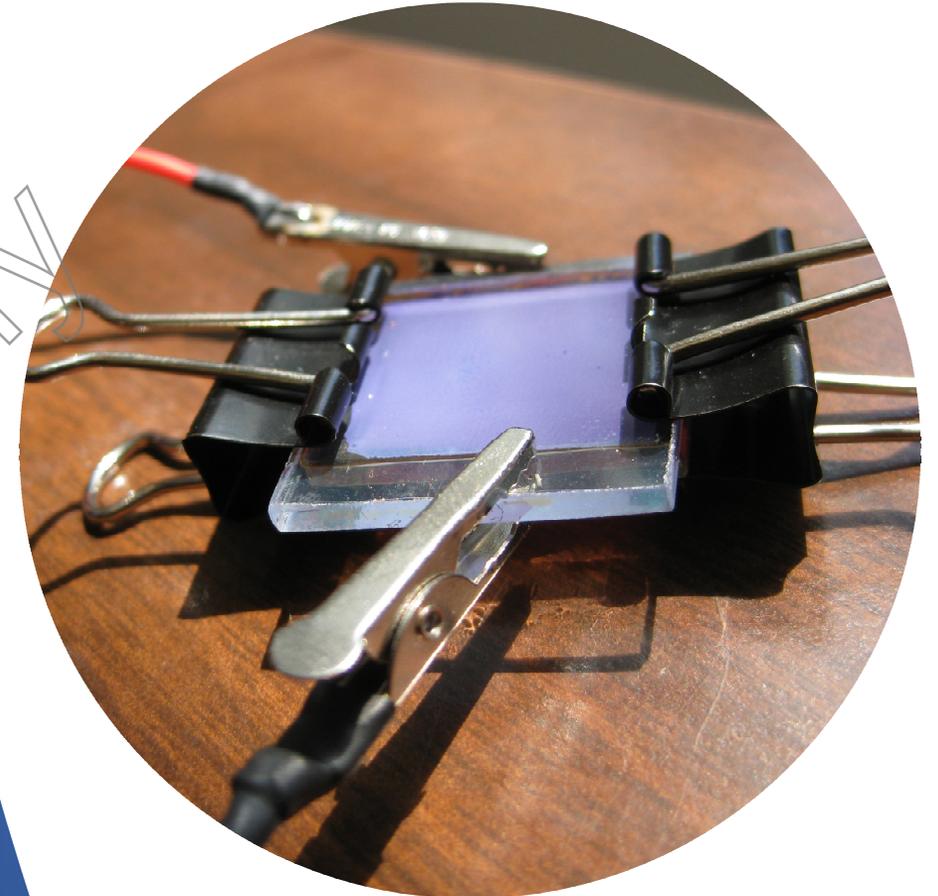
*Copper zinc tin sulphide (CZTS) PV cell*  
*Organic solar cell*  
*Perovskite Solar Cell*  
*Polymer PV cell*  
*Hybrid Solar Cell*  
*Buried Contact Solar Cell*  
*Concentrated PV Cell (CVP)*  
*Luminescent Solar Concentrator (LSC) Cell*  
*Multijunction Solar Cell (MJ)*  
*Nanocrystal Solar Cell*  
*Quantum Dot Solar Cell*  
*Dye-Sensitized Solar Cell (DSSC)*  
*Photoelectrochemical Cell (PEC)*  
*Etc.*



- 1<sup>st</sup> generation. Crystalline silicon, high efficiency, high cost
- 2<sup>nd</sup> generation. Thin film materials; amorphous silicon, CdTe, CIS. Better suited for mass production. Lower efficiency, lower cost
- 3<sup>rd</sup> generation. Technologies in development, offering high efficiency, low cost.

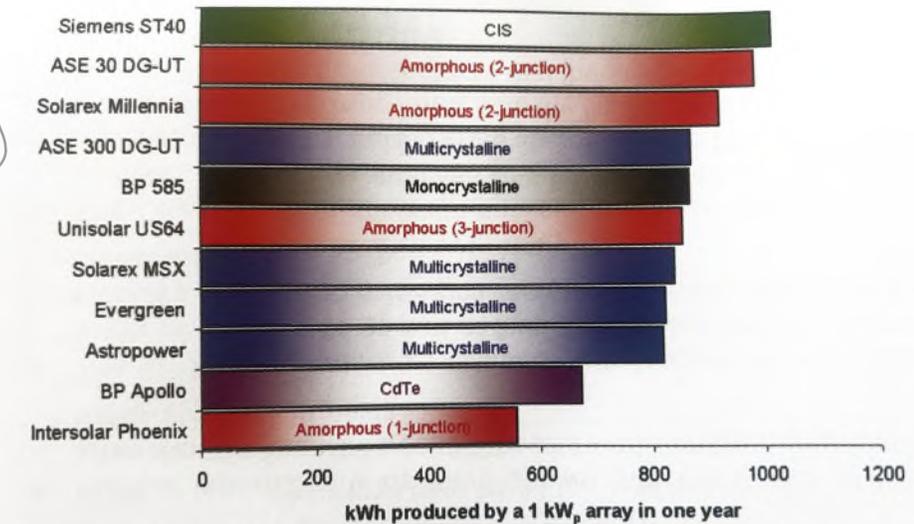
# Quick aside – Graetzel Cells

- One novel technology is dye-sensitised cells
- Uses a titanium dioxide substrate in conjunction with iodine and a liquid dye
- You can make a homemade solar panel out of sunscreen and Ribena!



# What PV Compare showed

- In UK, we get the majority of our solar energy at low light levels (i.e cloudy)
- CIS performed best in the UK, as it likes blue light and cold temperatures
- Amorphous silicon also performs well under blue light
- So, they'd be the technologies that get adopted, right?



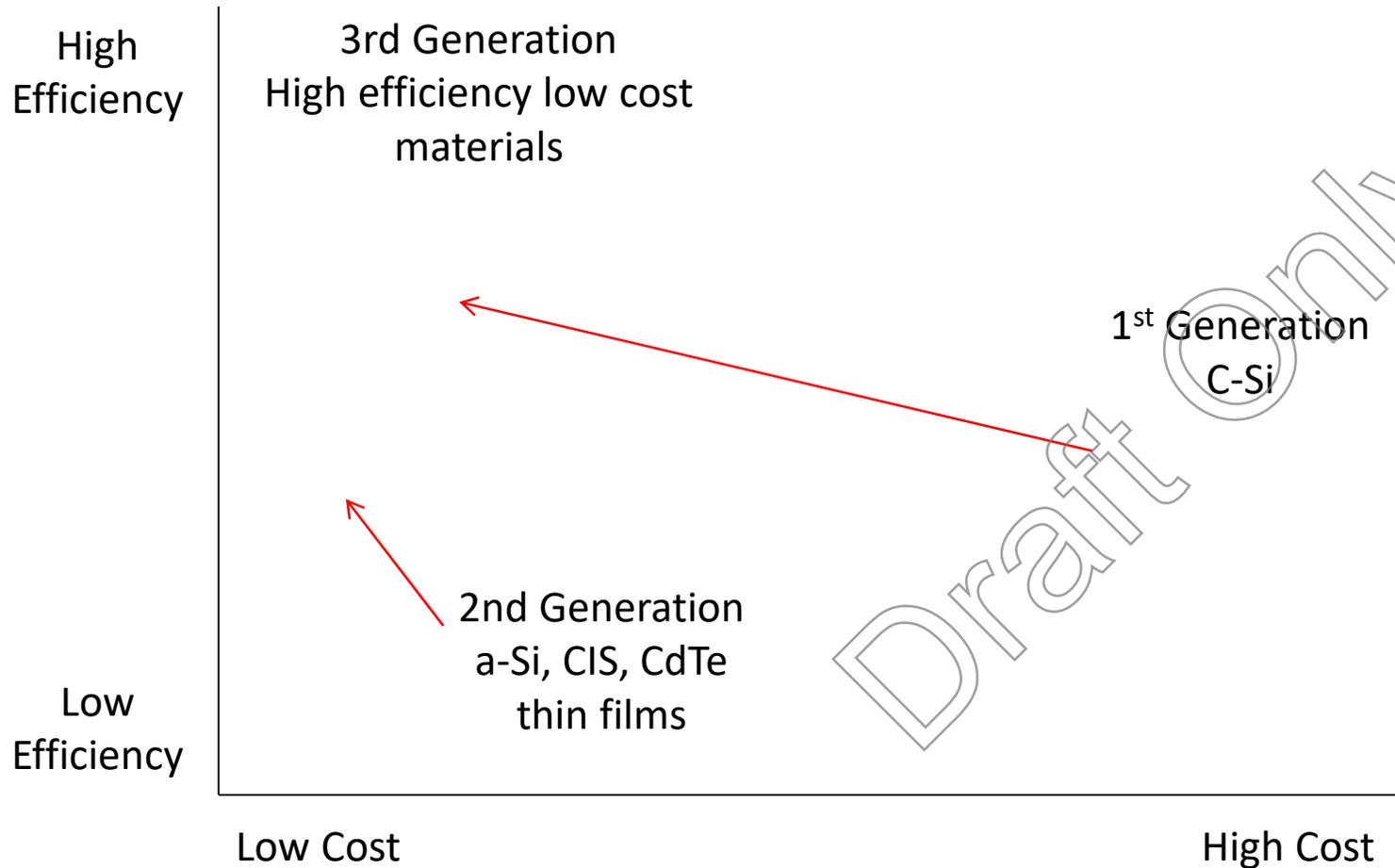
Electricity produced in one year at the UK test site by the different products.

# What we got wrong ...

Product	Technology	Oxford	
		kWh/kW <sub>p</sub>	kWh/m <sup>2</sup>
Unisolar US64	Amorphous	858.6	54.3
ASE 30 DG-UT	Amorphous	991.8	52.9
Solarex Millennia	Amorphous	926.6	48.8
Intersolar Phoenix	Amorphous	557.3	22.3
BP 585	Monocrystalline	871.8	117.2
Evergreen	Multicrystalline	824.8	60.8
Astropower	Multicrystalline	821.8	61.2
Solarex MSX	Multicrystalline	842.0	96.2
ASE 300DGUT	Multicrystalline	875.1	101.8
Siemens ST40	CIS	1025.3	99.2
BP Apollo	CdTe	673.7	48.9

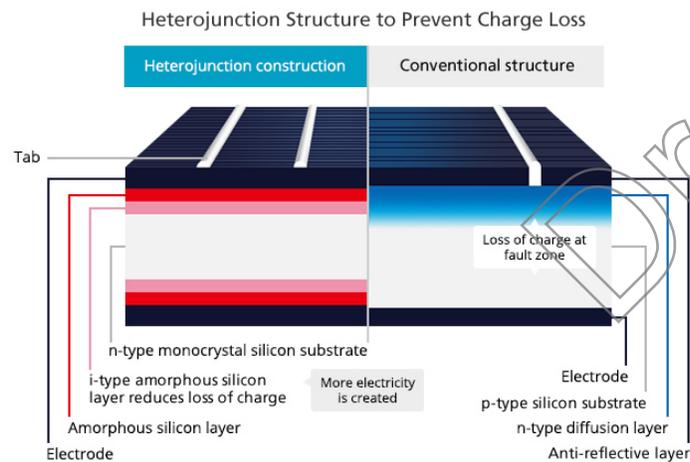
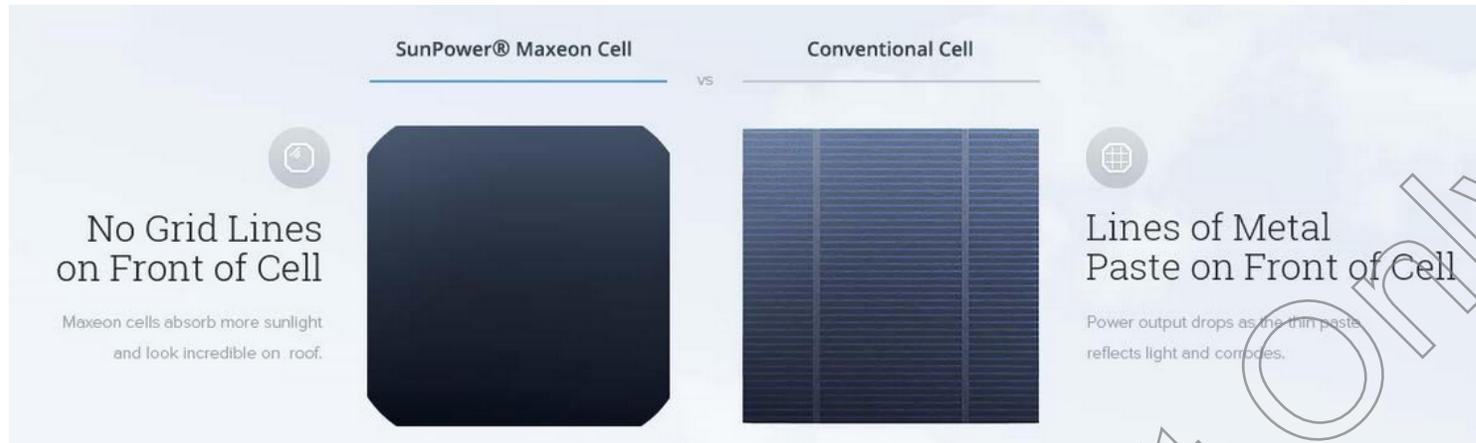
- Believed kWh/kWp was a key differentiator between panels
- Thought it was a consumer issue
- But MCS standards introduced with a single figure for all technologies
- Stops mis-selling
- Efficiency, to recover fixed costs, is more important – so crystalline silicon took over

# Technology progression



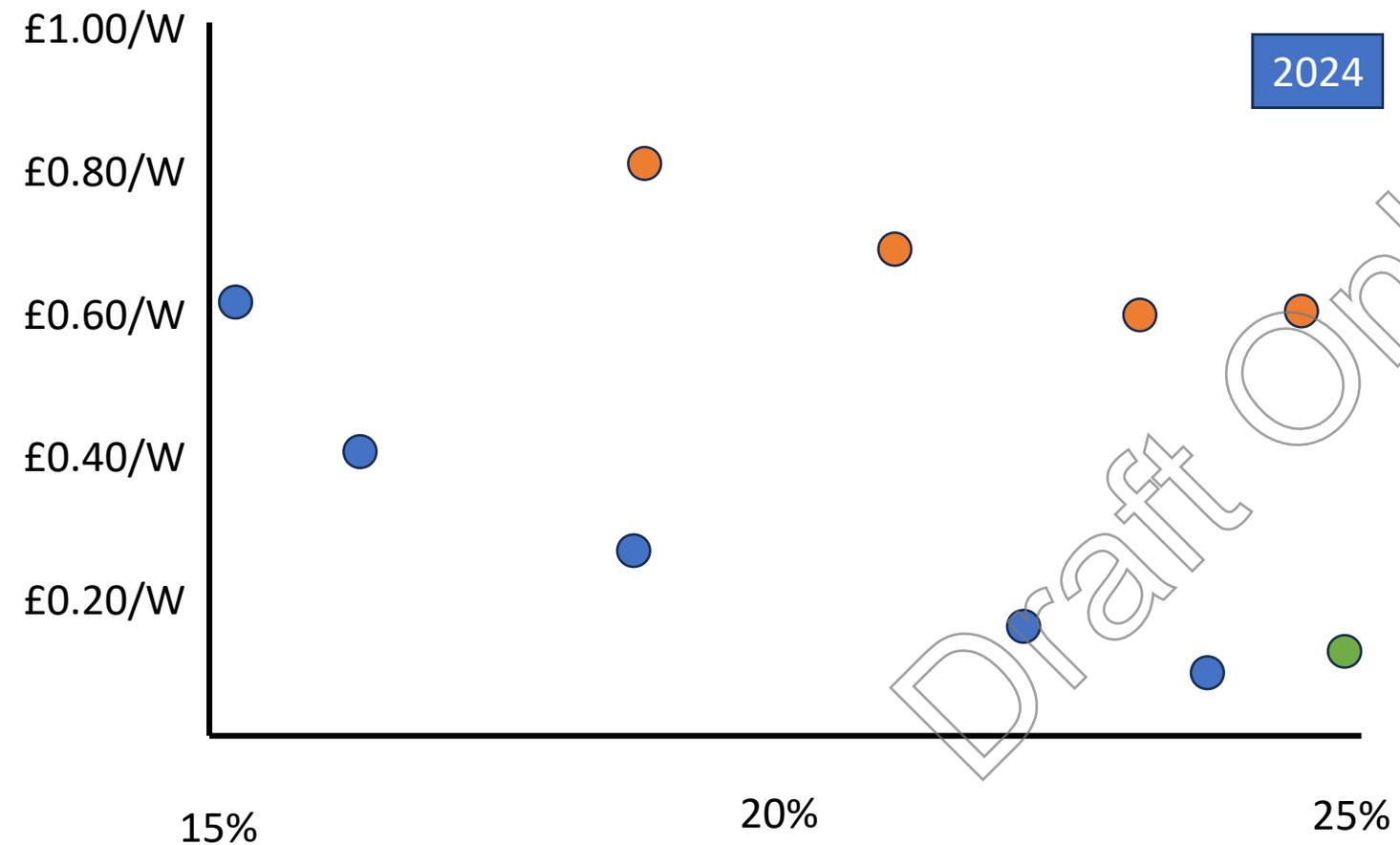
- Believed that technology would progress from 1<sup>st</sup> to 2<sup>nd</sup> to 3<sup>rd</sup>
- But mass production stopped 2<sup>nd</sup> generation getting to market in any real way
- And now 3<sup>rd</sup> generation have to be brilliant to get a foot in the door

# High efficiency panels



- In mid-2010s a new class of higher efficiency panels became available
- Notably Sunpower
- Passivated Emitter and Rear Contact Cells

# Premium Panels



- Trade-off between efficiency and cost

- No such thing as a premium panel anymore

- Implications for 3<sup>rd</sup> generation panels trying to enter the market

# Size of panels

- PV Compare panels as small as 14W, mainly around 100W
- Now 400W+, domestic
- 700W+ for commercial/ground mount
- Used to be able to fit underarm and carry up a ladder
- Larger panels = less mounting system and less labour



# Rise of all black panels

- All-black panels rising in popularity
- Black frames, black backing sheet
- Slightly less efficient
- But part of a trend towards more discrete aesthetics



# Recessed modules



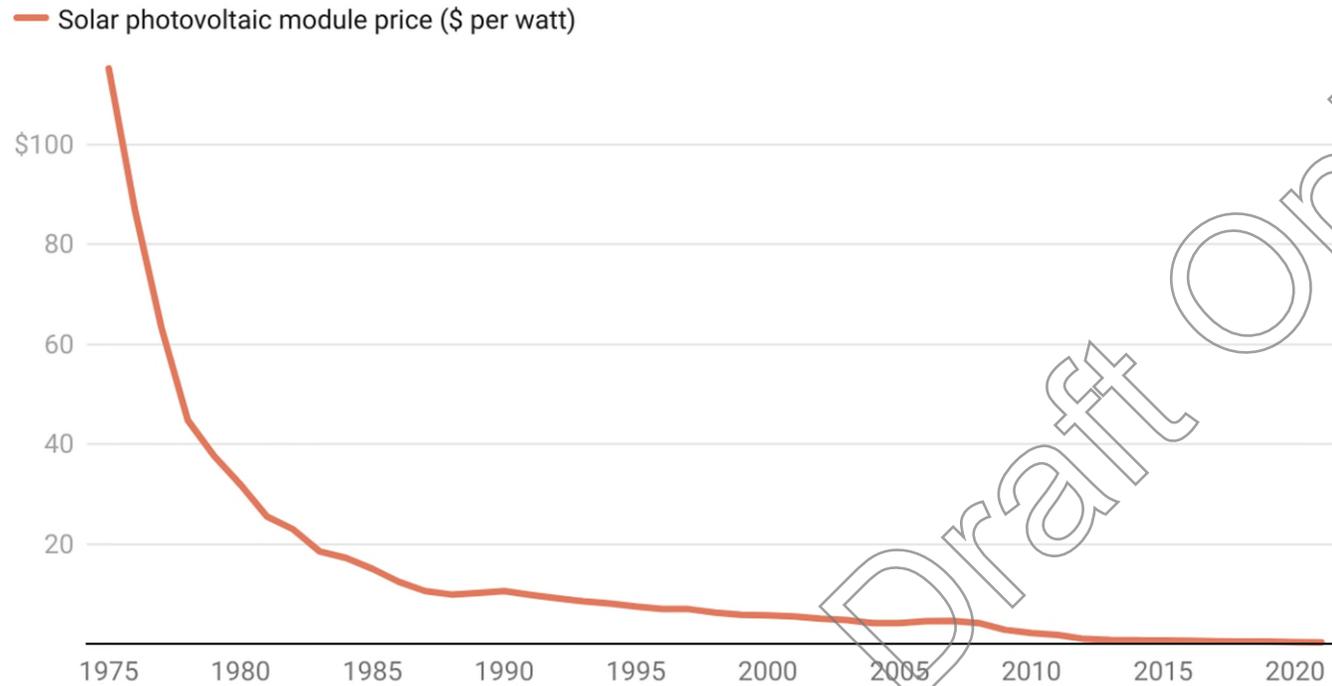
- Aesthetically can look better to remove tiles and recess modules into the space
- Waterproof membrane behind
- Sit flush with the tiles
- Especially black/black on slate



# Economics

# Module Costs

## Solar panel costs fell significantly for decades



Data is expressed in constant 2021 US\$ per Watt. Chart data found via Our World in Data.

Chart: Distilled / Michael Thomas • Source: Nemet (2009); Farmer & Lafond (2016); IRENA • Created with Datawrapper

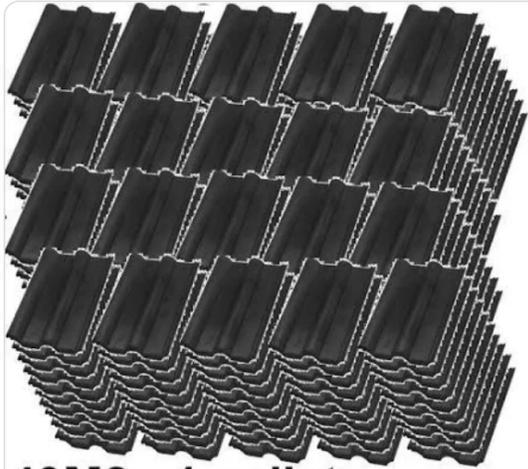
- Solar costs have been falling dramatically since the 1970s
- >\$100/W in 1975
- \$1/W by 2012
- \$0.1/W in 2025

# Solar panels are cheaper than fence panels



- If your fence needs replacing should you use solar panels instead of wood?
- 1mx1.8m = £40
- Lasts longer
- Even if you never plug them in

# They're pretty much as cheap as roof tiles



## 40M2 - 1 pallet

400 Roof Tiles

40 m2 Double Roman Graphite  
Grey Roof Tile

**£1,400.00**

[Stone Cladding Shop](#)

£75.00 delivery



Marley Mendip Roofing Tile  
Smooth Brown - Pallet of 192

3.3 ★★★★★ 3

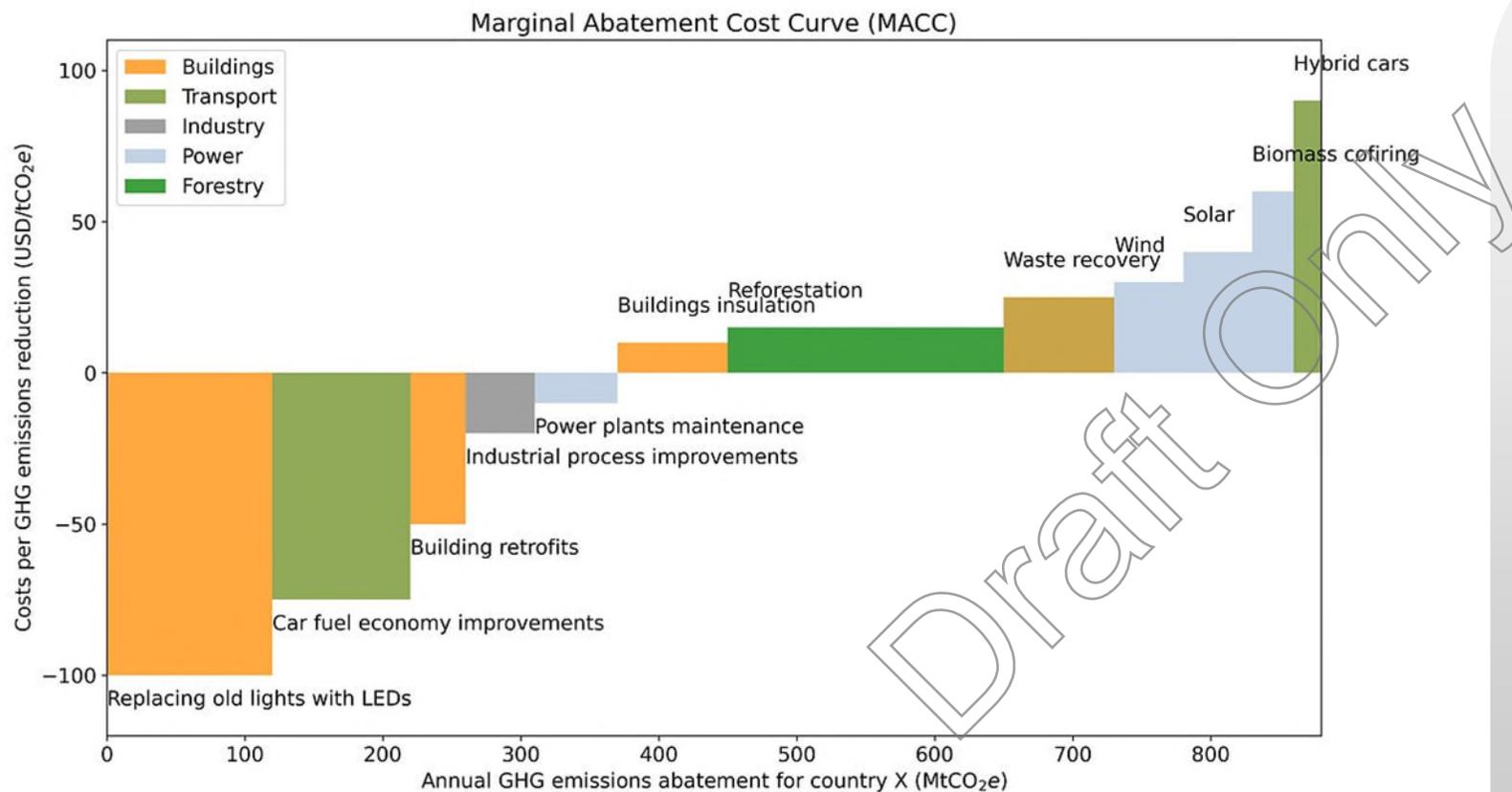
**£311.49**

[Trade Superstore Online](#)

Free delivery

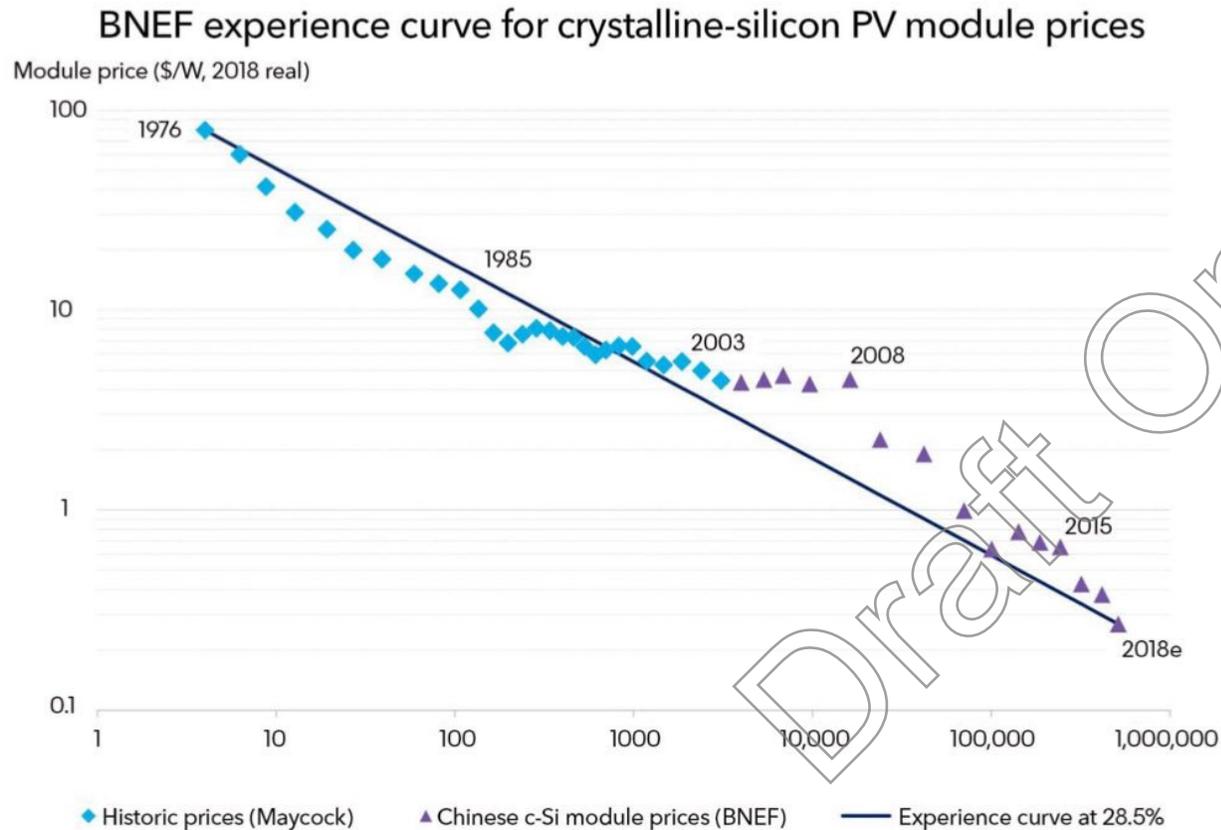
- Solar panels £25/m2
- Comparable to conventional roof tiles
- No serious cost penalty to legislating solar roofs on new build.

# Marginal Abatement Cost Curves



- PV historically one of the most expensive ways of saving carbon
- Not true anymore
- Implications for building design process

# Technology Learning



Source: Bloomberg NEF

- Long-term consistent 'learning curve'
- $\text{Log}(\text{Price})$  versus  $\text{Log}(\text{Cumulative capacity})$  is a straight line
- Every 10 fold increase gives a 28.5% decrease in price
- Solar is VERY modular cf. other technologies

# Technology Learning - Future

## Industrialization will yield significant cost reductions.

c-Si multicrystalline solar-photovoltaic system

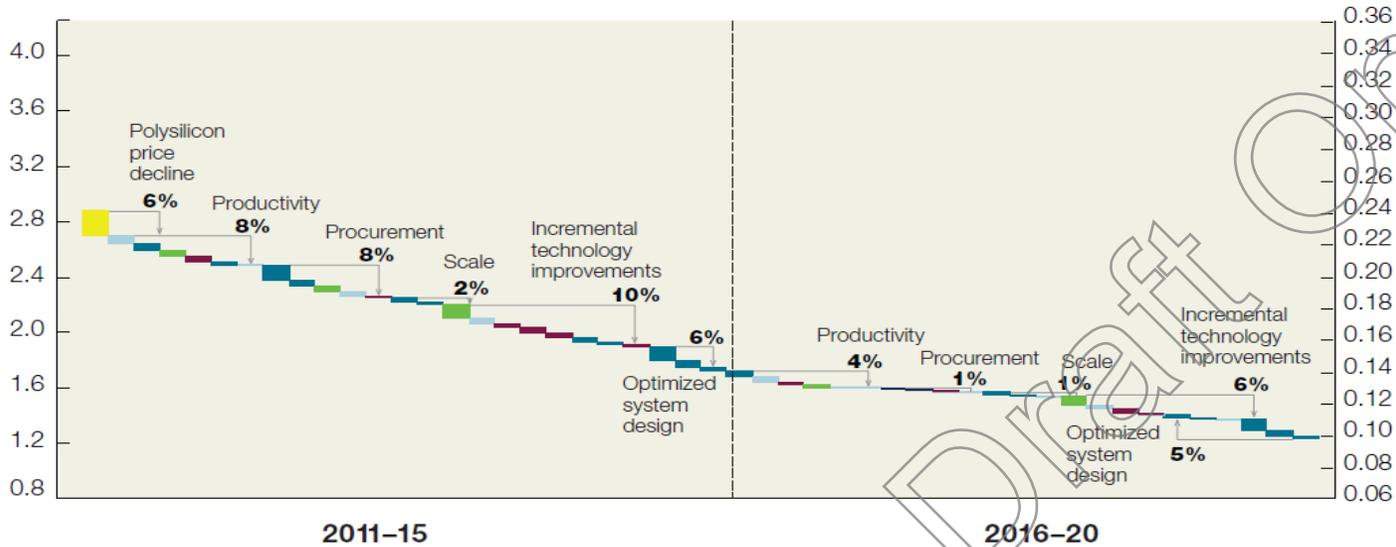
Polysilicon    Module    Cell    Wafer    Balance of system (BOS)

### Best-in-class installed system cost (no margins)

\$ per watt peak, 2011 dollars

### Levelized cost of electricity<sup>1</sup>

\$ per kilowatt hour, 2011 dollars



<sup>1</sup>Levelized cost of energy; assumptions: 7% weighted average cost of capital, annual operations and maintenance equivalent to 1% of system cost, 0.9% degradation per year, constant 2011 dollars, 15% margin at module level (engineering, procurement, and construction margin included in BOS costs).

Source: Industry experts; Photon; GTM Research; National Renewable Energy Laboratory; US Energy Information Administration; Enerdata; press search; company Web sites; McKinsey analysis

- Lots of small marginal gains through the supply chain
- No reason to expect this to stop

# Tech Learning - Components

- Modules from £2.20 in 2008 to £0.10 in 2025
  - Solar grade silicon supply chain
  - New (Chinese) market entrants, and becoming bankable
  - Improved tech and manufacturing
  - All equals low prices
- In the same period, Balance of System costs has halved
  - Inverters are also technology learning
  - Racking – more competitive market eliminating umbrella payments



# Tech Learning - Institutions

- And efficiencies have been reached in terms of installation
  - Technology learning applies to installers too
  - We're quicker and more efficient than we were 10 years ago
  - Project management slicker
  - Office processes better
  - Staff more experienced
  - Better at procurement – mature supply chains
  - Better at acquiring new work

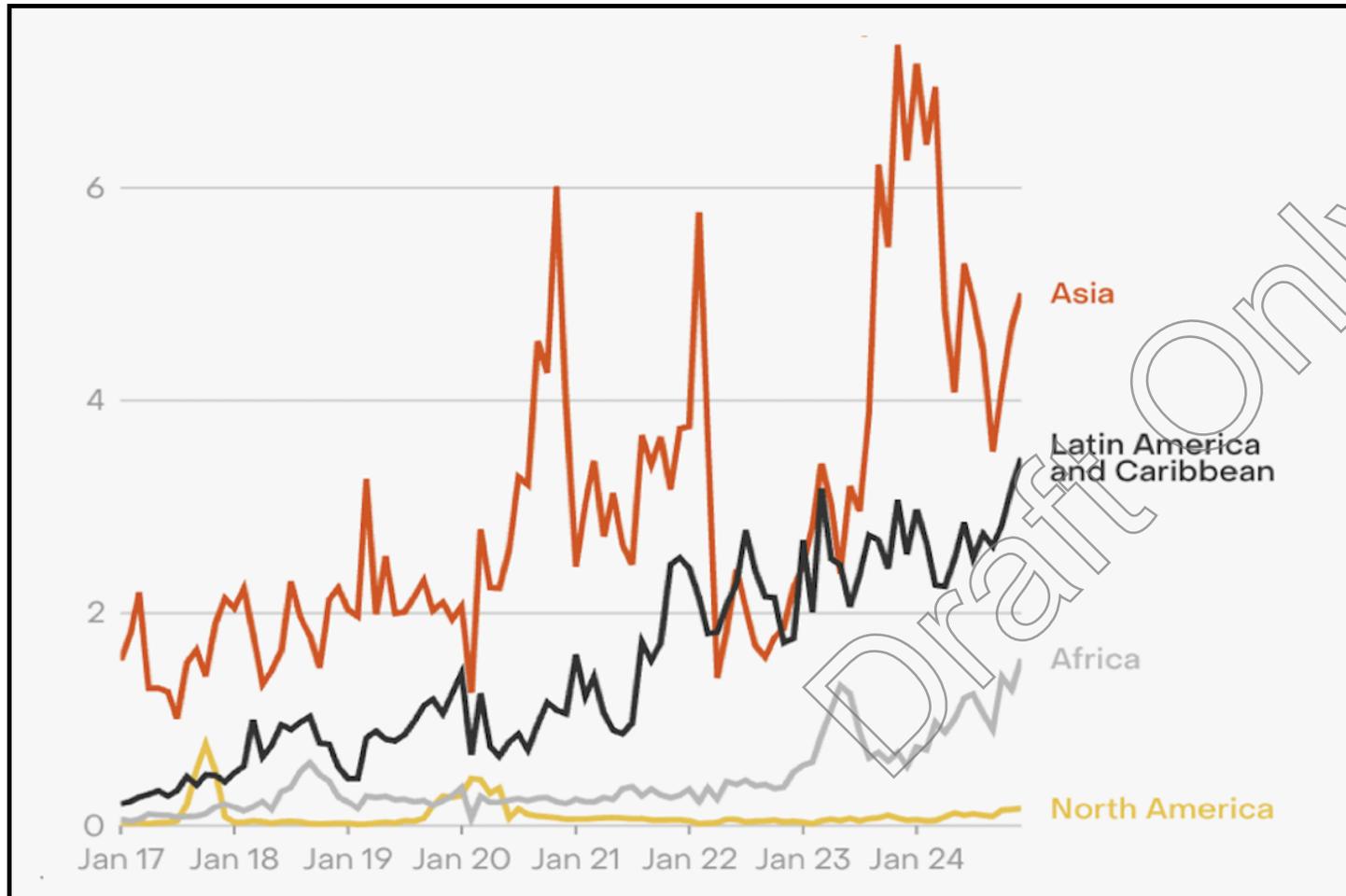


# Tariff Wars

- EU believed China was subsidising price of solar panels to drive European competitors out of the market
- June 2013, EU applied 47.6% anti-dumping tariff on Chinese manufactured panels
- China responded with tariff on EU wine
- Compromise on minimum price for Chinese imports



# US tariffs are working ...



- Chinese panels are not being exported to the US
- Good news! They're reaching the Global South instead



# Installer Markets

# Market History

- Take-off stimulated by subsidy schemes
- 100,000 roofs program in Germany
- 70,000 roofs program in Japan
- 1990s – Fossil companies diversifying BP Solar, Shell Solar.
- 2000s – Japanese and German solar specialists (Sharp, Kyocera, Sanyo)
- 2010s – cheaper Chinese manufactured panels (Trina, JA, Jinko, Aiko etc)

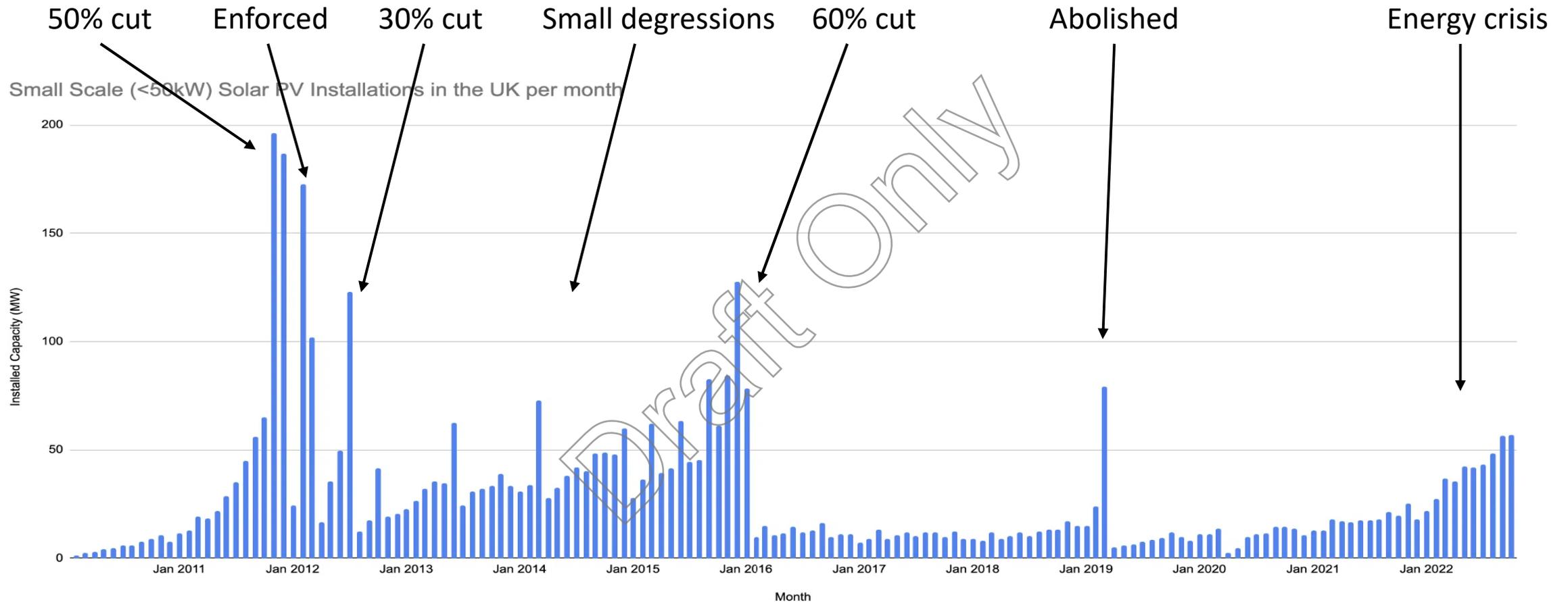


# Low Carbon Building Programme

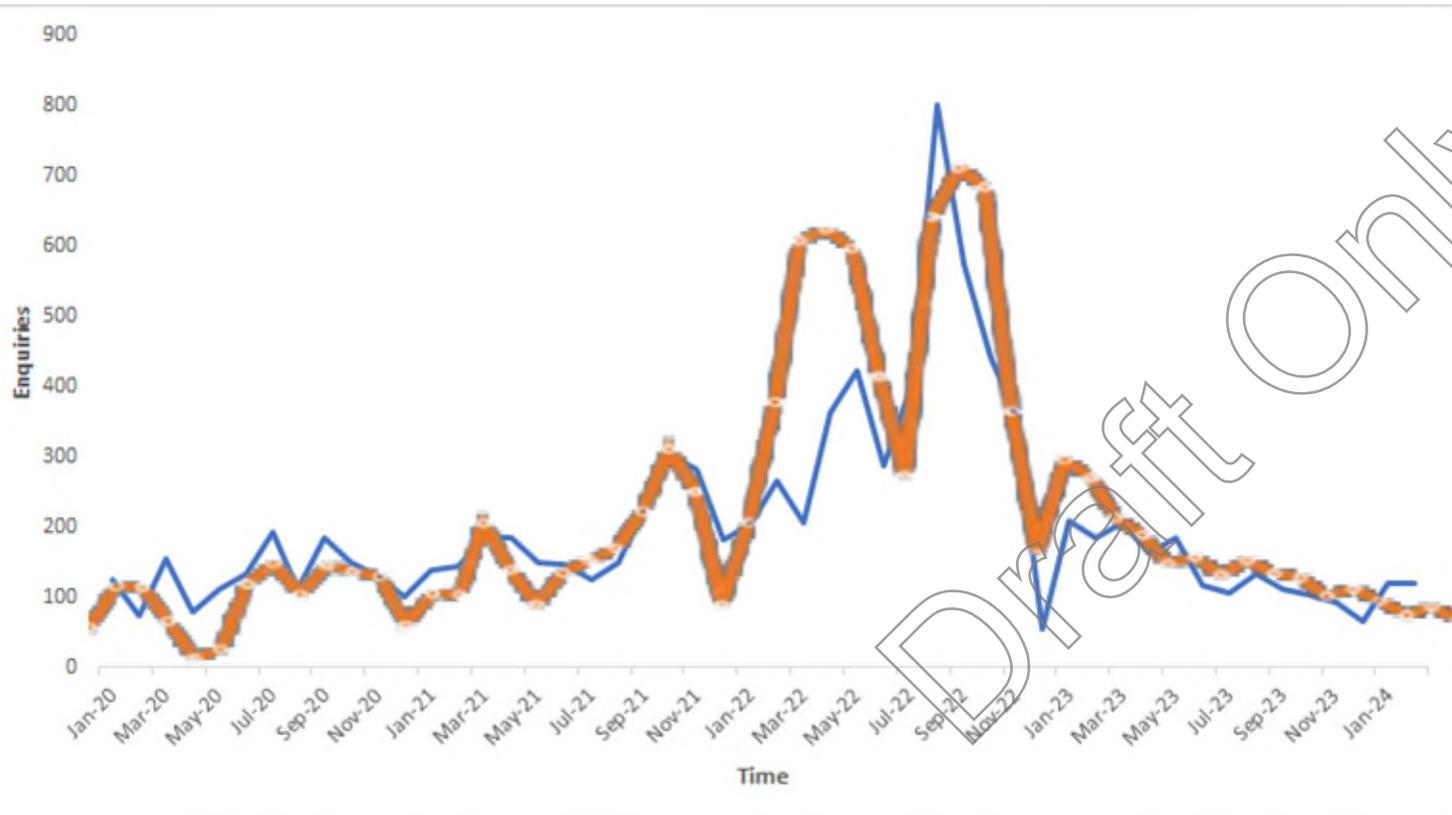
- Grants for microgeneration May 2006-May 2008
- 919 residential properties installed in 2 years
- But swamped by high demand
- 59 companies in the market
- Costs £5000/kW+£2000



# The UK Solarcoaster

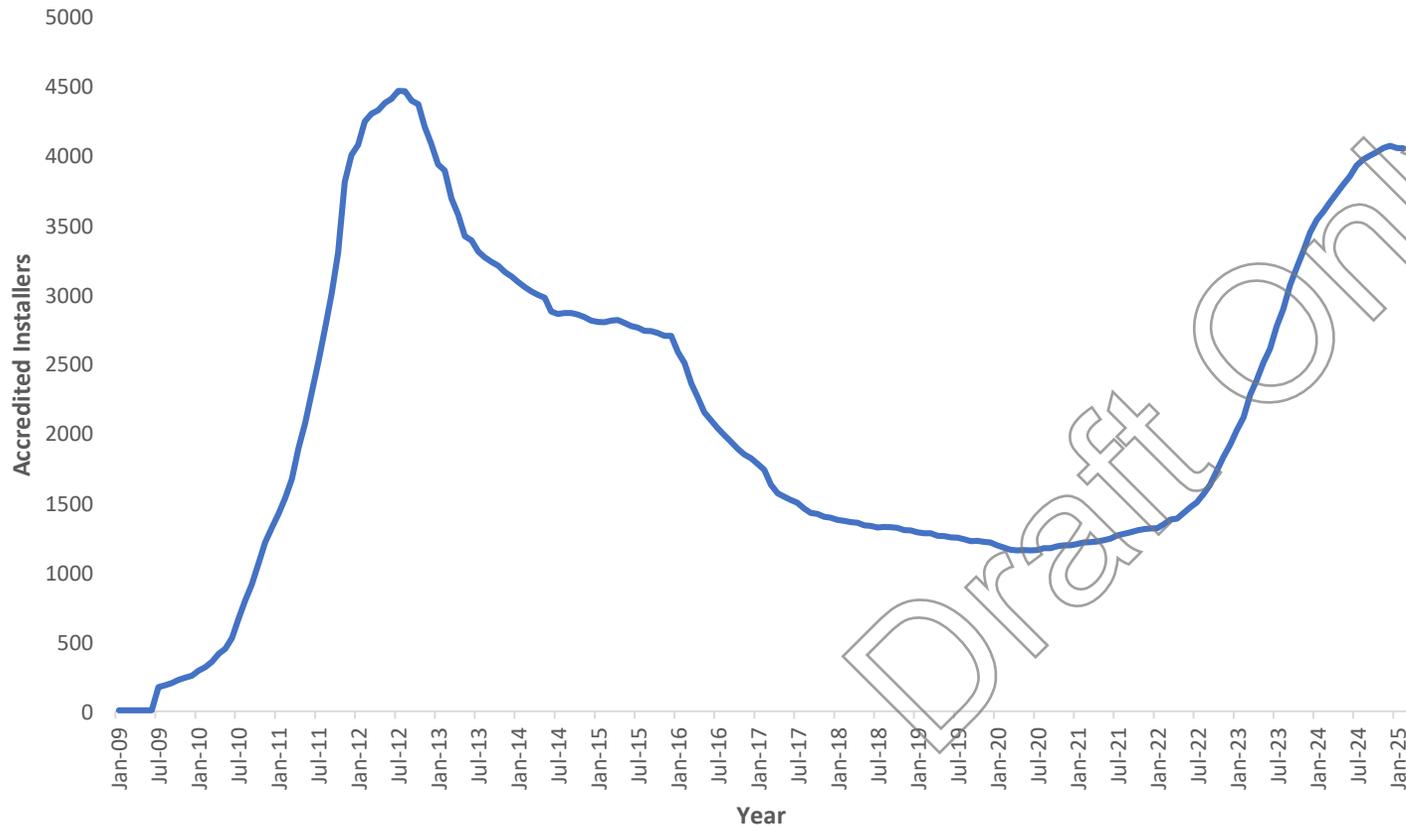


# The Energy Crisis



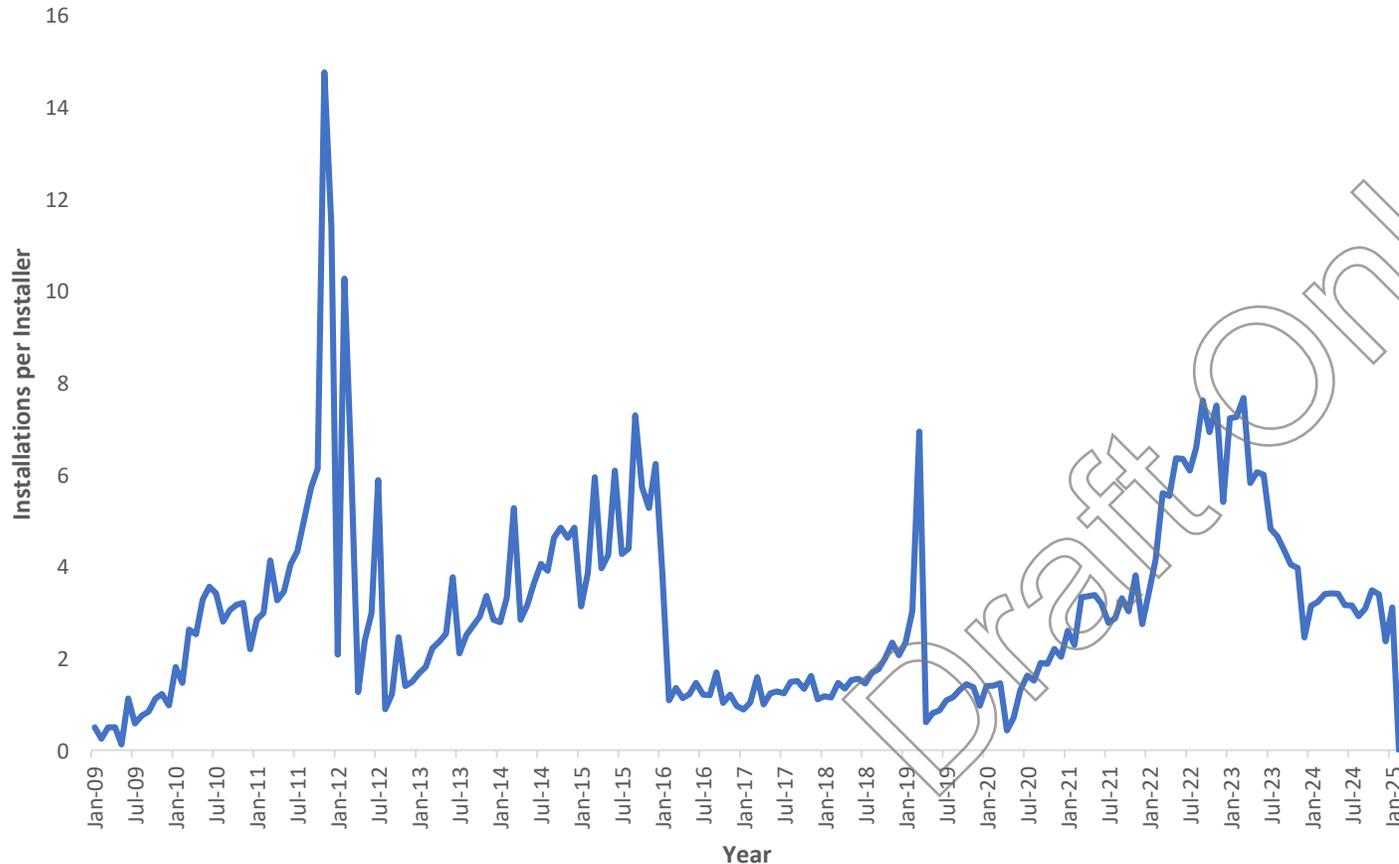
- Doubling electricity price halves the payback of solar PV
- Massive surge in enquiries
- Incumbent installers swamped
- Everyone restricting enquiries in some way
- Price went up

# Installers



- 59 different installers in 2008
- High demand leads to rush of new market entrants
- Currently about 70 installation companies per county

# Strong overall, not so good individually



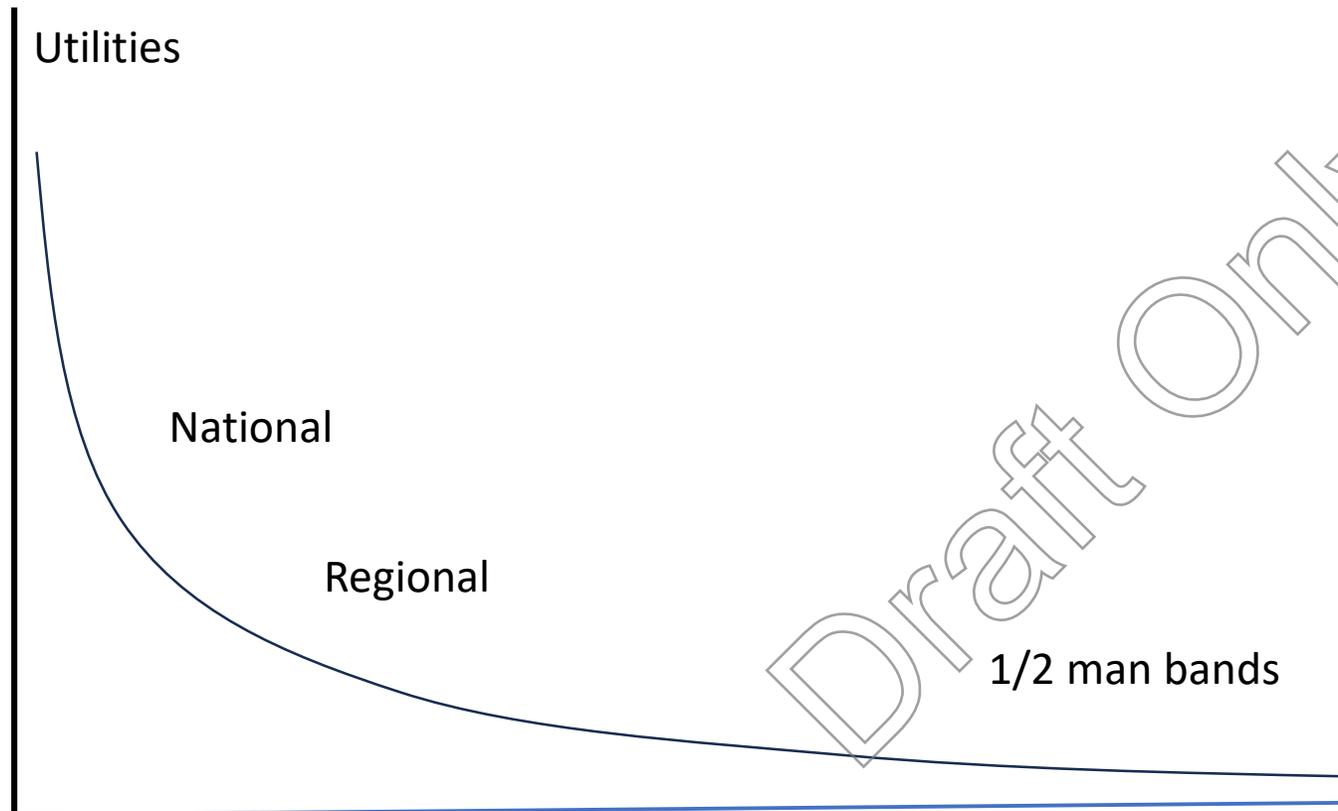
- Despite growth in overall market post-energy crisis, individual installers finding life tougher again due to increased competition

# Profitability in Residential Solar

- There's not a lot of profit in residential solar
- Small levels of profit generated over many years
- Off millions of pounds of turnover
- Implies its vocational work

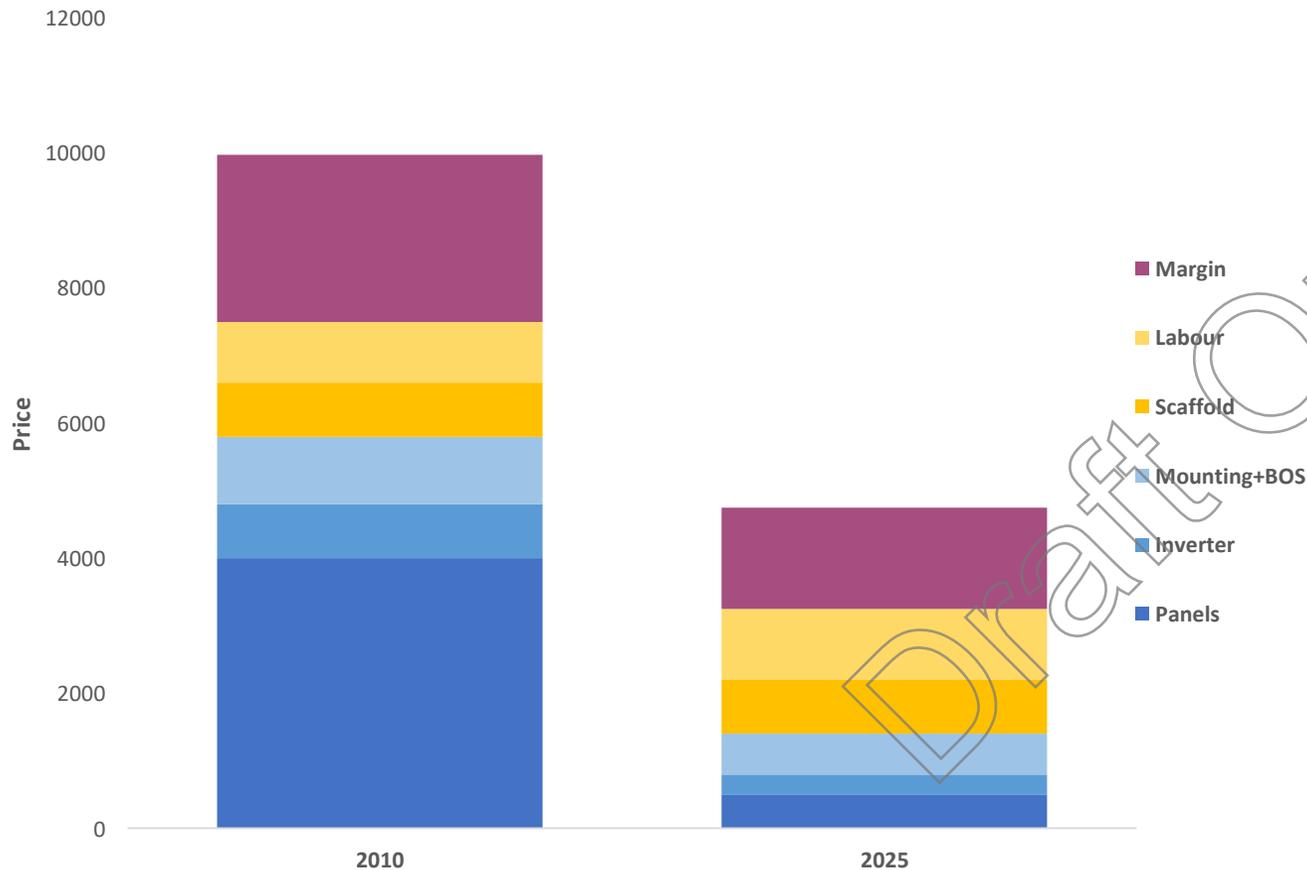
Company	Net Worth	Years Trading
Company1	-30000	4
Company2	24000	7
Company3	79000	11
Company4	142000	13
Company6	143000	5

# Range of Players



- Range of players
- Different business models
- Different routes to market
  - Existing customers
  - Digital
  - Word of Mouth

# Pricing



- Materials are no longer the dominant part of cost
- Labour > Materials
- Biggest line item is now internal staff (sales, project management, marketing, overheads)

# Other Actors

- Lead generation companies
- Farm addresses from social media, or comparison type sites
- Sell leads on to other companies
  
- Bulk Buy Schemes
- Notably Solar Together
- Get 1000+ customers in a region
- Tender to the lowest bidder
- Backed by local councils

 Spark Energy UK  
Sponsored · 🌐

WE'RE IN YOUR AREA! 🙌📍

T... See more



# The Race to the Bottom

- Use cheaper components of poorer quality
- Hard sell to improve conversion rates
- Outsource design to India
- Drive staff harder
- Don't bother surveying
- Slack installation methods
- Less qualified labour
- Take shortcuts with H&S
- Drop after-sales care



# Commercial Solar PV

- Currently very high prices of electricity
- And commercial (metal) rooftops are very cheap to install
- IRRs > 20%
- Margins on commercial solar projects are larger than residential (less competitive)
- Sales and project management are proportionally smaller
- All equals profitable sector

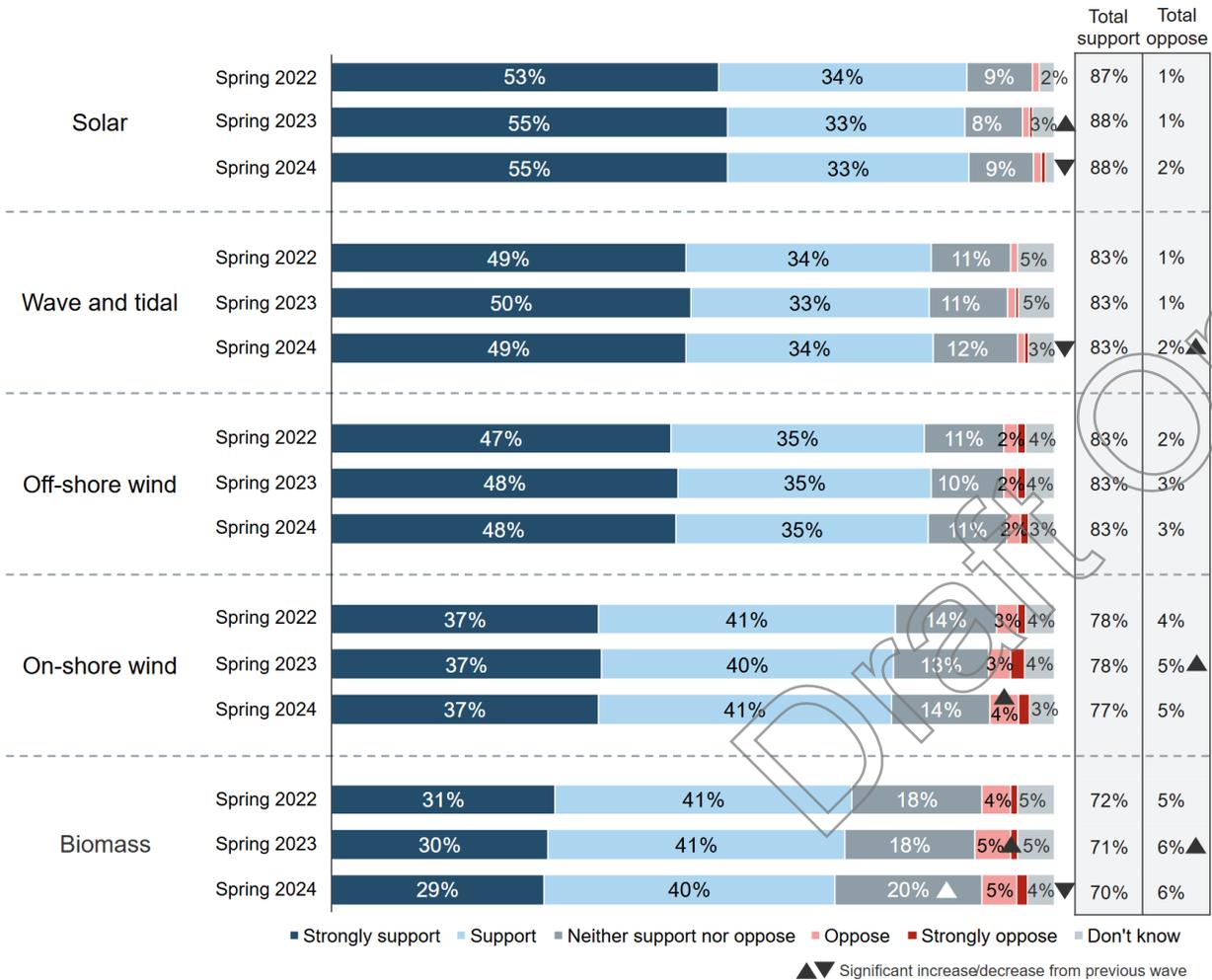


# But classic barriers remain

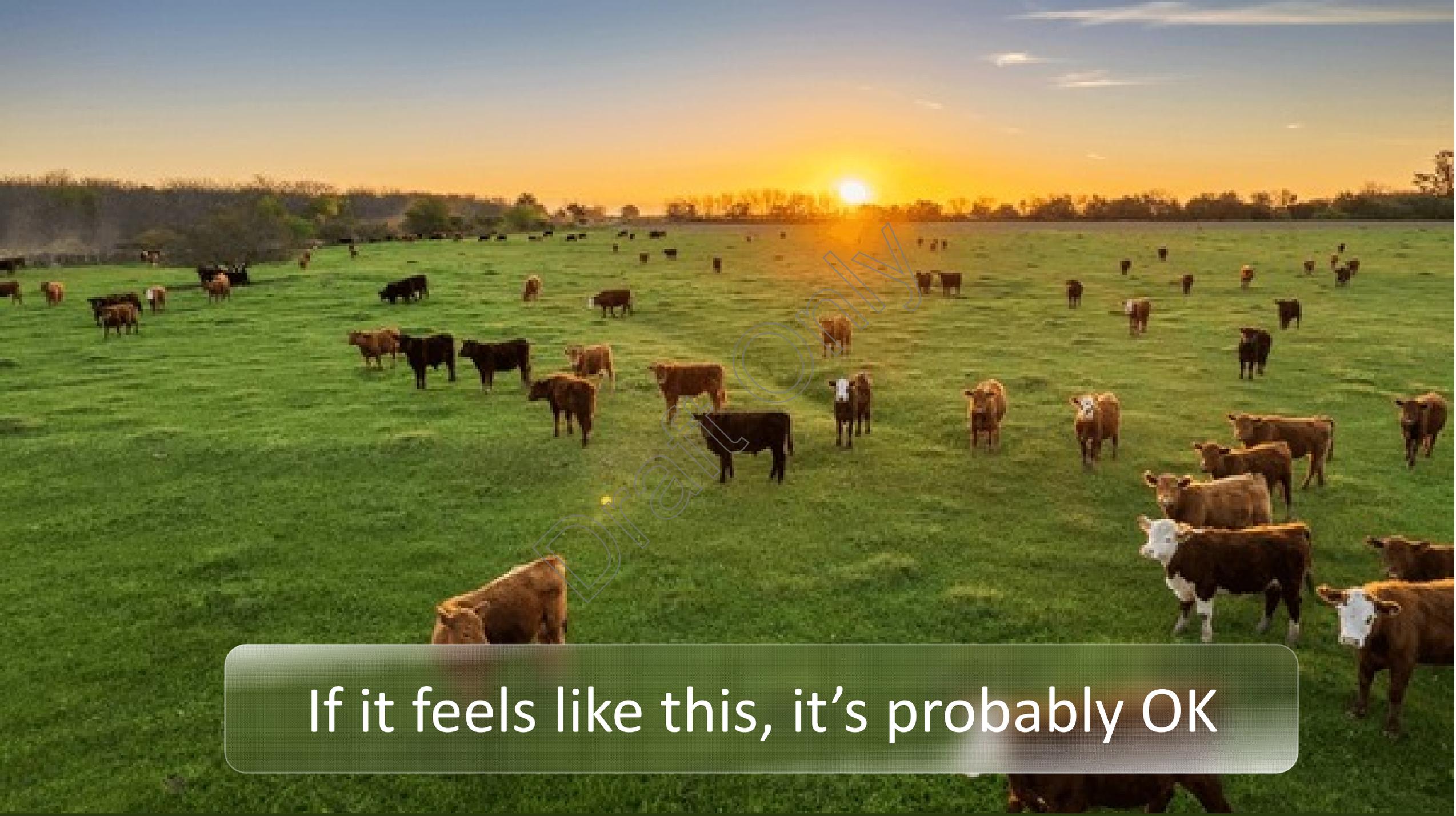


- Businesses would rather spend their capital on their core business
- Multiple decision makers
- Landlord tenant split

# Ground mount solar



- Public very supportive of solar
- But opposition to solar farms growing and very vocal
- How big is too big?



If it feels like this, it's probably OK



Draft Only

If it feels like this, then no

# Agrivoltaics

- Concern about land use can be alleviated by using the land twice
- Livestock, poultry, arable crops
- Increased yields of e.g grapes, wool, eggs as avoid heat stress
- Great for arid areas, as retains moisture
- Italy ran 1.5GW auction for agrivoltaics

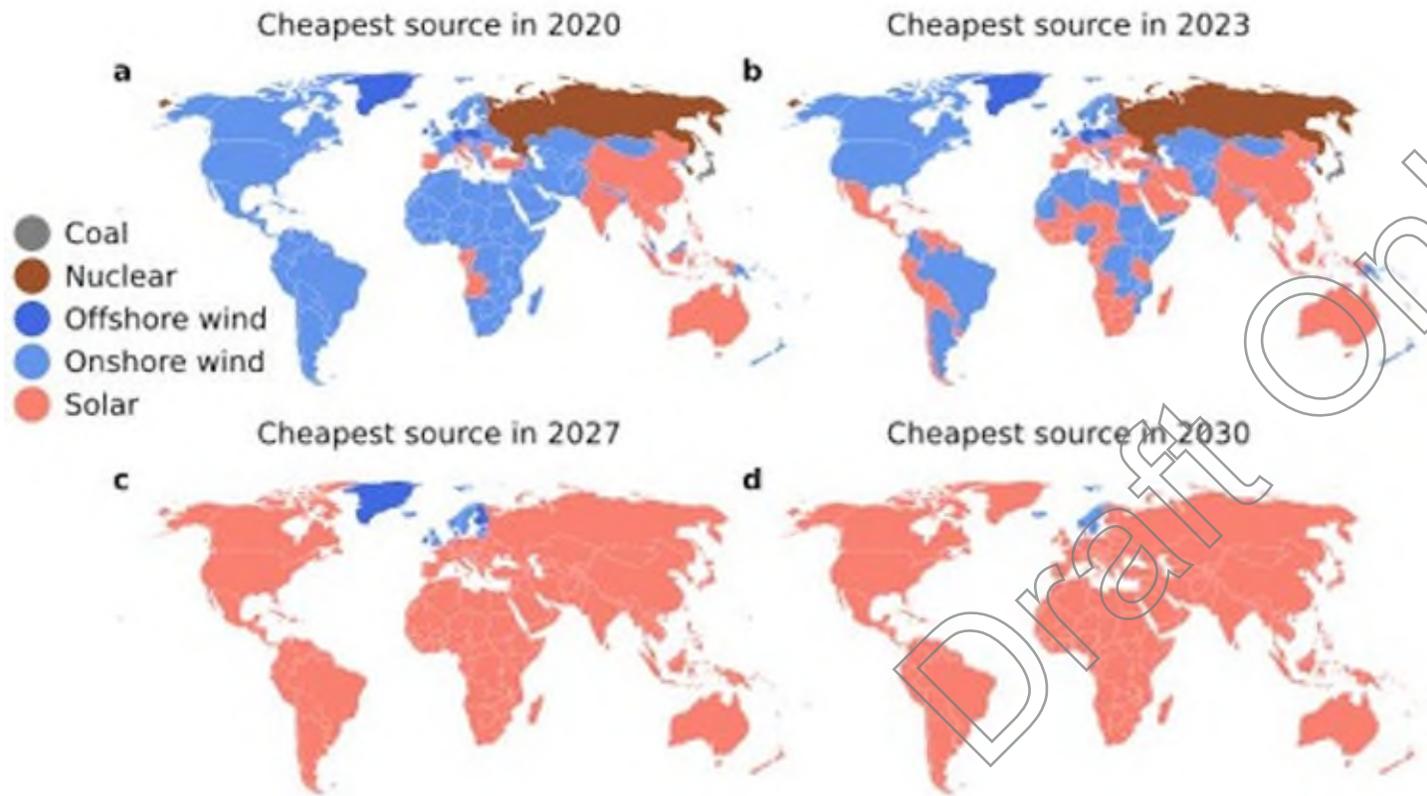


# Still going ...



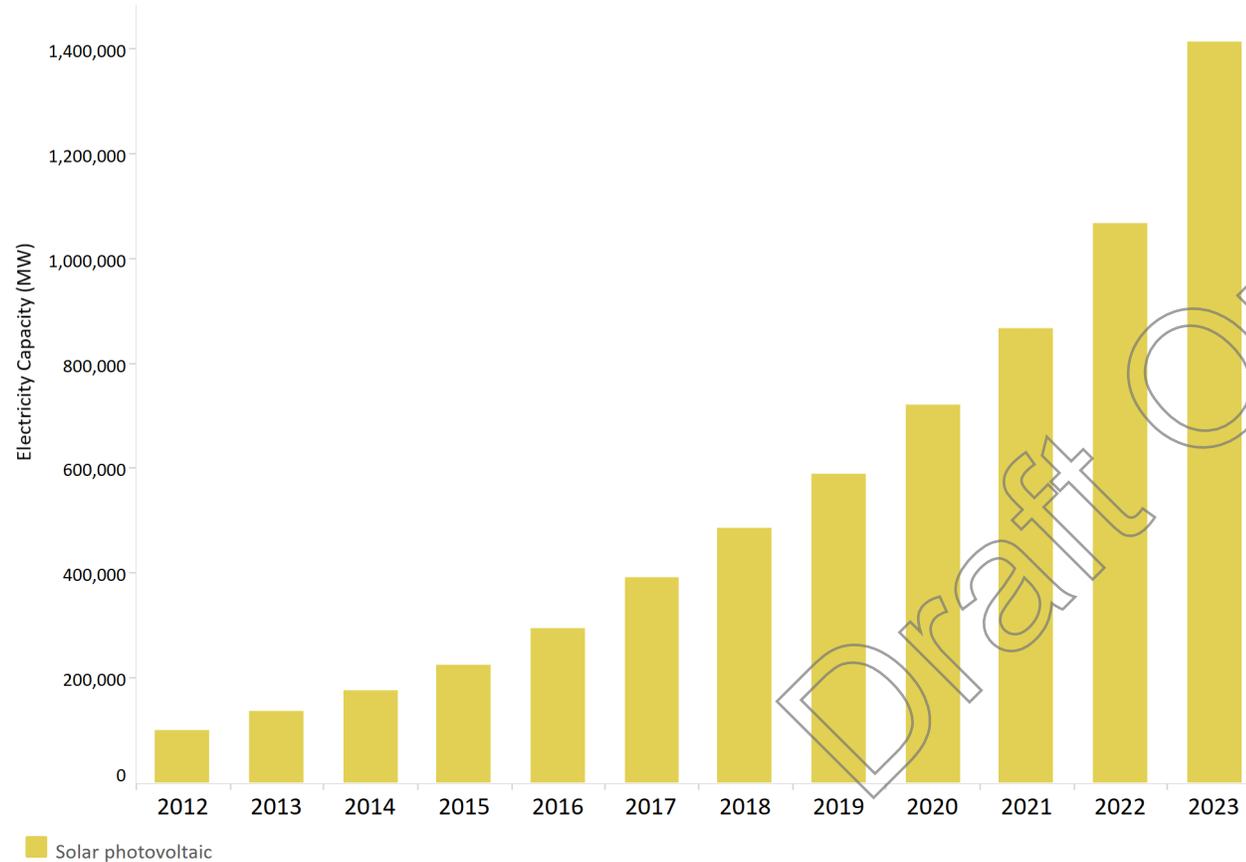
- Seriously, what did you expect?
- It's not going to have stopped in the last 45 minutes!

# Grid parity by region



- Solar is expected to be cheapest source of generation pretty much everywhere by 2030
- And where it isn't, is because wind resource is brilliant

# The Worldwide Market



- Market growing at average of 33% p.a. since 1996
- Worth more than \$1tn p.a in sales
- Total Installed capacity of 1.55 TW in 2023 (1GW in 2001)

Linked In: Chris Jardine  
Web: [www.chrisjardine.energy](http://www.chrisjardine.energy)  
Youtube: @chrisjardine.energy  
Instagram: chrisjardine.energy  
Tiktok: chrisjardine.energy  
Threads: chrisjardine.energy  
Bluesky: @chrisjardineenergy.bsky.social

Instagram