NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE | Institute of Advanced Studies

Lee Kong Chian Distinguished Professor
Public Lecture | 10 January 2024

The Role Solar Energy Will Play in Our Energy Future

by Professor Martin Green

Millennium Technology Prize 2022
University of New South Wales

UNSW SYDNEY | Australia's Global University

ARENA | Australian Government | Australian Renewable Energy Agency

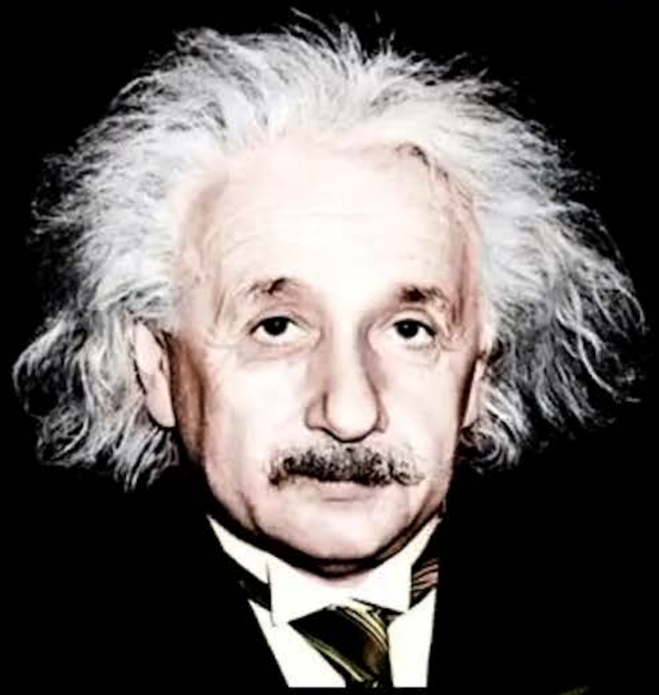
ACAP

The Role Solar Energy Will Play in Our Energy Future

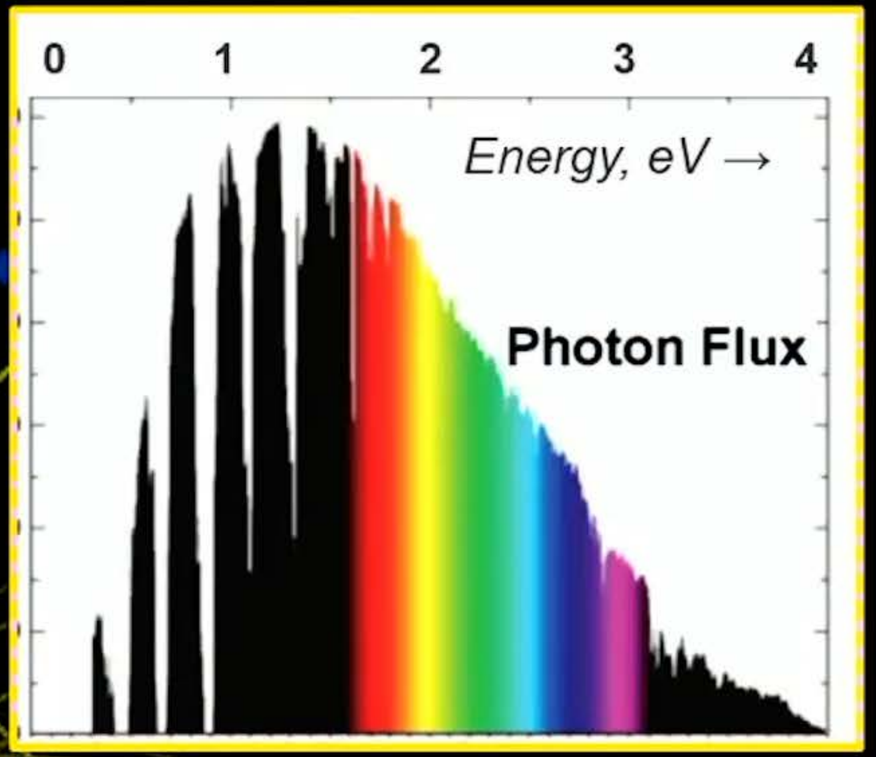
Martin Green, UNSW Sydney, Australia *(Millenium Prize 2022)*

Outline

1. Technology
2. Costs
3. Climate Change Mitigation

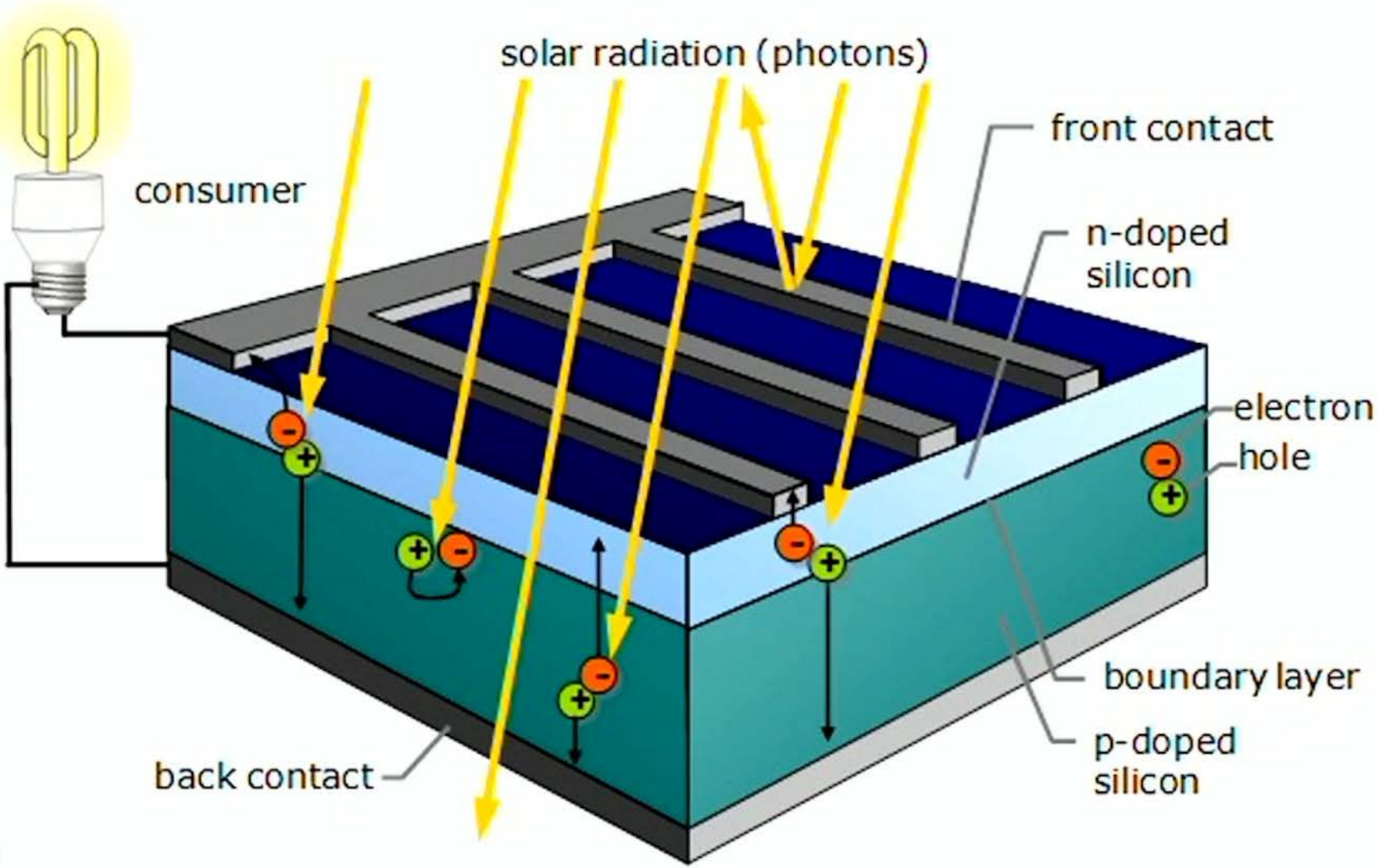


Photons



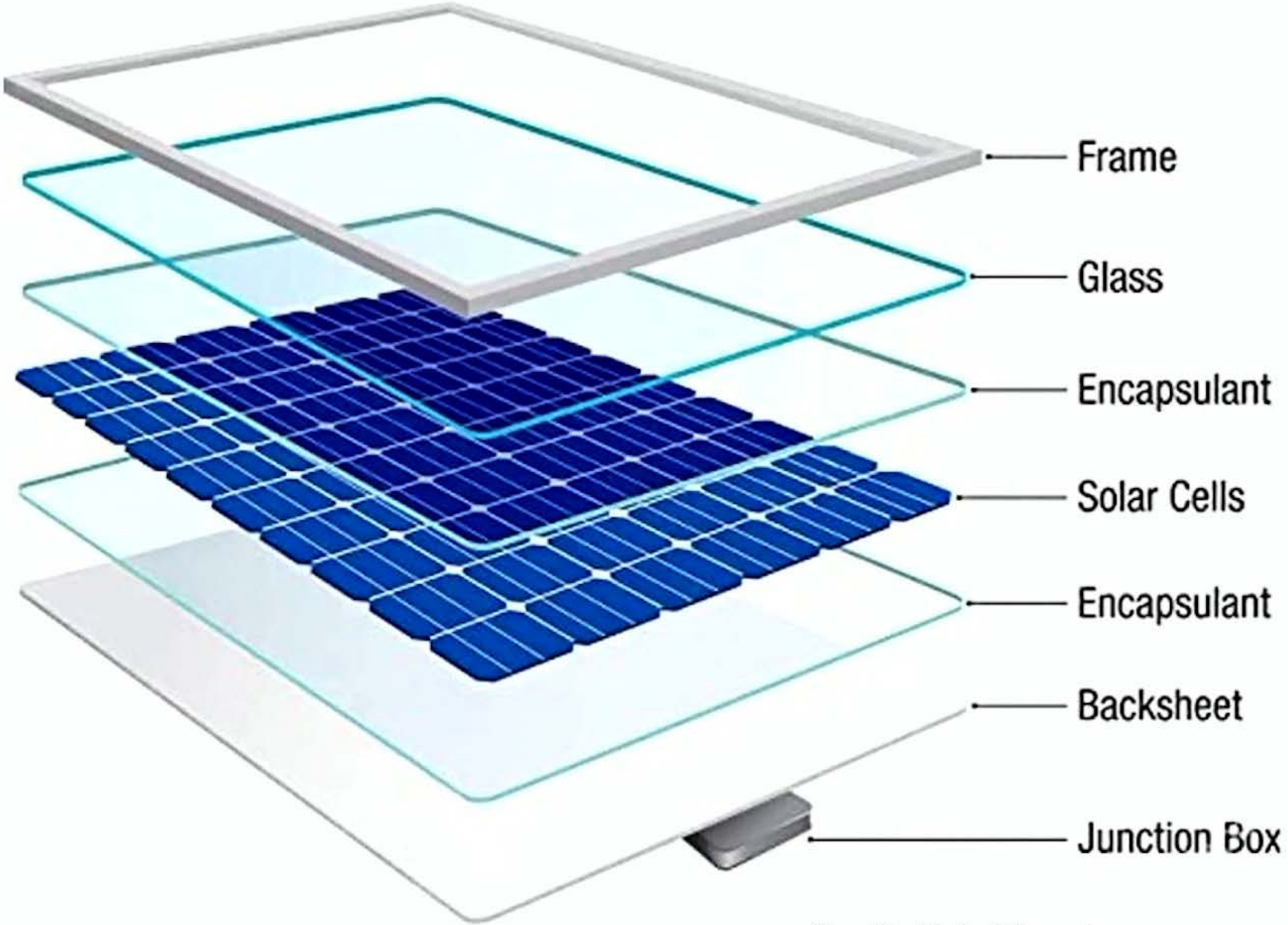
JFC
WWW.LACTAMME.POLYTECHNIQUE.FR

Solar cell operation



Credit: Volker Quaschning

Solar module

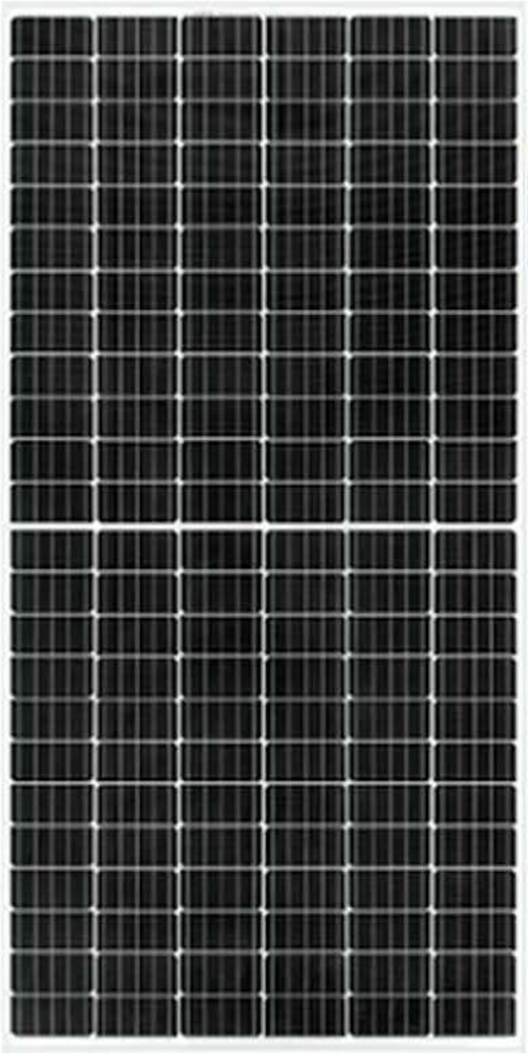


Credit: Alejo Miranda

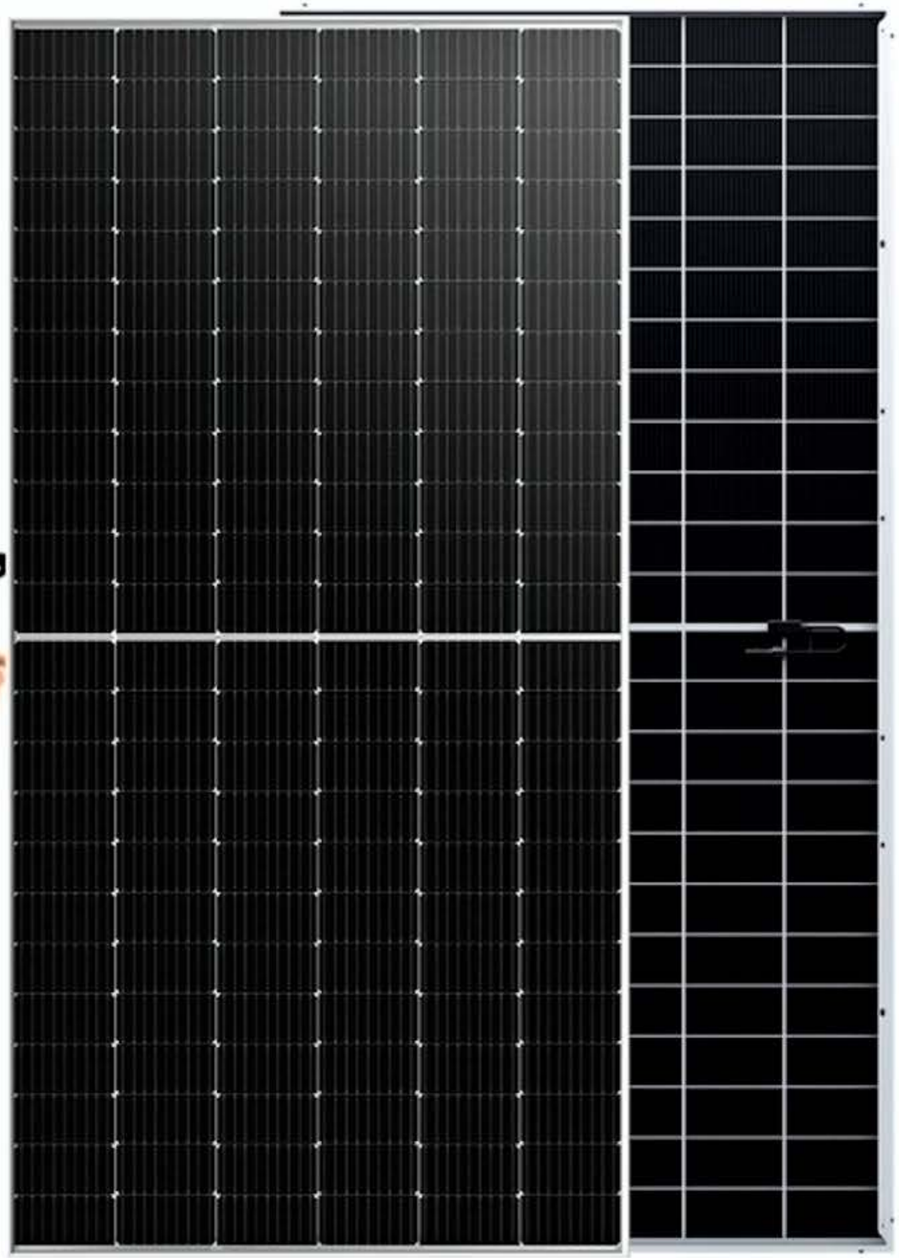
Module evolution

2015 Pre-PERC module (16%)

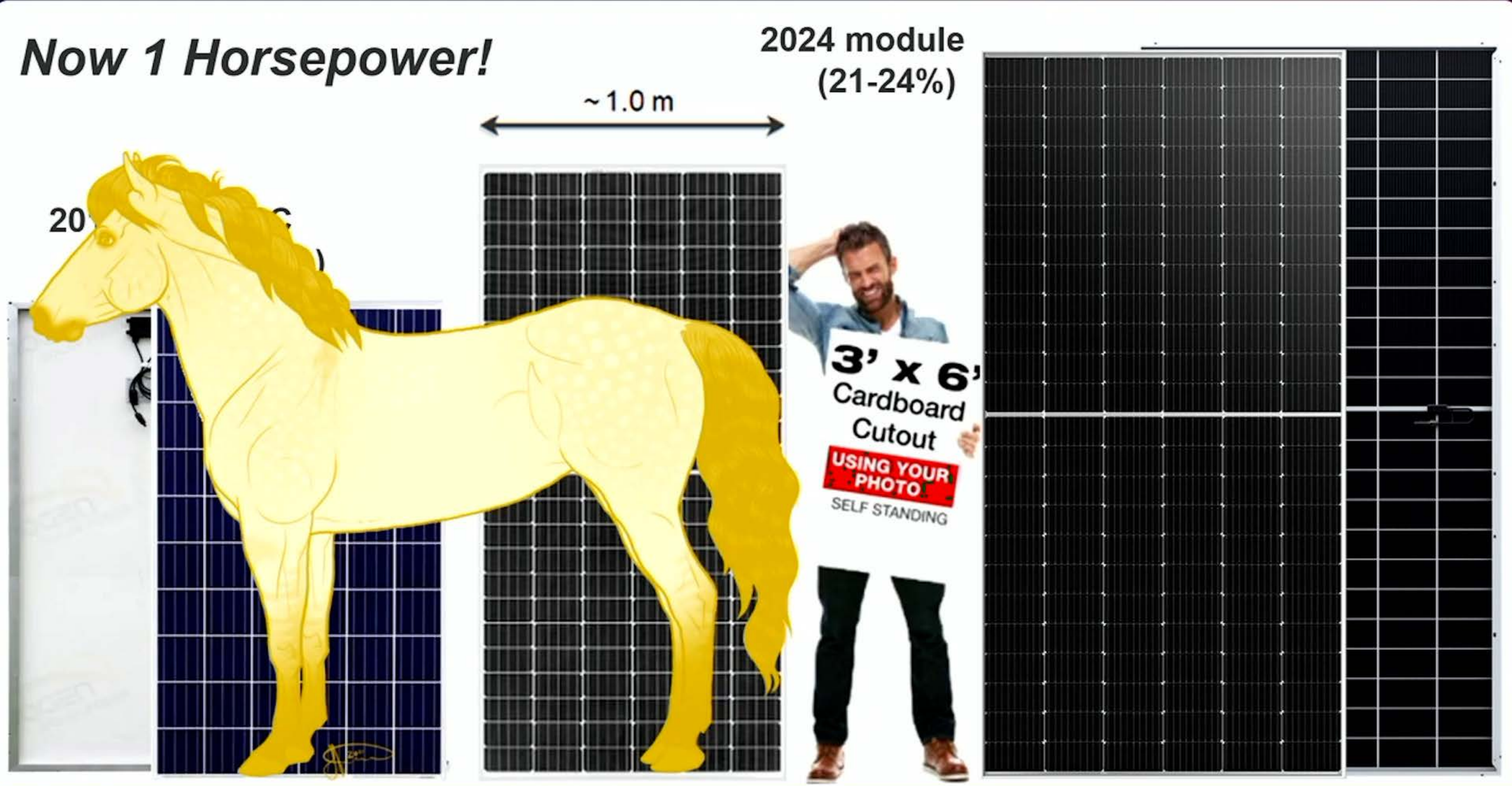
~1.0 m



2024 module (21-24%)



Now 1 Horsepower!



First efficient cells (1953/4)

Pearson, Chapin & Fuller

Credit: Bell Labs

"All the News That's Fit to Print"

The New York Times.

HENSEL REBUTTAL ACCUSES M'CARTHY OF 'MALICIOUS LIES'

Scientists See Harm In Monmouth Inquiry

PERLMAN ASSERTS HOUSING INQUIRY MAY DELAY FUNDS

U. S. and British Leaders on Two Active Diplomatic Fronts

QUILL STILL RANTS AT TIE-UP OF BUSES

AUSTRALIA SPURNS MOSCOW'S DEMAND

U. S. Backs Efforts by Paris To End War in Indo-China

FRENCH HAN UNDER FIRE'S FIRE

BAO WILL RECEIVE U. S. MILITARY HELP

Polio Vaccine Test Will Start Today

3 Killed During Argentine Voting; Clear Victory for Peron Conceded

Vast Power of the Sun Is Tapped By Battery Using Sand Ingredient

Special to The New York Times.

MURRAY HILL, N. J., April 25—A solar battery, the first of its kind, which converts useful amounts of the sun's radiation directly and efficiently into electricity, has been constructed here by the Bell Telephone Laboratories.

The new device is a simple-looking apparatus made of strips of silicon, a principal ingredient of common sand. It may mark the beginning of a new era, leading eventually to the realization of one of mankind's most cherished dreams—the harnessing of the almost limitless energy of the sun for the uses of civilization.

The sun pours out daily more than a quadrillion (1,000,000,000,000,000) kilowatt hours of energy, greater than the energy content of all the reserves of coal, oil, natural gas and uranium in the earth's crust.

With this modern version of Apollo's chariot, the Bell scientists have harnessed enough of the sun's rays to power the transmission of voices over telephone wires. Beams of sunlight have also provided electricity for a transistor in a radio transmitter, which carried both speech and music.

The Bell scientists reported they had achieved an efficiency of 6 per cent in converting sunlight directly into electricity. This, they asserted, compares favorably with the efficiency of steam and gasoline engines, in contrast with other photoelectric devices, which have a rating of no more than 1 per cent.

With improved techniques the efficiency may be expected to be increased substantially, they added. They observed that nothing is consumed or destroyed in the energy conversion process and there are no moving parts, so the solar battery "should theoretically last indefinitely."

The experimental solar battery uses strips of wafer-thin silicon about the size of common razor blades. These strips are extremely sensitive to light. They can be linked together electrically and can deliver power from the sun at the rate of 50 watts a square yard of surface.

The atomic battery recently announced by the Radio Corporation of America delivers one-millionth of a watt. The new Bell solar battery thus delivers 50,000,000 times the power of the R.C.A. atomic battery.

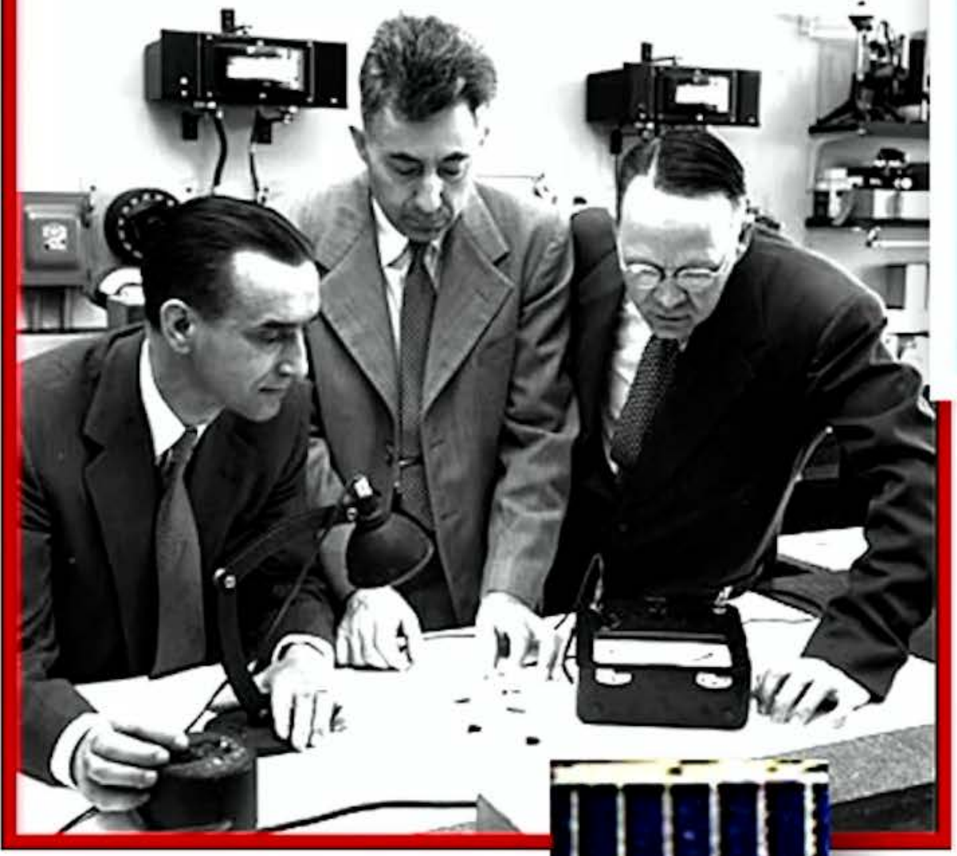
Silicon is a semiconductor,

Continued on Page 11, Column 4

April 26, 1954

First efficient cells (1953/4)

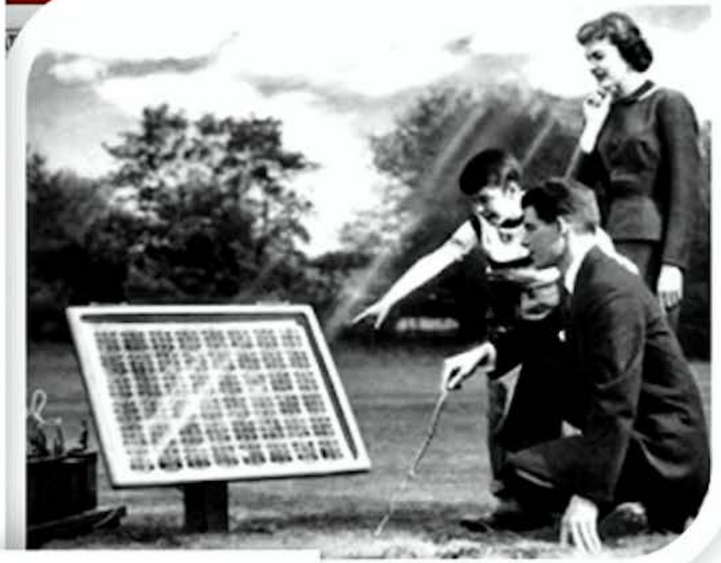
Pearson, Chapin & Fuller



Credit: Bell Labs

Vanguard 1, 1958

Credit: Wikimedia Co



Telstar 1962

Credit: D. Darling

April 26, 1954

of the Sun Is Tapped
Using Sand Ingredient

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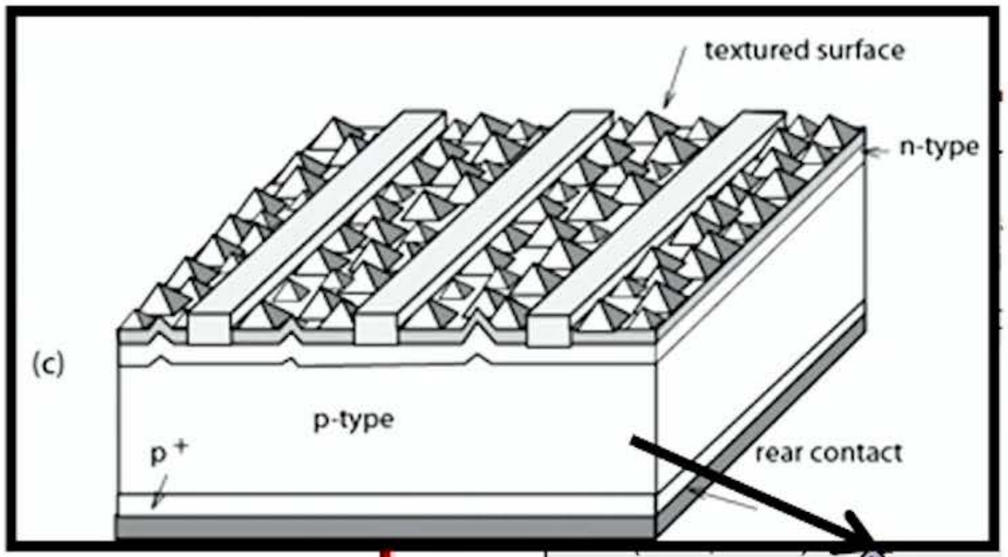
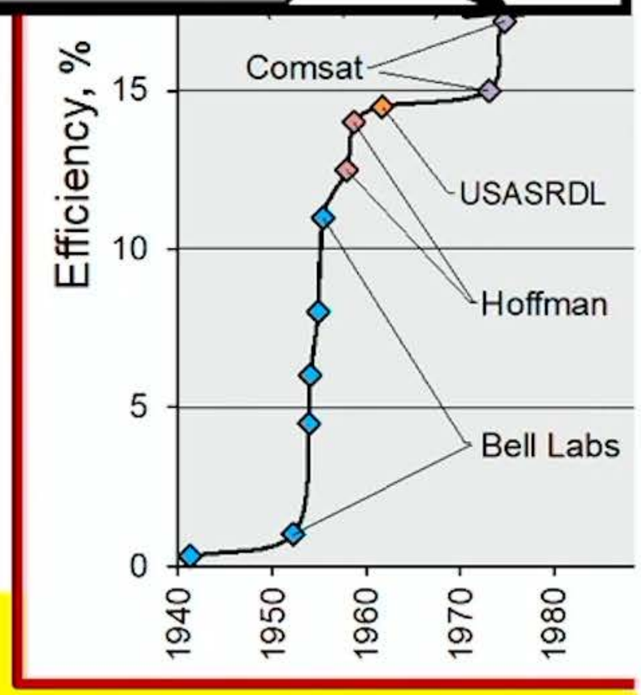
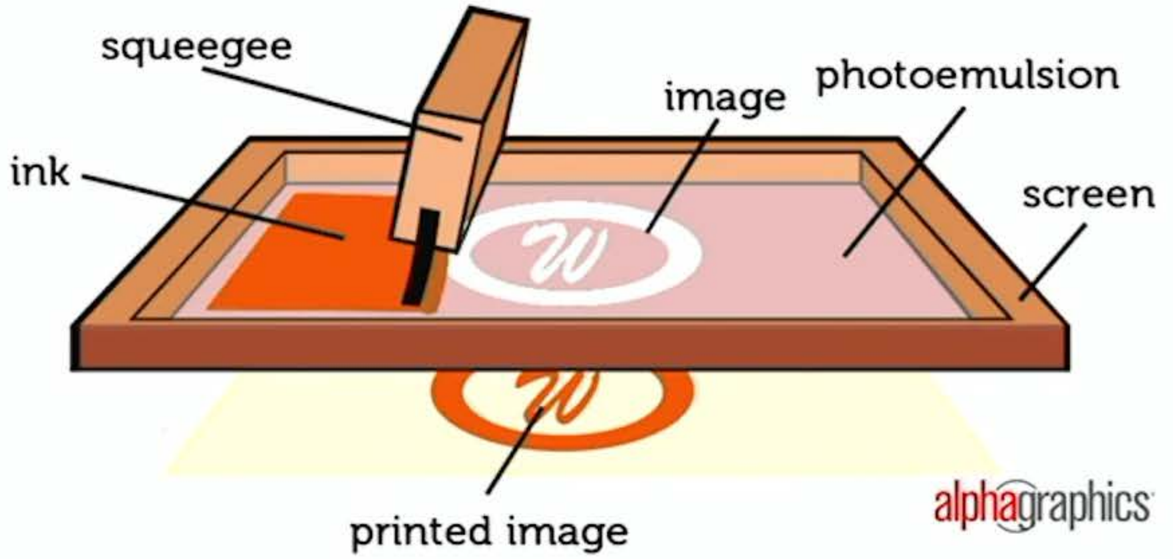
Silicon is a semiconductor,

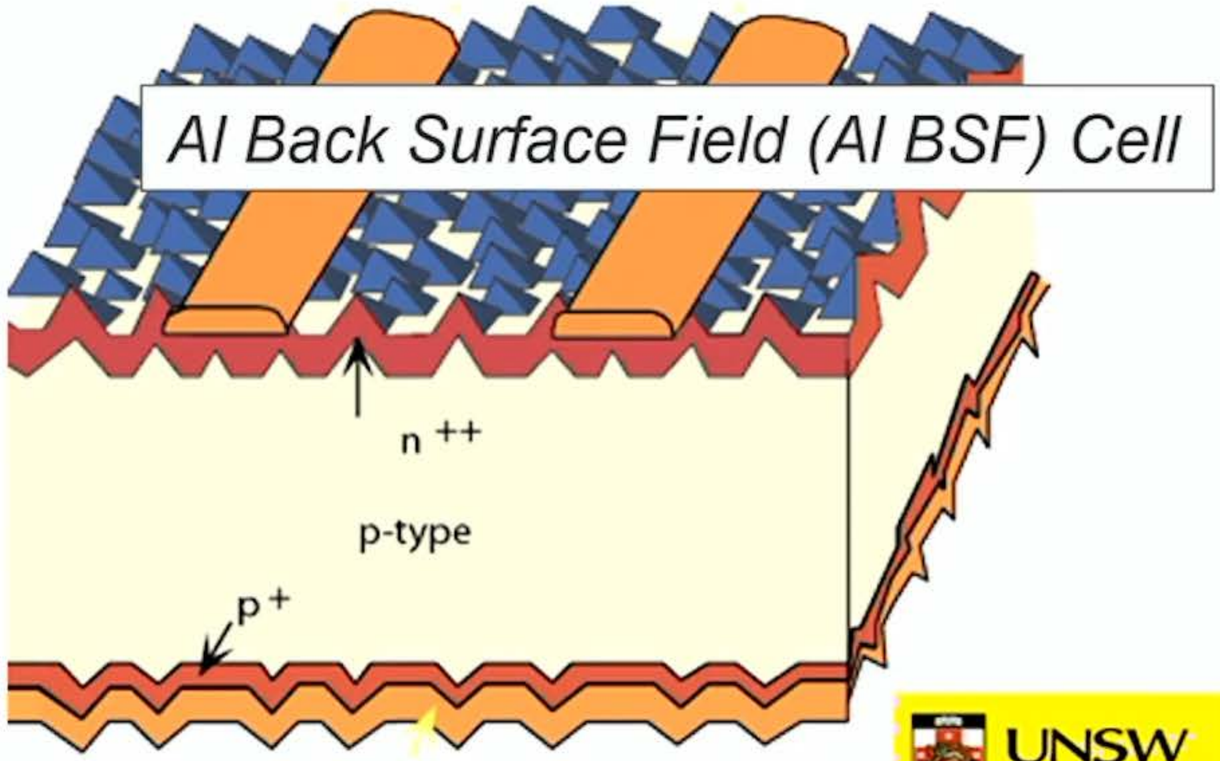
Continued on Page 11, Column 4

Black cell (1974)/Screen-printing (1975)

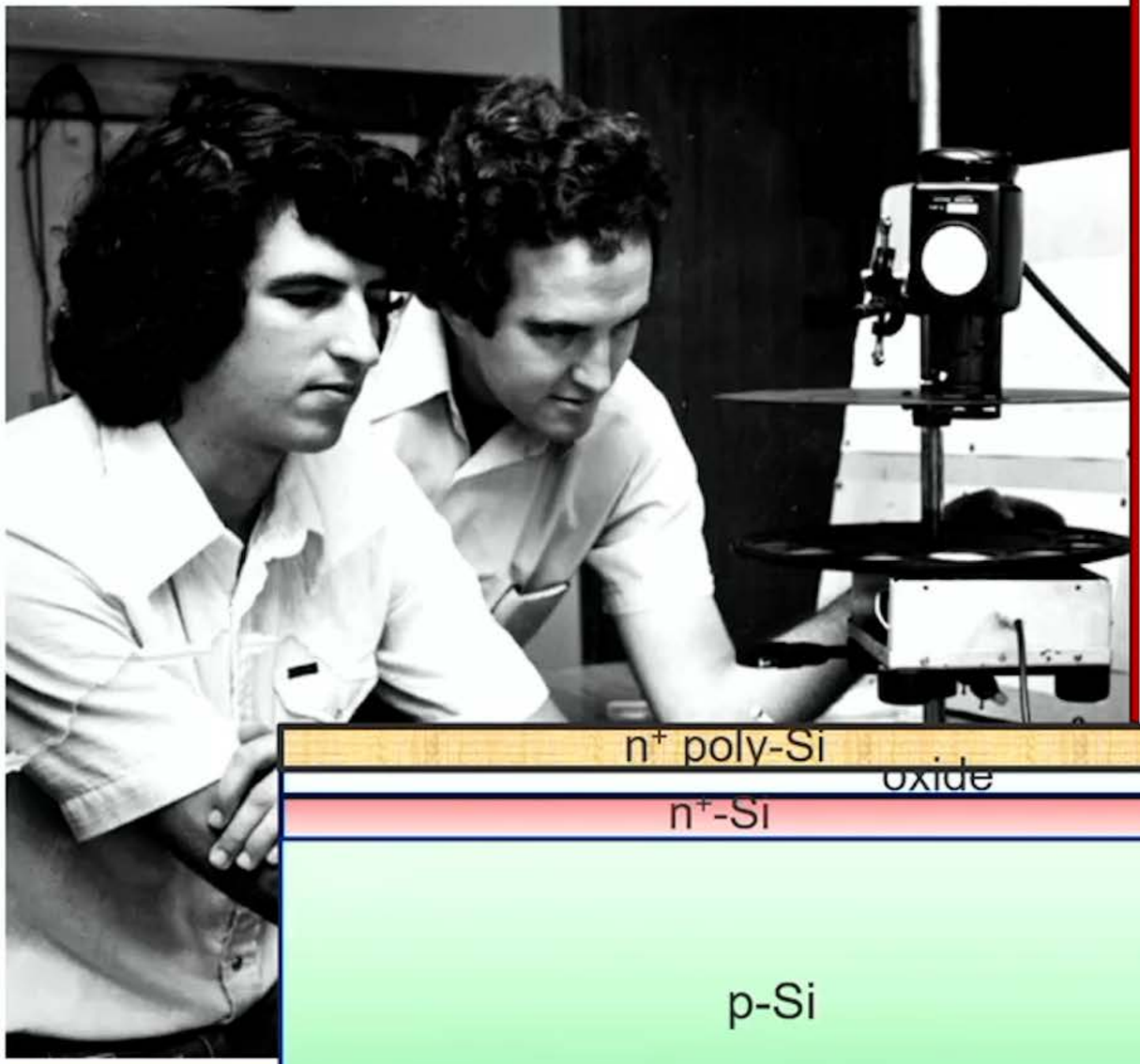


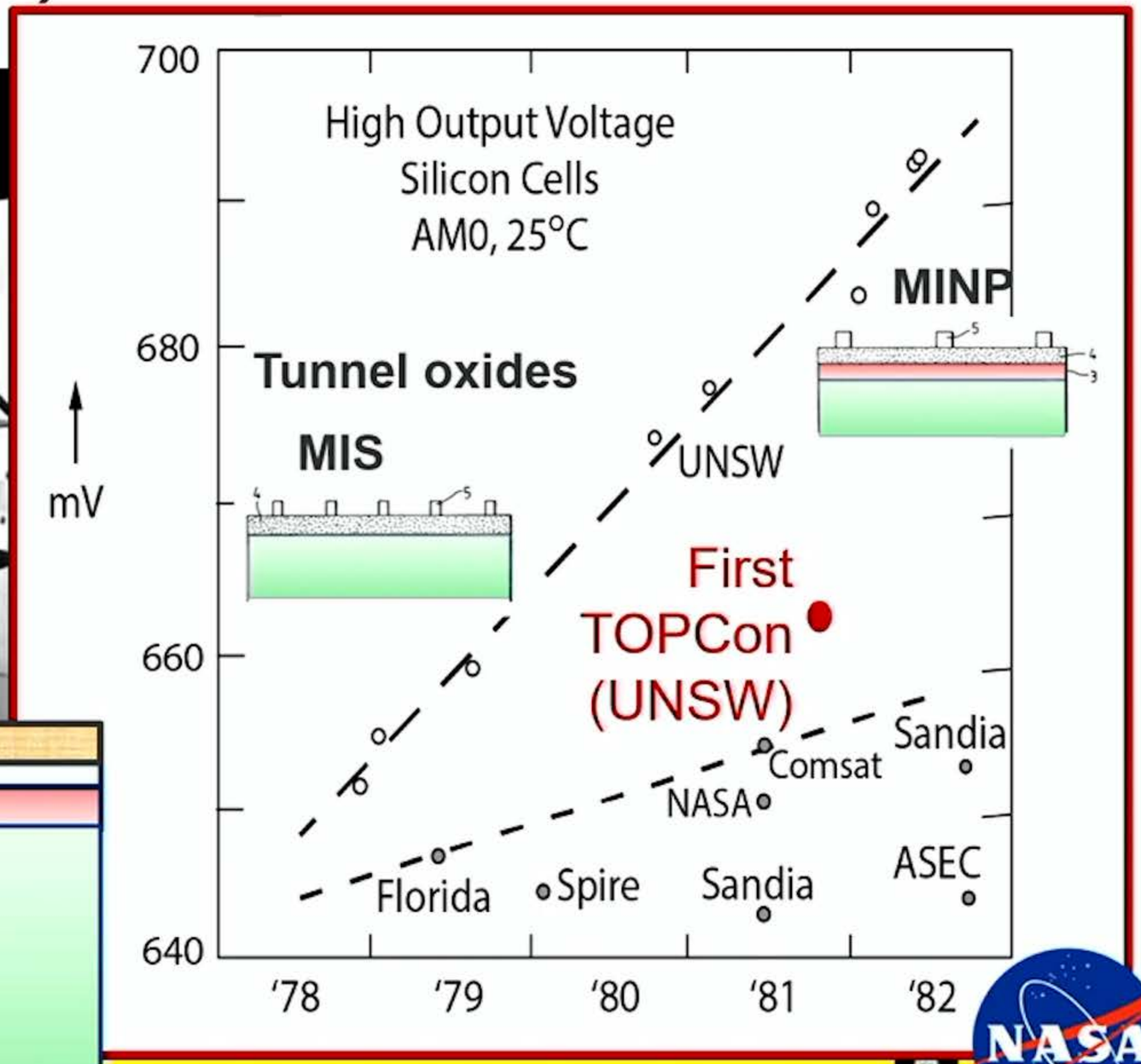




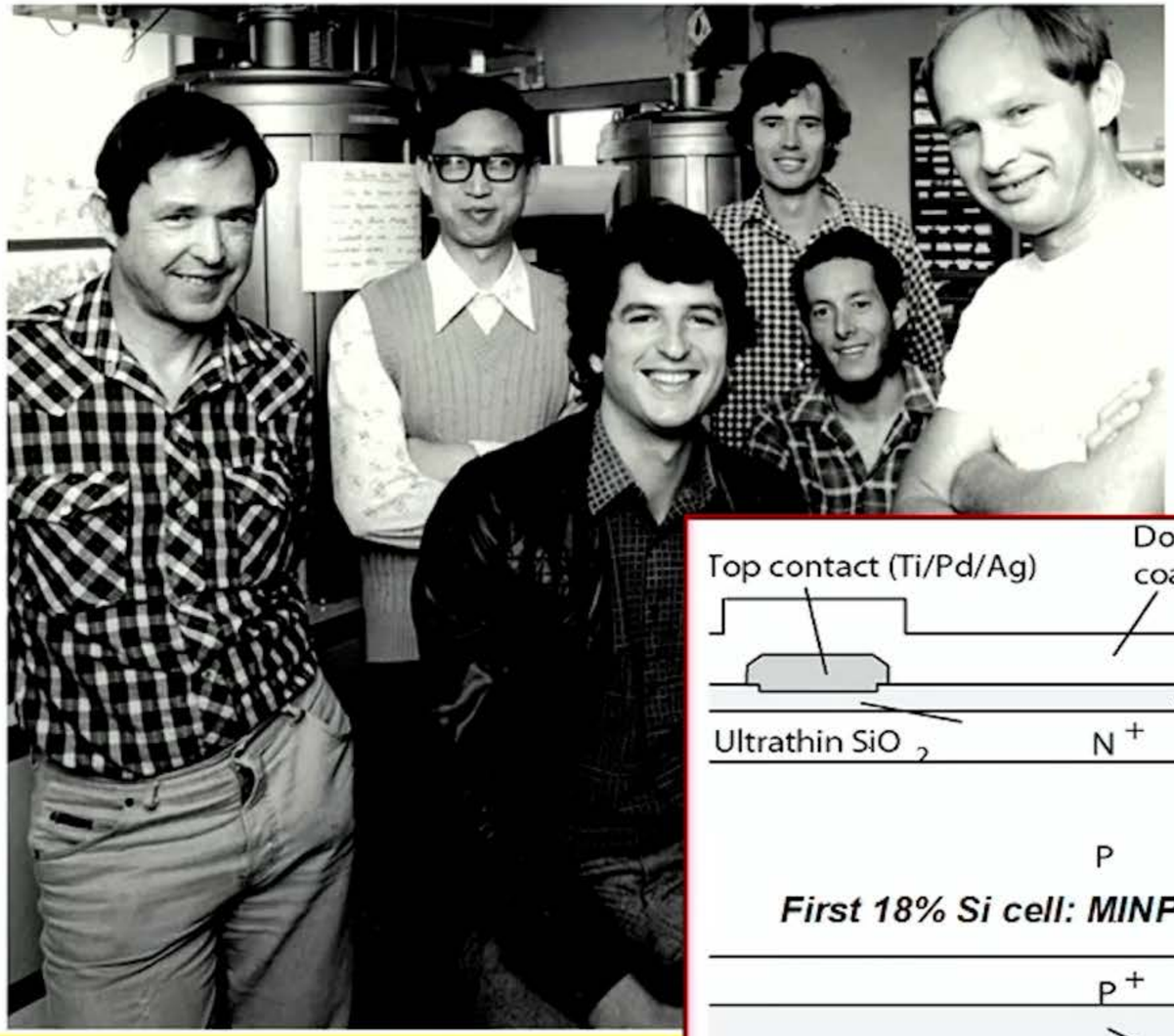


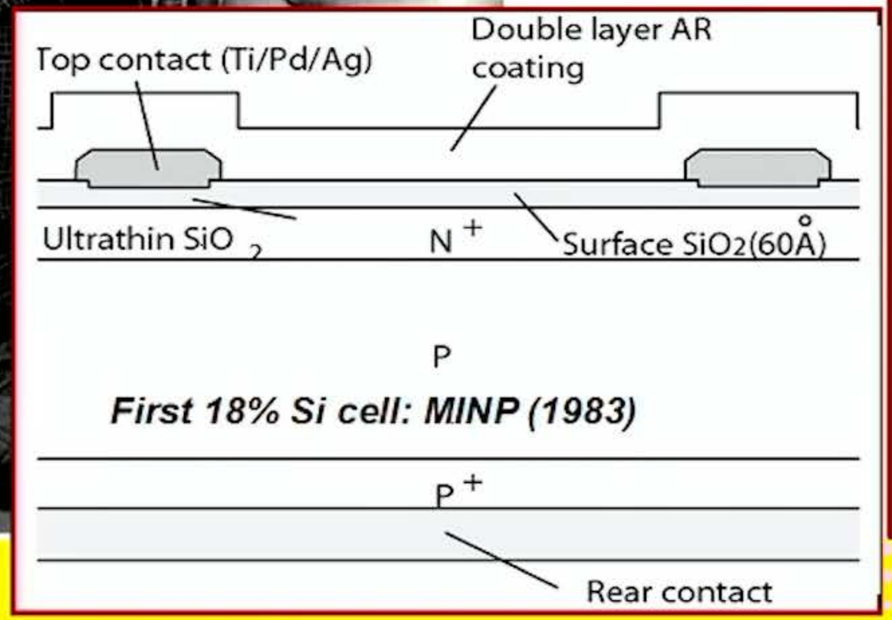
Early days UNSW (1974-1982)

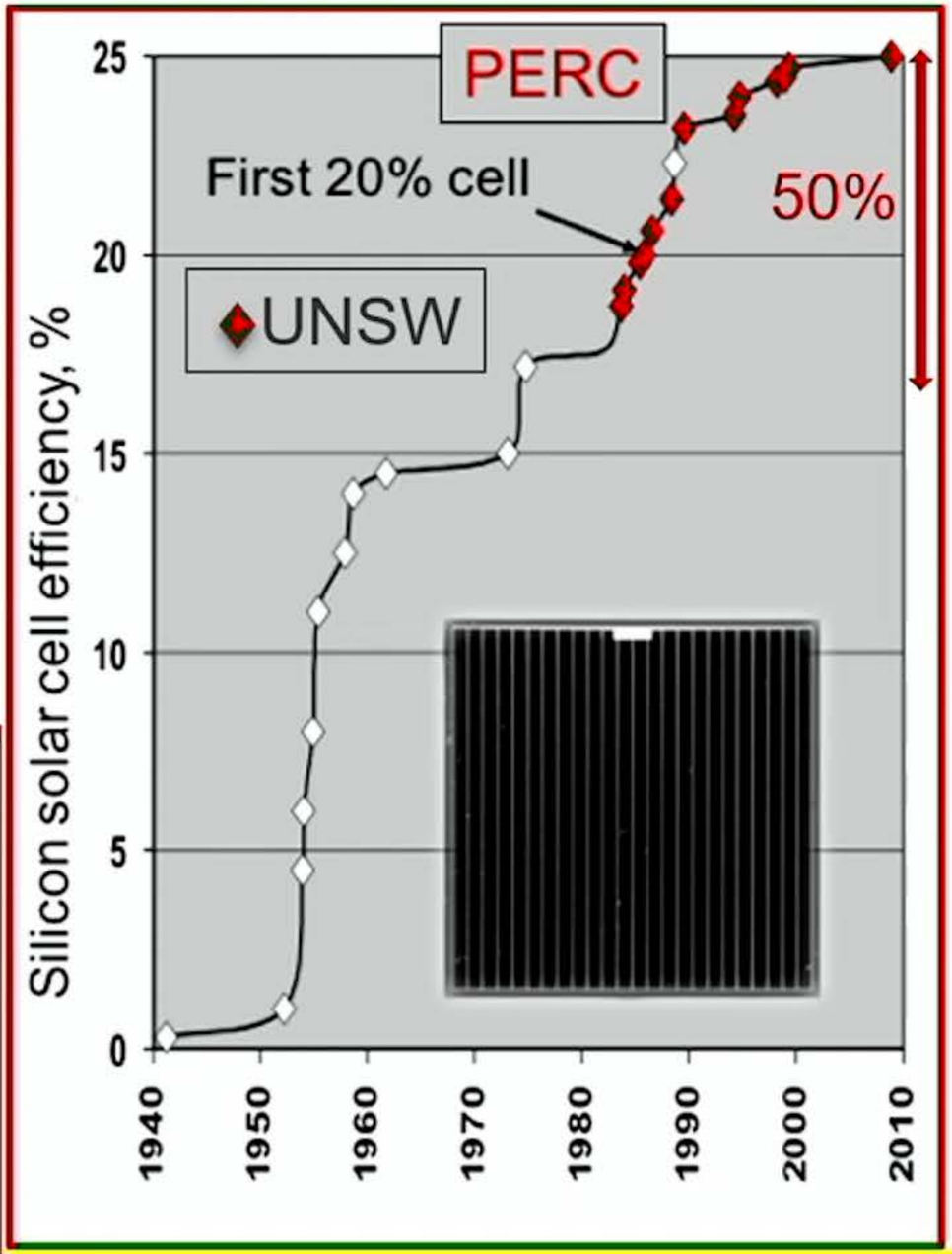




First world record (1983: 18.7% cell)

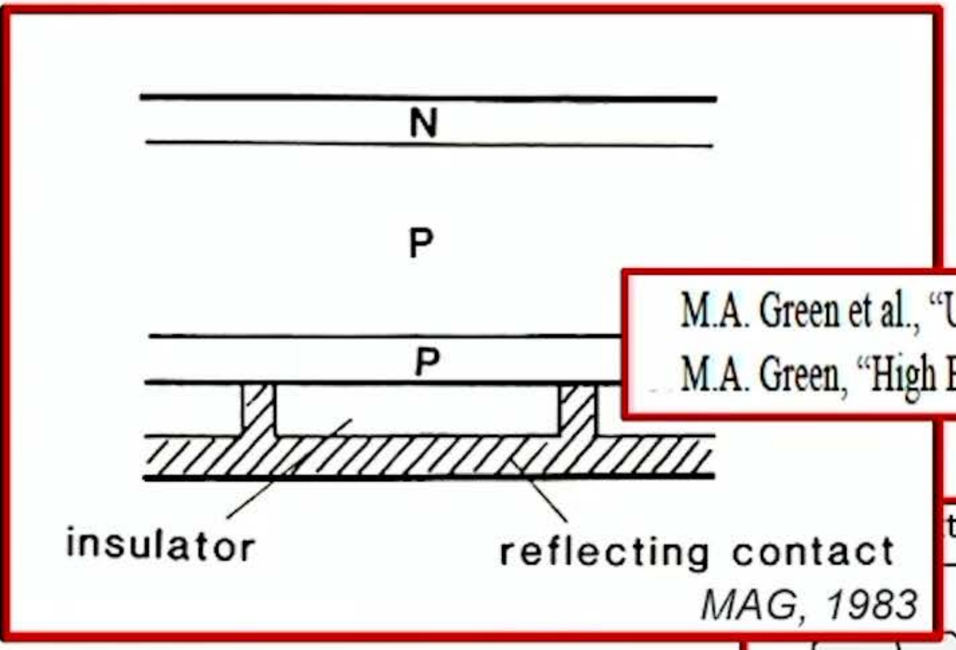






2nd world record (1983: 19.1% cell)

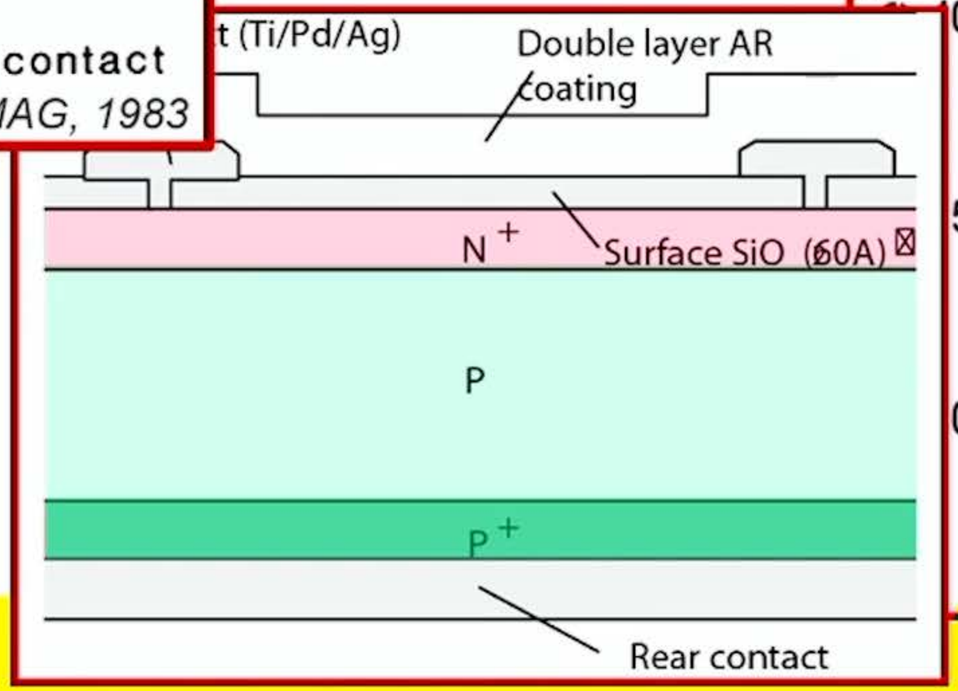
First PERC sketch (2 reports)

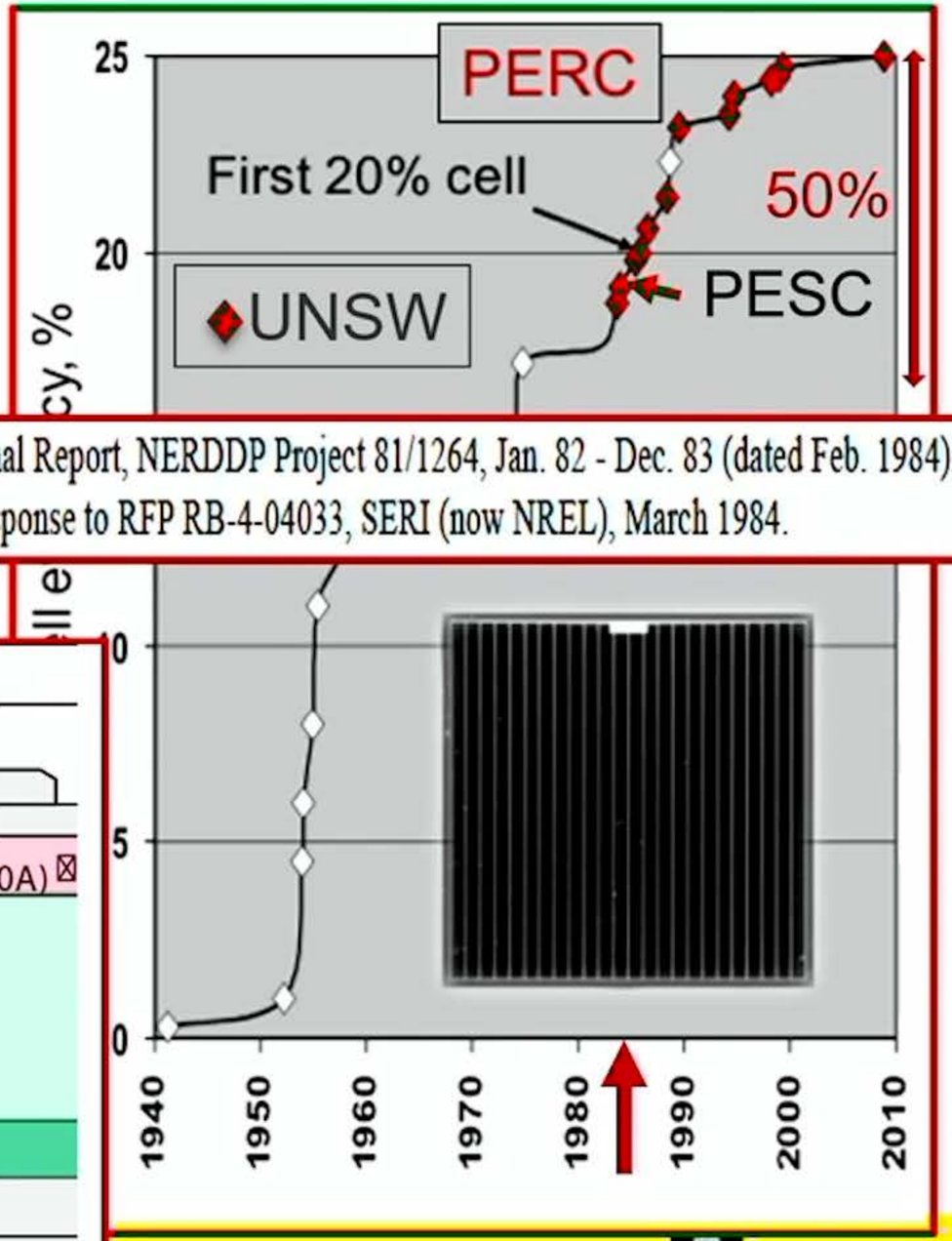


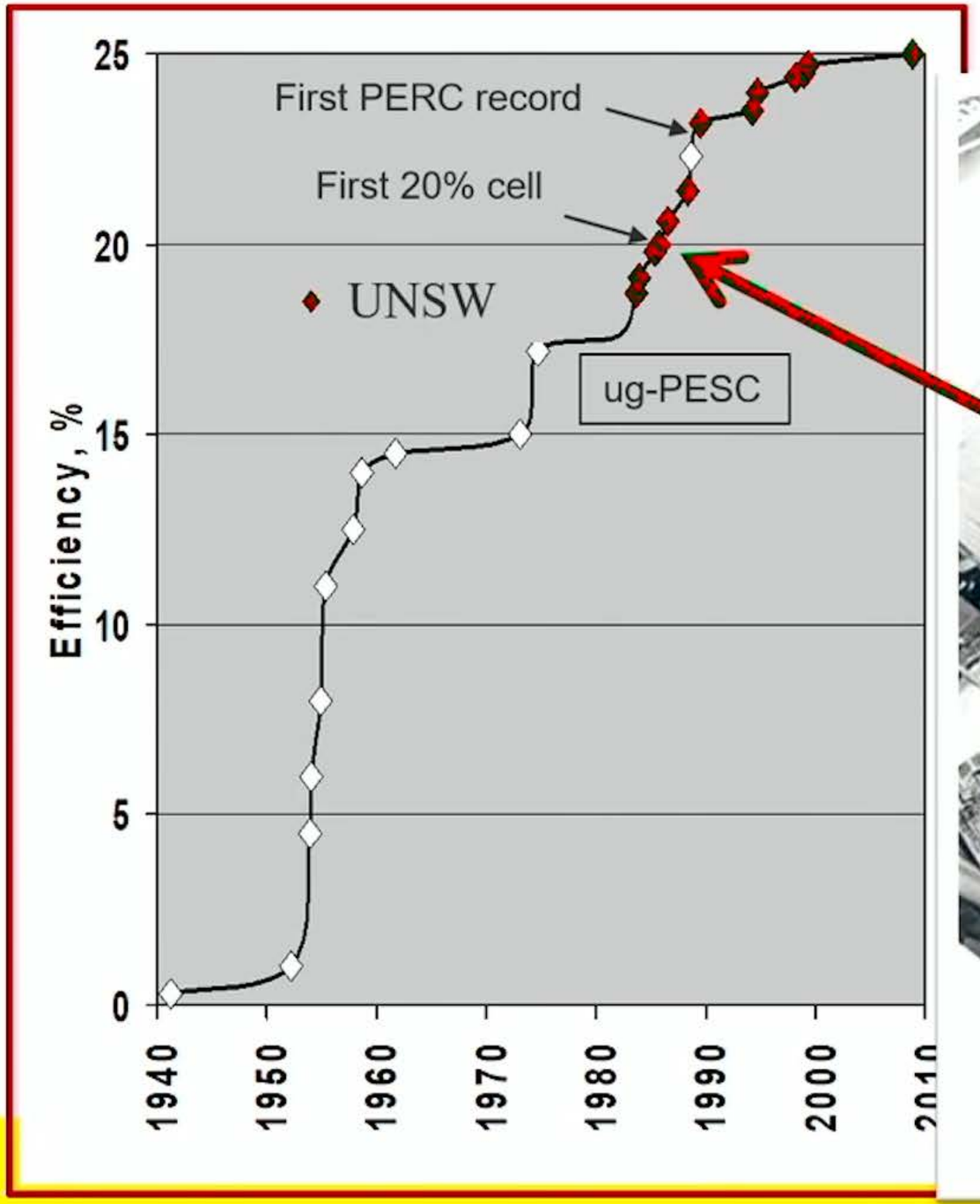
MAG, 1983

M.A. Green et al., "Ultimate Performance Silicon Solar Cells", Final Report, NERDDP Project 81/1264, Jan. 82 - Dec. 83 (dated Feb. 1984).

M.A. Green, "High Efficiency Silicon Solar Cells", Proposal in response to RFP RB-4-04033, SERI (now NREL), March 1984.







First 20% Si cell (1985)

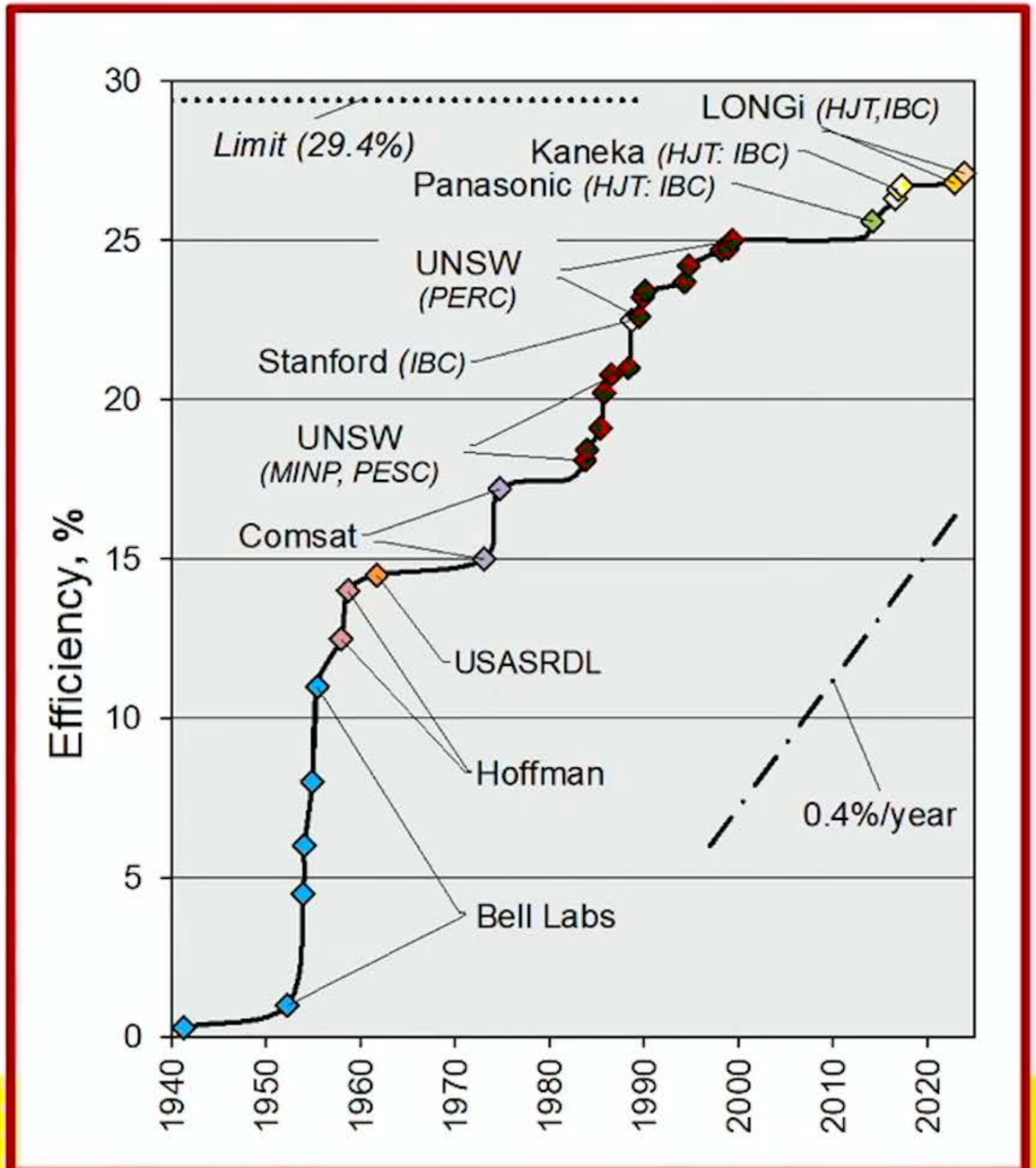
Adele Milne
1st PERC thesis

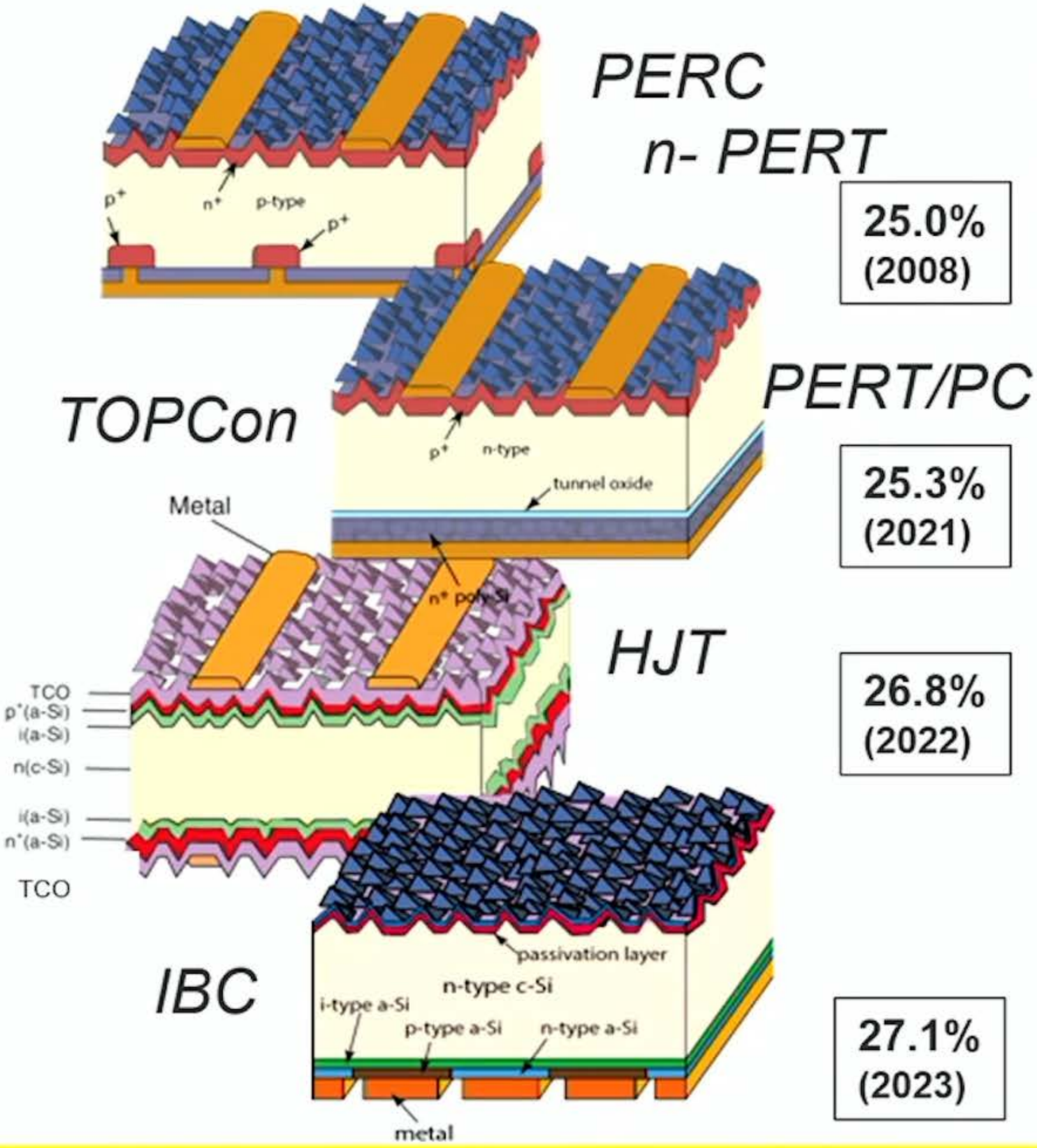
Aihua Wang
CSUN founder/CTO

Ximing Dai
JA founder/CTO

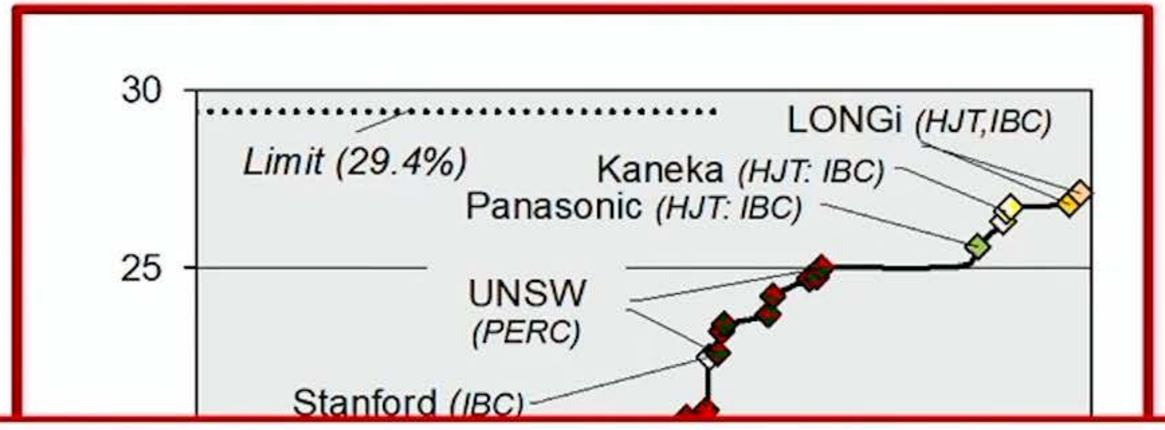
UNSW SYDNEY

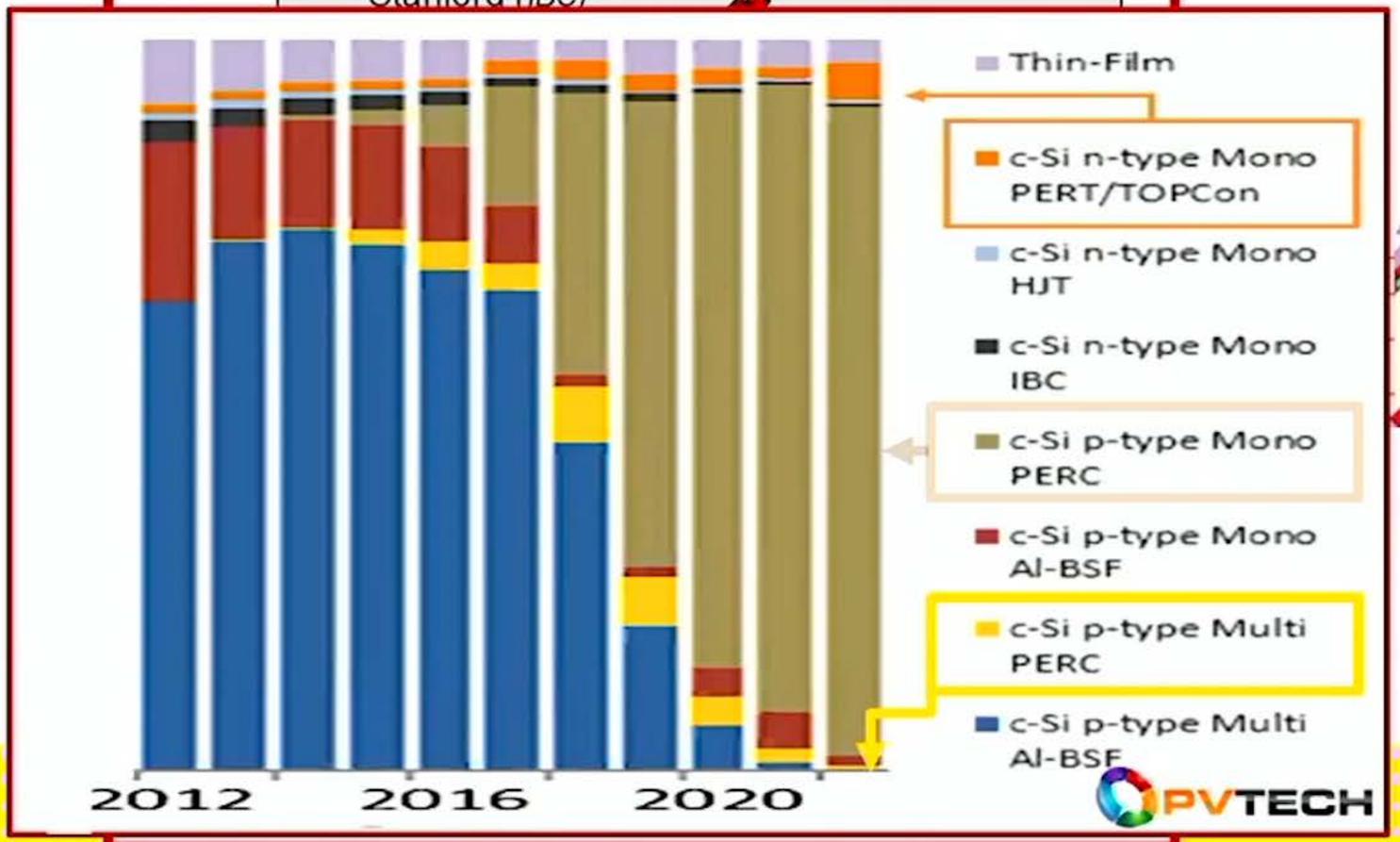
Subsequent progress

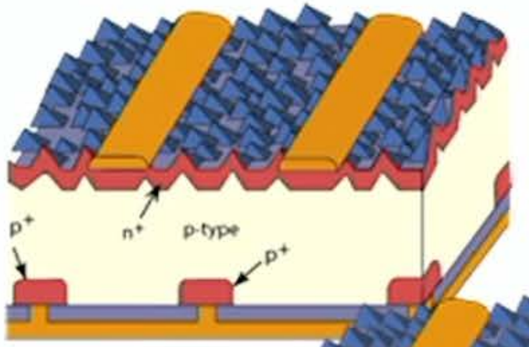




Subsequent progress

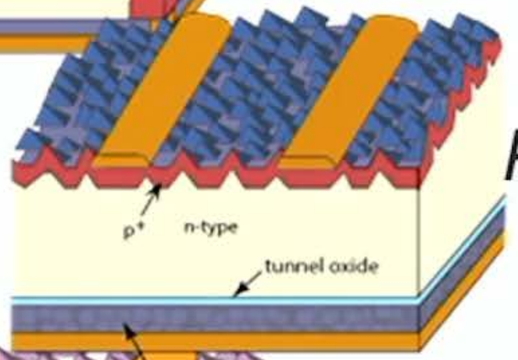






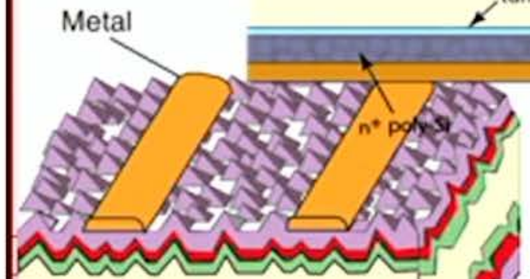
PERC
n- PERT

25.0%
(2008)



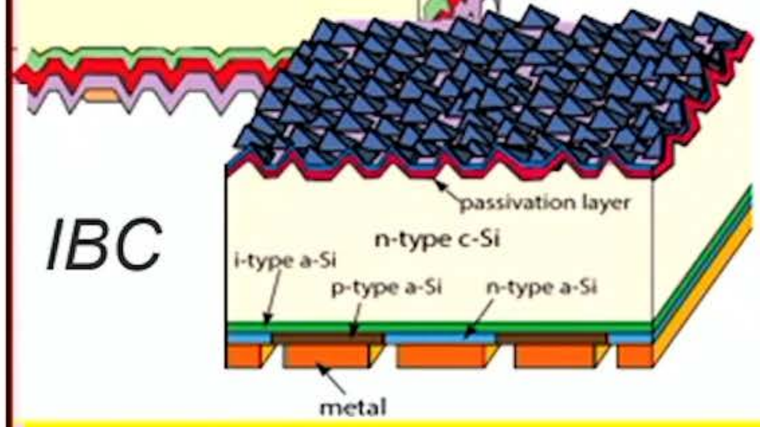
TOPCon
PERT/PC

25.3%
(2021)



HJT

26.8%
(2022)



IBC

27.1%
(2023)

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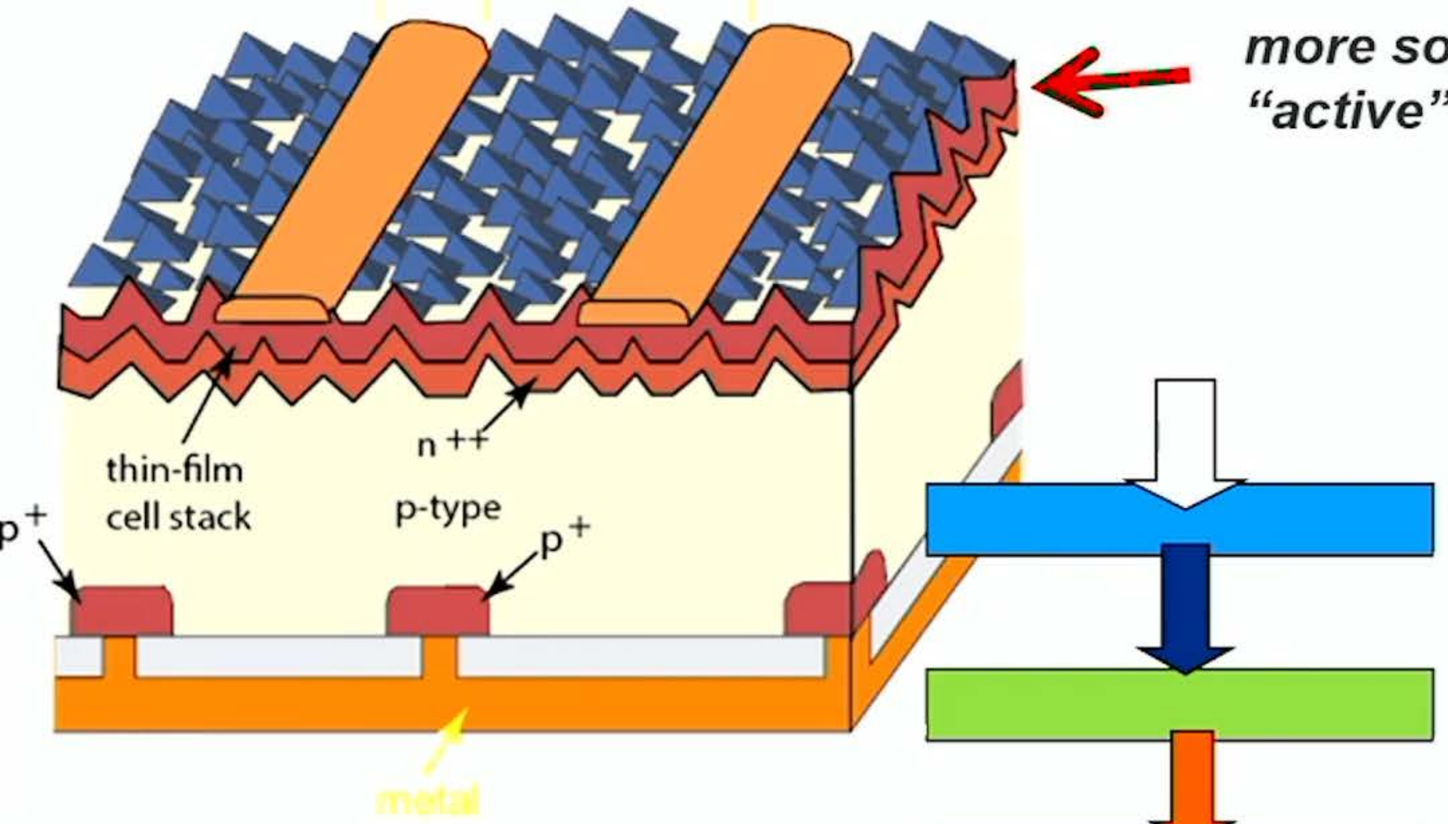
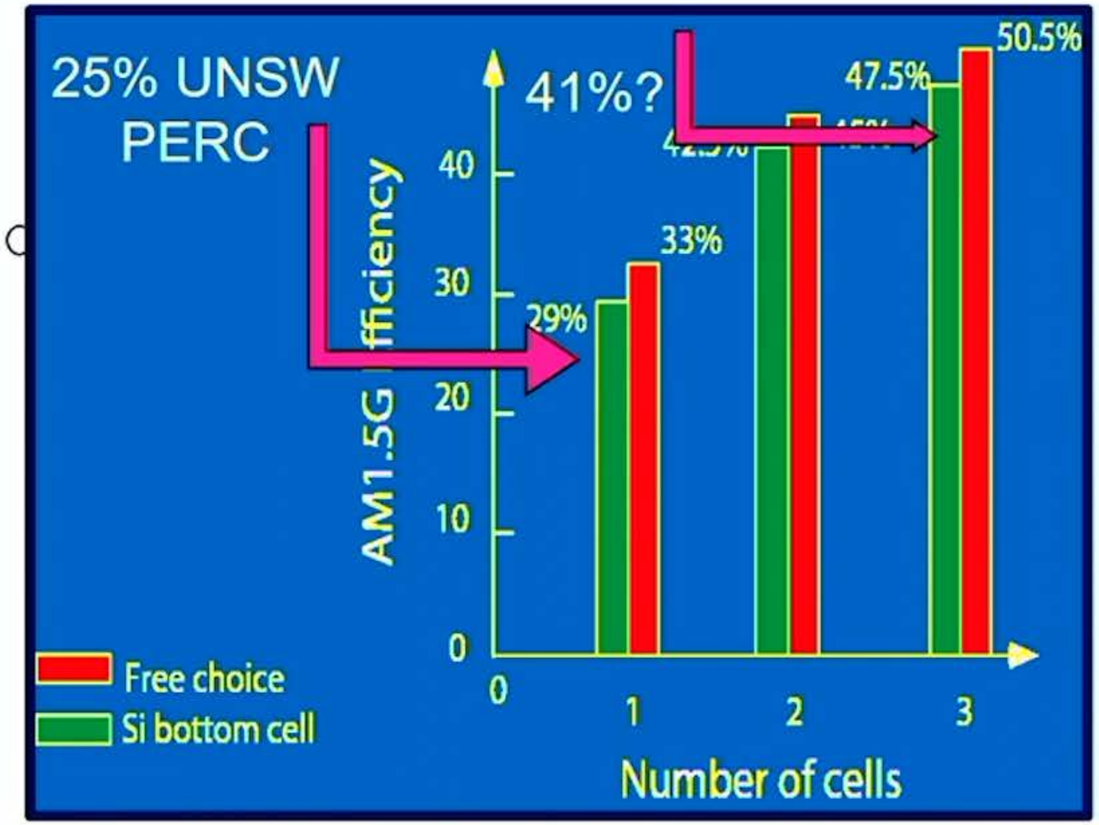
What comes longer term?



more sophisticated
"active" AR coat?

Free choice or Si



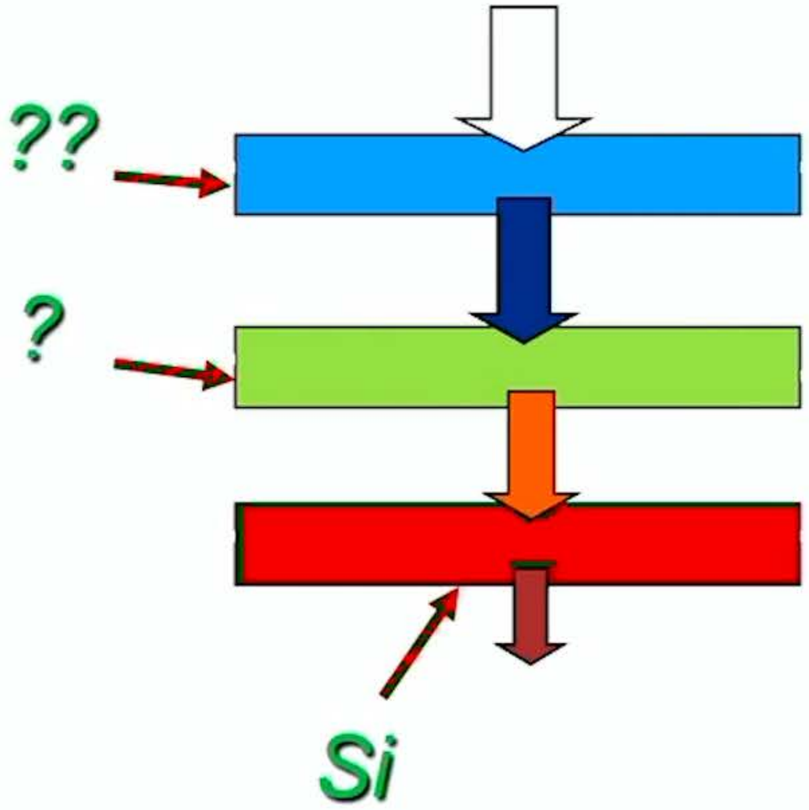
Supercharged tandem

PERC, TOPCon, HJT, IBC?

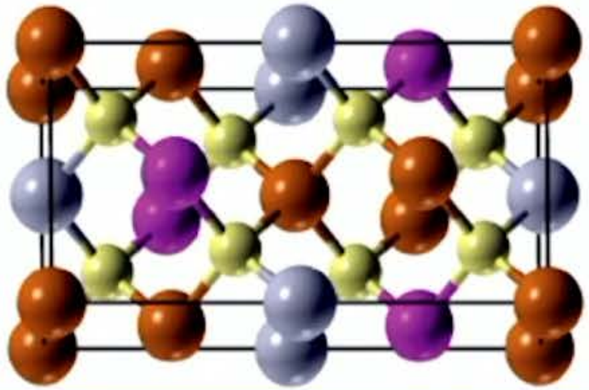
UNSW SYDNEY

What comes longer term?

Like silicon, ? needs to be abundant, non-toxic, stable, efficient (>20%)

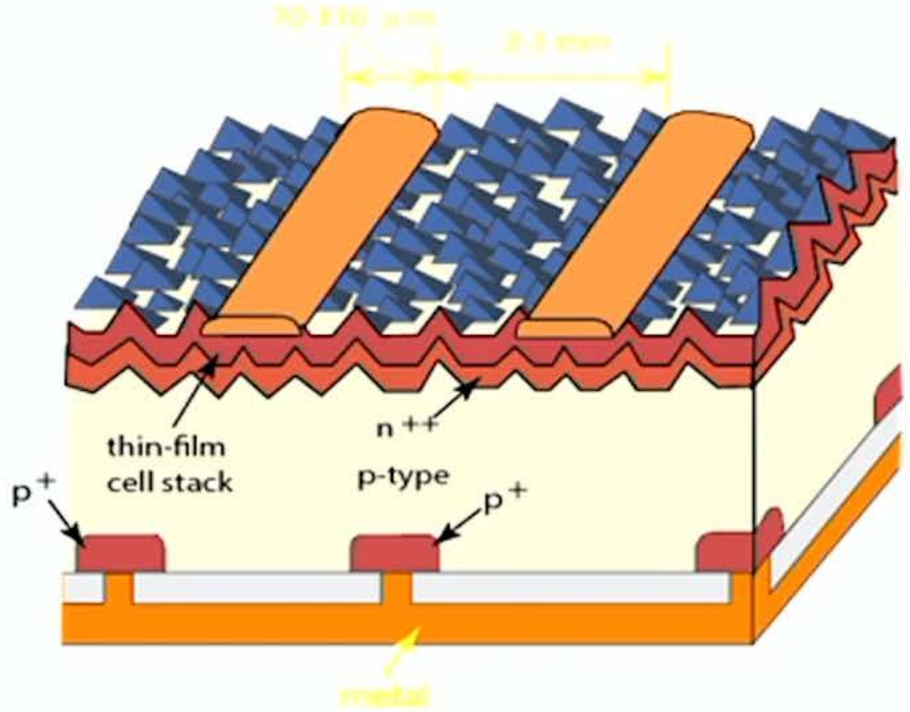


	Perovskite	✓	✗	✗	✓
	Organics (OPV)	✓	✓	✗	✗
II-VI	$Cu_2Zn(Sn:Si)S_4$	✓	✓	✓	✗
II-VI	$Cu(In:Ga)(S:Se)_2$	✗	?	✓	✗
II-VI	*(Cd:Zn:Mg)(Se:Te)*	✗	✗	✓	?
III-V	*(Al:Ga:In)(As:P)*	✗	?	✓	?

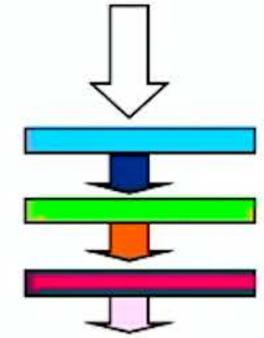


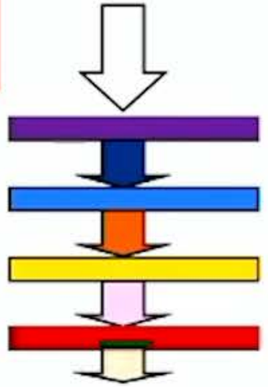
When found – *the end for silicon?*

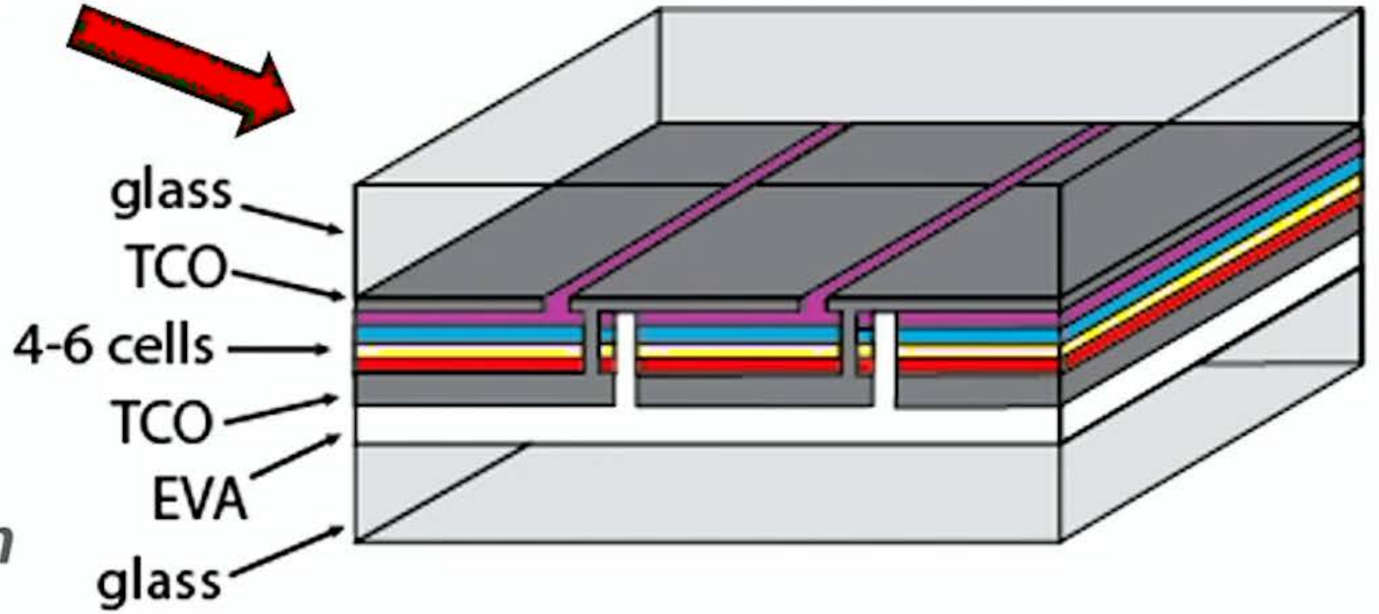
$$\eta \approx \sum_{i=1}^{N} \eta_i / i$$



Si - 3 cell tandem

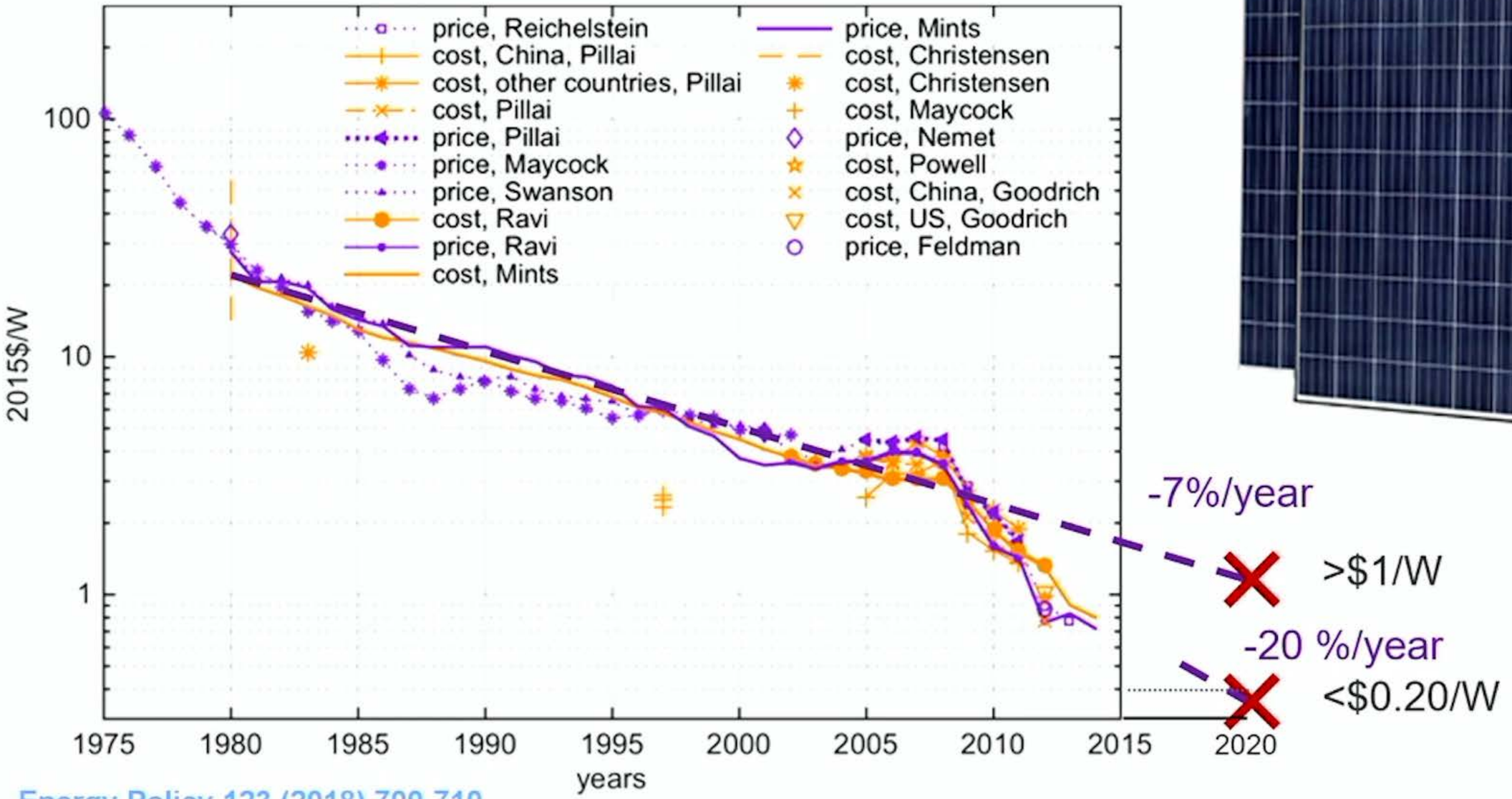






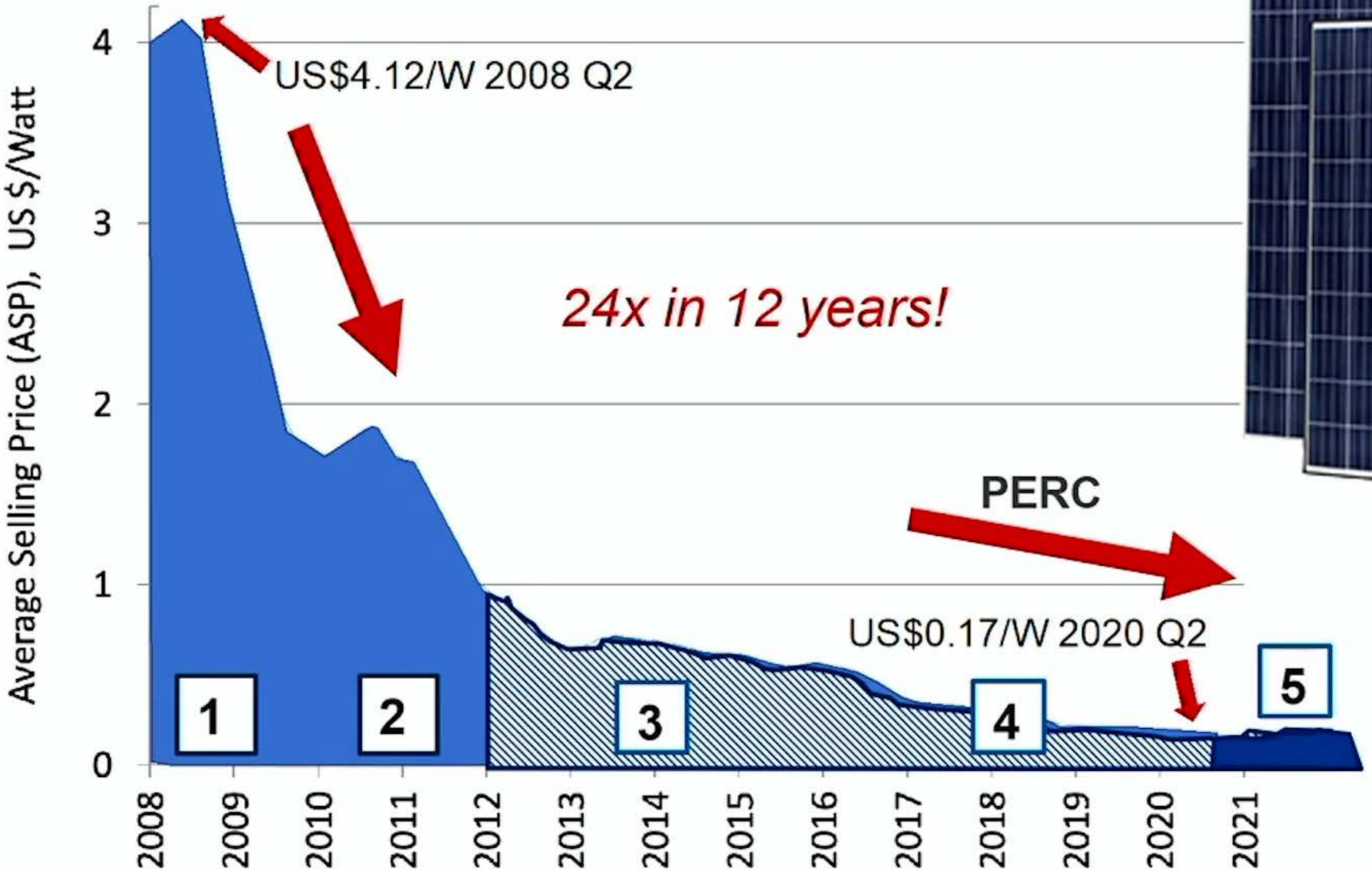
4-6 cell thin-film tandem

History of PV cost/price reduction



Kavlak et al., Energy Policy 123 (2018) 700-710

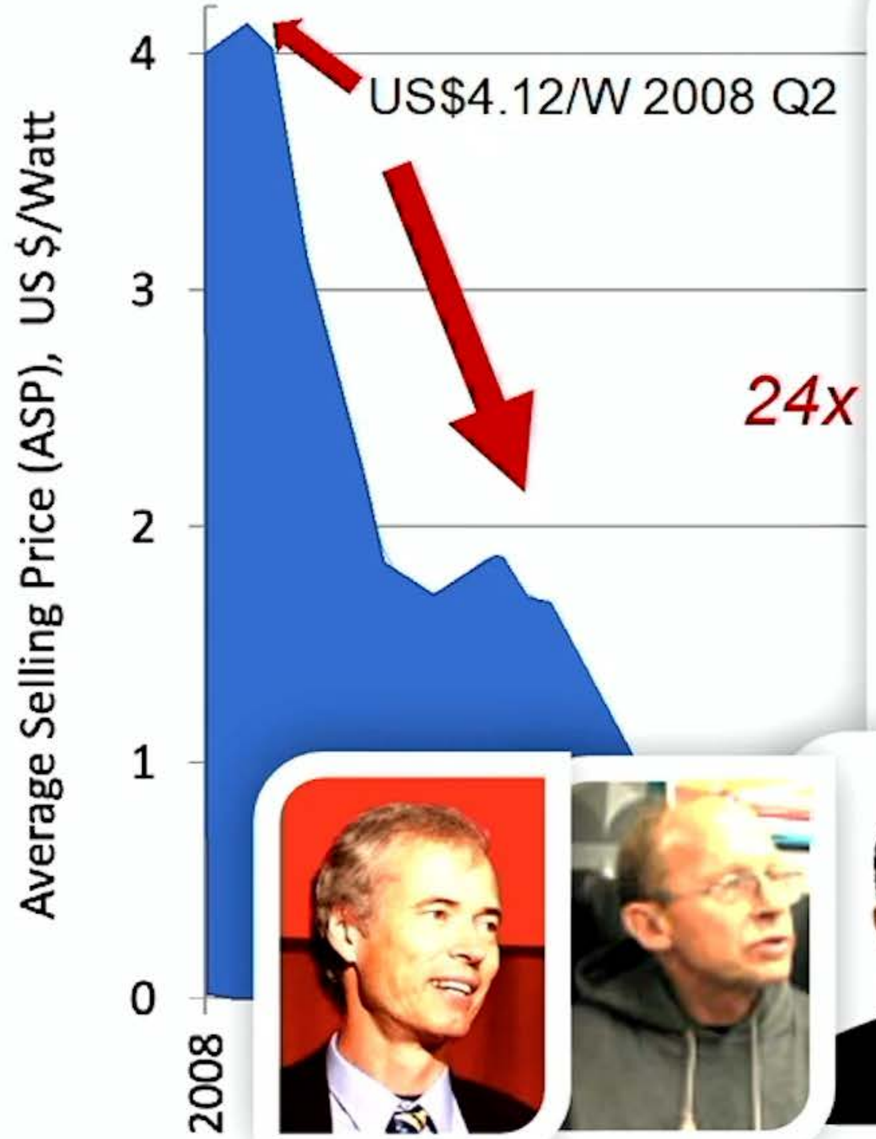
Module price history



Dr Zhengrong Shi (12th PhD student)

UNSW SYDNEY

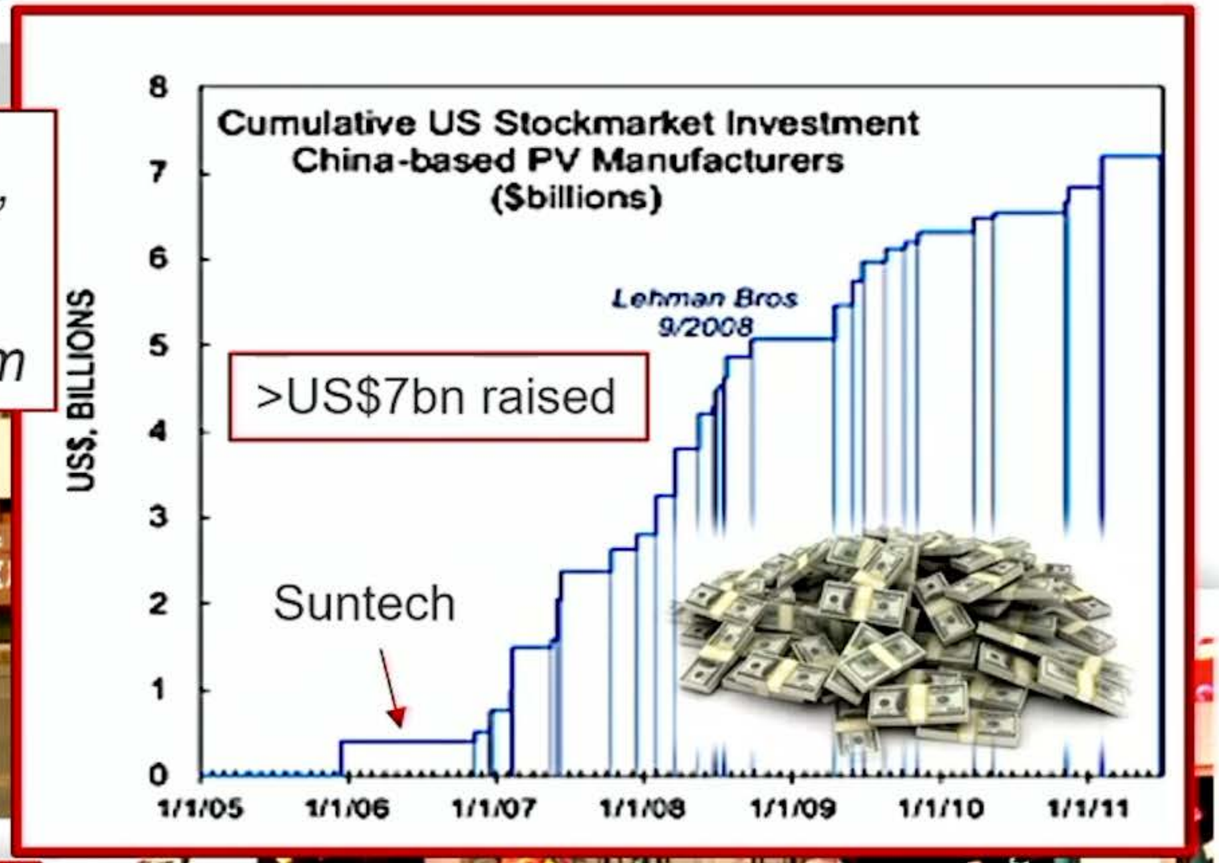
Module price history



CEO

CTO Co-Founders

. raised US$400m
. "top tech IPO this year"
. "first solar billionaire"
. Goldman Sachs $200m



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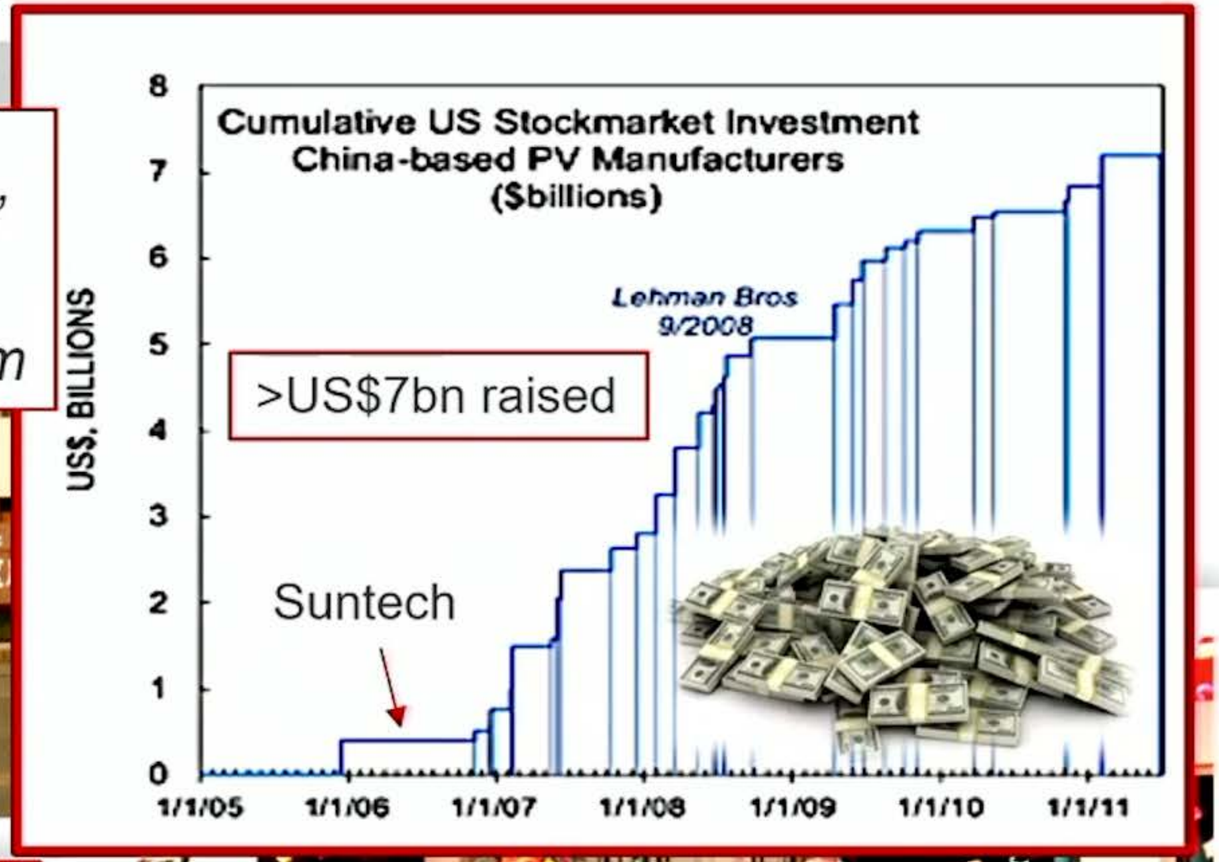
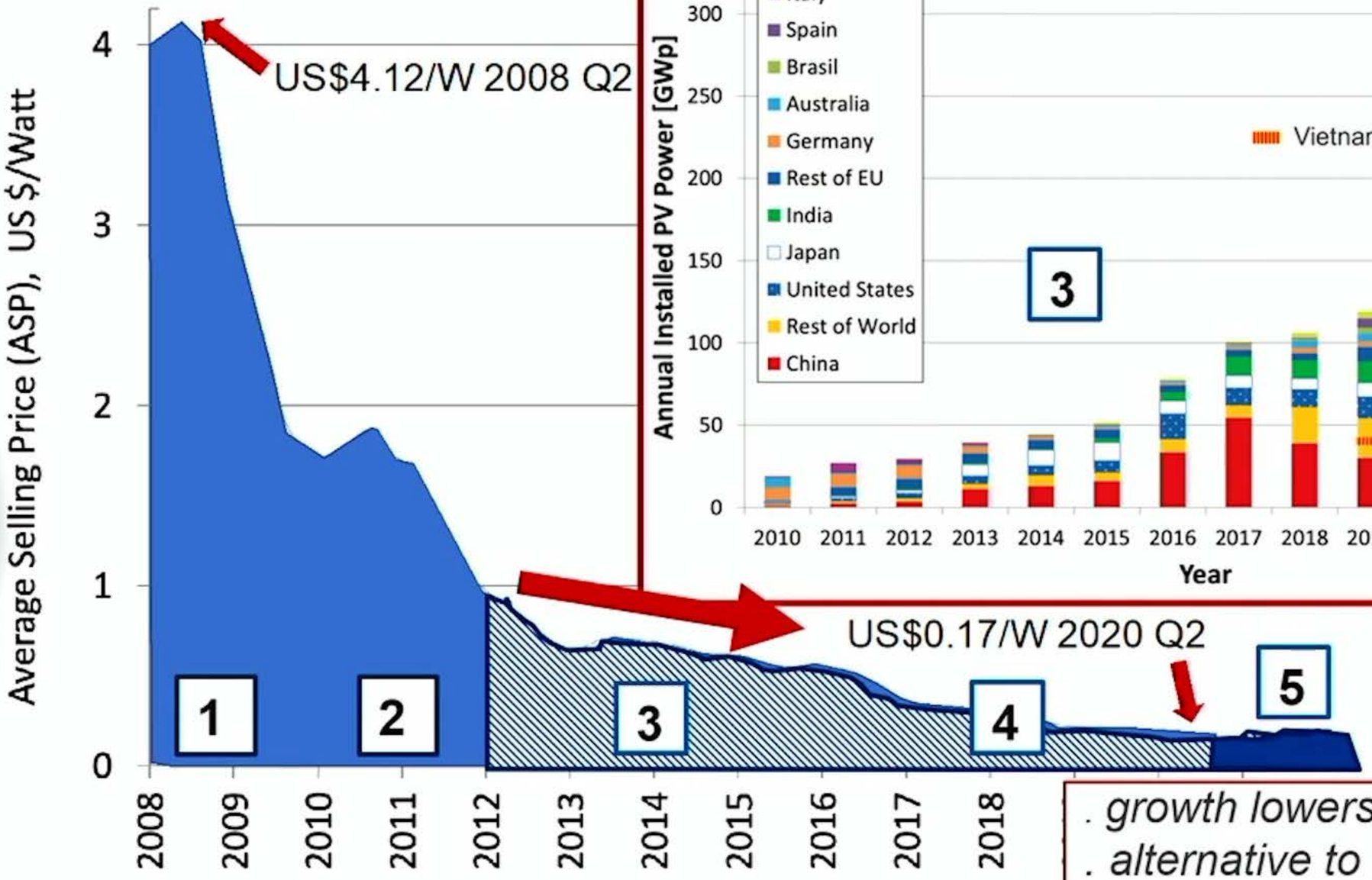


Companies listing 2005-2010 *(2021 world rank)*: *Suntech[f] (9th), CSI[a] (5th), Trina[c] (2nd), Solarfun[c'] (now Hanwha) (7th), JA Solar[f] (3rd), CSUN[f], LDK[a], Yingli[c], Renesolar, Jinko[c] (4th).*

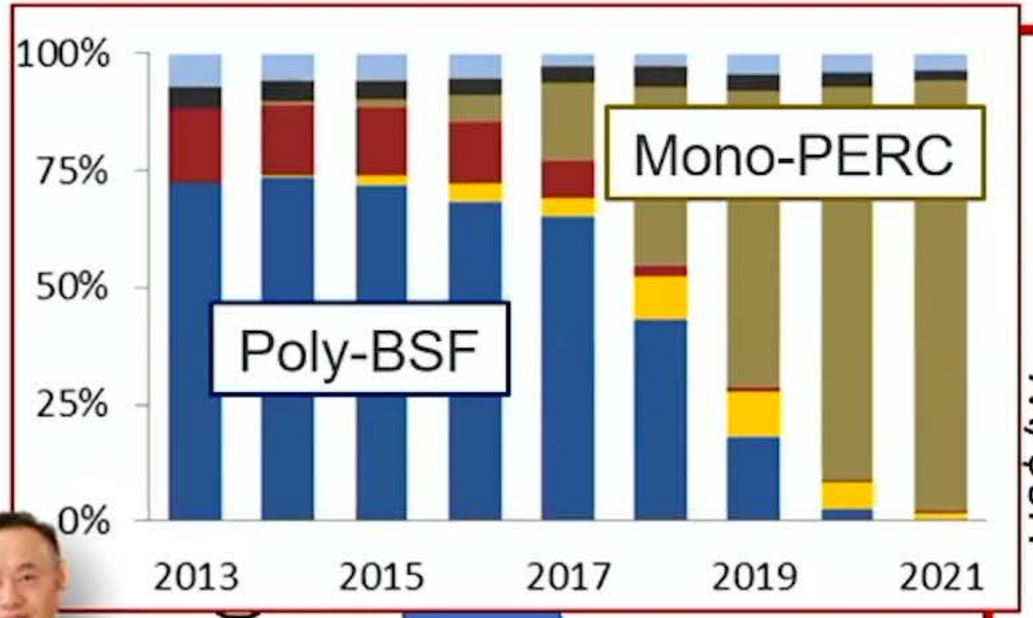
Module cost history

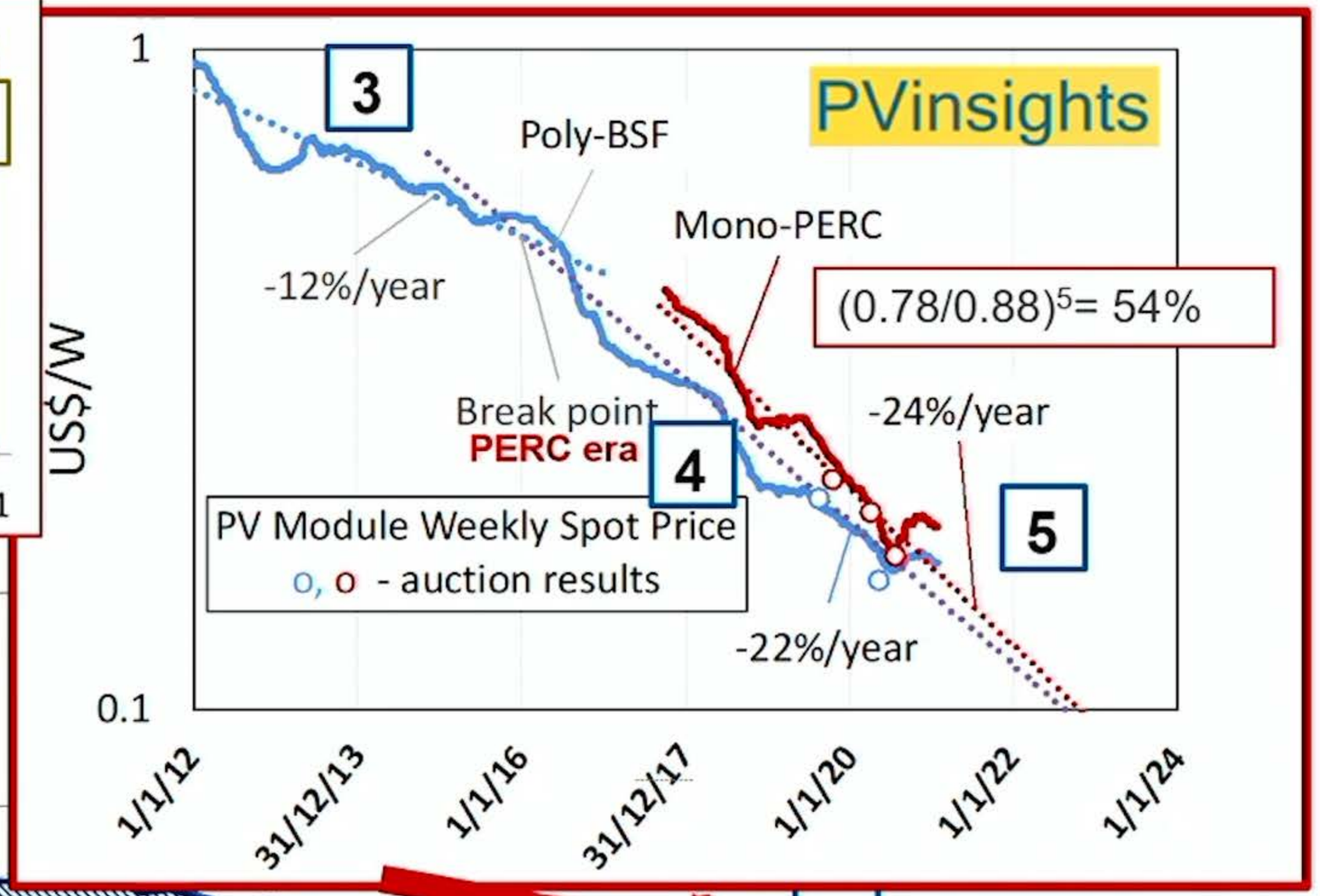


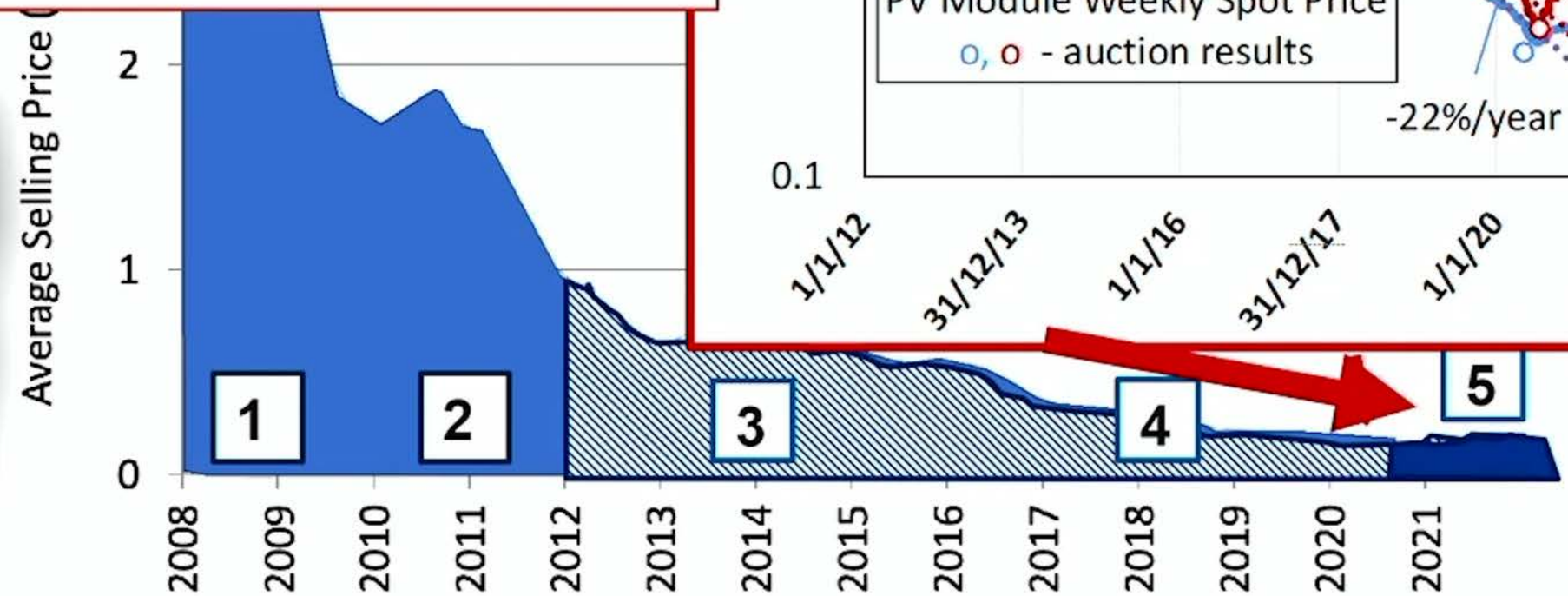
. growth lowers global prices
. alternative to more coal!

China leads the way: takes over market development

UNSW SYDNEY







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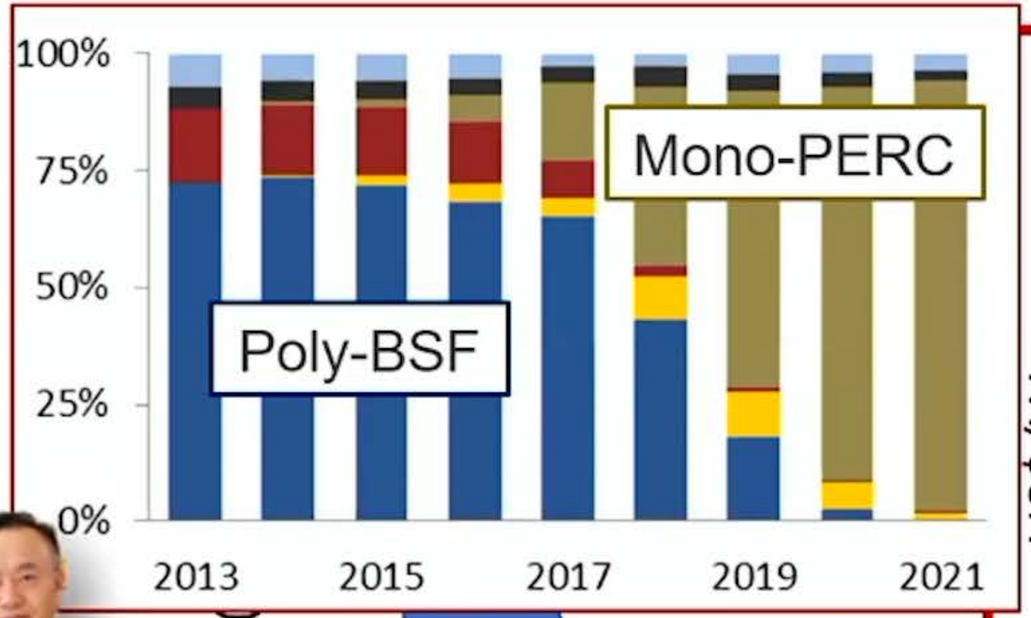
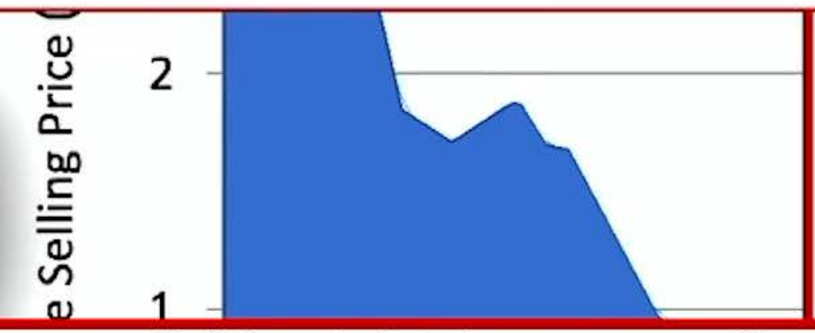
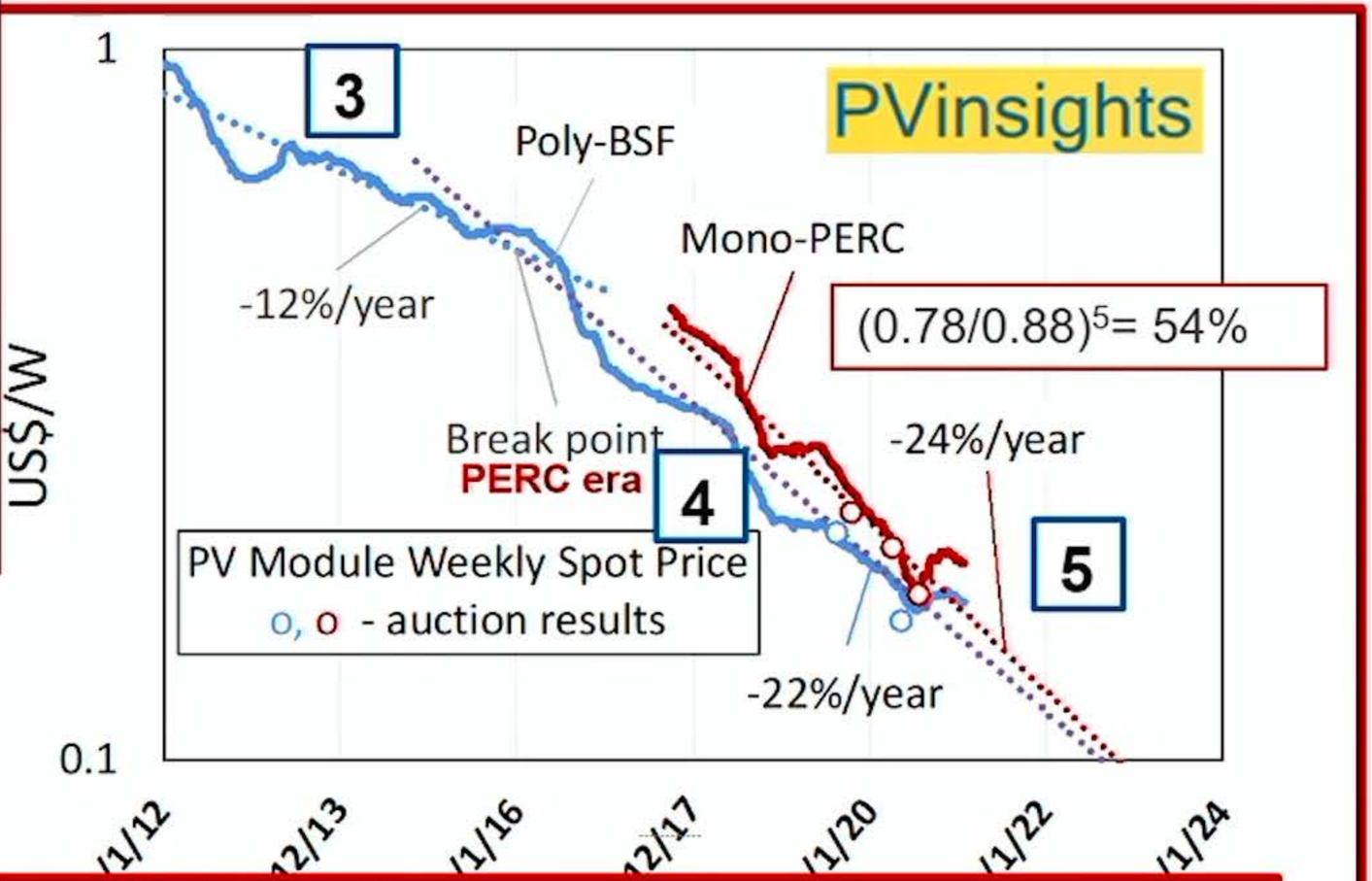






IEA says *(World Energy Outlook 2020):*

- *"solar – 'new king' of energy markets"*
- *"now the cheapest source of electricity in most countries"*
- *"now offers some of the lowest cost electricity ever seen"*

Ramez Naam

Home Speaking

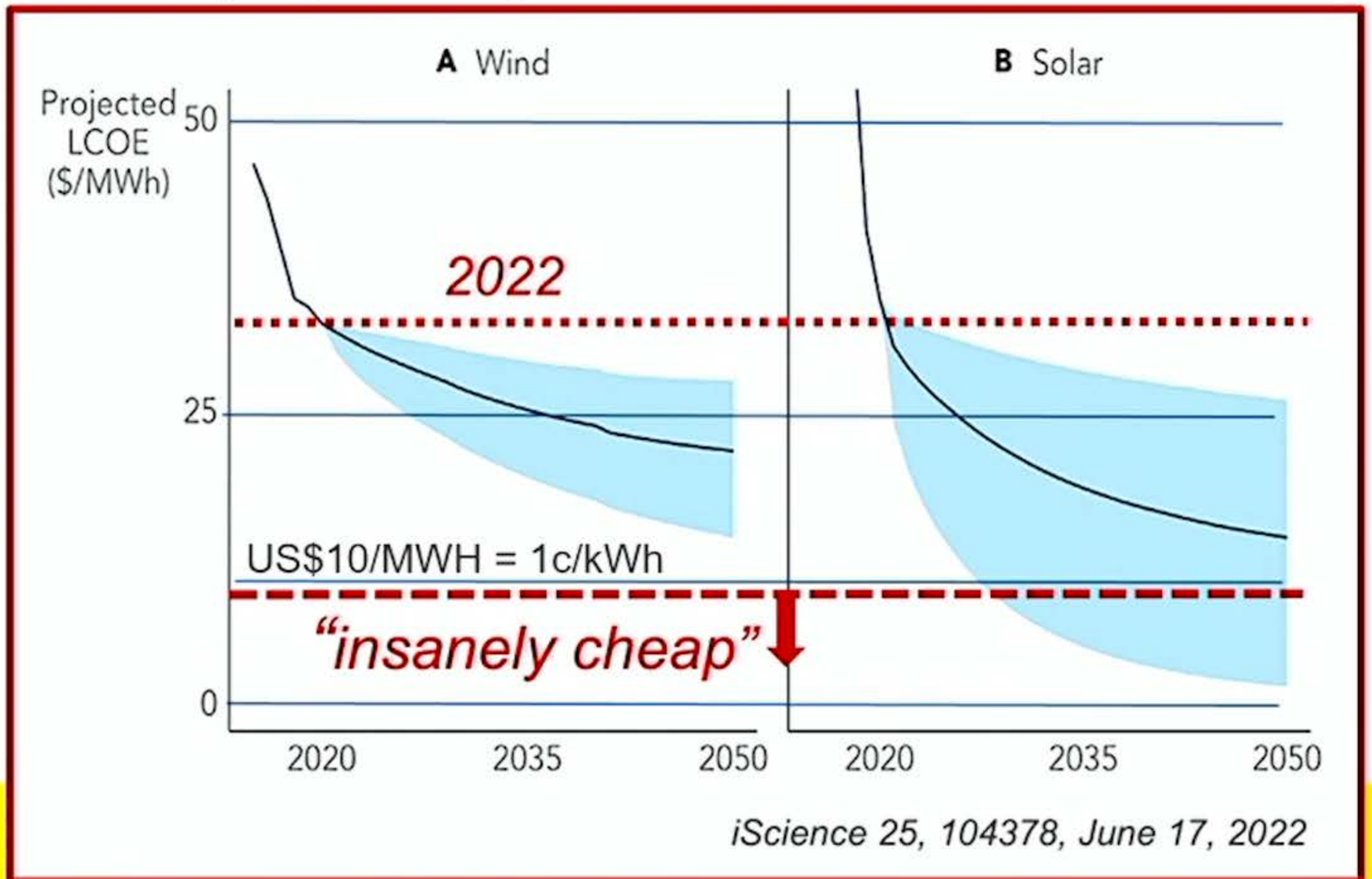
14 May, 2020

Solar's Future is Insanely Cheap (2020)

Carbon Tracker Initiative

The sky's the limit

Solar and wind energy potential is 100 times as much as global energy demand



iScience 25, 104378, June 17, 2022

Module cost history

Dr Zhengrong Shi (12th PhD student)

UNSW SYDNEY

Outline

1. Technology
2. Costs
3. **Climate Change Mitigation**

Net Zero by 2050

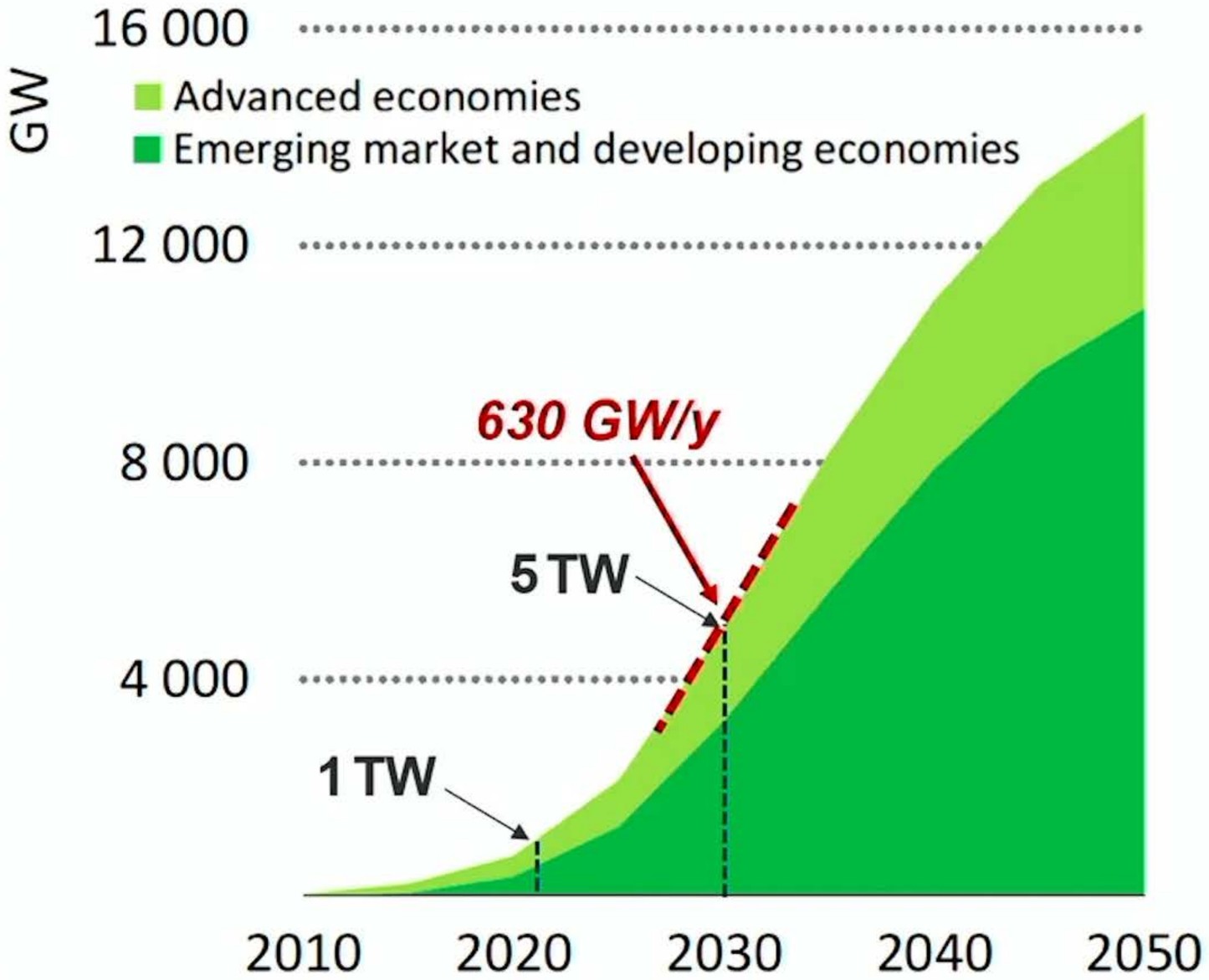
A Roadmap for the Global Energy Sector

International Energy Agency

"our pathway calls for scaling up solar and wind rapidly this decade"

May 2021

iea



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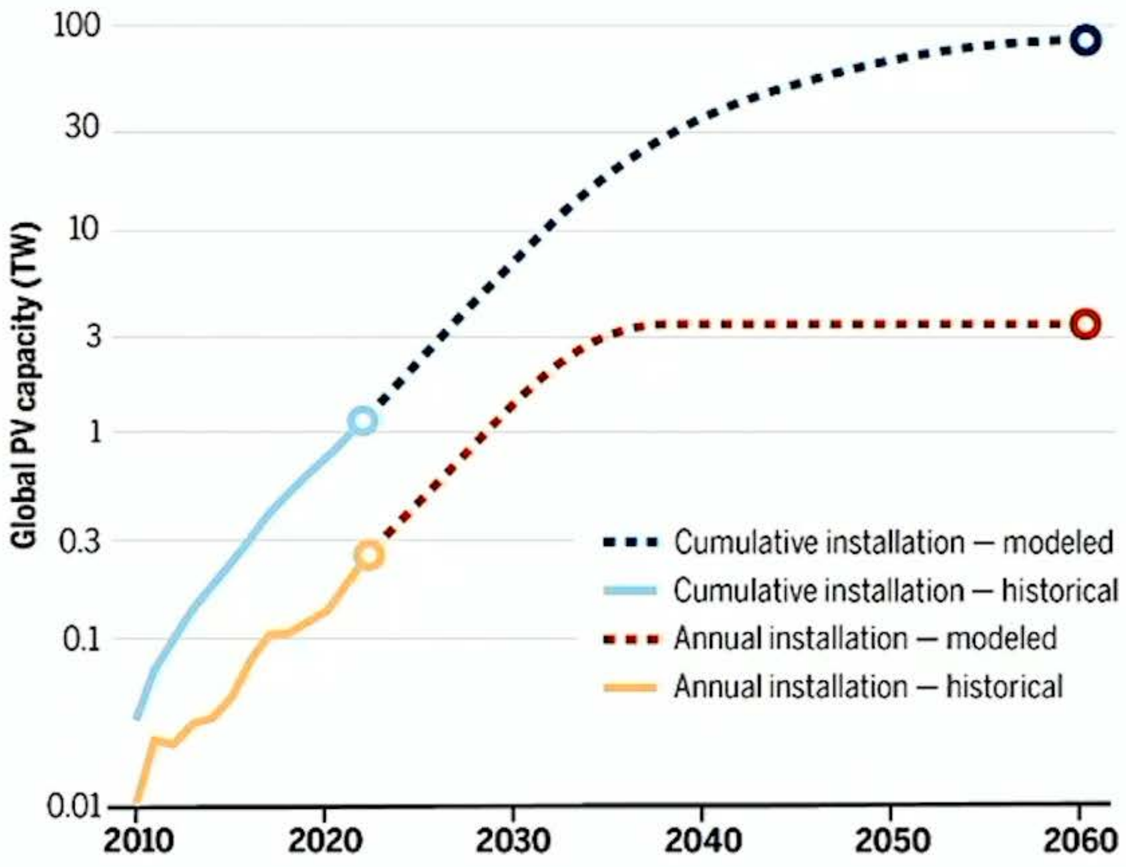
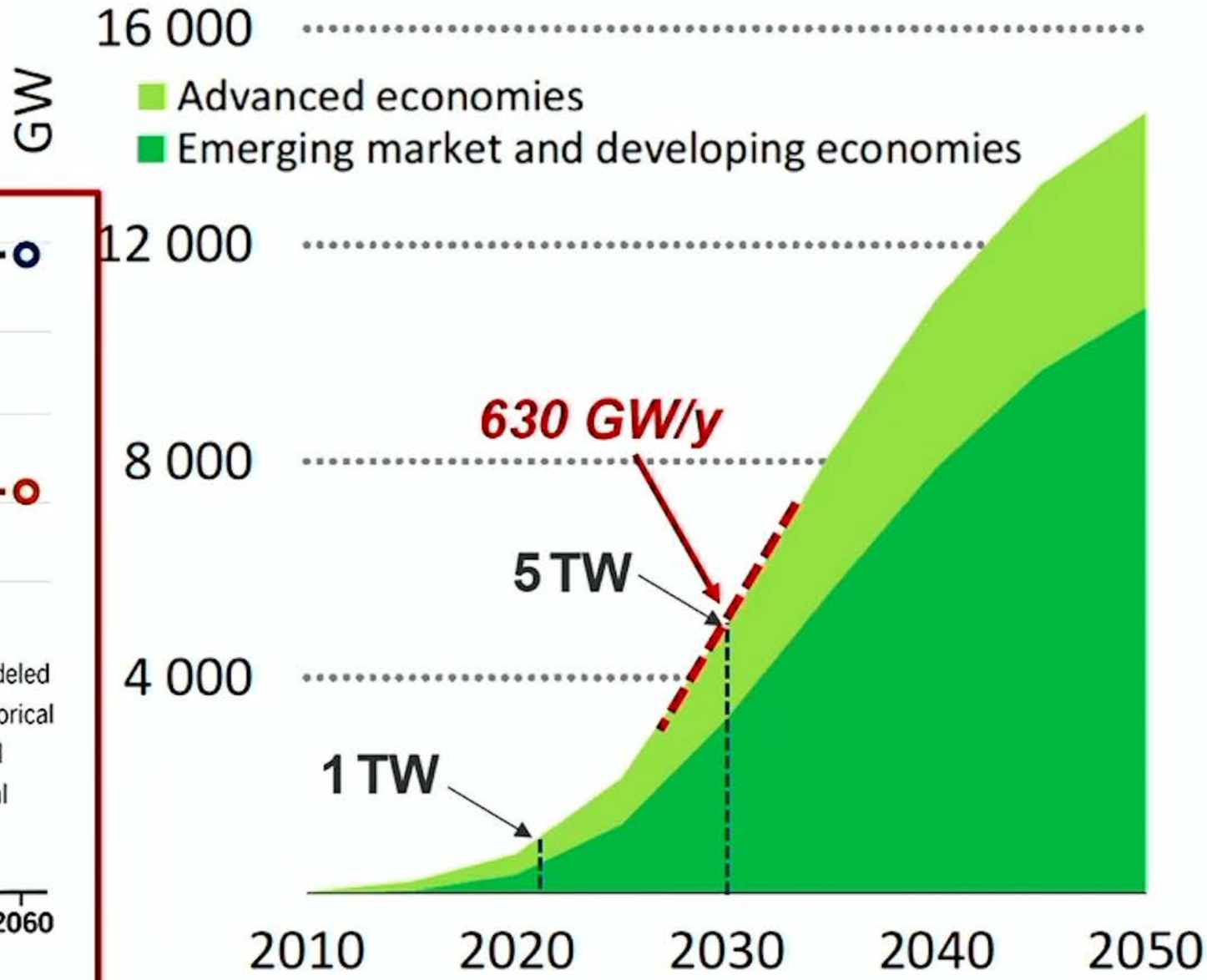
Net Zero by 2050



N Haegel et al. SCIENCE, APRIL 2023 • VOL 380 ISSUE 6640, p 39



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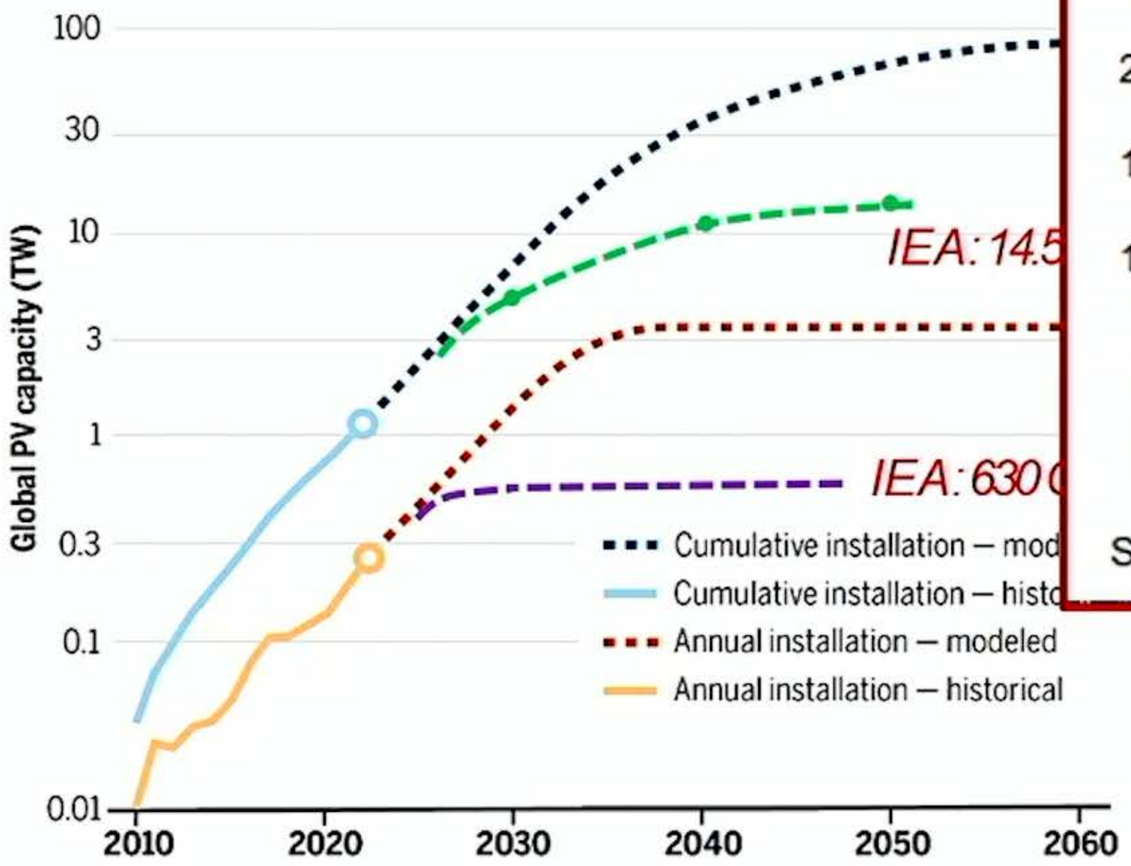
Net Zero by 2050



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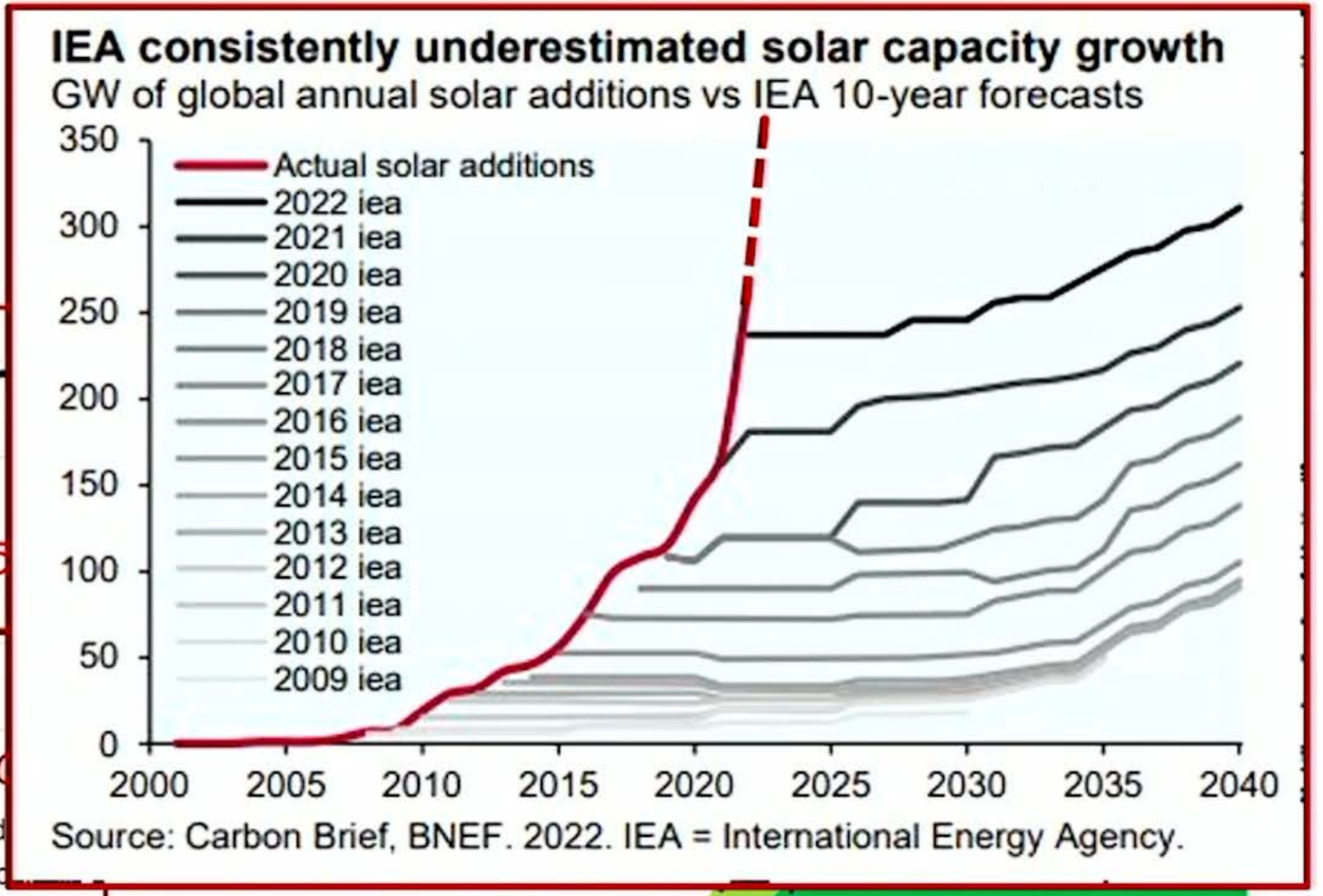

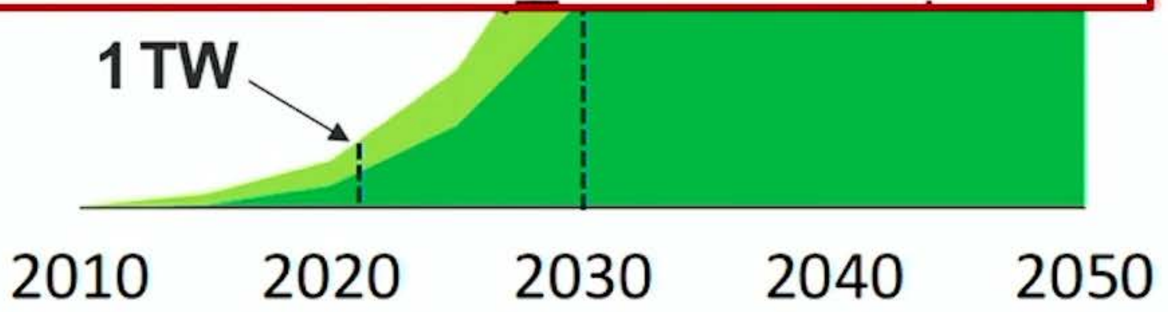

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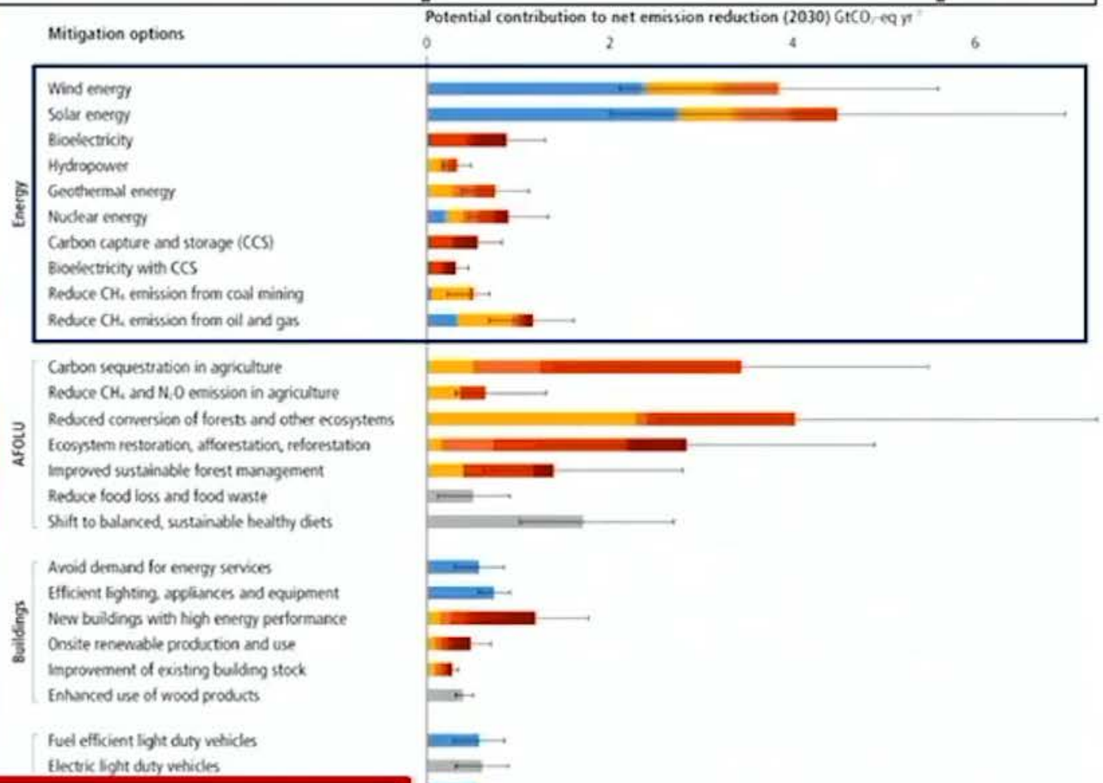
Mitigation options + costs & potential 2030 impact

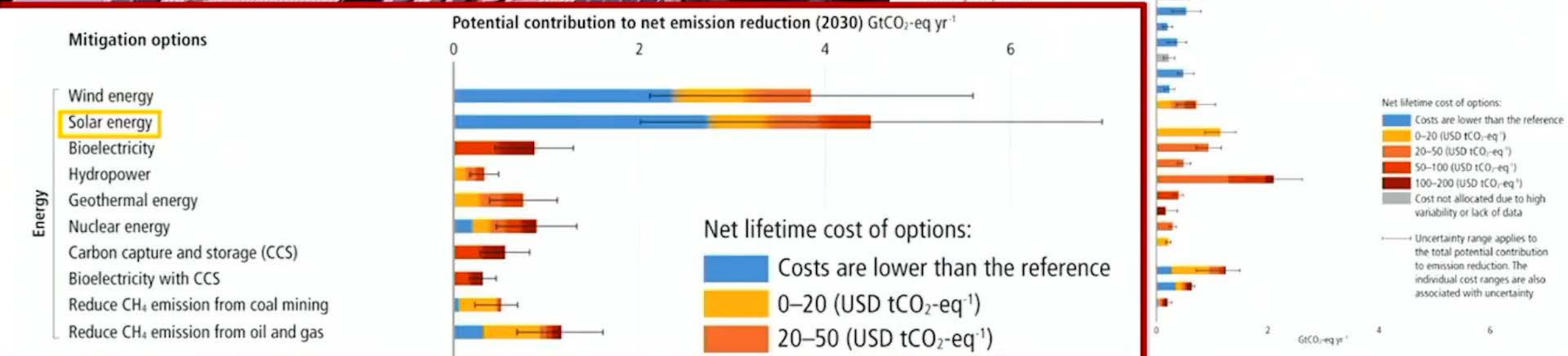
ipcc
INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2022

Mitigation of Climate Change

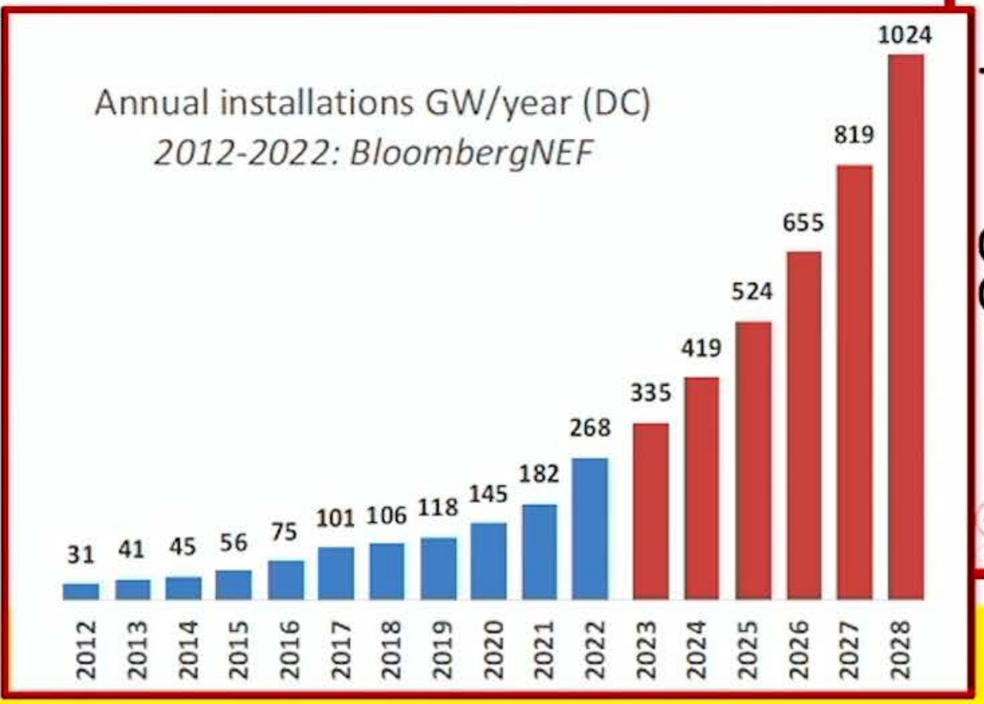
4 April 2022

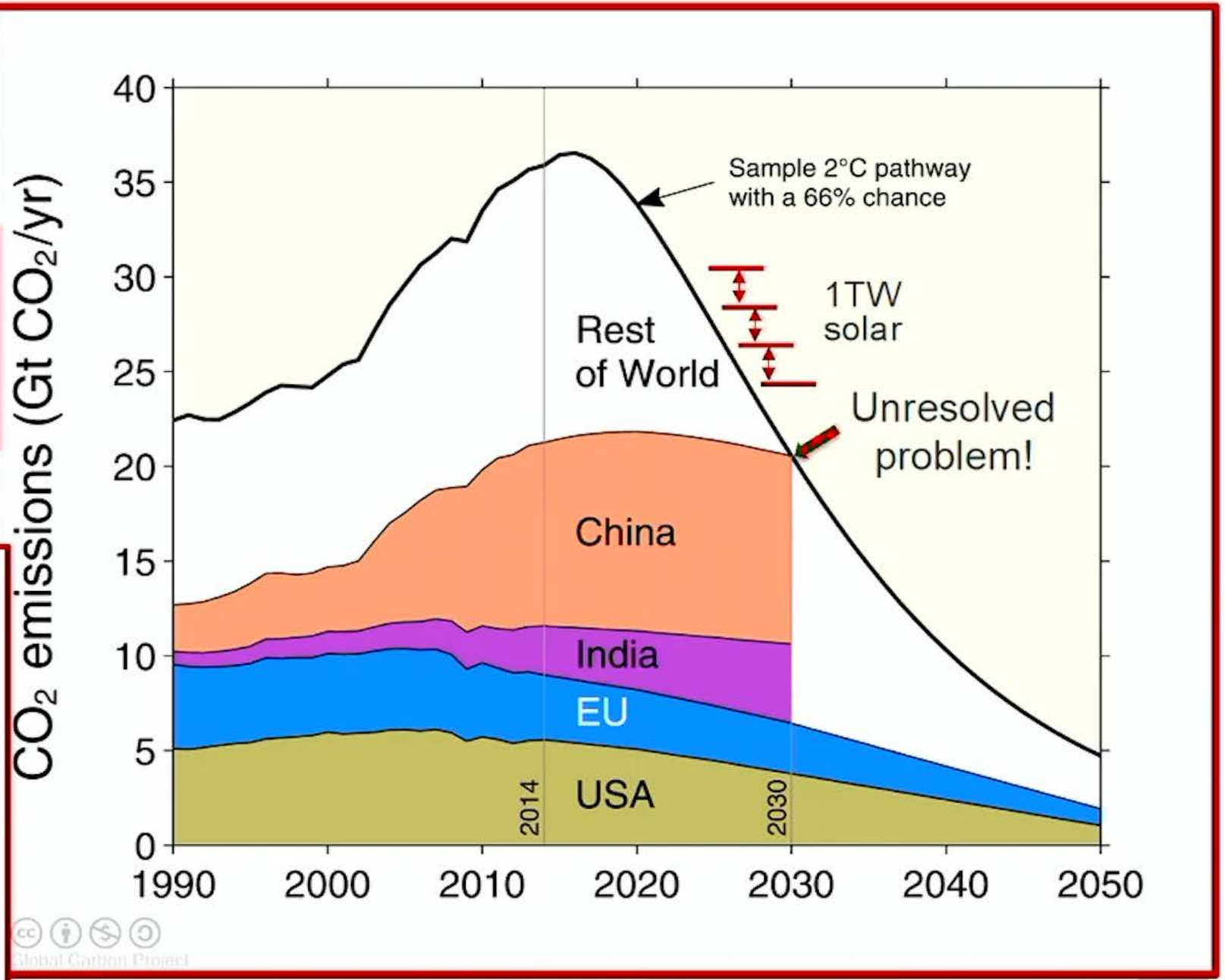




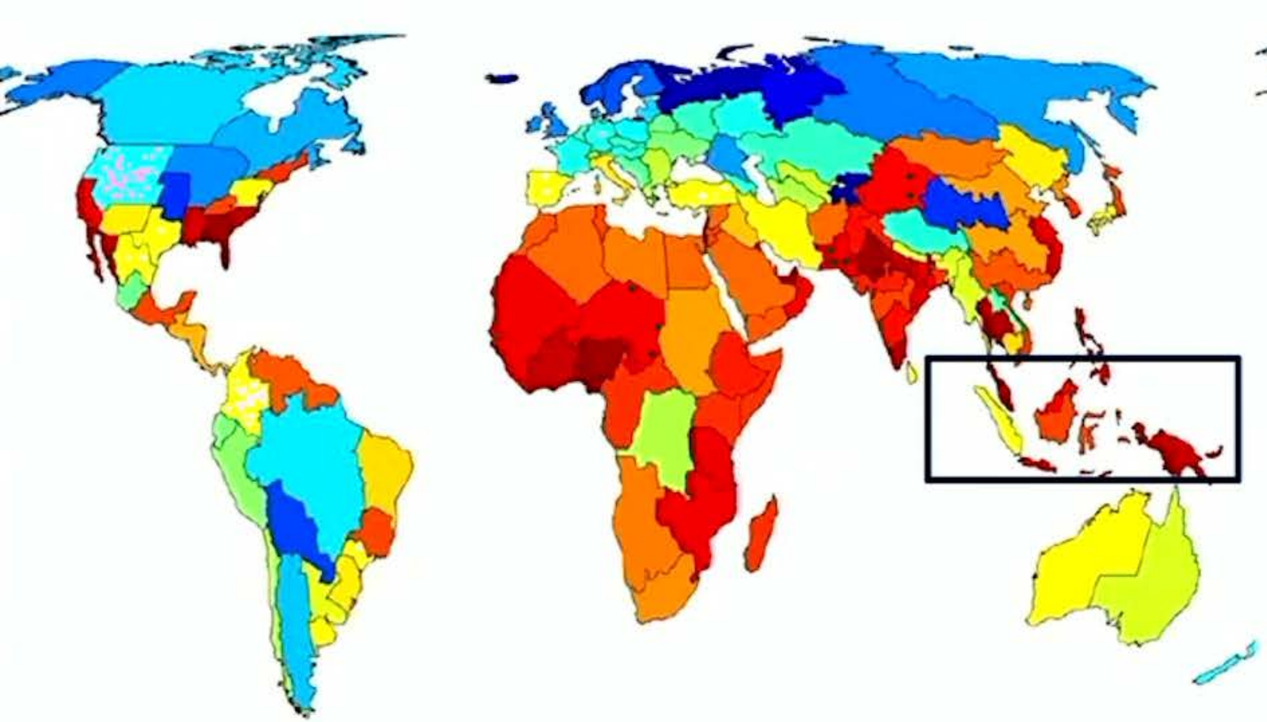
Impact 1TW/year

- *>400 GW/y in 2023*
- *doubling every 3 years*
- *2 doublings possible by 2030*
- *gives 1 TW/y by 2027 or 2028?*





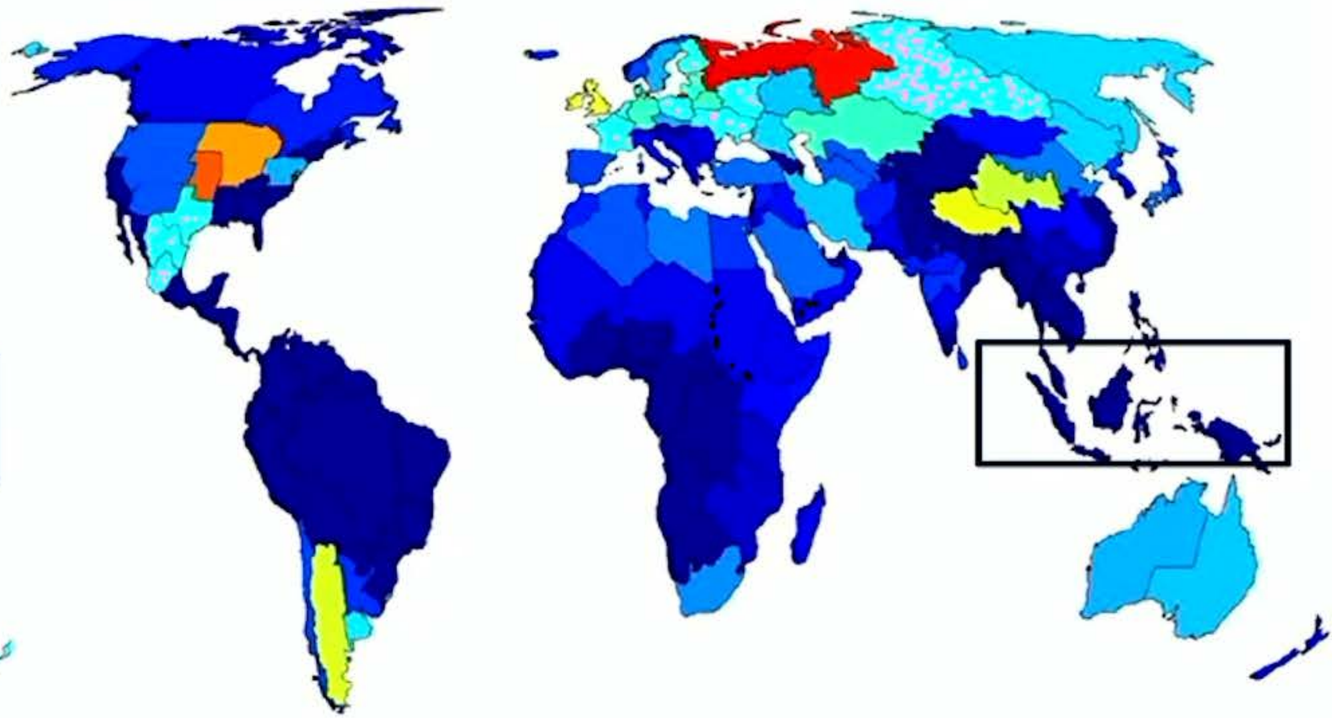
Zero carbon future: Solar, wind, hydro, storage



global weighted average: 68.6%

0 25 50 75 100

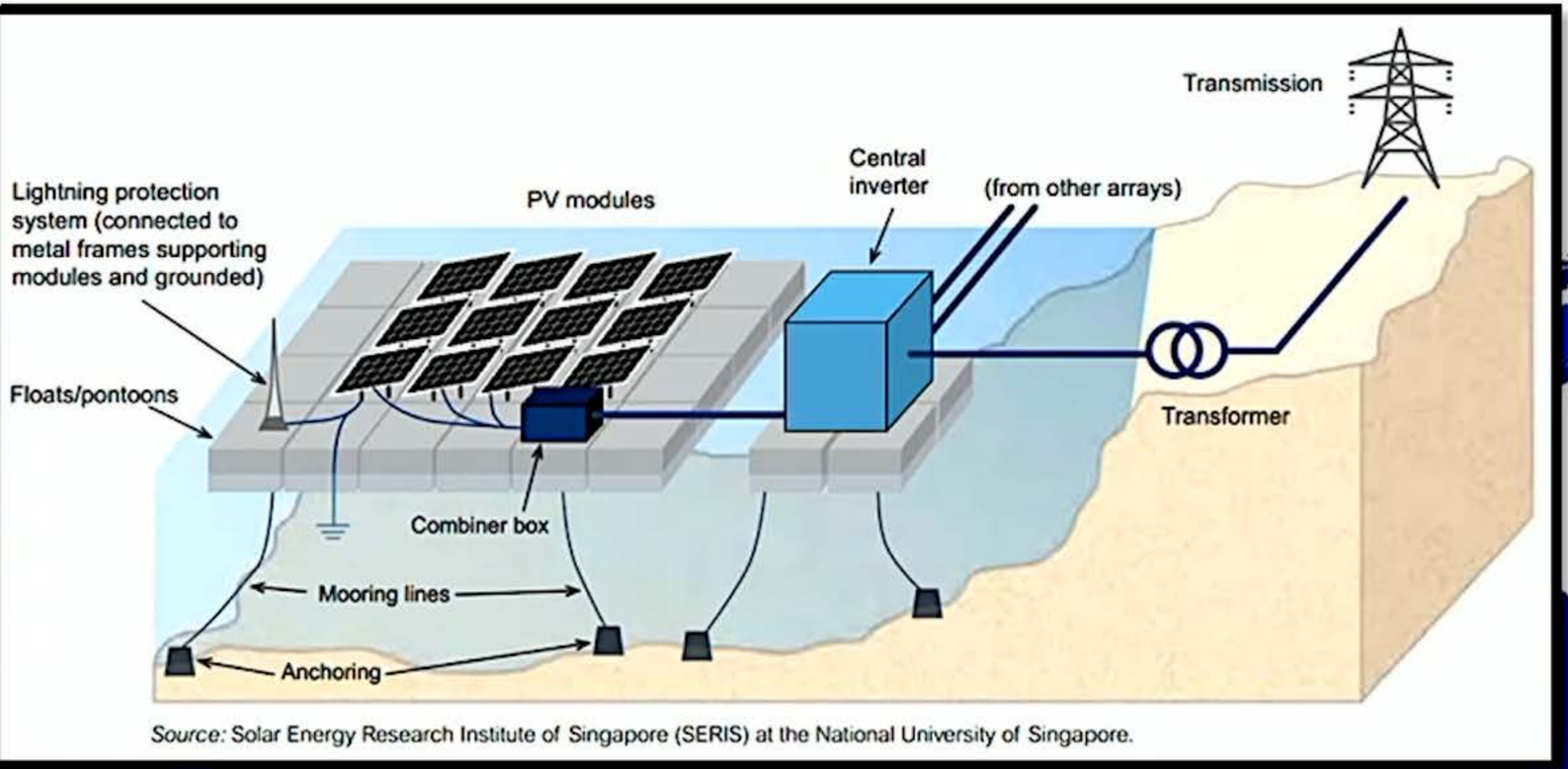
Solar PV total generation share (2050) [%]
(Total)



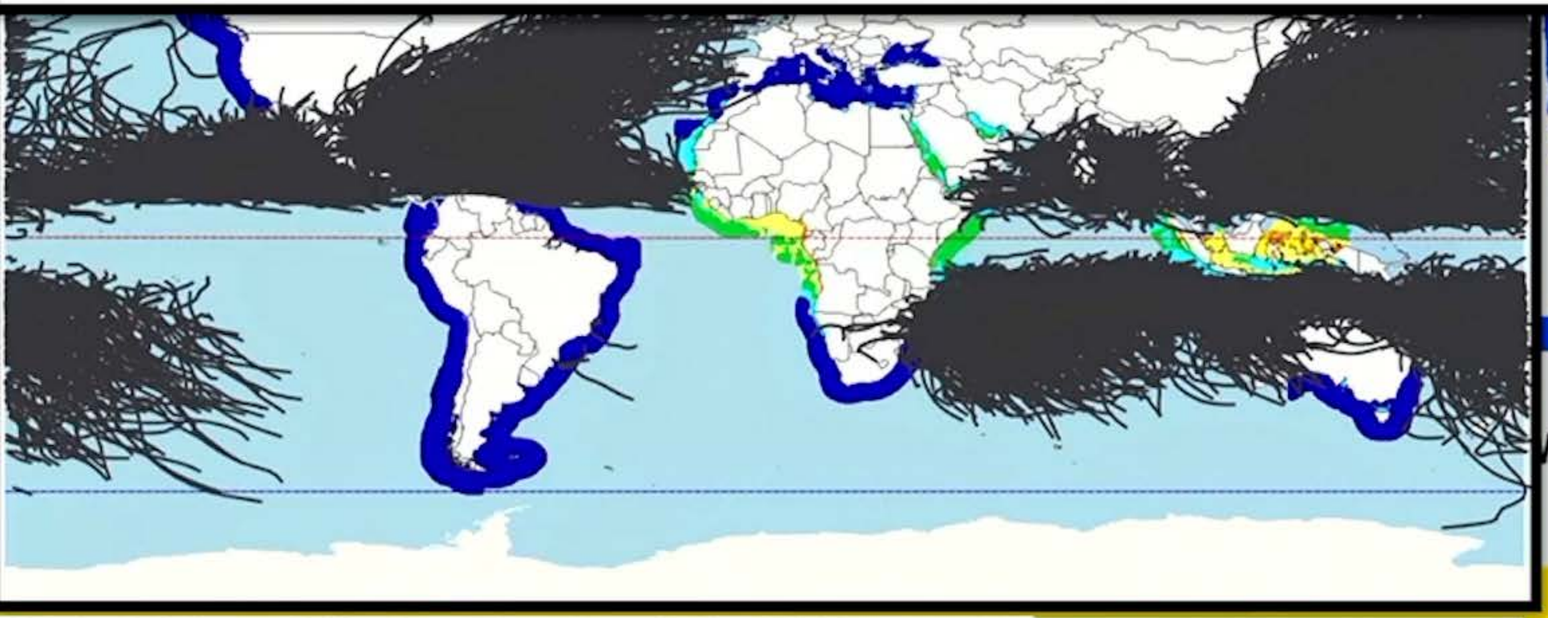
global weighted average: 18.3%

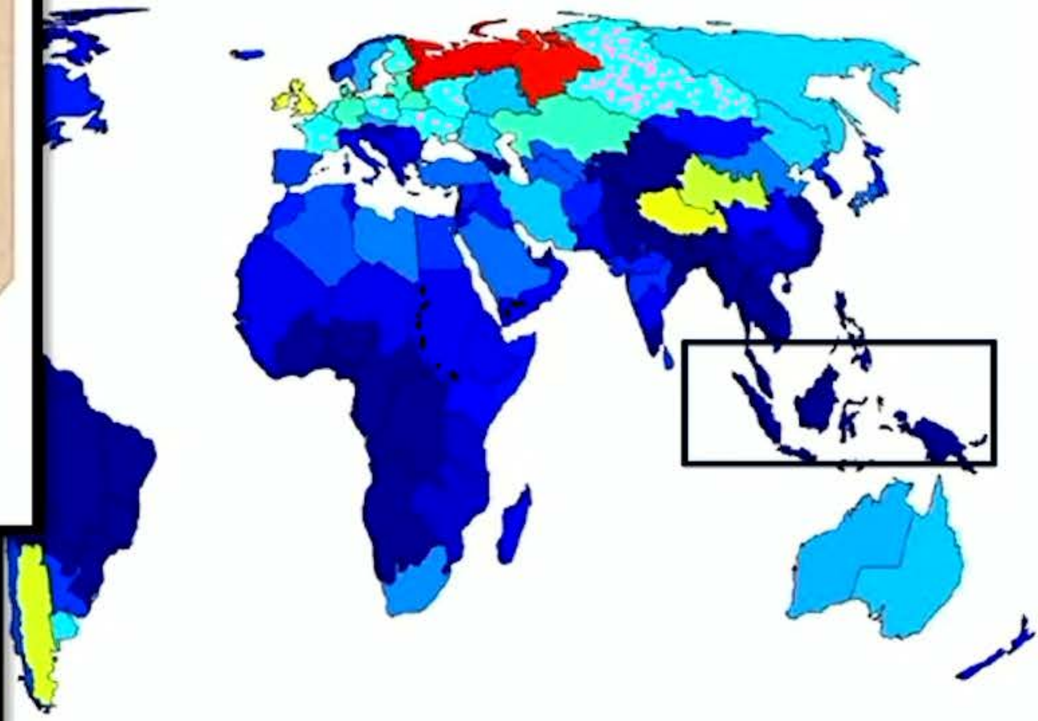
0 25 50 75 100

Wind total generation share (2050) [%]
(Total)



Source: Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore.





global weighted average: 18.3%

25 50 75 100

Wind total generation share (2050) [%]
(Total)

Global Atlas of Marine Floating Solar PV Potential *Solar* **2023**, *3*(3), 416-433;

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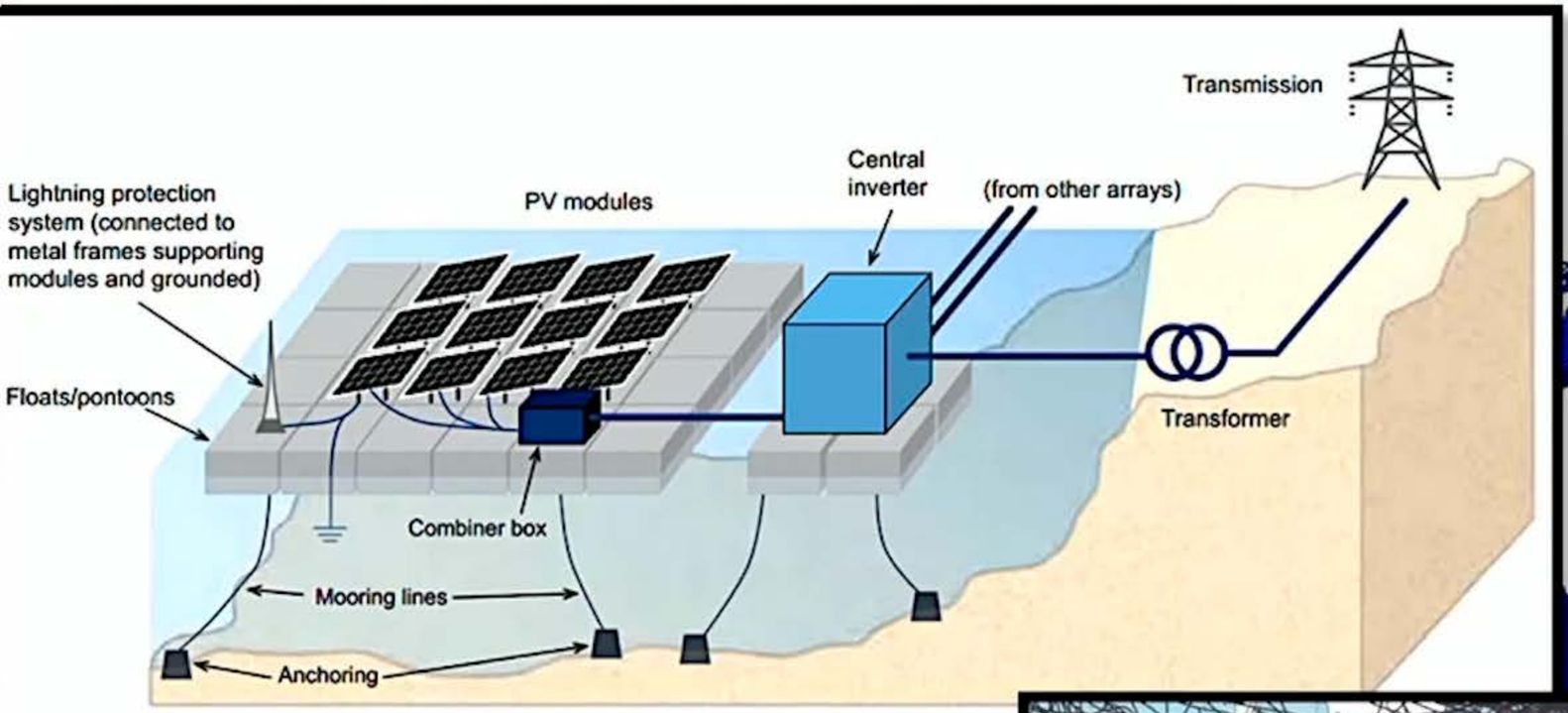

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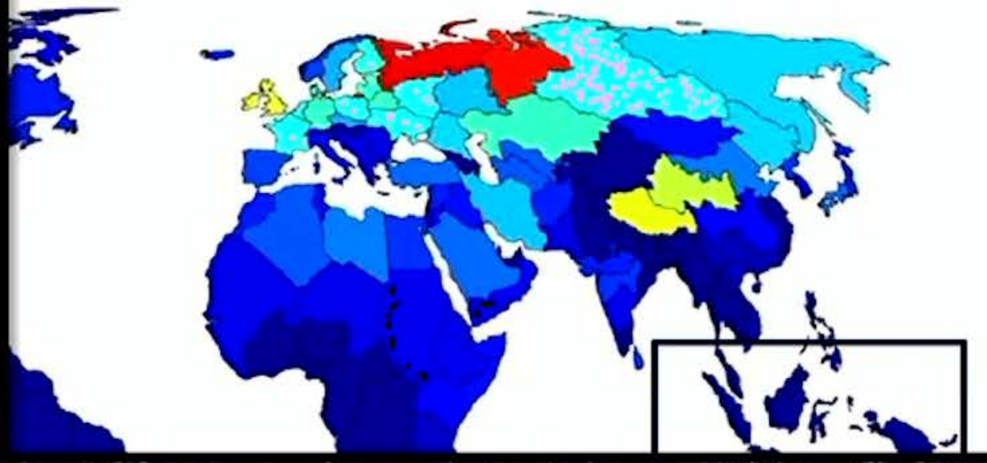
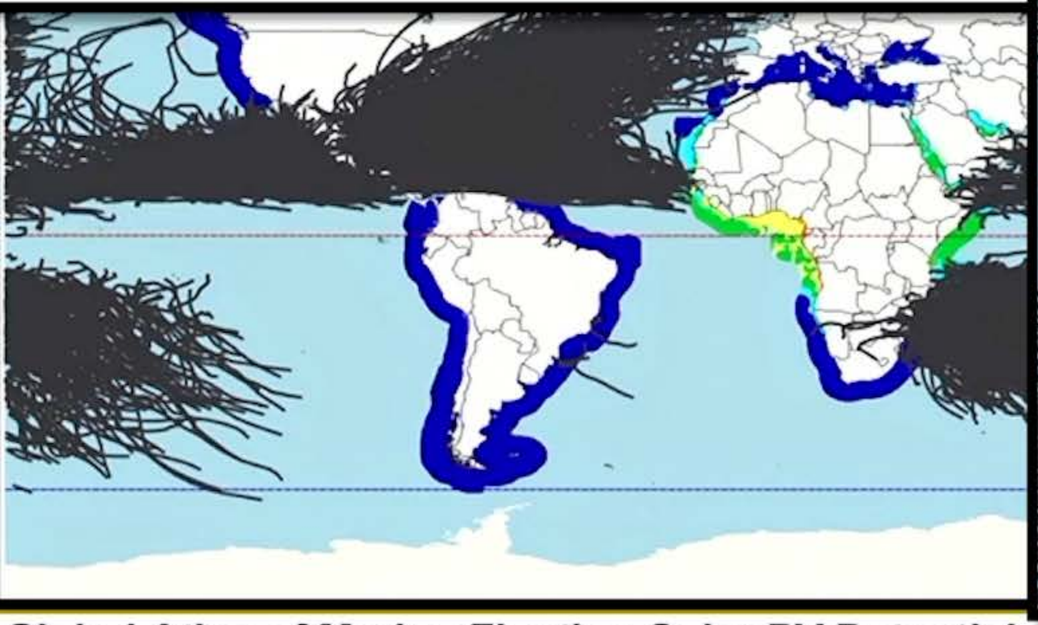
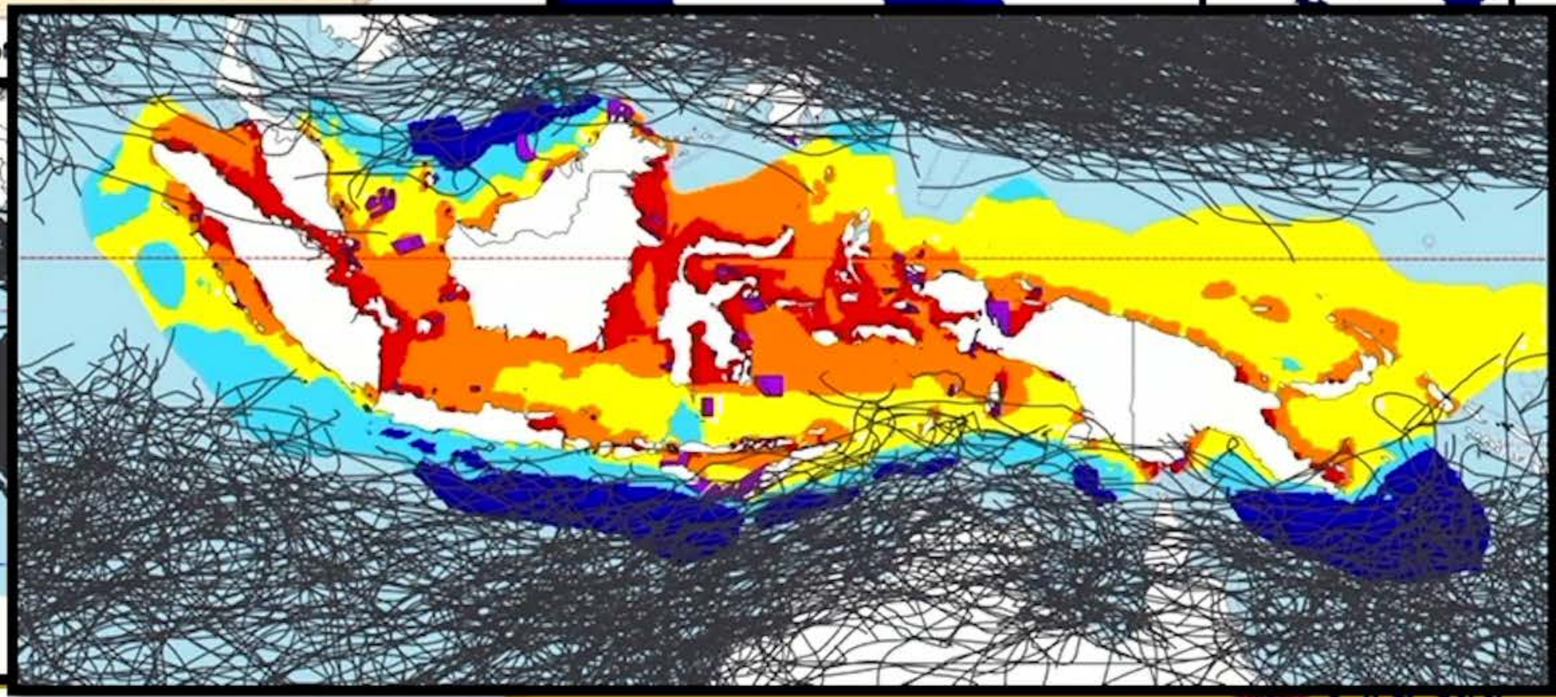






Global Atlas of Marine Floating Solar PV Potential *Solar* **2023**, *3*(3), 416-433;

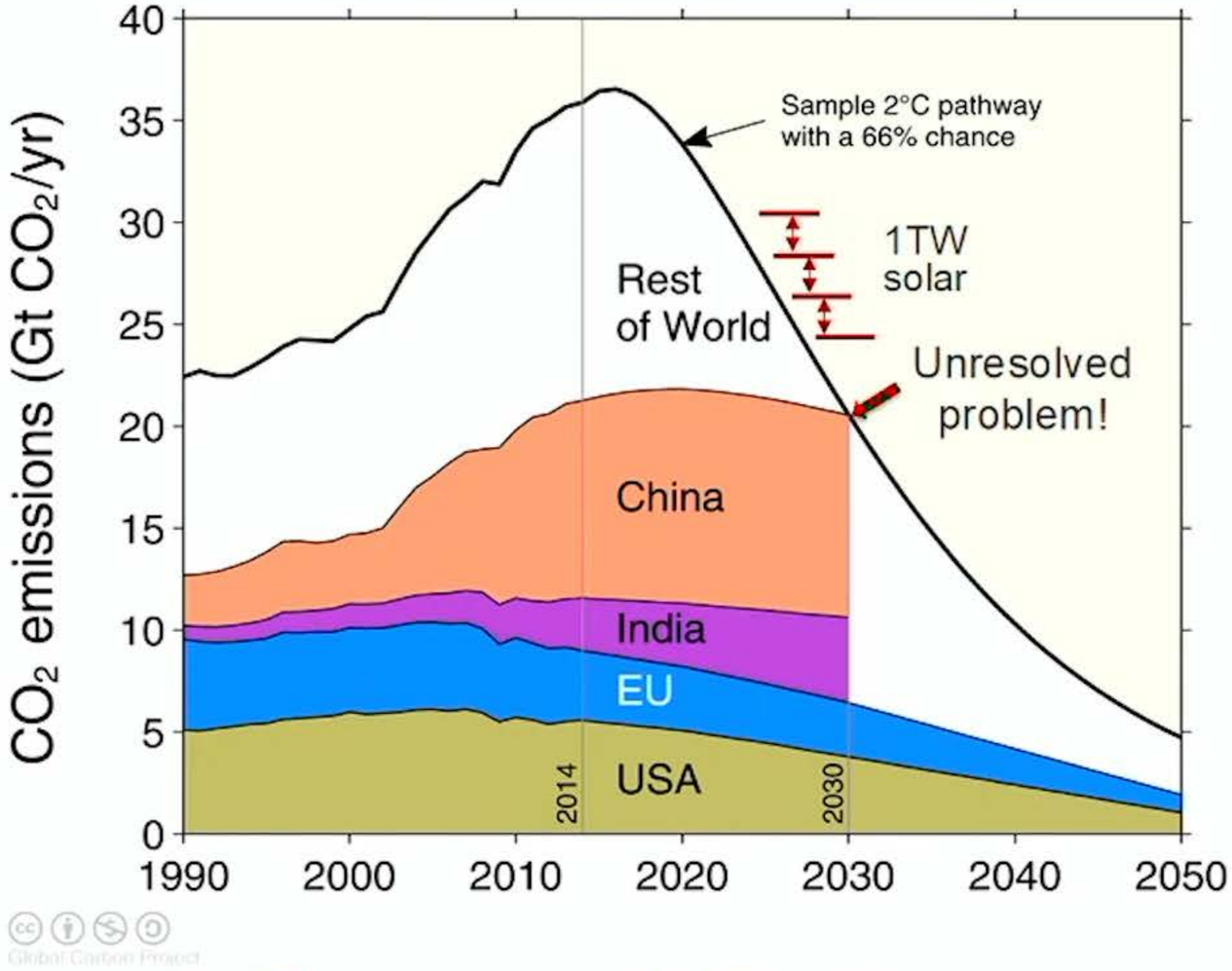
Solar photovoltaics: Recent developments & climate change mitigation

. To become "insanely cheap"?
(Ramez Naam)

. New technology accelerates pace of change

. 10c/Watt (US$) modules imminent (& 1c/kWh electricity prices in near future)!

. Solar to play a major role in mitigating global warming.



ARENA

Australian Government
Australian Renewable Energy Agency

ACAP

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