Faculty of Engineering
School of Photovoltaic and Renewable Energy Engineering

Path towards sustainable, low-cost PV systems for terawatt scale deployment

2022/TRAC003
2022/TRAC010

2023 Asia-Pacific Solar Research Conference, 7th December 2023

Associate Professor Brett Hallam

Contributors: Yuchao Zhang, Moonyong Kim, Li Wang, Ran Chen, Atom Chang, Sisi Wang, Nathan Chang

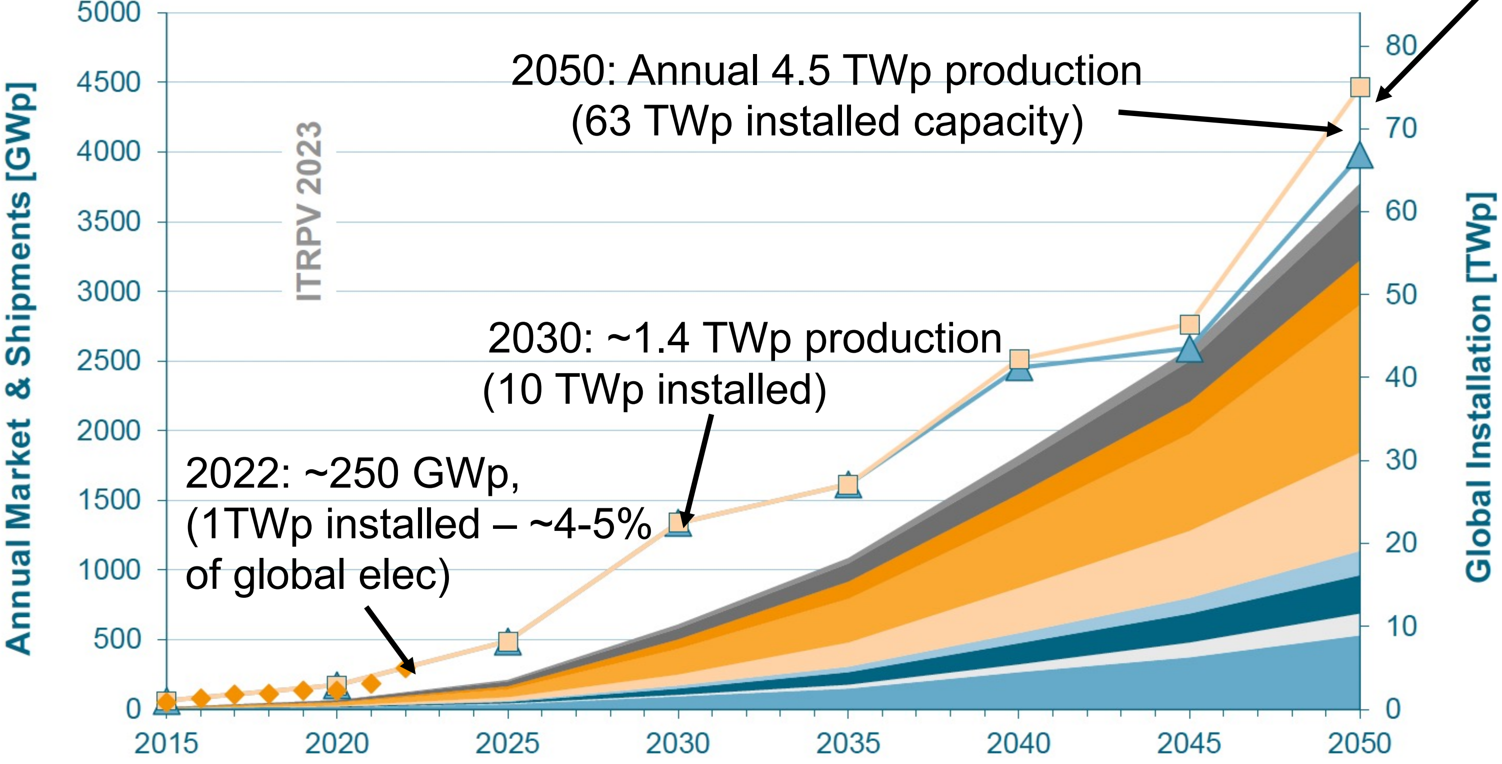
School of Photovoltaic and Renewable Energy Engineering, UNSW Sydney, Australia

2023: Silicon 2 Solar

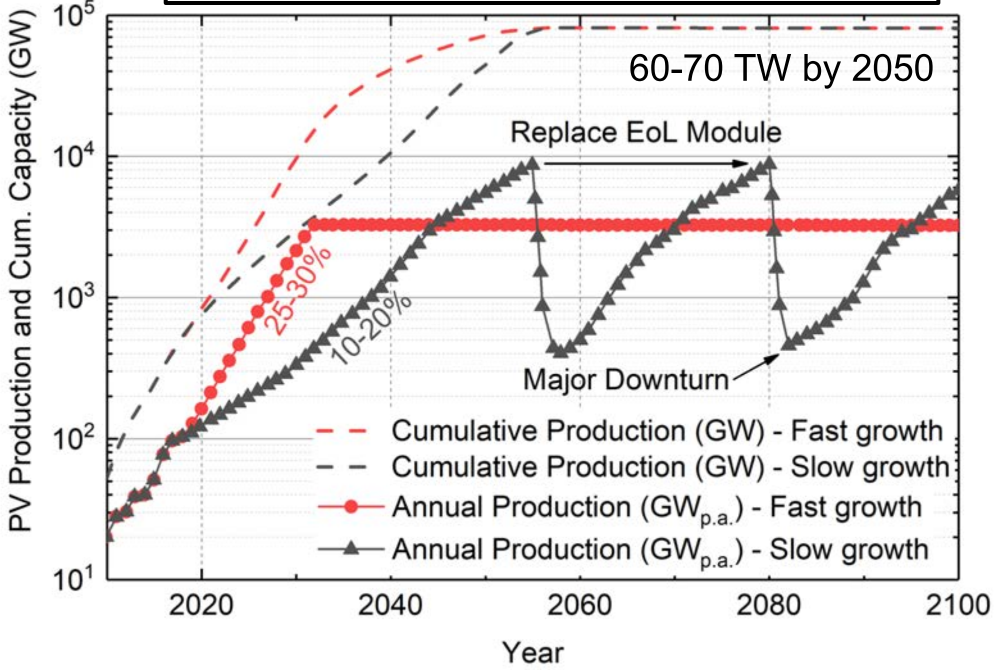
Motivation – The Time-Bomb is Rapidly Ticking to TW Scale PV

- ‘Net-zero’ emissions required by 2050 to give us the chance to limit warming to 1.5°C
  - PV/Wind >20 TW installed by 2050 [1]
- ‘Broad electrification’: 60 TW (69% of primary energy demand) by 2050 - (ITRPV 2022)

60 TW of PV by 2050 means an average of 2.1 TW/yr STARTING in 2023 (not realistic!), OR…..25-30% p.a. growth to 3 TW/yr by 2030



Digitised from P. Verlinden, J. Renewable Sustainable Energy 12, 053505 (2020);

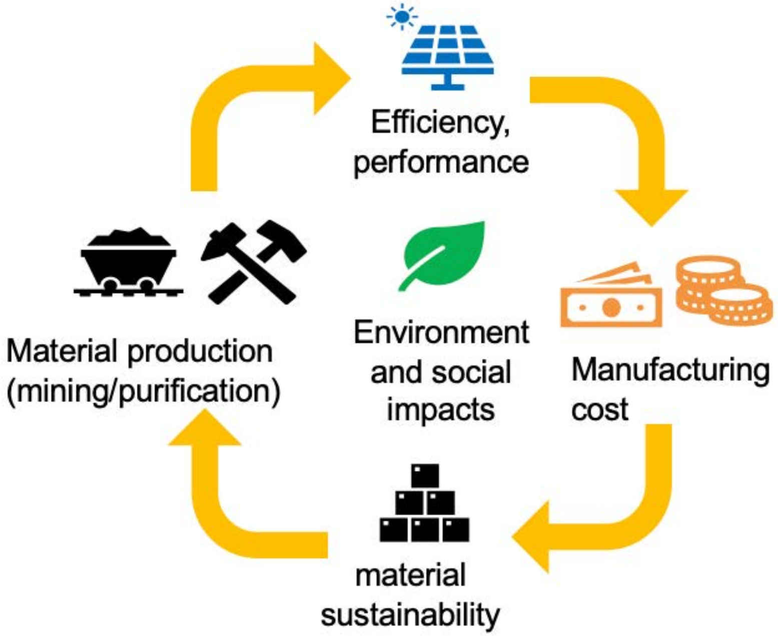


[1] IEA – Net zero by 2050. 2021. https://www.iea.org/reports/net-zero-by-2050
Adapted from 2022 ITRPV – www.itrpv.net. Graphic from https://www.istockphoto.com/illustrations/time-bomb

UNSW SYDNEY

Sustainability

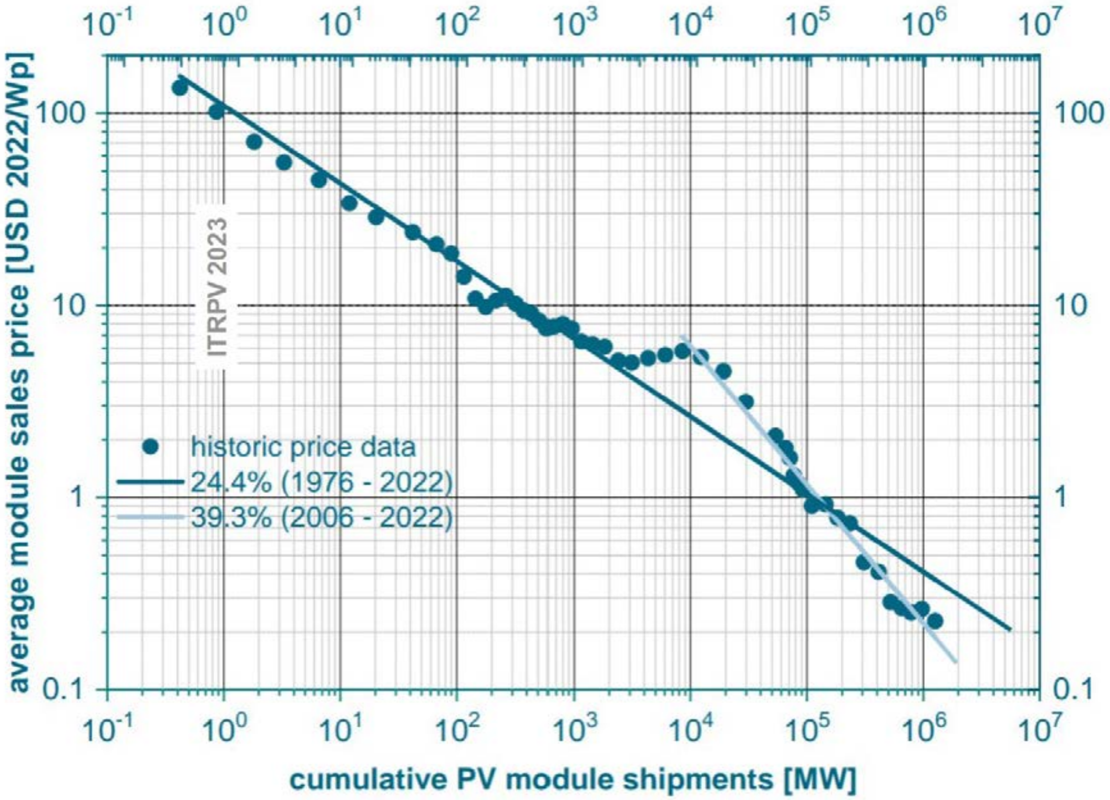
- Sustainability covers three key pillars (below)
- For sustainable TW scale PV deployment we need:
  - **Environmental**
    - Responsible production
    - Manage resource depletion
    - Reduce emissions generated
    - Waste/EOL management etc
  - **Economics**
    - Affordable, low-cost solar
  - **Social impacts**
    - Ethical supply chains
    - Affordable, clean energy

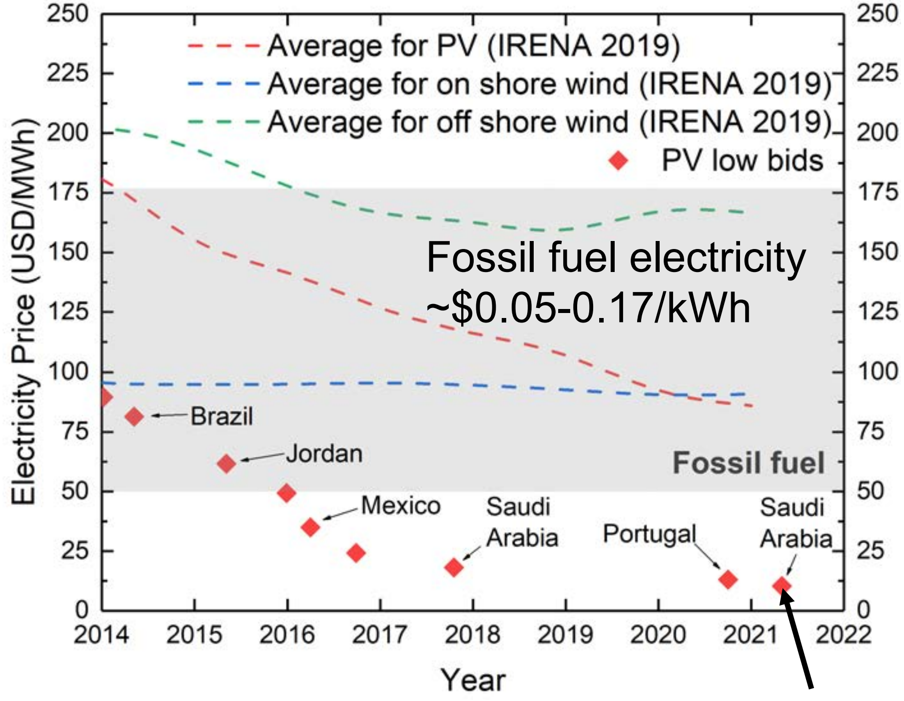


Solar Cells and Panels are Now a Low-Cost Commodity

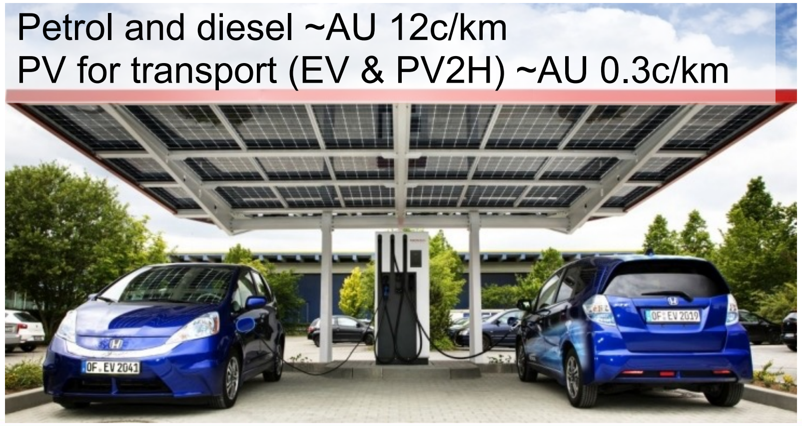
M.E. Mondejar et al. Science of The Total Environment (2021) 148539.

- Dramatic cost reductions enabling multi-TW markets
- Cost of solar panels heavily driven by material costs





PV electricity ~$0.01/kWh



Solar Cells and Panels are Now a Low-Cost Commodity

M.E. Mondejar et al. Science of The Total Environment (2021) 148539.

- Dramatic cost reductions enabling multi-TW markets
- Cost of solar panels heavily driven by material costs
  - Module price increase from $0.20/W to $0.30/W in 2021 due to material/shipping increases [1]

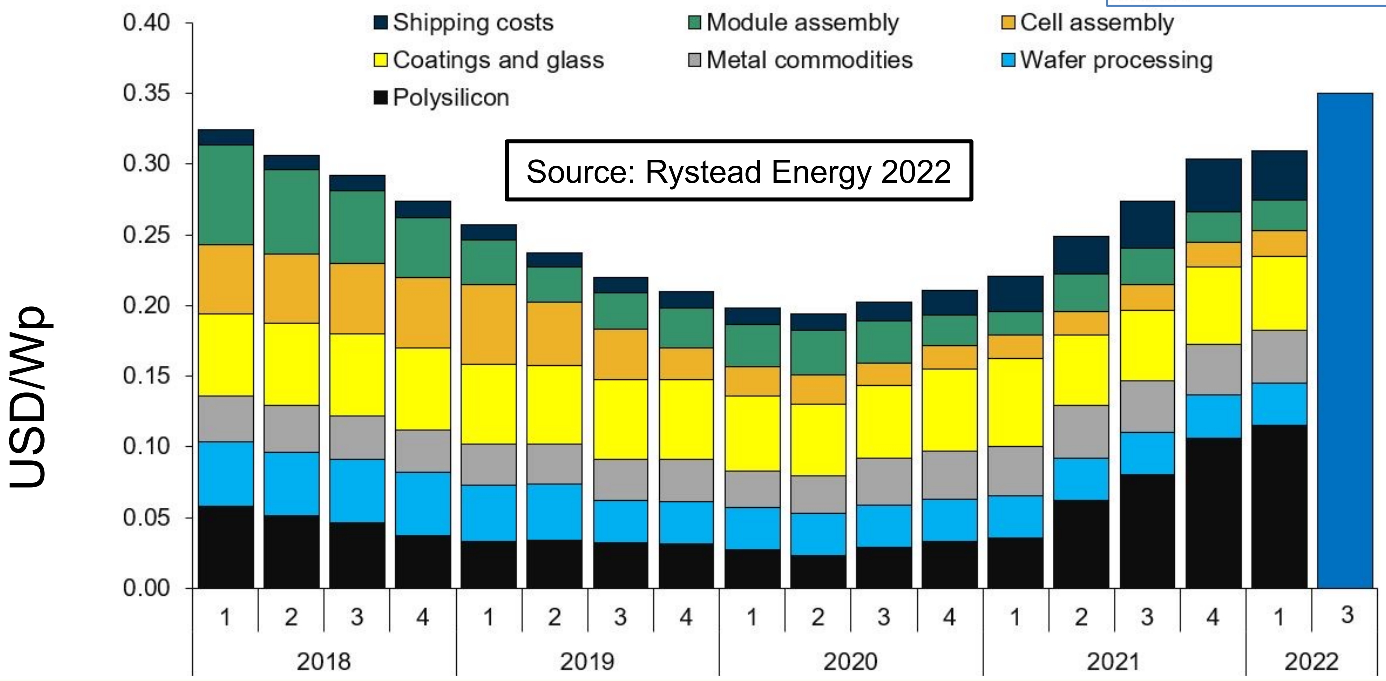

ANALYSIS | October 26, 2021

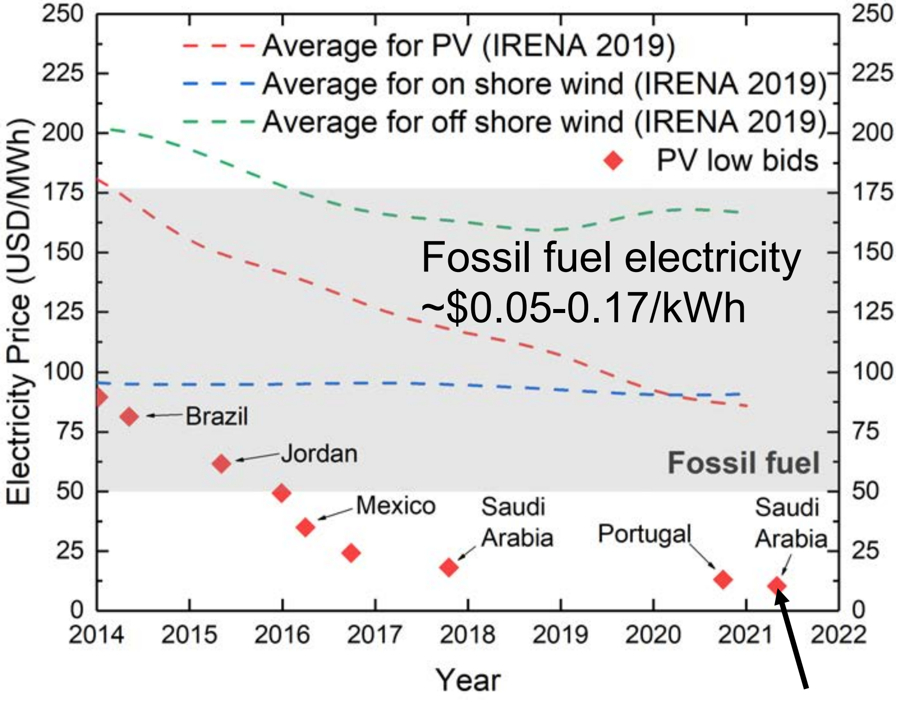
Price surges push up solar costs, threatening half of 2022 pipeline

Solar power shines a guiding light for expensive, newly-emerging renewables. After a spectacular fall in cost, what barriers will solar need to overcome for greater affordability?

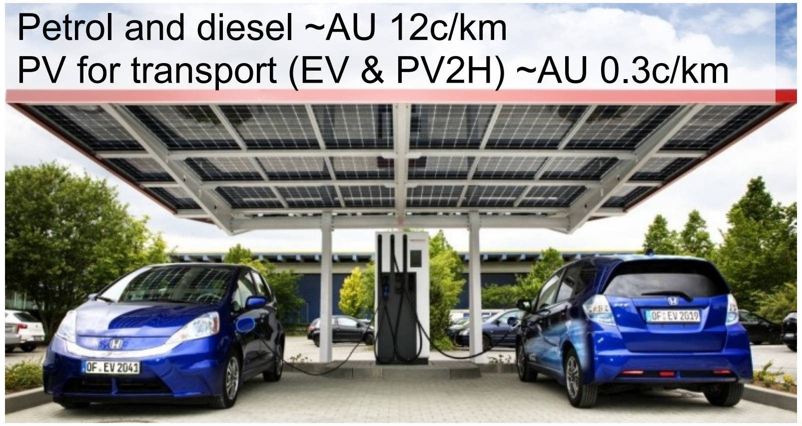
By Matt Farmer

Figure 3: Evolution in solar PV module costs by quarter, 2018-2022*
USD per watt peak (Wp)





PV electricity ~$0.01/kWh



[1] https://www.rystadenergy.com/newsevents/news/newsletters/SupplyChainArchive/supply-chain-march-2022/
https://www.power-technology.com/analysis/solar-price-raw-material-costs-shortage-silver-polysilicon-aluminium-steel-copper/

Solar Cells and Panels are Now a Low-Cost Commodity

M.E. Mondejar et al. Science of The Total Environment (2021) 148539.

- Dramatic cost reductions enabling multi-TW markets
- Cost of solar panels heavily driven by material costs
  - Module price increase from $0.20/W to $0.30/W in 2021 due to material/shipping increases [1]

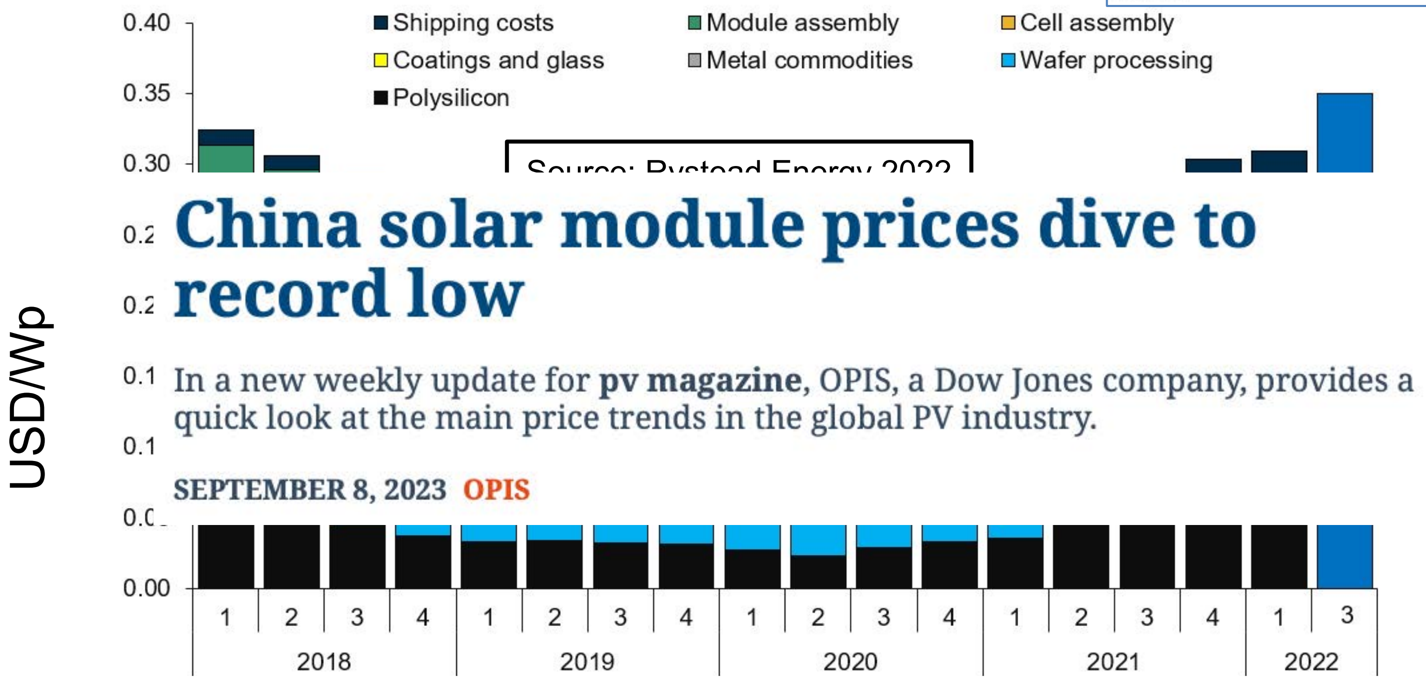

ANALYSIS | October 26, 2021

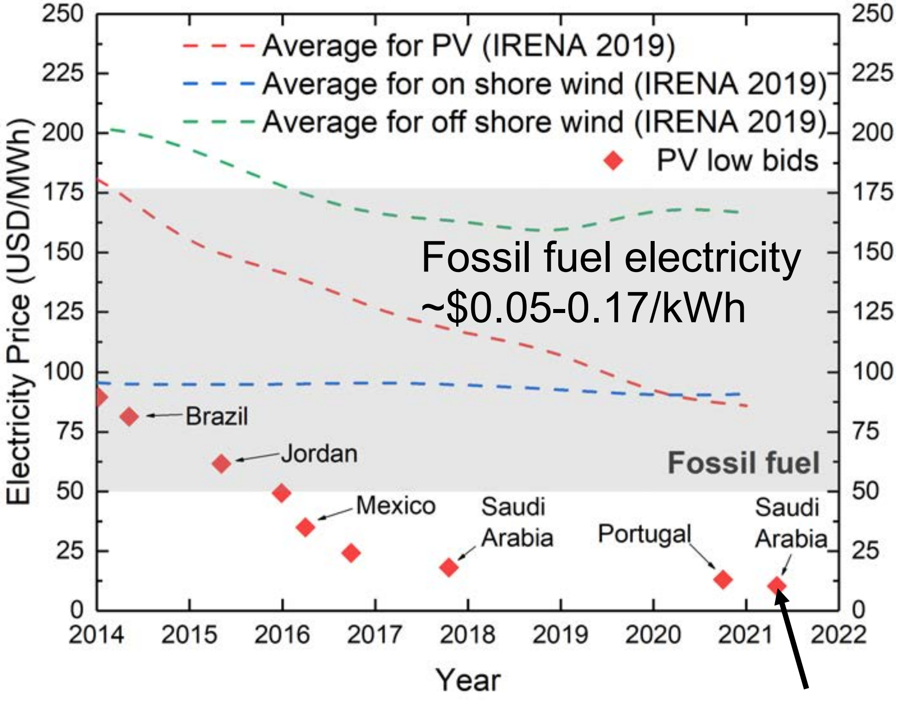
Price surges push up solar costs, threatening half of 2022 pipeline

Solar power shines a guiding light for expensive, newly-emerging renewables. After a spectacular fall in cost, what barriers will solar need to overcome for greater affordability?

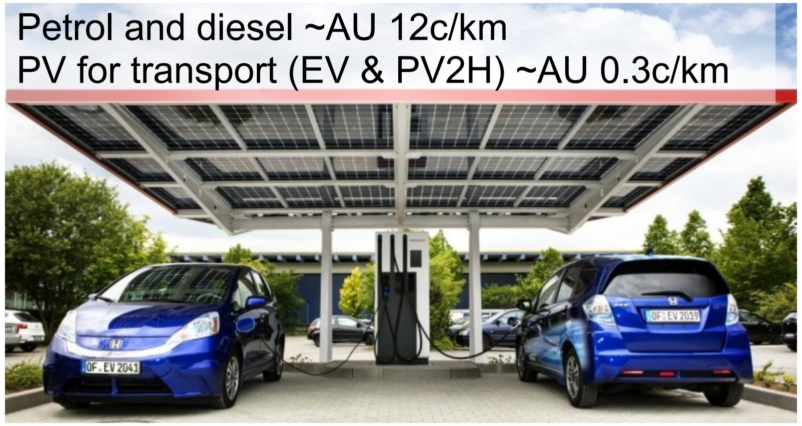
By Matt Farmer

Figure 3: Evolution in solar PV module costs by quarter, 2018-2022*
USD per watt peak (Wp)





PV electricity ~$0.01/kWh

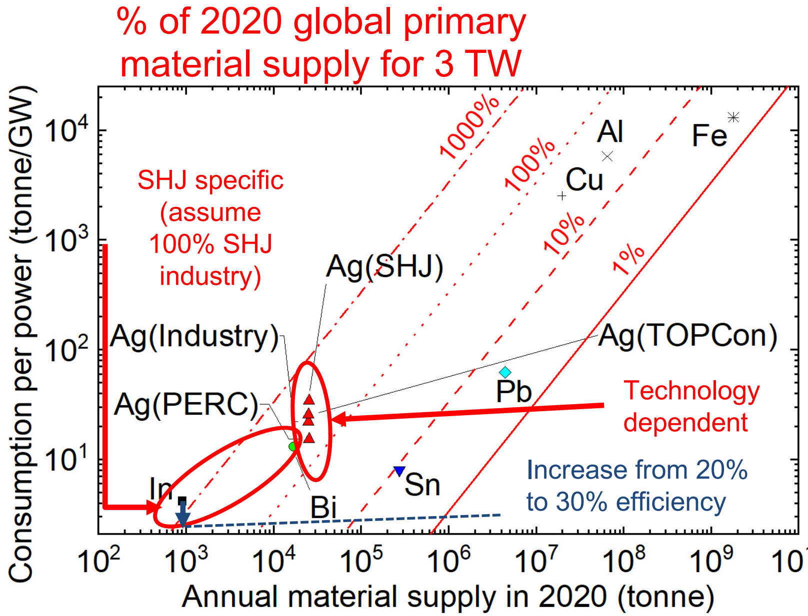


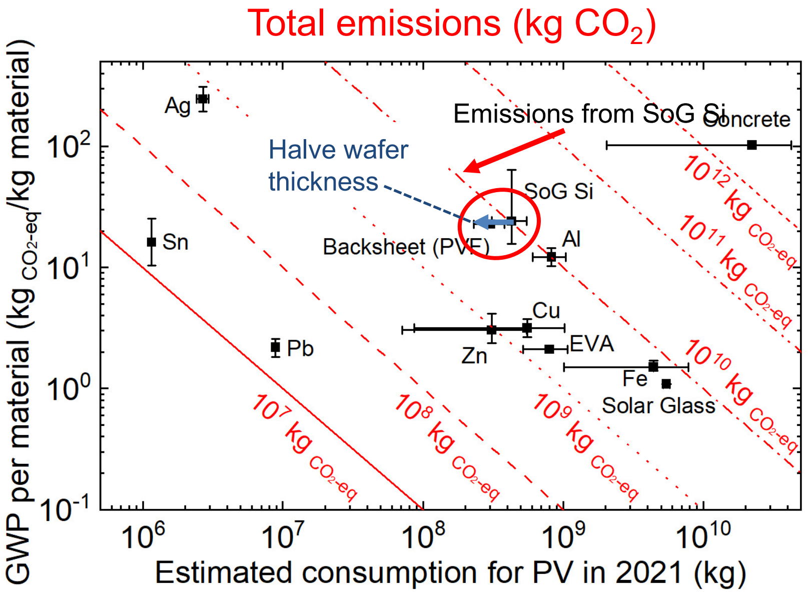
[1] https://www.rystadenergy.com/newsevents/news/newsletters/SupplyChainArchive/supply-chain-march-2022/
https://www.power-technology.com/analysis/solar-price-raw-material-costs-shortage-silver-polysilicon-aluminium-steel-copper/

Shifting Primary Focus from Efficiency or Cost to Material Consumption

- TW Scale PV will require massive quantities of materials/metals
  - Need careful technology choices without adding new challenges
- **Sustainable supply: define SMC as capacity using 20% of global primary material supply (US Geological Survey [1])**
  - **30-year module life – can't use secondary supply**
- **BUT** also need to consider environmental impact (mining/purification, manufacturing, transport, etc..

$$\frac{\text{mg}}{\text{W}} \quad \text{OR} \quad \frac{\text{mg}}{\text{kWh}} \qquad \frac{\$}{\eta}$$





Focus on reducing material consumption for larger savings!

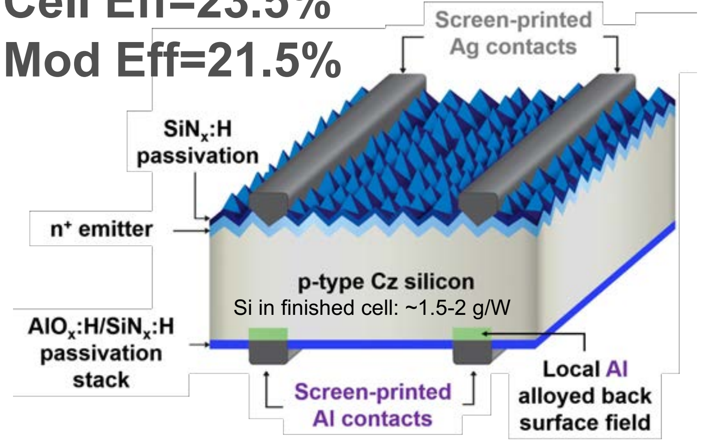
[1] U.S. Geological Survey, *Mineral Commodity Summary.* (2021). https://www.usgs.gov/centers/national-minerals-information-center/
Left figures use some data from M. Azadi et al. Nature Geoscience 13, pp. 100-104 (2020).

Material Consumption in Silicon Solar Cell Technologies

10 mg ITO/pcs
(replaced 2-3 years)

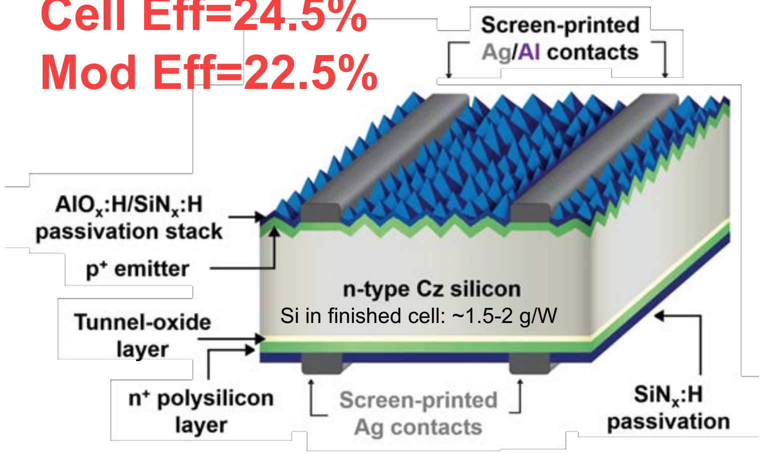
PERC/PERL
Cell Eff=23.5%
Mod Eff=21.5%

~85 mg Ag/pcs
Ag: 5-10 mg/W



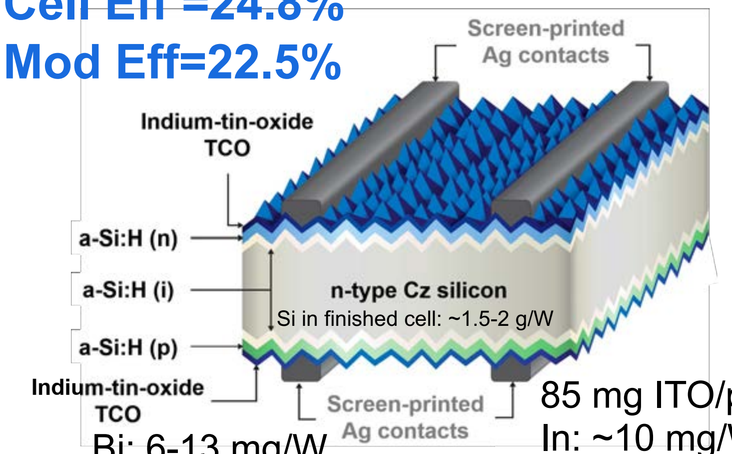
TOPCon
Cell Eff=24.5%
Mod Eff=22.5%

~160 mg Ag/pcs
Ag: 10-20 mg/W



SHJ
Cell Eff =24.8%
Mod Eff=22.5%

~200 mg Ag/pcs
Ag: 17-25 mg/W



Bi: 6-13 mg/W

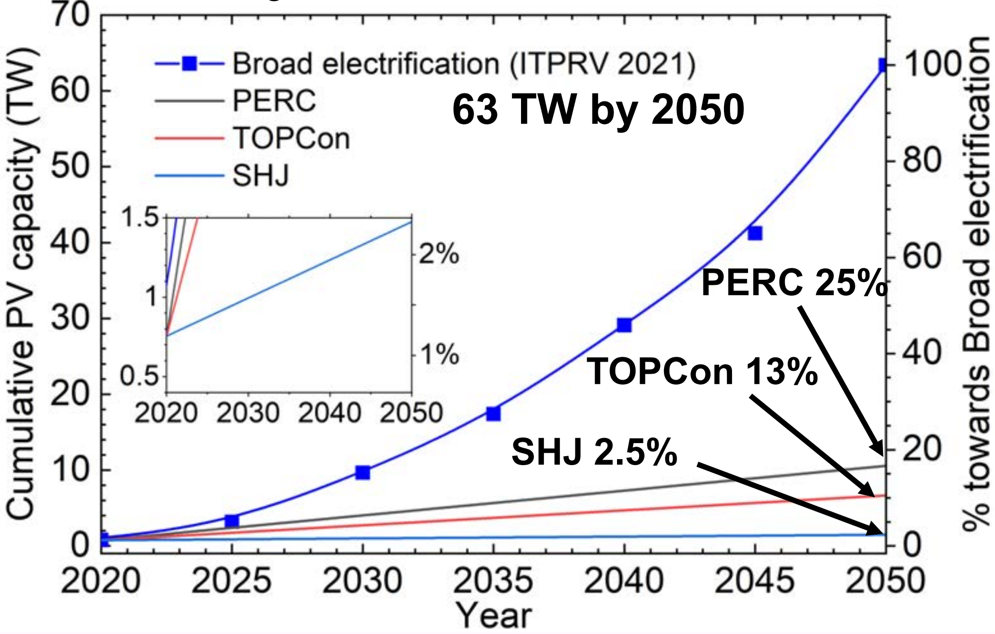
85 mg ITO/pcs
In: ~10 mg/W

Smart Phone

Ag: 200-300 mg/pcs
$1000/pcs

- Solar cell power: 7.6-7.8W (182 mm solar cell)
- ~39 billion solar cells manufactured in 2022 (~300 GW)
- Contribution towards Broad Elec. is technology dependent

	PERC	TOPCon	SHJ
SMC_{Ag} (GW)	570-1100	290-570	230-340
SMC_{In} (GW)	N/A	N/A	~18
SMC_{Bi} (GW)	N/A	N/A	528 (MBB), 250 (SmartWire)
SMC (GW)	**570-1100 (Ag)**	**290-570 (Ag)**	**18 (In)**



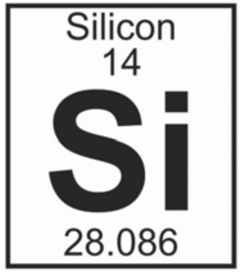
Y. Zhang et al. En. Environ. Sci. 2021 https://doi.org/10.1039/D1EE01814K
Values also extracted from ITRPV 2023 and consultation with solar cell manufacturers

UNSW SYDNEY

Material Sustainability Issues for PV in This Talk

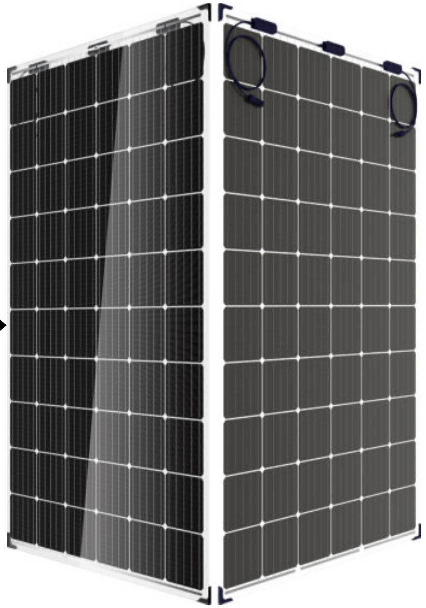
- ALL material are of potential concern for TW scale PV deployment
  - This talk primarily focuses on…..

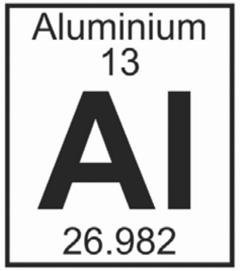
Wafers



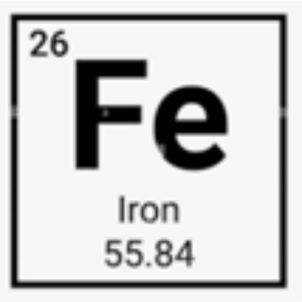
Cells

Modules





Systems



Silicon Supply Chain Issues

Silicon
14
Si
28.086

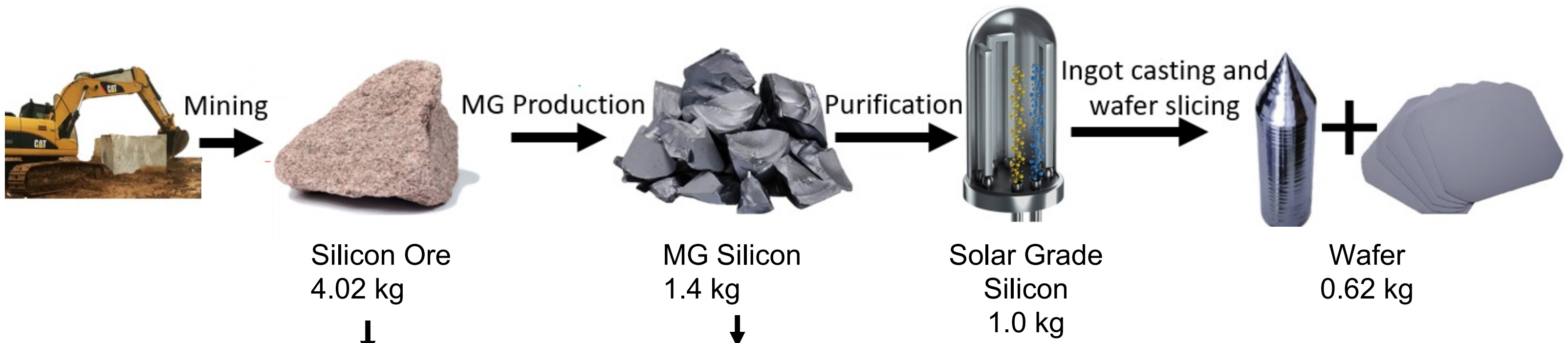
- ~4 kg silicon ore required for 0.6 kg of Si wafers
- Polysilicon shortage: \$7/kg (2020) → \$45/kg in (2022) [2]
- PV to overtake Al industry for MG Si use with ~500 GW/yr
- Learning rate of ~29% for Poly-Si
  - Scope to reduce Poly-Si consumption by > 50%
- Ethical supply chain issues

Polysilicon prices rise over 200% in 2022 amid supply shortages

Polysilicon, a key material in the creation of solar panels, has undergone steady price climbs as output has been cut for a variety of reasons.

JULY 6, 2022 RYAN KENNEDY

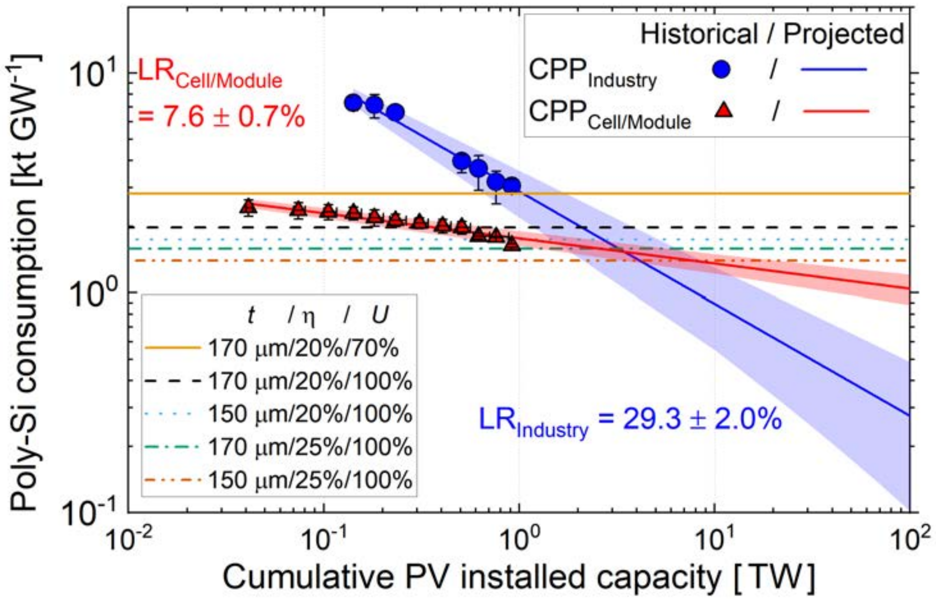
Si in finished modules	2022 Poly-Si usage	2022 Poly-Si Production	Poly-Si Required for 1 TW	2022 global Si production [2]
1.4 – 1.7 g/W	2.1 – 2.3 g/W	~450 kt [1]	2.2 Mt	~8.8 million tons



Steel industry uses ~6 Mt Si in Si Ore (ferrosilicon)

Aluminium industry uses ~1 Mt Si in MG Si

B. Hallam et al. Solar RRL 2022, 6, 2200458.



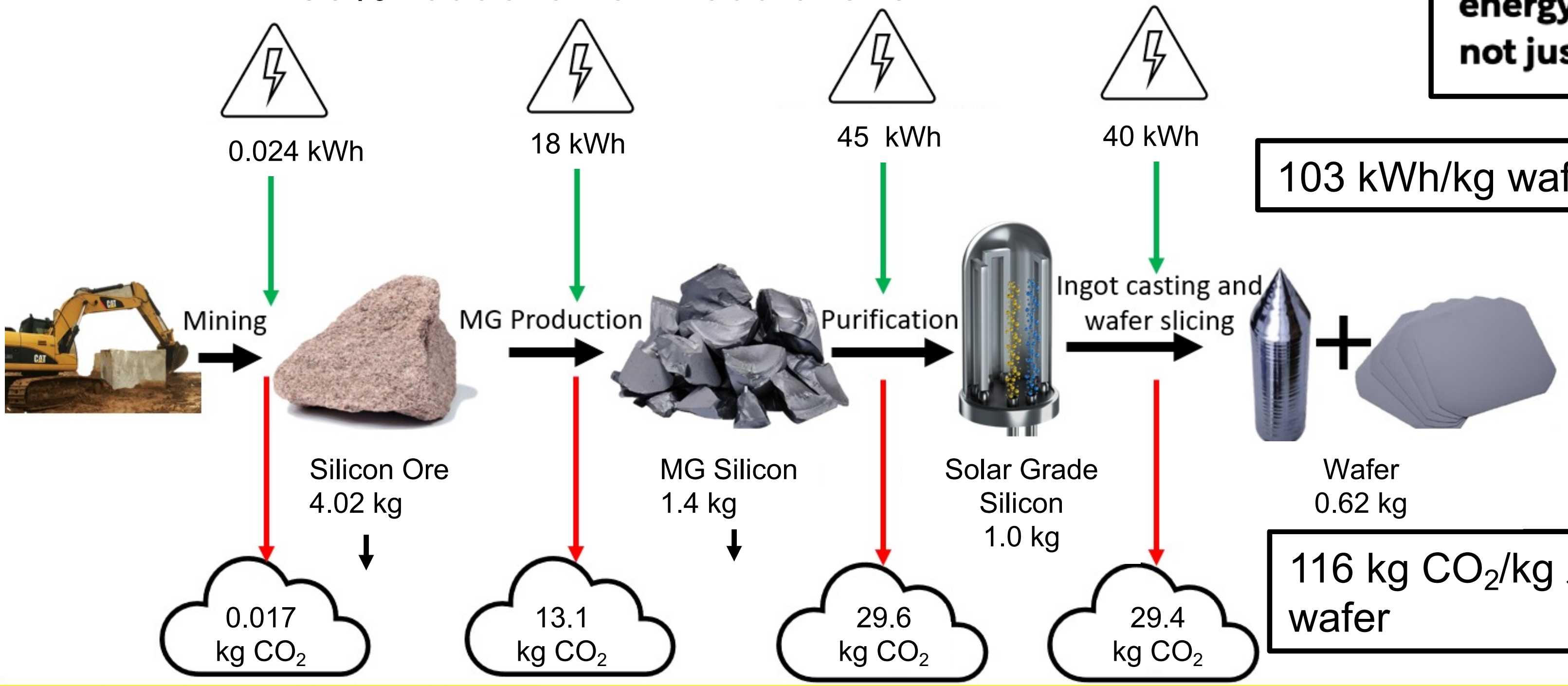
[1] https://www.pv-magazine.com/2021/10/26/whats-next-for-polysilicon/
[2] https://pv-magazine-usa.com/2022/08/30/polysilicon-price-relief-in-2023-as-industry-scales-to-500-gw-capacity/
[3] U.S. Geological Survey, Mineral Commodity Summaries 2022
https://www.globenewswire.com/news-release/2021/06/11/2245794/0/en/Global-Silicon-Metal-Market-Is-Expected-to-Reach-USD-10-25-billion-by-2028-Fior-Markets.html

The Emissions Issue for Silicon Purification

- Silicon purification/wafer production is energy/emissions intensive
  - Large contributor to emissions at module level (~50%)
- Scope to significantly reduce emissions with RE
  - **A circular economy using PV to make PV materials**
  - ~90% reduction in emissions intensity for wafers
  - ~50% reduction at module level

Electricity source	**Emissions (kg CO_2/kWh elec.)**
Coal: (USA/Germany)	0.650
Hydro: (Norway)	0.025
PV: (Trina Solar)	0.014
PV: (future)	0.005

On a mission to accelerate the adoption of sustainable energy solutions, US$30 billion Chinese tech firm Longi is not just selling solar – but using it



103 kWh/kg wafer

116 kg CO_2/kg wafer

PV: 10.8 kg CO_2/kg wafer

Presentation by Li Wang at this conference

Estimates from Life Cycle Analysis (LCA)

[1] https://www.pv-magazine.com/2021/10/26/whats-next-for-polysilicon/. [2] U.S. Geological Survey, Mineral Commodity Summaries 2021. [3] Z. Liu et al., Energy Environ. Sci., 2020,13, 12-23. [4] 4] S. Bhattacharya & S. John, Scientific Reports 9, 12482 (2019). [5] Fan et al. LCA of Crystalline Silicon Wafers for PV Power Generation. Silicon 13,(2021). [6] https://www.recsilicon.com/technology/rec-silicons-fluidized-bed-reactor-process/. https://www.epd-norge.no/getfile.php/1317087-1612352671/EPDer/Byggevarer/NEPD-2651-1357_NorSun-mono-crystalline-silicon-wafer.pdf

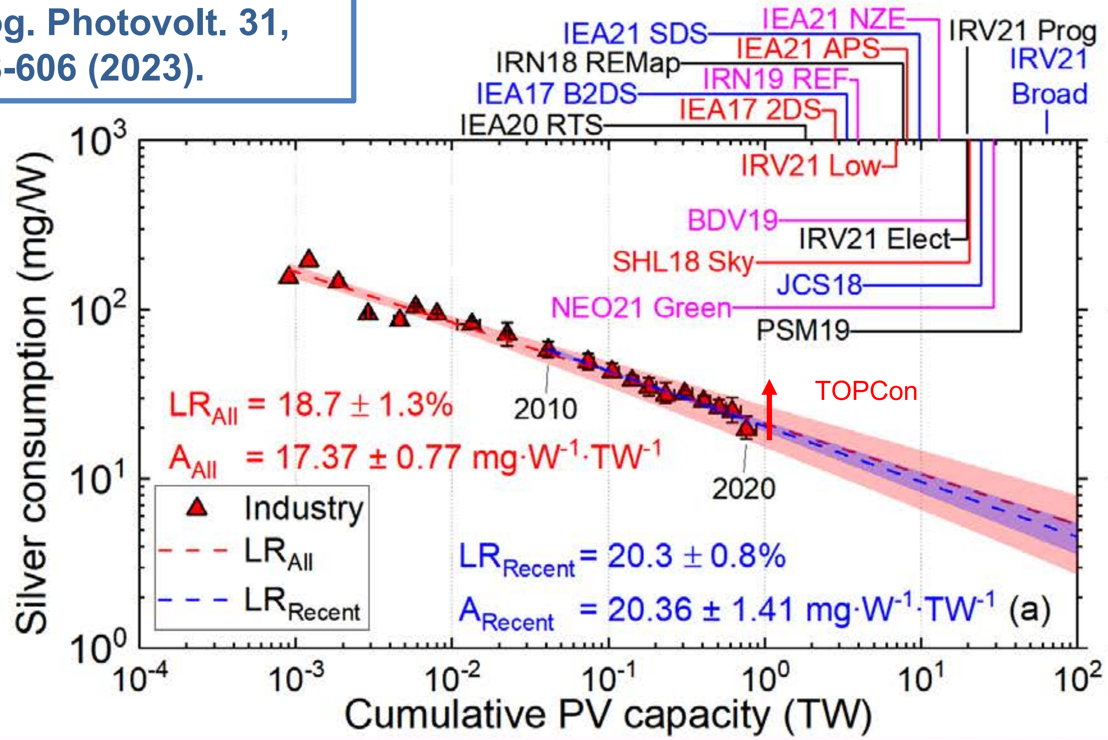
UNSW SYDNEY

The Critical Material Issue for Cells - Silver

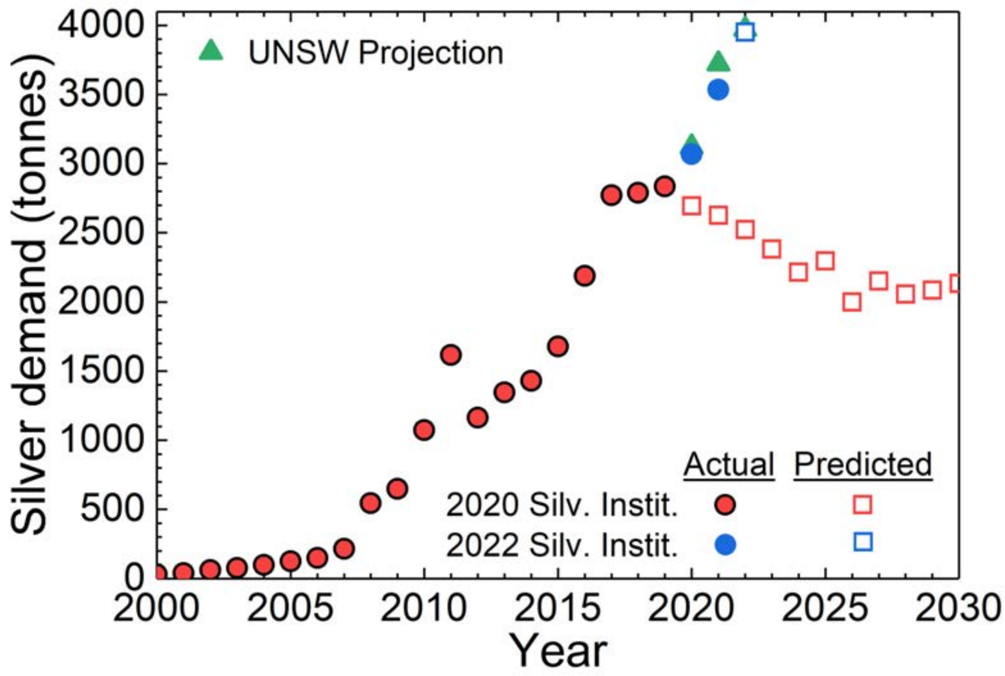
- In 2022, PV industry used ~15% of global Ag supply (~4kt)
- Ag learning rate of ~20% (insufficient)
- Shift to TOPCon/SHJ technologies will increase Ag demand
  - Sticking with PERC will reduce silver supply risks
- Estimate of 4300 tons in 2023

Silver
47
AG
107.87

B. Hallam et al. Prog. Photovolt. 31, 598-606 (2023).



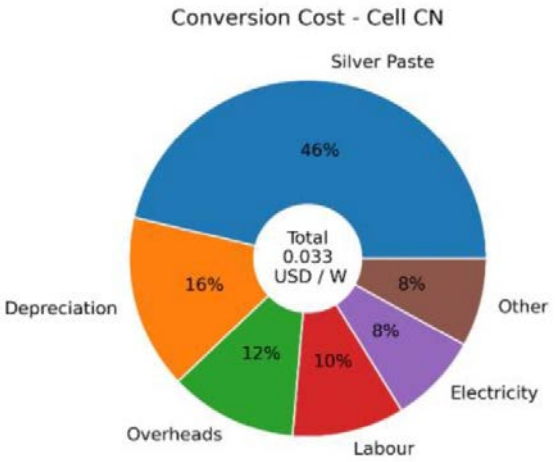
2022 Global reserves (tonnes)	2022 Global supply (tonnes)	Years of supply with current reserves
550,000 [2]	26,000	~19-21

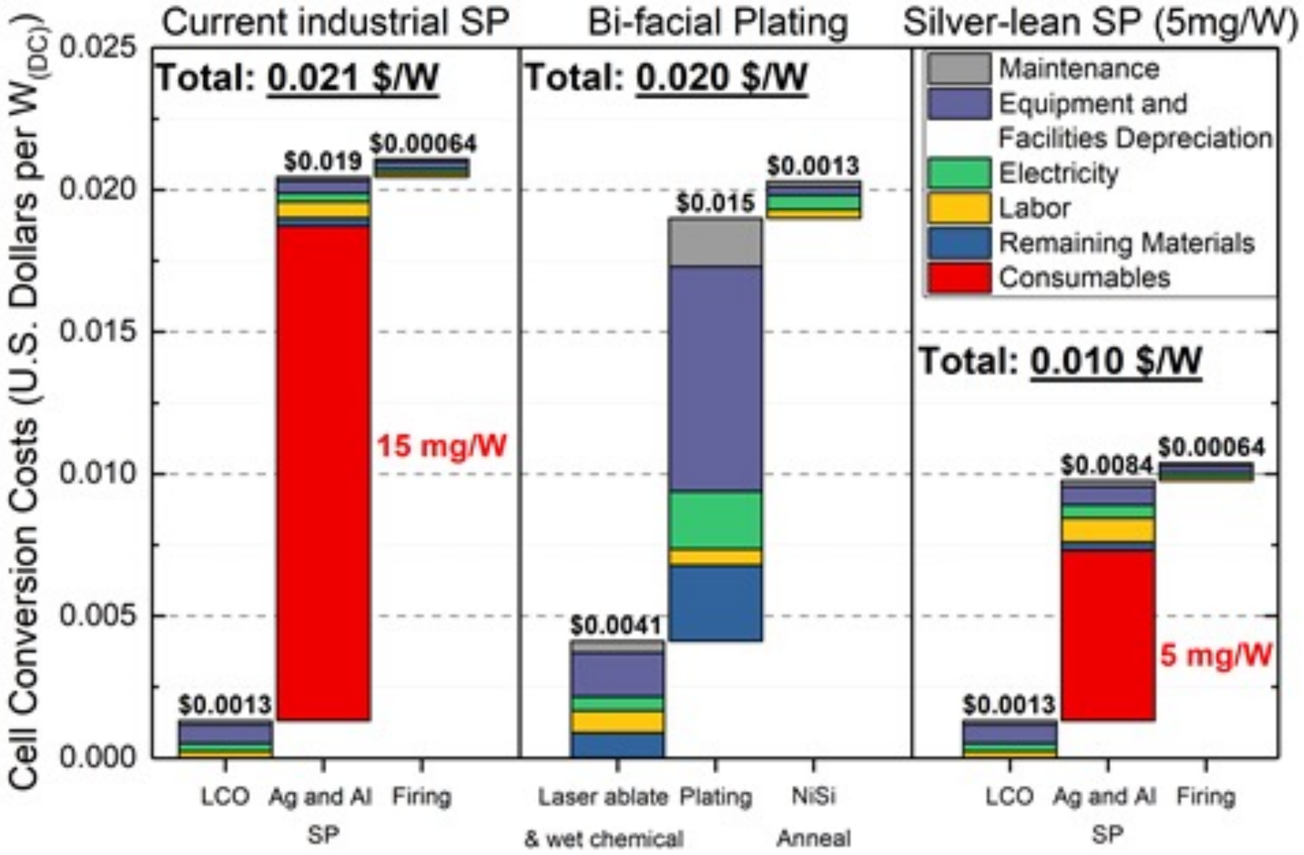


[1] 2023 World Silver Surveys from the Silver Institute. www.silverinstitute.org
[2] USGS 2023. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-silver.pdf
[3] Y. Zhang et al. En. Environ. Sci. 2021 https://doi.org/10.1039/D1EE01814K

Cost Impact of Silver

- Silver is the largest non-silicon cost for making a solar cell (1.5-2c/W for TOPCon)
  - Reducing Ag consumption down to 5 mg/W could save 1-1.5 c/W → $10-15M per GW
- Routes for Ag reduction
  - Plating
    - Needs new production tools (Capex)
    - Adds process complexity
  - **Screen-printing**
    - **Fast path to market**
    - **Needs new pastes and innovation**



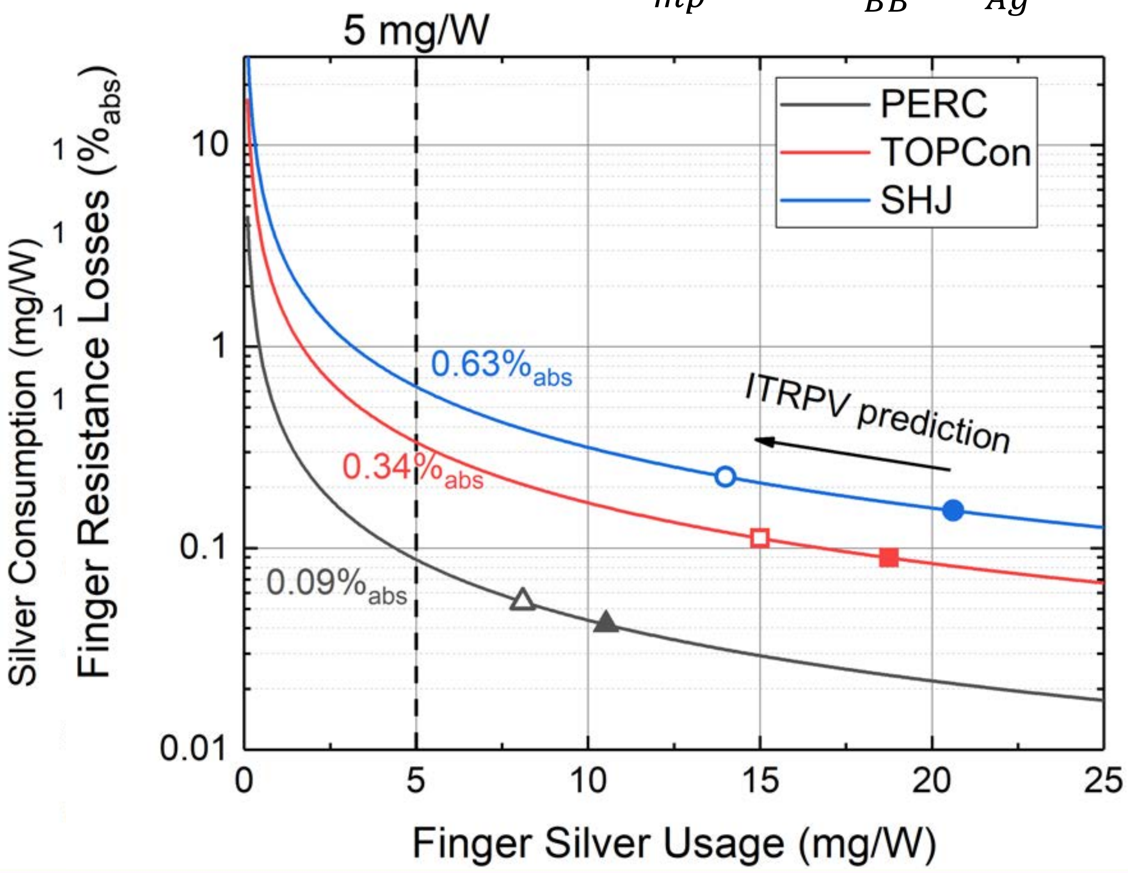


UNSW SYDNEY

Ultra-Low Silver Consumption with Screen Printing

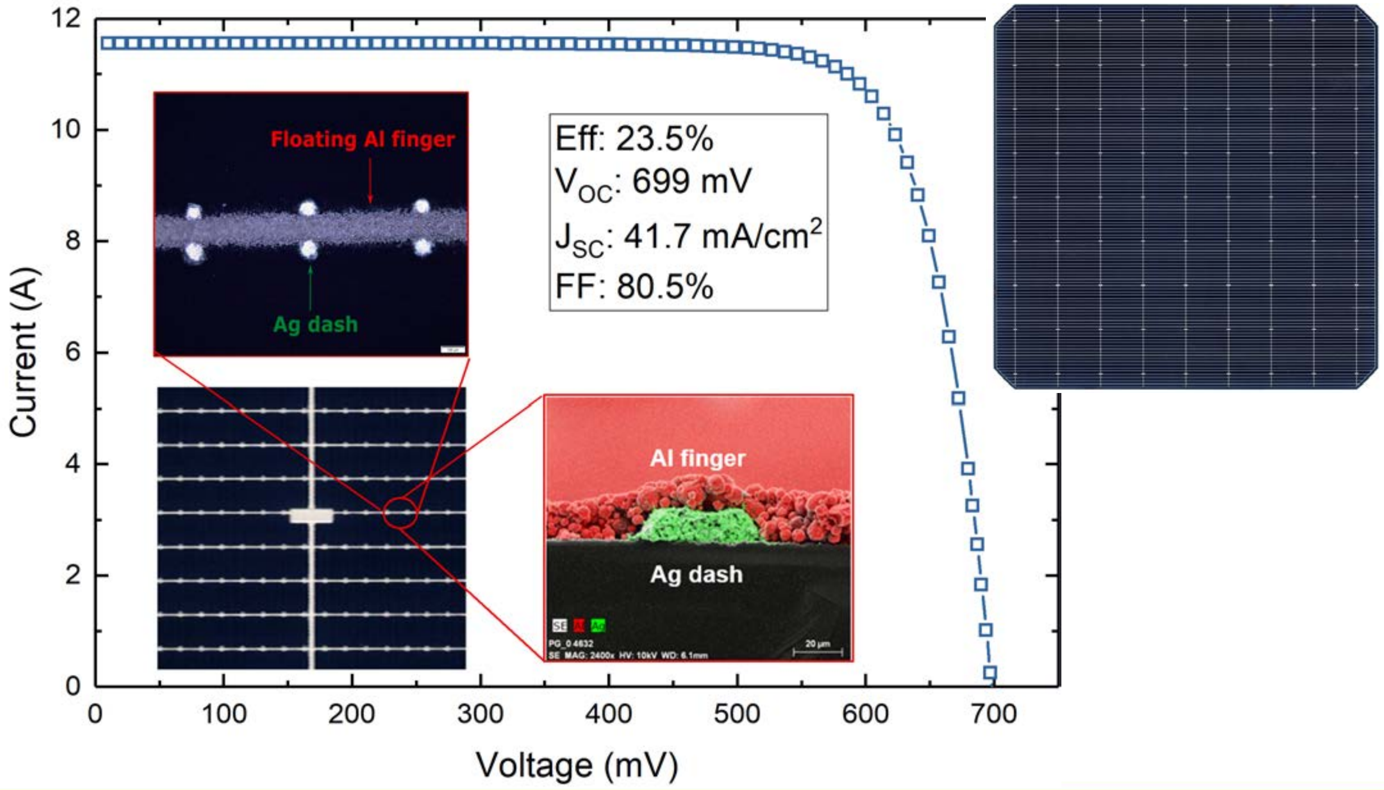
- Multi-TW scale PV requires <2 mg/W Ag
- Relationship between $P_{loss\ finger\ Rs}$ and mass of Ag used (M_{Ag}) favours PERC

$$Ploss_{finger\ Rs} = \frac{J_{mp}}{V_{mp}} \cdot \frac{\rho_m \cdot \rho_f \cdot W_{cell}^4}{12 \cdot N_{BB}^2 \cdot M_{Ag}} \cdot \eta$$

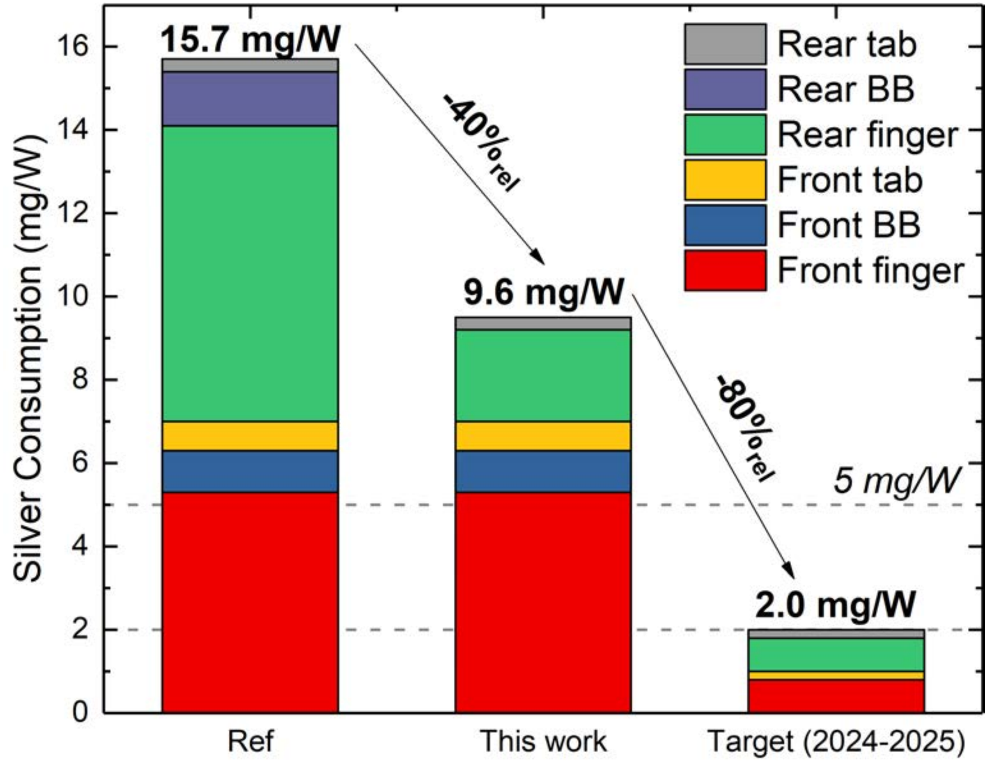


Ultra-Low Silver Consumption with Screen Printing

- Multi-TW scale PV requires <2 mg/W Ag
- Relationship between $P_{loss\ finger\ Rs}$ and mass of Ag used (M_{Ag}) favours PERC
- UNSW Silver-lean screen printing overcomes this limitation
  - ~ 40% Ag reduction demonstrated on TOPCon
  - **Roadmap to 2 mg/W using current technology**

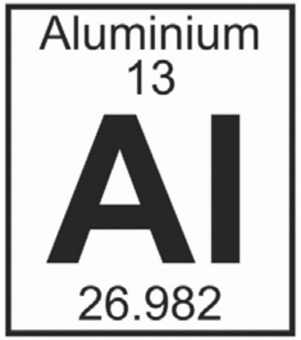


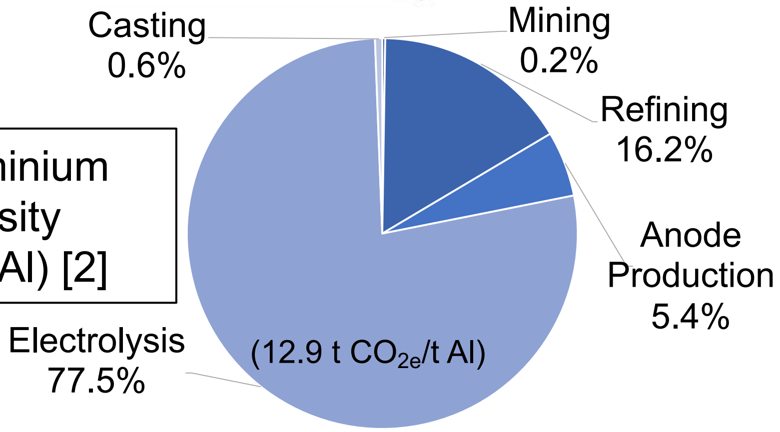
SP Al fingers & BBs



A Key Module Issue - Aluminium

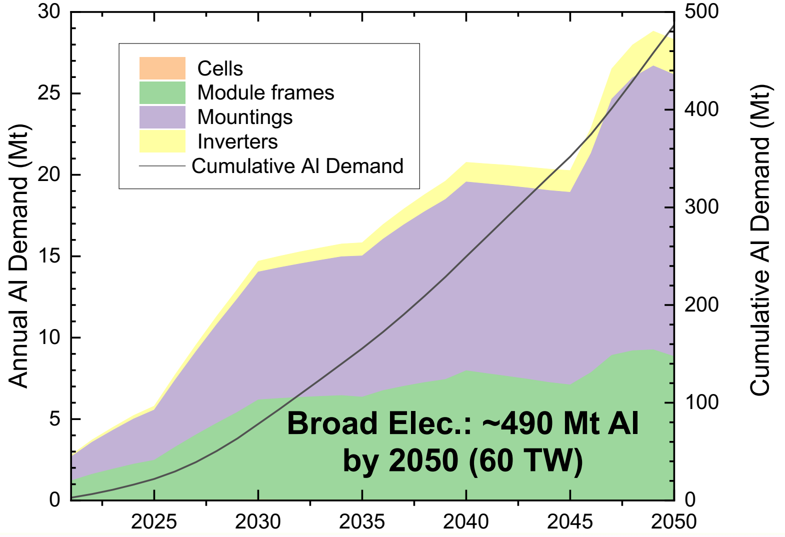
- 400W module uses ~2.4 kg Al frames (~5.3-6 g/W)
  - Dominates Al consumption for centralized PV
- 1 TW of PV frames will use 7-9% of global Al supply
- Emissions intensity Al: 12 - 16 t CO_2 / t Al [1,2]
  - 14 MWh elec. / t Al → 40% production cost
  - Rising electricity prices affecting Al supply/cost





2021 Primary Aluminium Emissions Intensity (Total 16.6 t CO_2/t Al) [2]

A. Lennon et al. Nature Sustainability 2022.



3 minute read · September 7, 2022 3:12 AM GMT+10 · Last Updated 2 months ago [4]

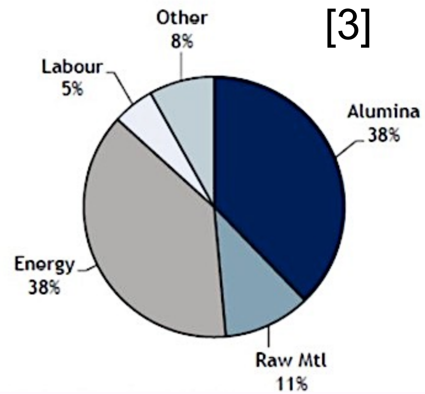
French aluminium smelter to cut output as electricity prices soar

By Caroline Pailliez and Gus Trompiz

Even with decarbonization efforts, PV's Al demand could add 1 Gt CO_2

Source: Wood Mackenzie, RBC Capital Markets estimates

Exhibit 35: 2015E Aluminium Total Cost (C2)** Components



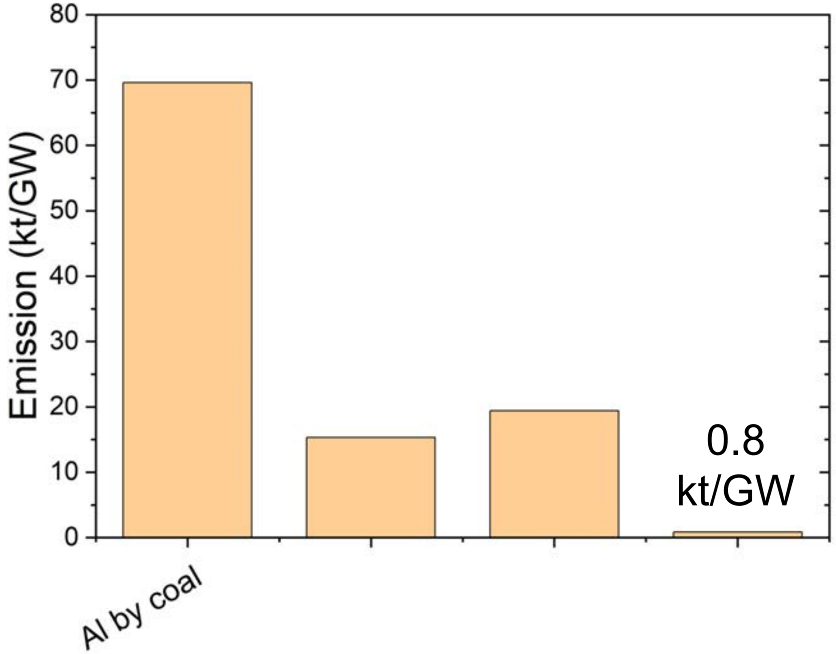
[3]

[1] Department of Industry, Science, Energy and R. (2020) 'Australia's emissions projections 2020'. [2] https://international-aluminium.org/statistics/greenhouse-gas-emissions-intensity-primary-aluminium/ [3] http://www.anfre.com/global-aluminium-smelters-production-costs-on-decline/ [4] https://www.reuters.com/markets/commodities/french-aluminium-smelter-cut-output-by-20-due-power-costs-source-2022-09-06/

UNSW SYDNEY

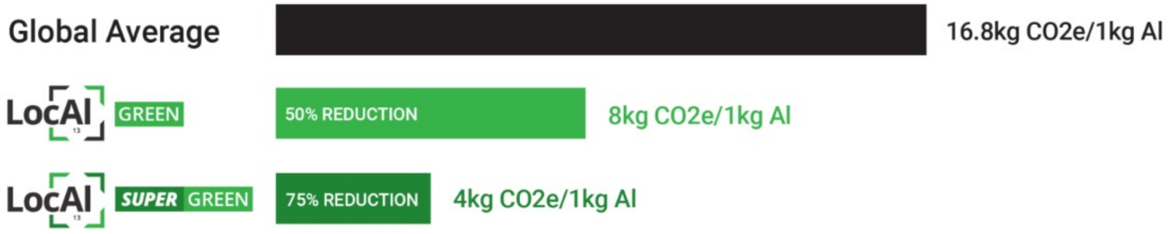
Reducing the Emissions of Aluminium Frames for PV

- Locating smelters in renewable energy/PV zones
  - **A circular economy using PV to make PV materials**
- New green Al options down to 1.6 t CO_2/t
- Reduced Al frames/large PV modules
- Replace Al with steel (currently ~1.8 t CO_2/t)
  - Green steel down to 0.08 t CO_2/t)
  - **Scope to reduce frame emissions by 99%**



Lower carbon aluminium for Australian manufacturers

November 2, 2022 News



Rio Tinto to expand its AP60 low-carbon aluminium smelter in Quebec

12 June 2023

Risen Energy switches to steel frames on solar panels because of aluminum's high carbon-footprint

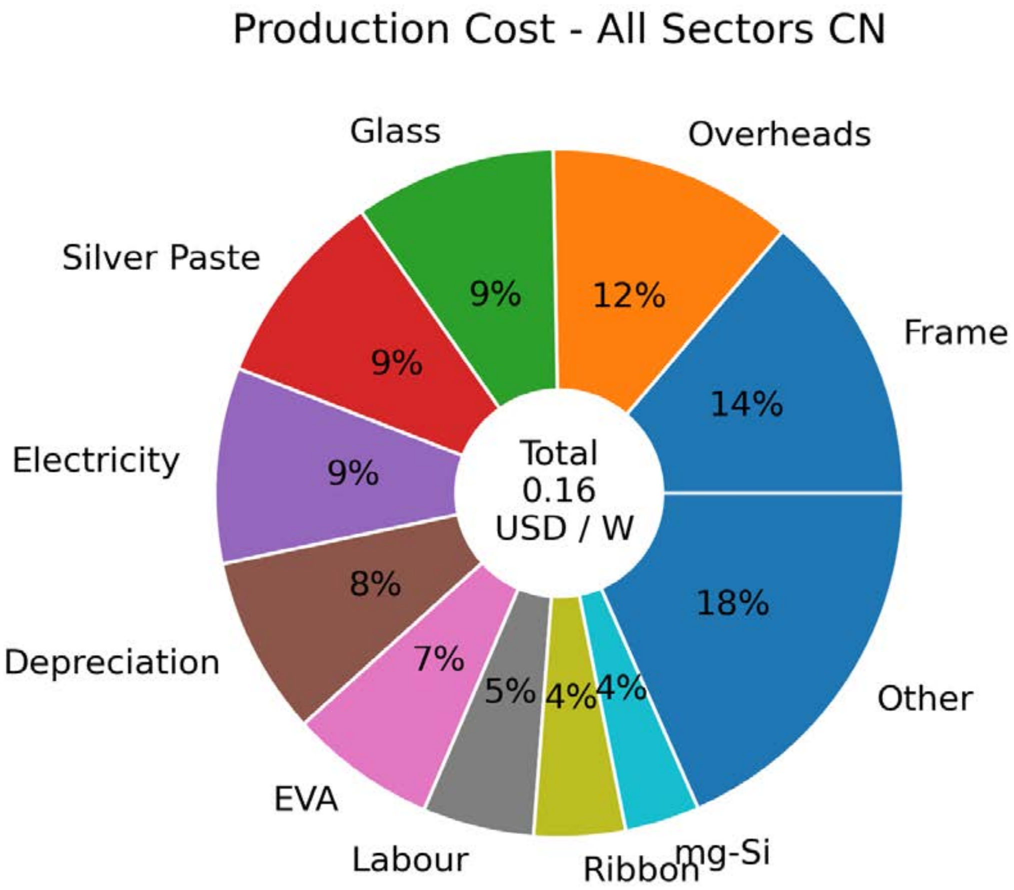
By Kelly Pickerel | November 10, 2021

https://www.manmonthly.com.au/news/local-lower-carbon-aluminium/
https://www.solarpowerworldonline.com/2021/11/risen-energy-switches-to-steel-frames-on-solar-panels-because-of-aluminums-high-carbon-footprint/
[3] https://international-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/
[5] https://international-aluminium.org/statistics/greenhouse-gas-emissions-intensity-primary-aluminium/
[6] B. Cushman-Roisin and B. T. Cremonini, "Materials," Data, Statistics, and Useful Numbers for Environmental Sustainability, pp. 1–16, 2021.

Electricity – a significant cost for PV modules

- At $60/MWh – electricity contribute 15% of module cost
  - Impact of electricity often hidden in materials
- Using PV generated electricity at 1c/kWh could reduce module manufacturing cost by >10%

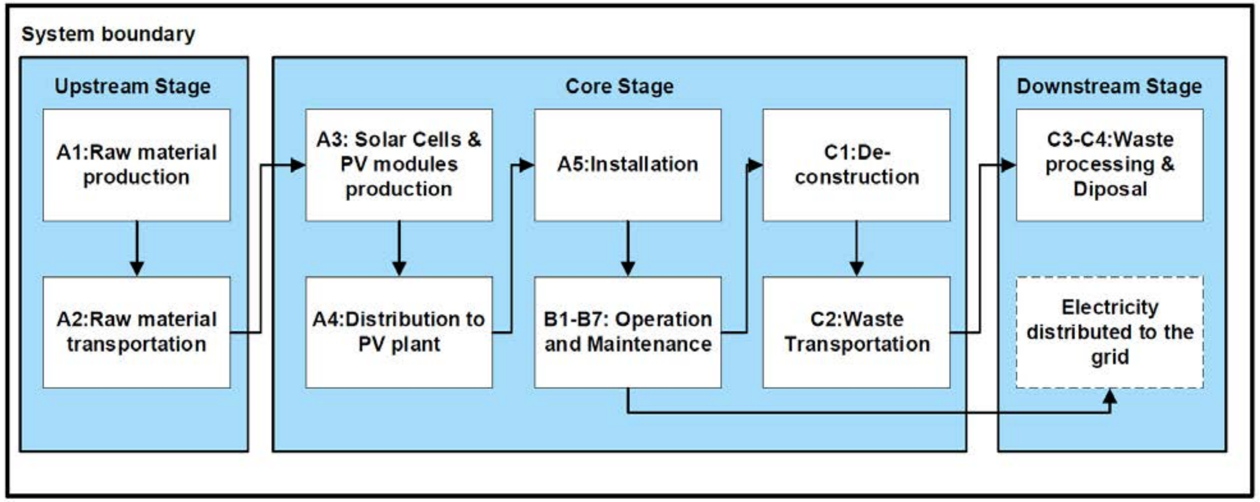
	MWh per MW	c/W at 6 c/kWh	% cost of production step
MG silicon purification	29	0.17	30-40%
Polysilicon purification	110	0.66	30-40%
Ingot/wafering	60	0.36	16%
Cell production	50	0.30	6%
Al frame (smelting)	72	0.43	30-40%
Module assembly	13	0.08	1%
TOTAL	**334**	**2.00**	**15%**



Impact of a Carbon Tax at the Module Level

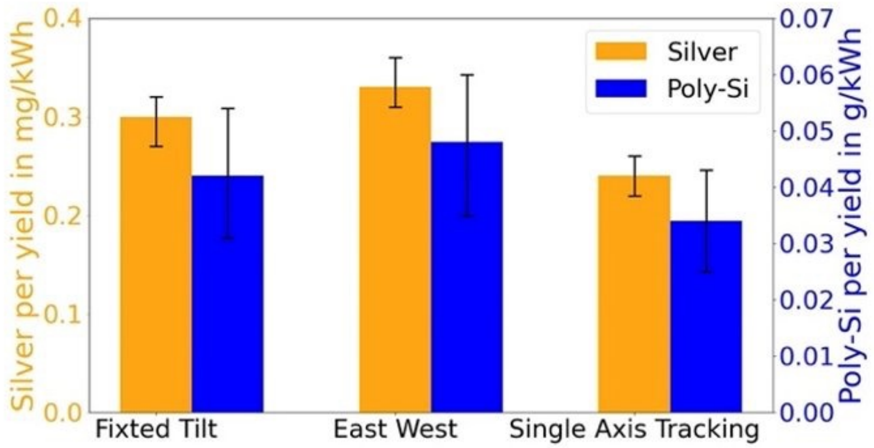
- Essentially all emissions for PV occurs during the manufacturing phase
- $40/ton carbon tax could increase up-front module cost by 10%
- Decarbonising the supply chain can reduce susceptibility by 80-90%
  - Extra savings when considering system level improvements

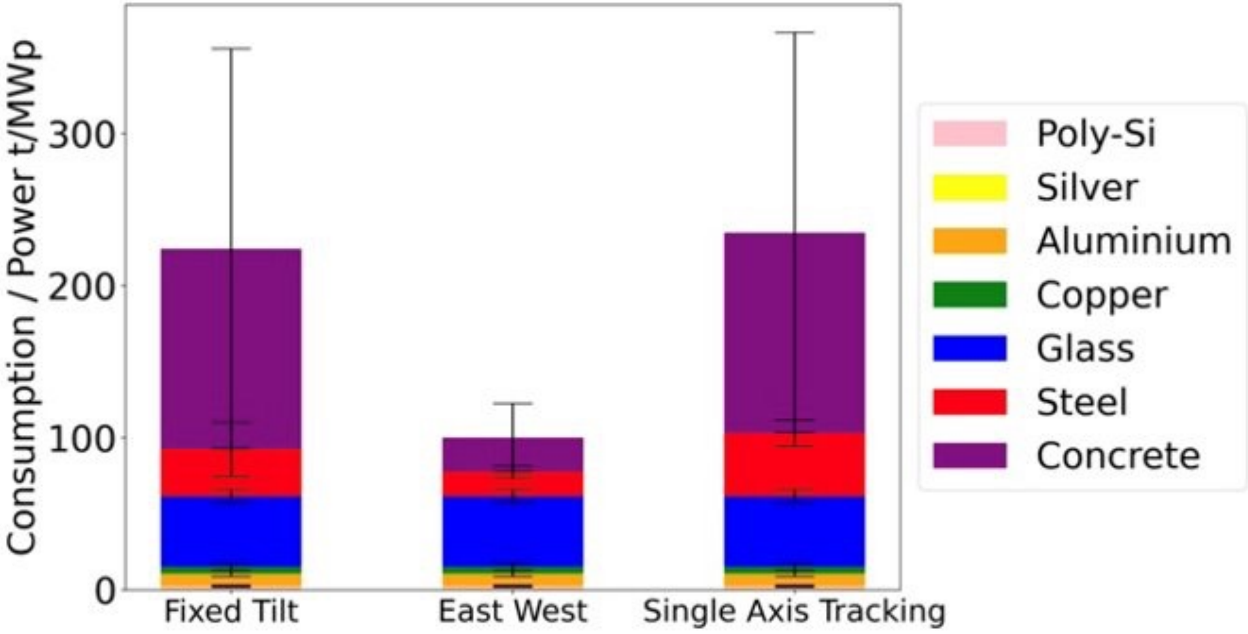
	Emissions (g/kWh)	Emissions (t CO_2/MW)	Impact of carbon tax (US c/W)
Current module	6.9	0.350	1.40
Decarbonised module	1	0.051	0.20
Green steel frame module	0.9	0.044	0.18

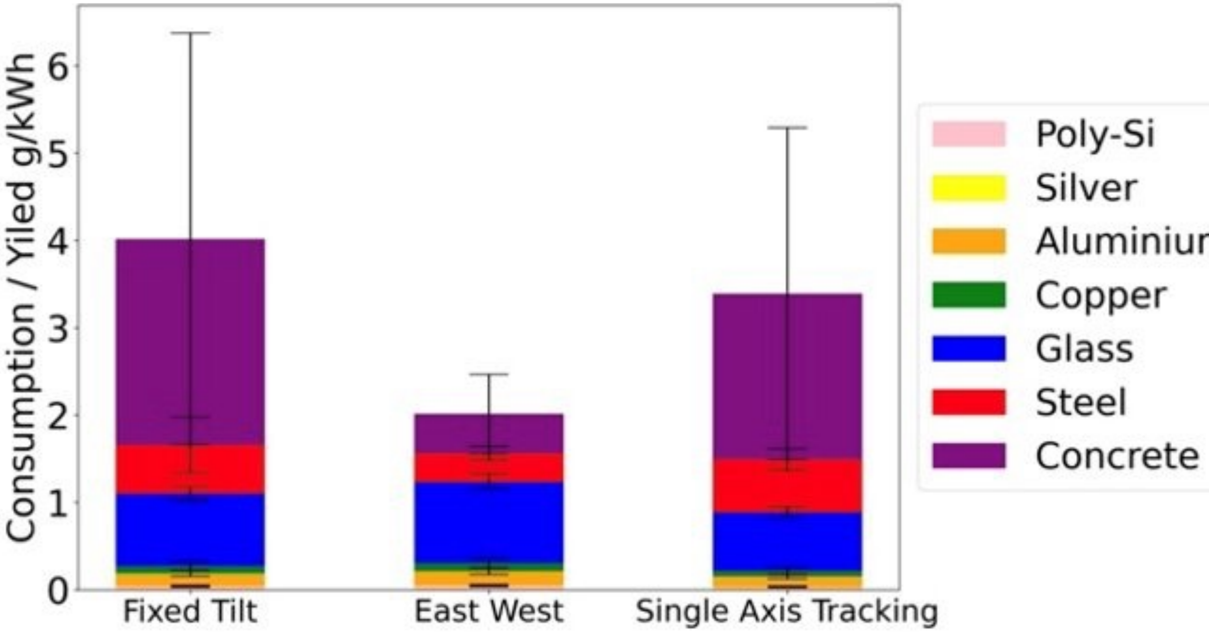


System Mounting Greatly Impacts Material Consumption

- Module mounting can impact material consumption directly (g/W)
  - Steel and concrete
- And indirectly for the module (g/kWh)
  - EW lower total material usage than SAT/FT
  - BUT EW has highest silver consumption

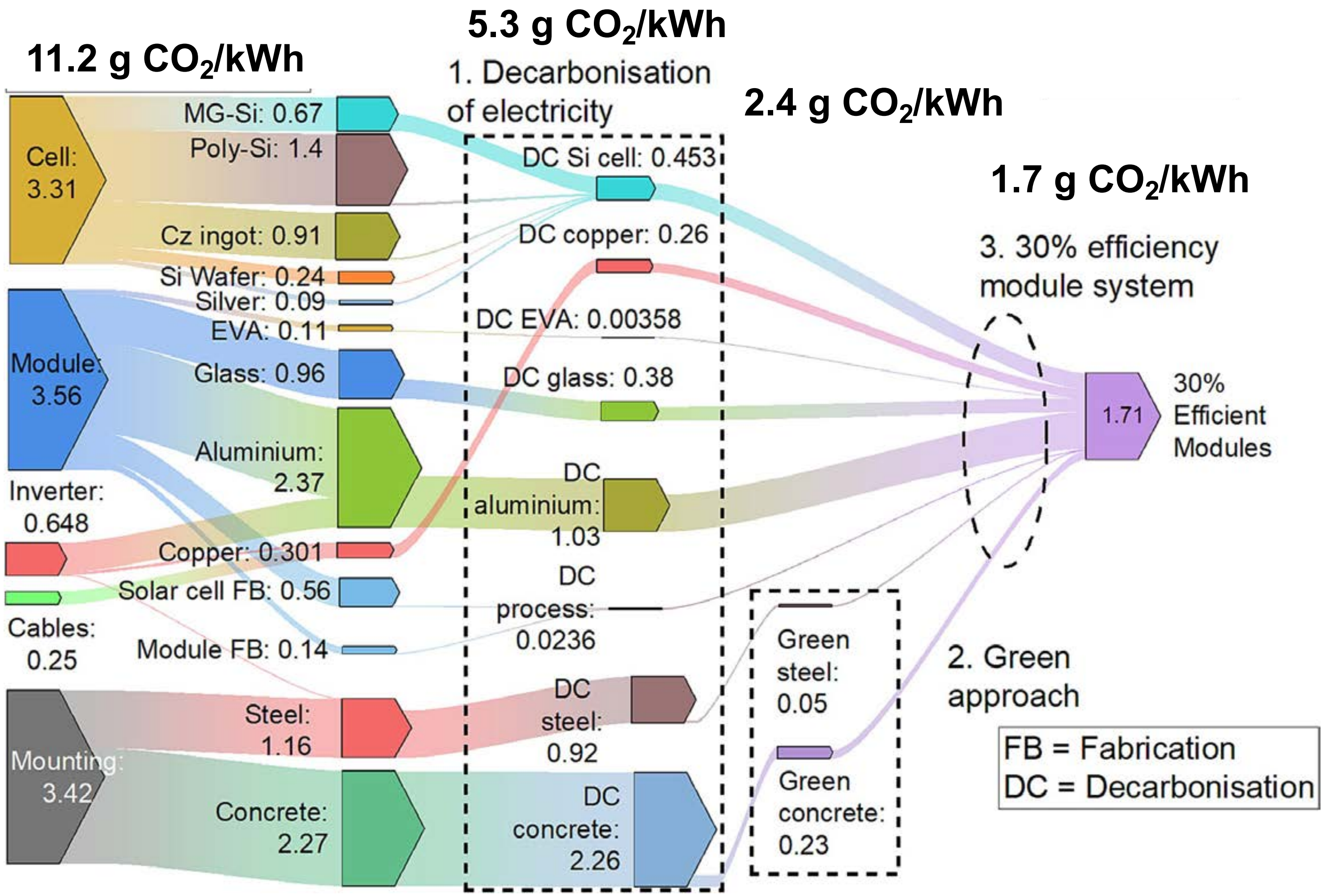






Ultra-Low Emissions PV – as Easy as 1, 2, 3

- **Step 1: Decarbonise PV supply chain with PV/renewable electricity**
  - Silicon supply chain
  - Al smelting
- **Step 2: Green materials**
  - Low emissions Al
  - Green steel
- **Step 3:** 30% efficient modules
  - ……..maybe not so easy



Summary

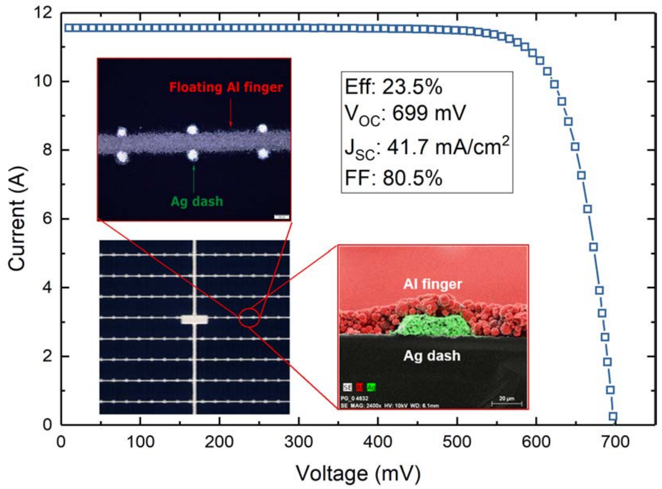
Silicon 14 **Si** 28.086

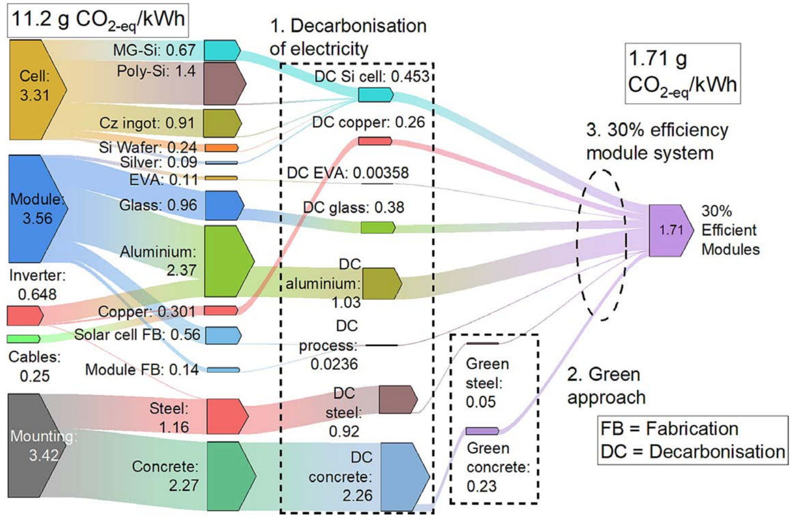
Silver 47 **AG** 107.87

Aluminium 13 **Al** 26.982

26 **Fe** Iron 55.84

- **PV can be sustainable at the multi-TW scale with technology available now**
- **Wafer level:** Need to reduce emissions intensity of Si purification
  - **Decarbonise electricity grid/Si purification using PV → save >$0.01/W**
- **Cell level:** Silver is the most pressing material issue
  - **Ultra-lean Ag screen printing <2 mg/W → save >$0.015/W**
  - Copper plating as insurance policy
- **Module level:** Aluminium/shipping of concern
  - **Decarbonise Al production/alternative frames → save $0.005/W**
  - **Decarbonised modules could avoid >$0.01/W carbon tax**
- **Systems level:** Mounting can impact material consumption
  - Requires holistic approach across PV value chain
  - **SAT/FT higher total material consumption than EW**
  - **EW has highest effective use of critical materials in the module**





These Projects received funding from the Australian Renewable Energy Agency (ARENA) as part of ARENA's TRAC Program. The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein. The work is supported by the Australian Centre for Advanced Photovoltaics (ACAP) and received funding from the Australian Renewable Energy Agency (ARENA).

brett.hallam@unsw.edu.au