School of Photovoltaic & Renewable Energy Engineering

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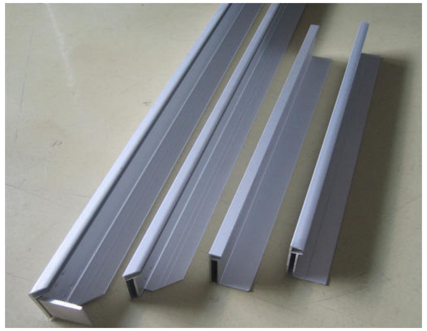
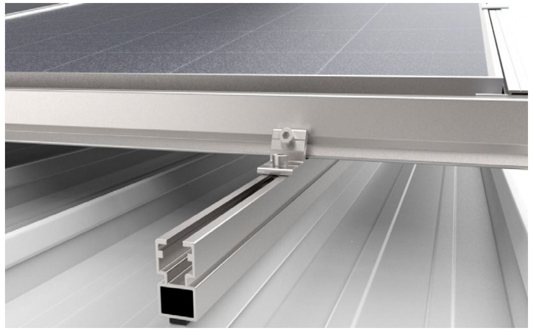
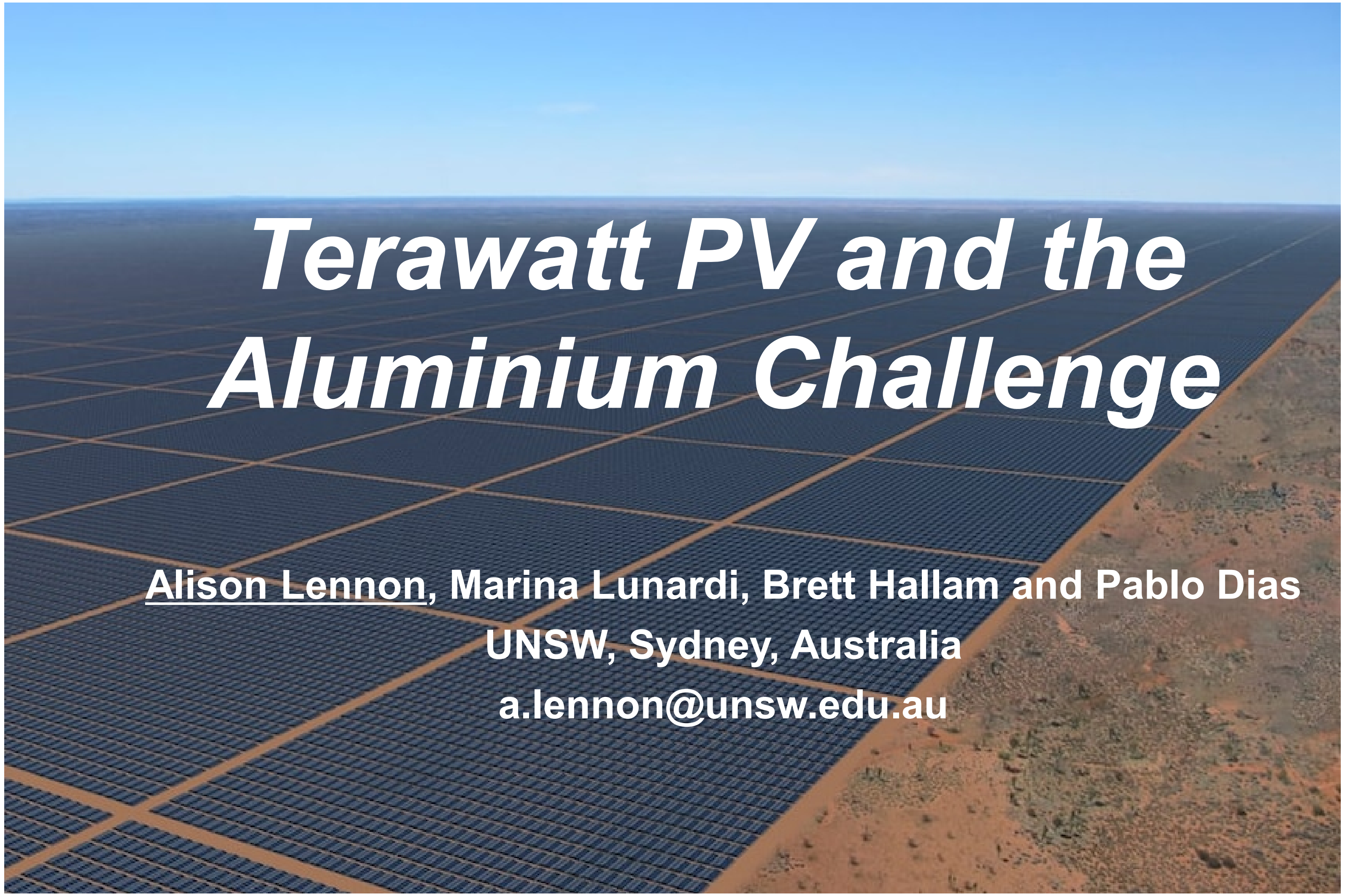
Light, low-cost and is resistant to corrosion







Terawatt PV and the Aluminium Challenge

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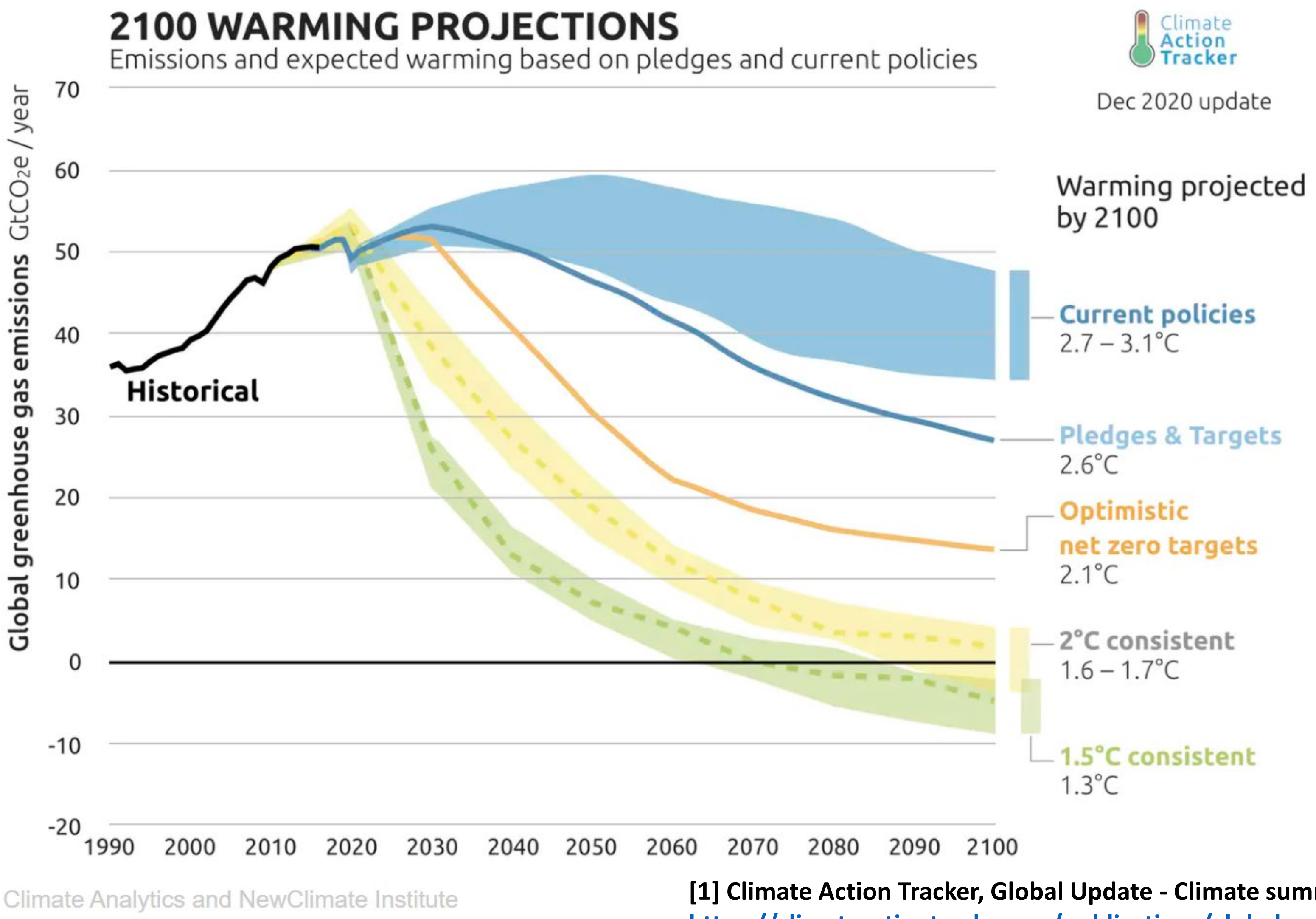
https://www.abc.net.au/news/2021-09-23/nt-sun-cable-project-solar-farm-cost-size-increase/100487452

Presentation Outline

- *Extent of Emissions Reduction Required*
- *Broad Electrification Scenario of ITRPV*
- *Quantifying the Aluminium Demand*
- *GWP of the Demand*
- *Strategies for Addressing the GWP*
- *Conclusions*

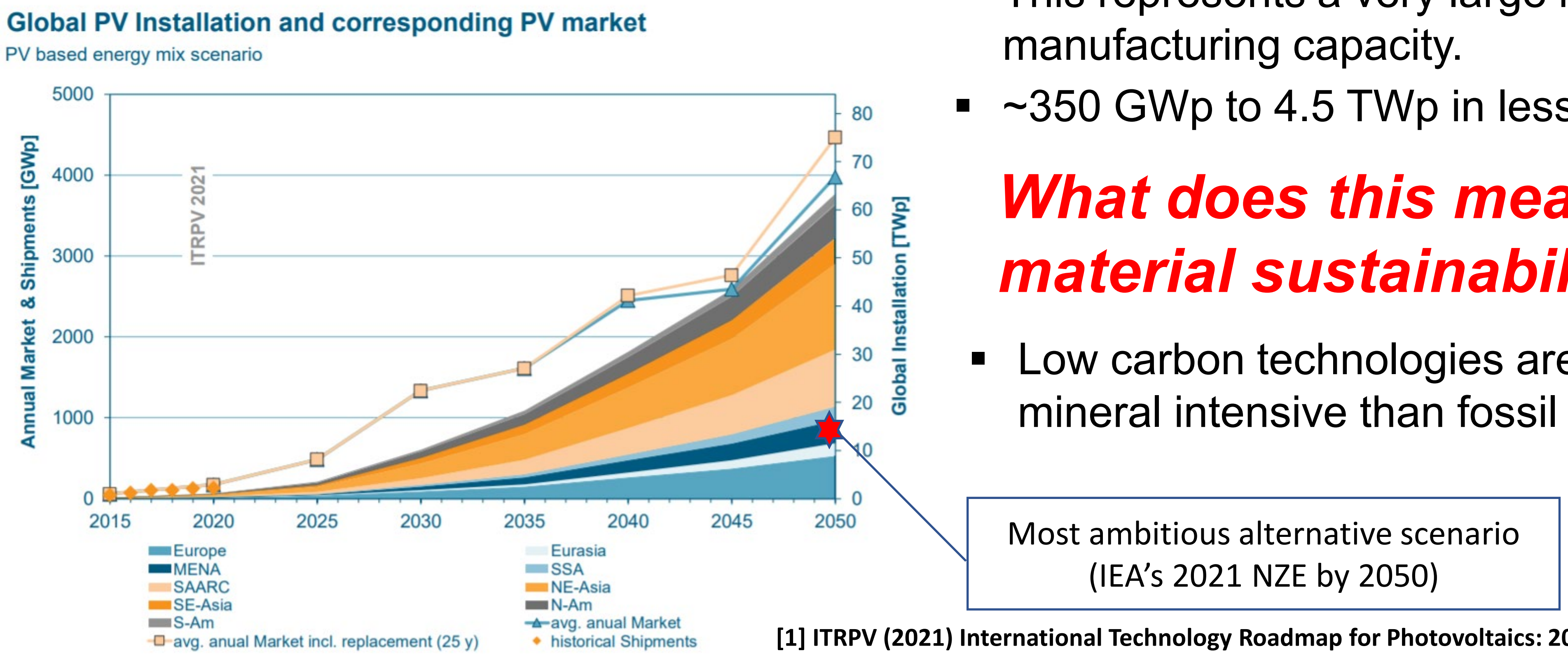
Projected Emissions and Associated Warming



[1] Climate Action Tracker, Global Update - Climate summit momentum - May 2021, https://climateactiontracker.org/publications/global-update-climate-summit-momentum/

ITRPV Broad Electrification Scenario

- Most ambitious scenario (for PV) technology mitigation scenario.
- Installed PV capacities of more than 60 TWp and annual added capacity of 4.5 TW have been projected for 2050 [1].



- This represents a very large increase in manufacturing capacity.
- ~350 GWp to 4.5 TWp in less than 30 years!

What does this mean for material sustainability?

- Low carbon technologies are more mineral intensive than fossil fuels [2].

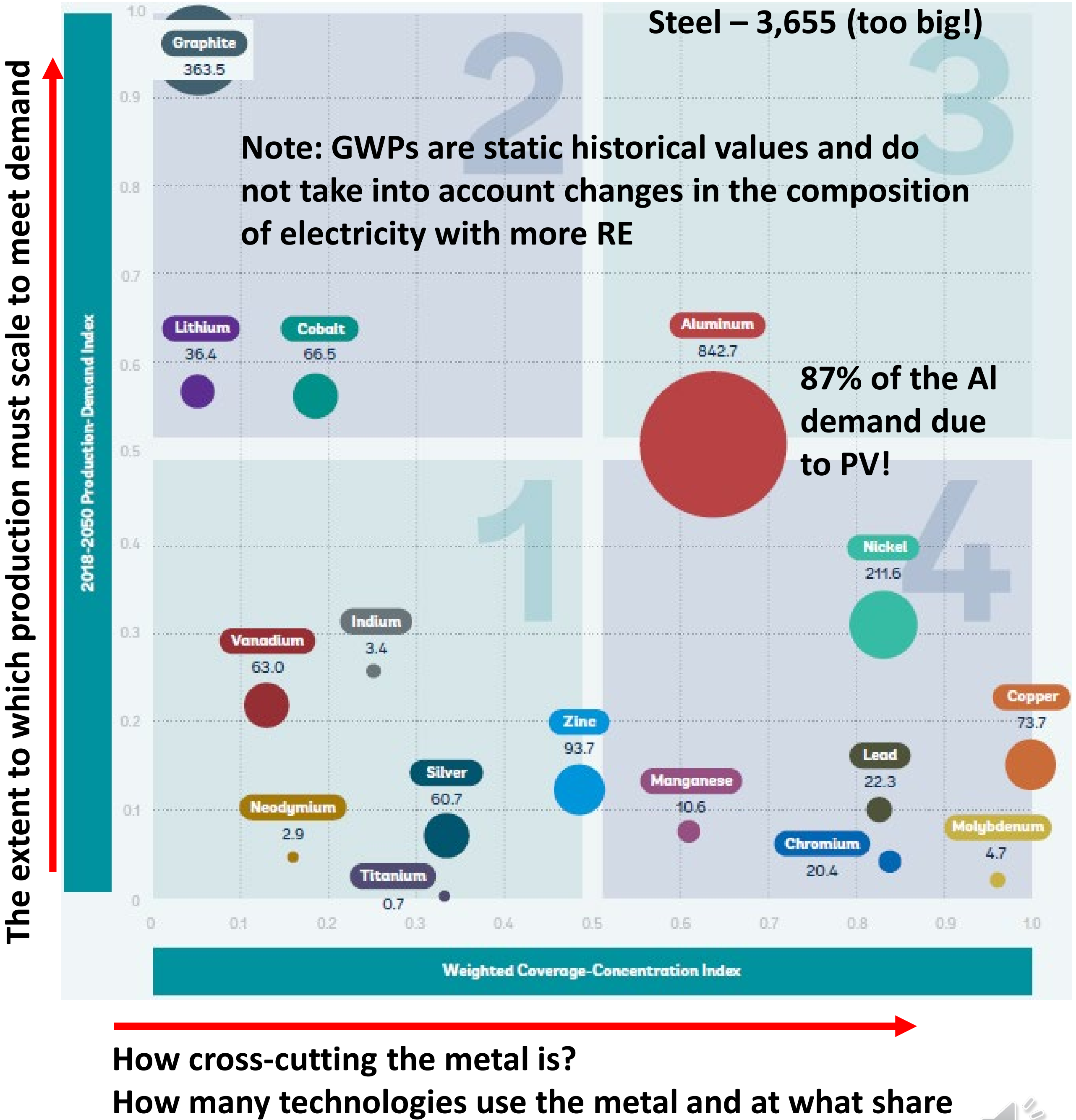
[1] ITRPV (2021) International Technology Roadmap for Photovoltaics: 2020 Results. https://itrpv.vdma.org/en/
[2] Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition, The World Bank, 2020; The Role of Critical Minerals in Clean Energy Transitions

World Bank 2020 Analysis

- Demand risk matrix is computed for all energy technologies for the earlier IEA 2DS.
- This scenario assumed :
  1. ~ 4 TW by 2050; and
  2. c-Si PV share reducing to 50% by 2050.
- Much less than 60 TW of mostly c-Si as predicted by the 2021 ITRPV report.
- The Al demand for PV was 103 Mt (65 Mt produced globally in 2020)
- Large GWP ~ 843 Mt CO_2e
- Although Al is highly recyclable, large increases in primary production required.

2DS = IEA's 2019 2°C scenario
GWP = Cumulative emissions up to 2050 (t CO_2e)

[1] Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition, The World Bank, 2020; The Role of Critical Minerals in Clean Energy Transitions.



What is the Aluminium Demand for the ITRPV's Broad Electrification Scenario?

60 TW of installed PV capacity as compared to just 4 TW by 2050!

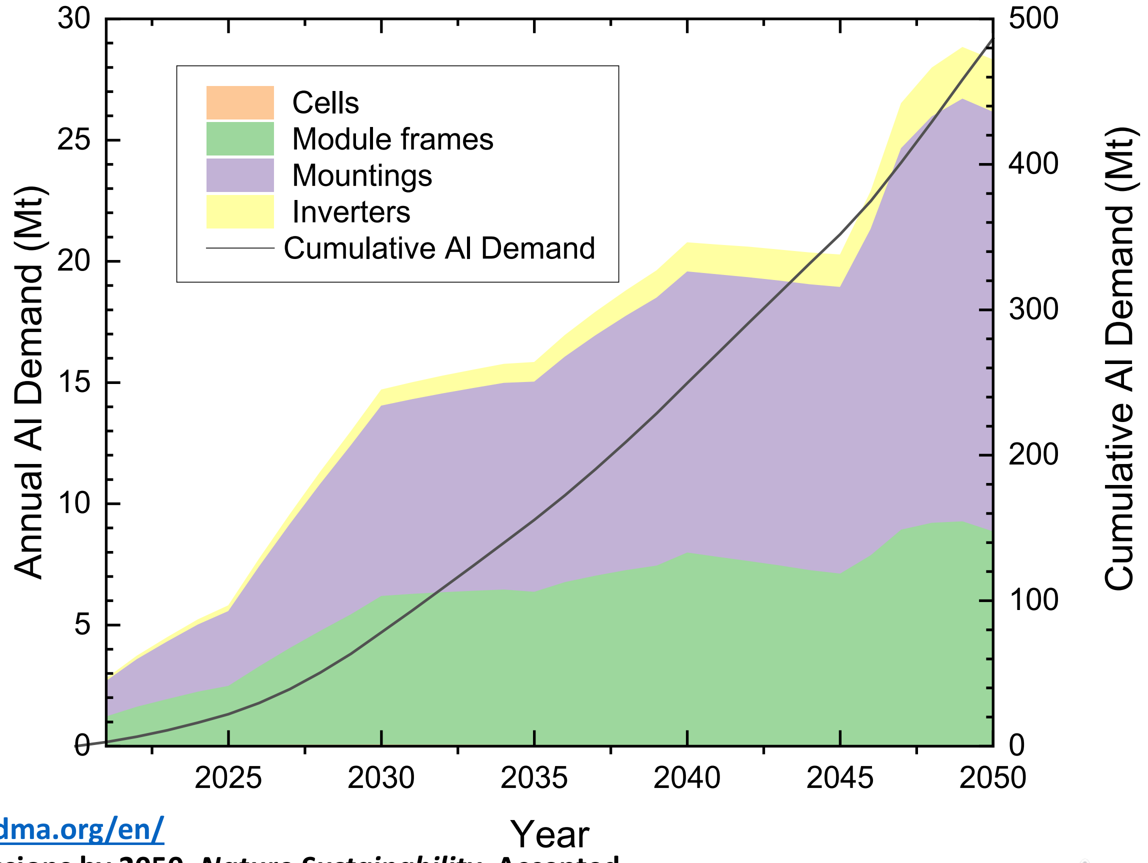
Aluminium Demand up to 2050 (ITRPV Analysis)

- Aluminium demand can also be estimated for the ITRPV's broad electrification scenario.
- Demand calculated for mountings, frames, cells and inverters.

Al cumulative demand = 486 Mt Al
Al clean energy demand (WB, 2020) = 103 Mt
Peak demand = 28.5 Mt (2050)
Global Al production (2020) = 65 Mt

Key assumptions [2]

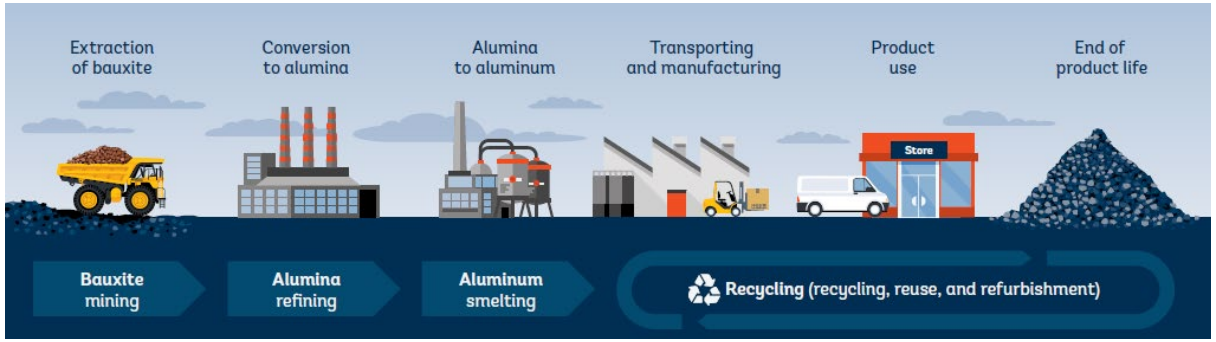
- Crystalline silicon PV remains dominant (≥ 95%)
- Al mountings only required for rooftop (2.84 kg/m^2)
- Rooftop fraction decreasing from 50% to 40% in 2050
- Frames use ~ 1.2 kg/m^2, but Al usage estimated to reduce due to increases in module power and adoption of frameless modules.
- Inverters require ~ 0.5 kg/kW
- Cell-level Al is insignificant

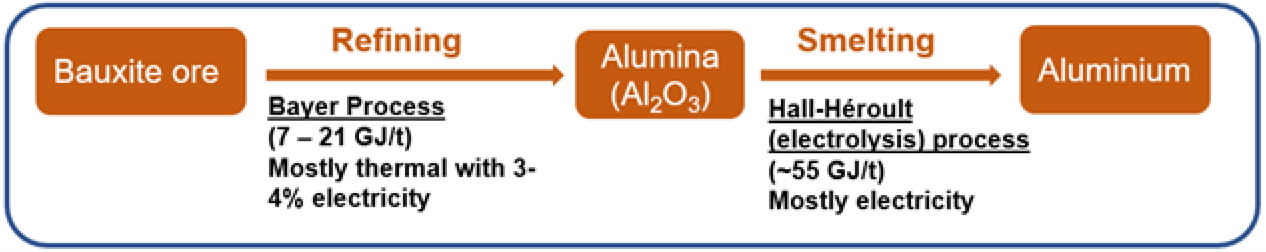


[1] ITRPV (2021) International Technology Roadmap for Photovoltaics: 2020 Results. https://itrpv.vdma.org/en/
[2] A. Lennon et al. (2021) The Aluminium Demand Risk of Terawatt Photovoltaics for Net Zero Emissions by 2050, *Nature Sustainability*, Accepted

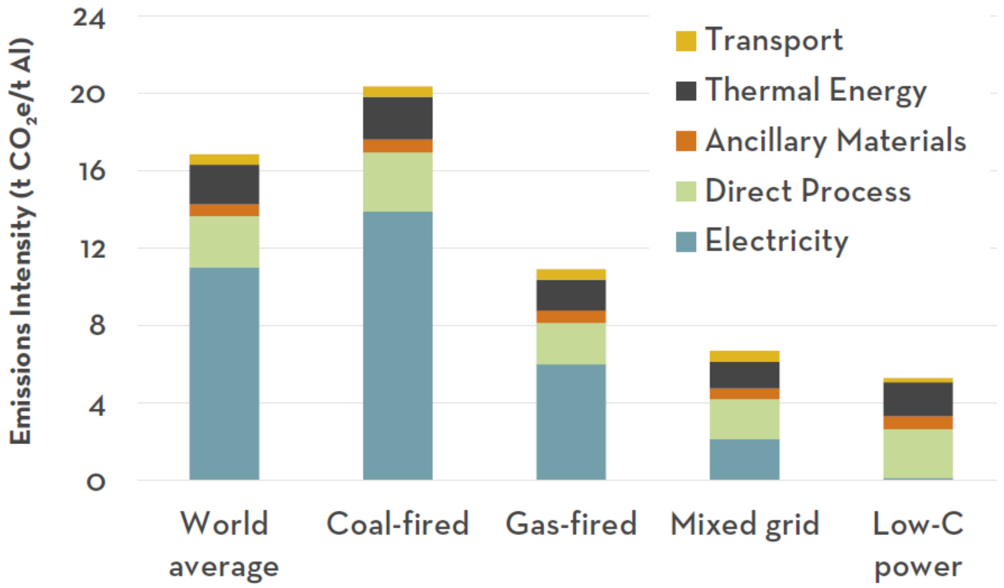
Primary Aluminium Production

- Involves extraction, refining and smelting
- Very energy intensive!





- Since 2000, most Al is produced in China due to cheaper electricity.
- In 2020, 37 Mt of the total global aluminium production of 65 Mt was produced in China.



World average 2018 cradle-to-gate emissions from primary Al by power source [2]

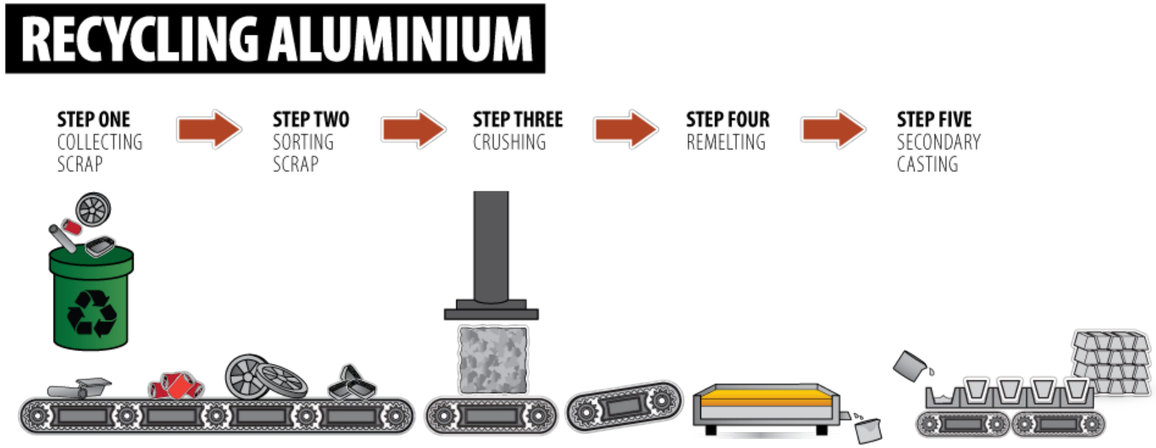
[1] A. Lennon et al. (2021) The Aluminium Demand Risk of Terawatt Photovoltaics for Net Zero Emissions by 2050, *Nature Sustainability*, under review
[2] Aluminium Sector Greenhouse Gas Pathways to 2050, March 2021, https://www.world-aluminium.org/media/filer_public/2021/03/16/iai_ghg_pathways_position_paper.pdf

Secondary Aluminium

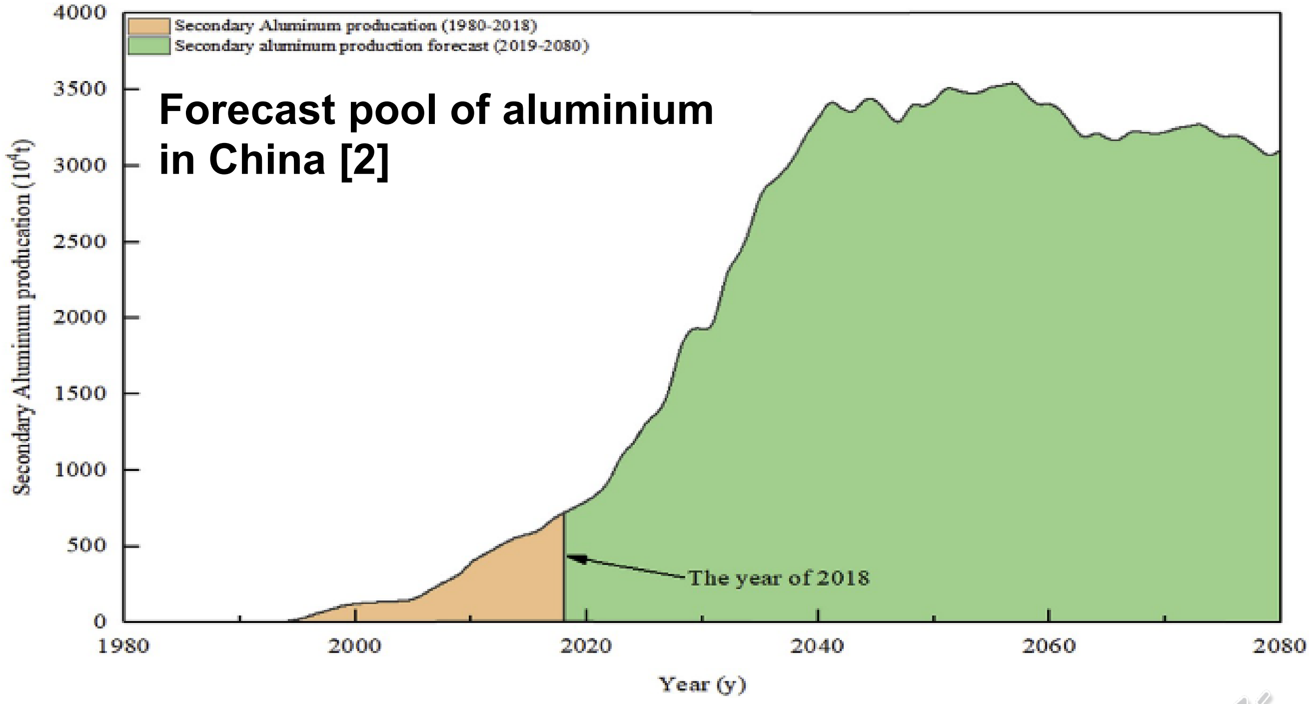
Al is highly recyclable!
75% of all the Al produced is still in use today.

Secondary (recycled Al)

- Uses ~ 5% of the energy and generates 3-5% of the emissions of primary Al.
- Amount of resource depends on available scrap.
- Secondary Al pool in China was as forecast by Li et al. [2]



From: https://aluminium.org.au/how-aluminium-is-made/recycling-aluminium-chart/

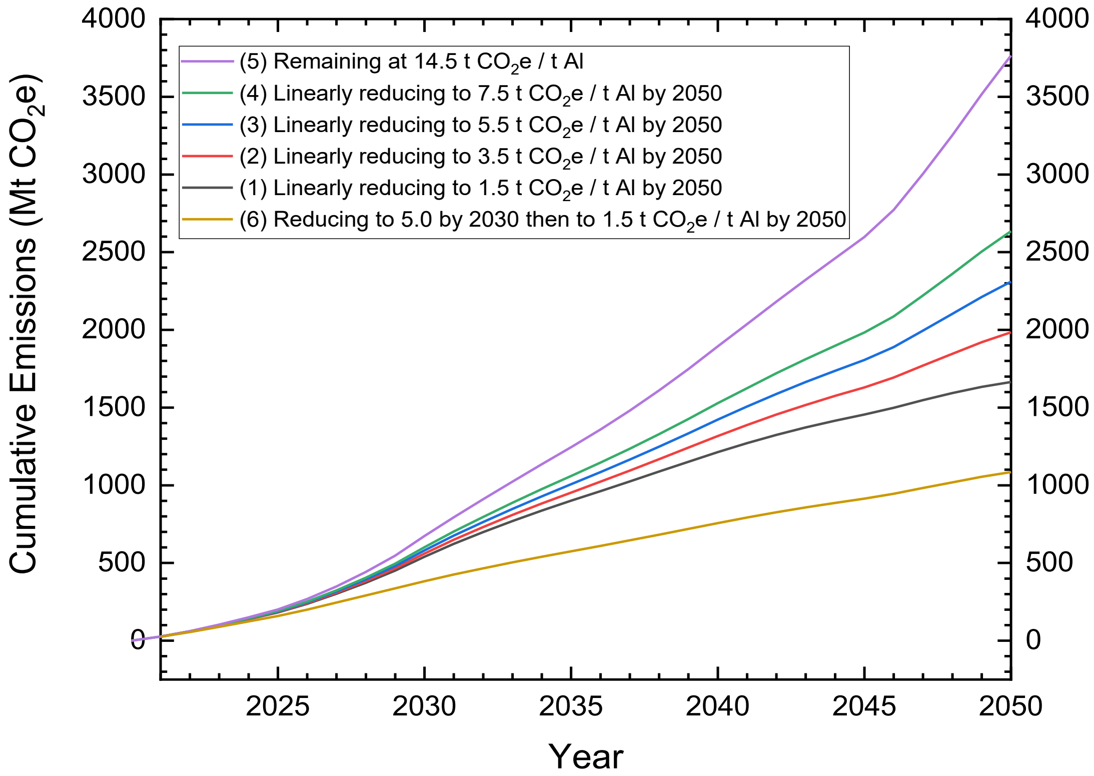


[1] A. Lennon et al. (2021) The Aluminium Demand Risk of Terawatt Photovoltaics for Net Zero Emissions by 2050, *Nature Sustainability*, Accepted
[2] Y. Li et al (2020). When will the arrival of China's secondary aluminium era? *Resources Policy* 65, 101573,

The GWP of Aluminium Demand

<u>Key assumptions [1]</u>

- Both Al and PV modules are manufactured in China.
- 33% of the recycled Al pool as forecast by Li et. al [2]
- Recycled Al content is 34% (2020) increasing to 75% in 2050
- Secondary emissions intensity reduced from 0.65 to 0.5 t CO_2e / t Al from 2020 to 2050
- Vary primary emissions intensity reduction



Scenario		Peak Emissions (year)		GWP (Mt CO_2e)
		Annual Emissions (Mt CO_2e)	% China's 2019 Emissions	
1	Linearly reducing to 1.5 (2050) t CO_2e / t Al	90 (2030)	0.75%	1,665
2	Linearly reducing to 3.5 (2050) t CO_2e / t Al	95 (2030)	0.79%	1,985
3	Linearly reducing to 5.5 (2050) t CO_2e / t Al	104 (2049)	0.89%	2,310
4	Linearly reducing to 7.5 (2050) t CO_2e / t Al	143 (2049)	1.2%	2,635
5	Remaining at 14.5 t CO_2e / t Al until 2050	263 (2049)	2.2%	3,765
6	Reducing to 5.0 t CO_2e / t Al by 2030 and then more slowly to 1.5 t CO_2e / t Al by 2050	46 (2028)	0.37%	1,085

[1] A. Lennon et al. (2021) The Aluminium Demand Risk of Terawatt Photovoltaics for Net Zero Emissions by 2050, Nature Sustainability, Accepted

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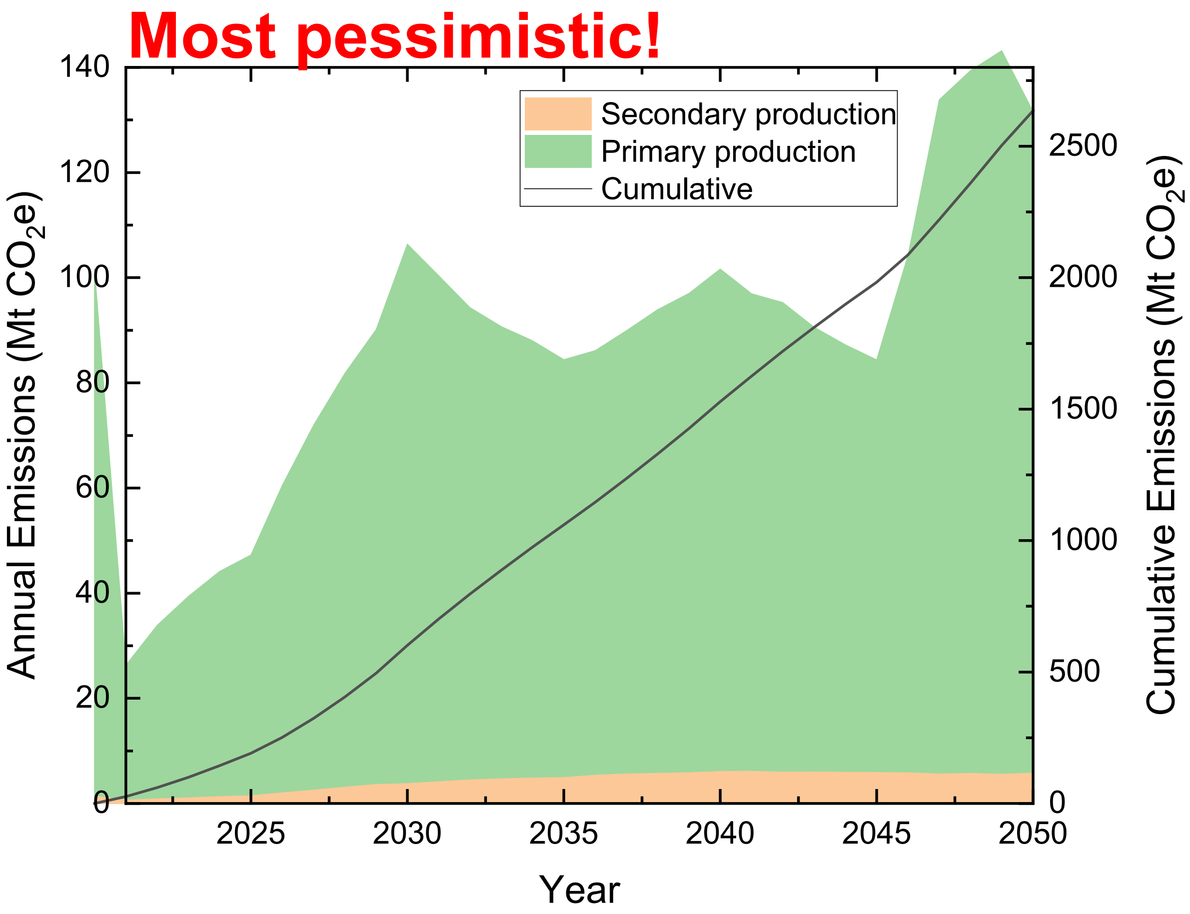
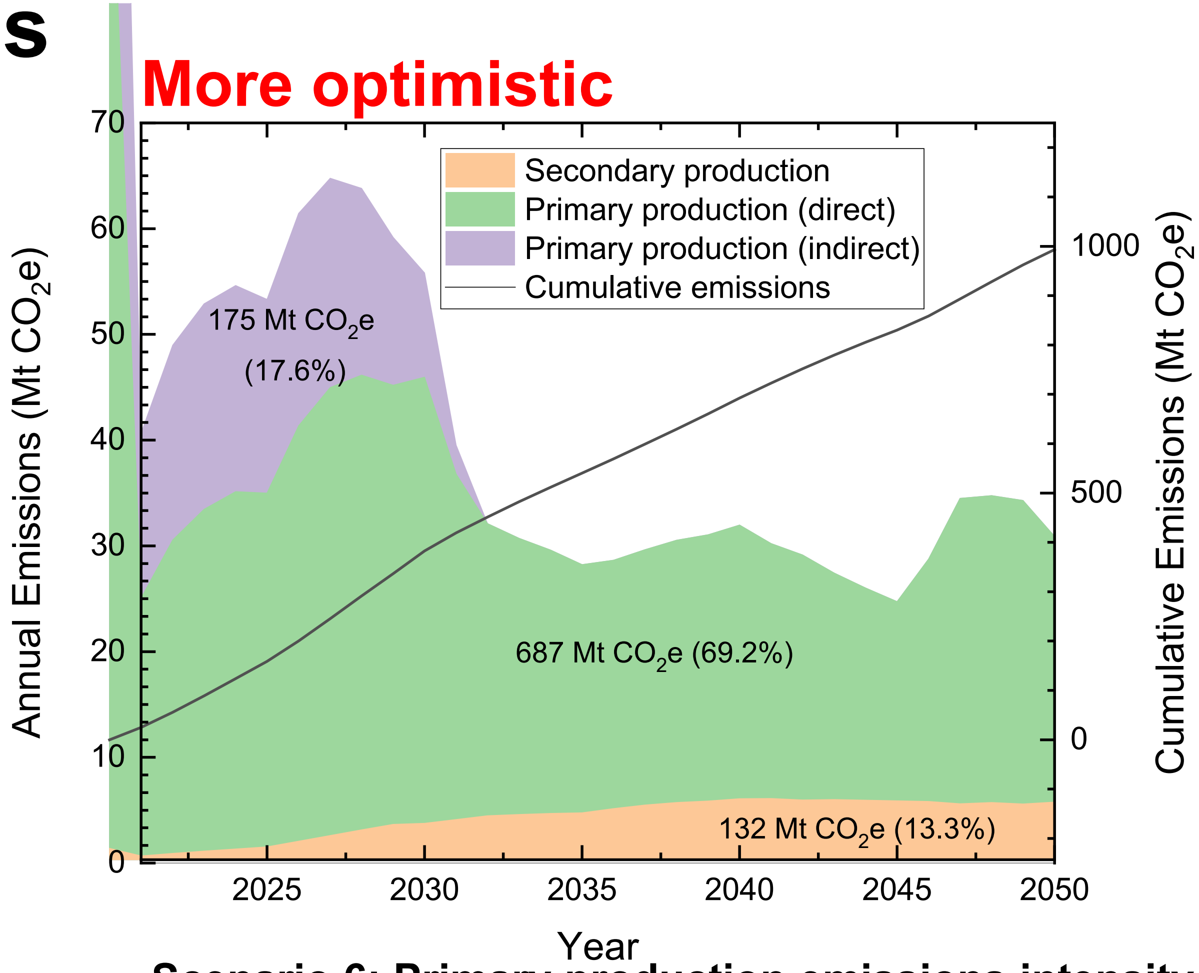
Emissions Reduction Scenarios



Scenario 5: Primary production emissions intensity remains at 14.5 t CO_2e / t Al

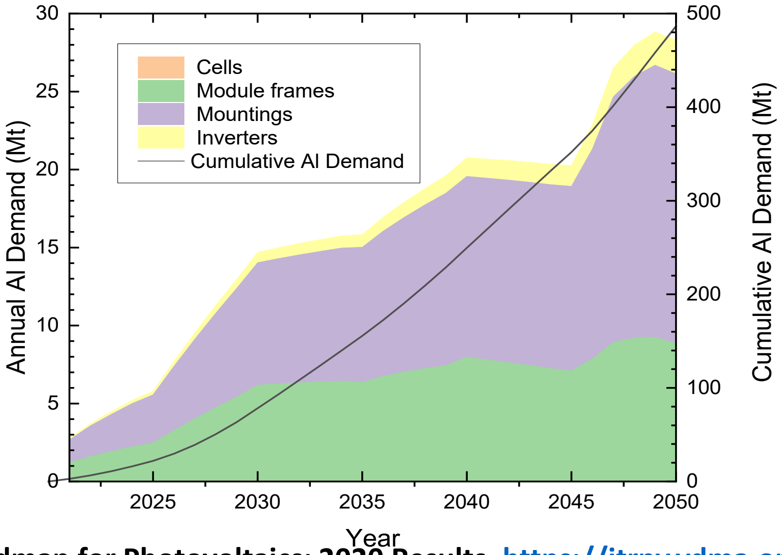


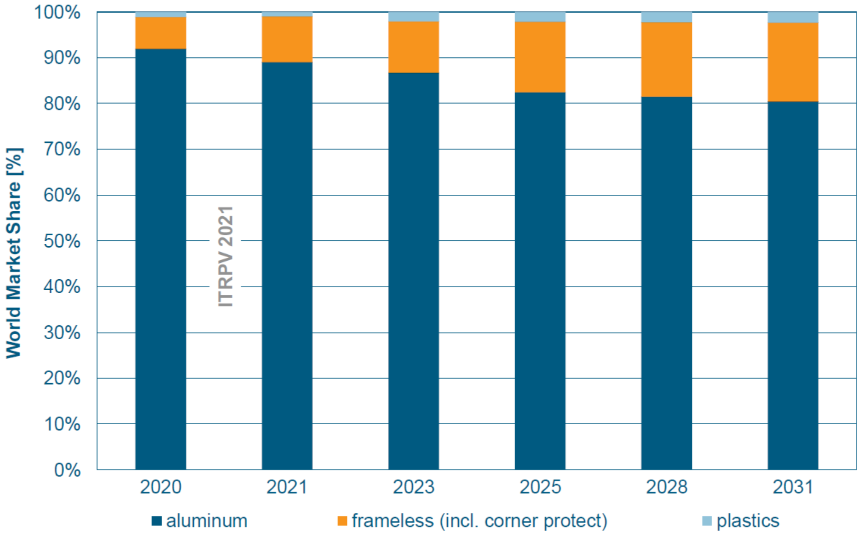
Scenario 6: Primary production emissions intensity reduces to 5.0 by 2030 (electricity decarbonisation) and then linearly reduces to 1.5 t CO_2e / t Al by 2050 (direct emissions reductions)

[1] A. Lennon et al. (2021) The Aluminium Demand Risk of Terawatt Photovoltaics for Net Zero Emissions by 2050, Nature Sustainability, Accepted.

Strategies for reducing the GWP of the required Aluminium

i. Reduce emissions intensity of Al production
ii. Faster adoption of frameless modules
iii. Alternative mountings/inverter materials
iv. <u>Local manufacturing</u>



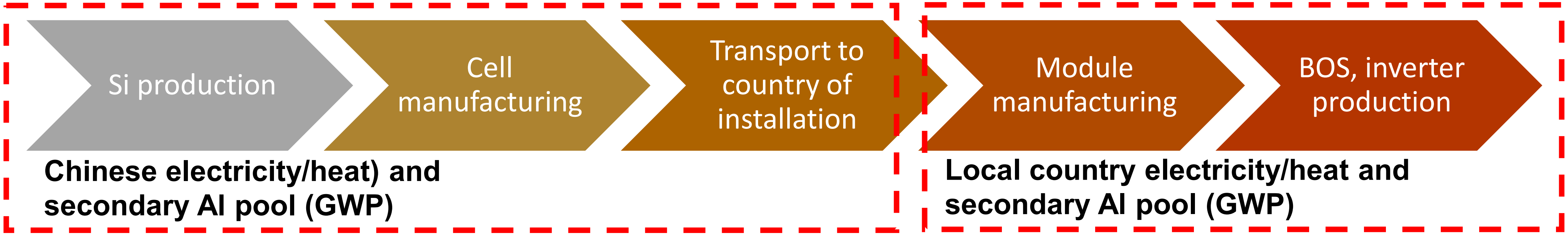


[1] ITRPV (2021) International Technology Roadmap for Photovoltaics: 2020 Results. https://itrpv.vdma.org/en/
[2] A. Lennon et al. (2021) The Aluminium Demand Risk of Terawatt Photovoltaics for Net Zero Emissions by 2050, *Nature Sustainability*, Accepted

Local Module Manufacturing

Cells are ~3% of the module weight and < 1% of the module volume

- Can access low emissions Al production (e.g., in Europe)
- Larger pool of secondary Al becomes available.
- Reduce emissions due to shipping



So we need to:

- Decarbonise electricity worldwide; and
- Decrease direct emissions intensity of primary Al; and
- Use frame & BOS components from country of installation to access lower emissions Al and increase secondary Al pool that is available; and
- Increase collection and re-use of Al worldwide.

Al Smelters in Australia

- Australia has four Al smelters

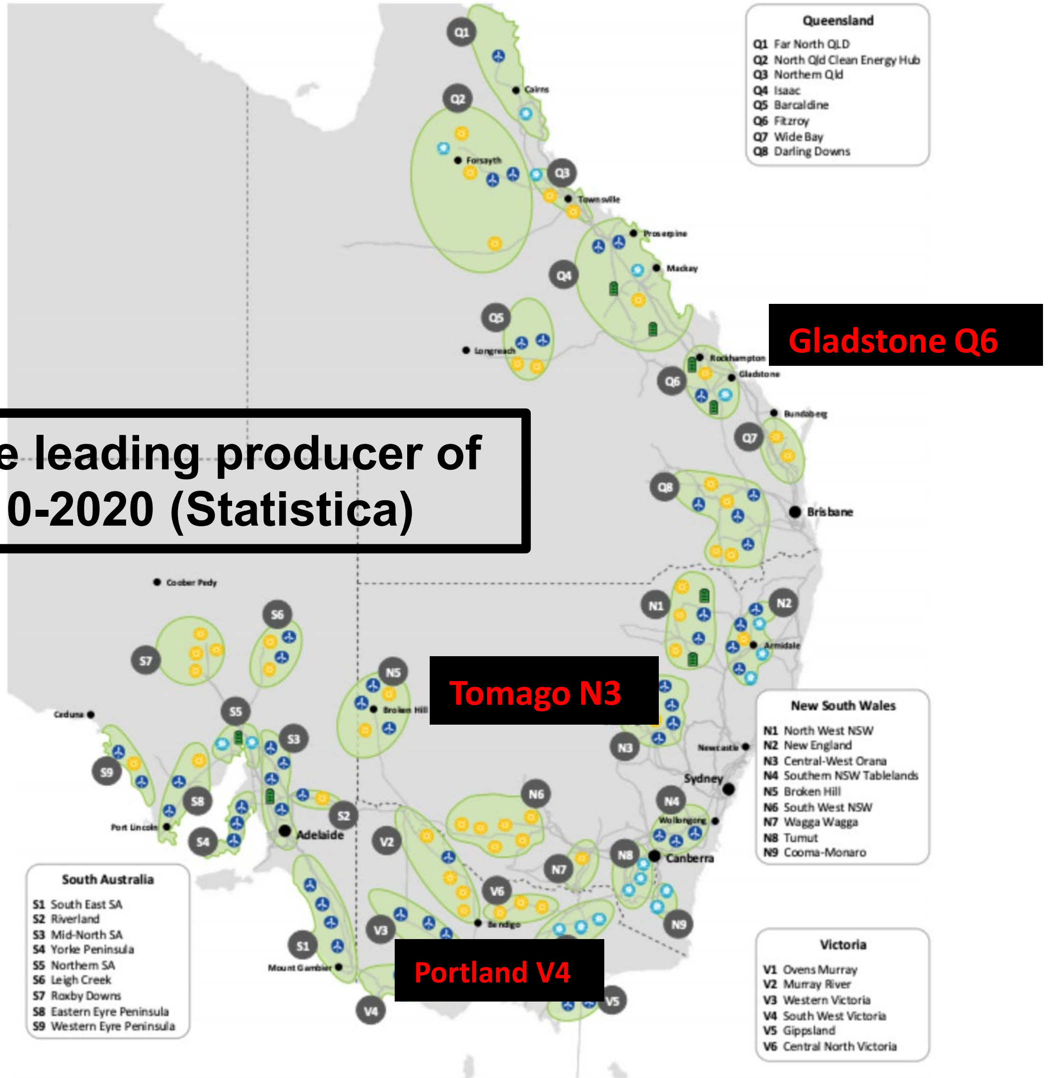
  - Tomago (NSW) ~ 0.59 Mt
  - Boyne Island (Gladstone, Queensland) ~ 0.507 Mt
  - Portland (Victoria) ~ 0.358 Mt
  - Bell Bay (Tasmania) ~ 0.19 Mt

Australia was the leading producer of bauxite from 2010-2020 (Statistica)

Table 21: Aluminium Production emissions (Mt CO_2-e) and emissions intensity (Mt CO_2-e/Mt Al) in the projections

Sector	2020	2025	2030
Electricity (indirect emissions)	16	12	10
Industrial processes and Stationary energy	3	3	3
Total emissions	**19**	**15**	**13**
Emissions intensity	**12.2**	**9.7**	**8.4**

Average emissions intensity of Al refining in China was 14.5 t CO2e/t Al in 2017 [2,3]

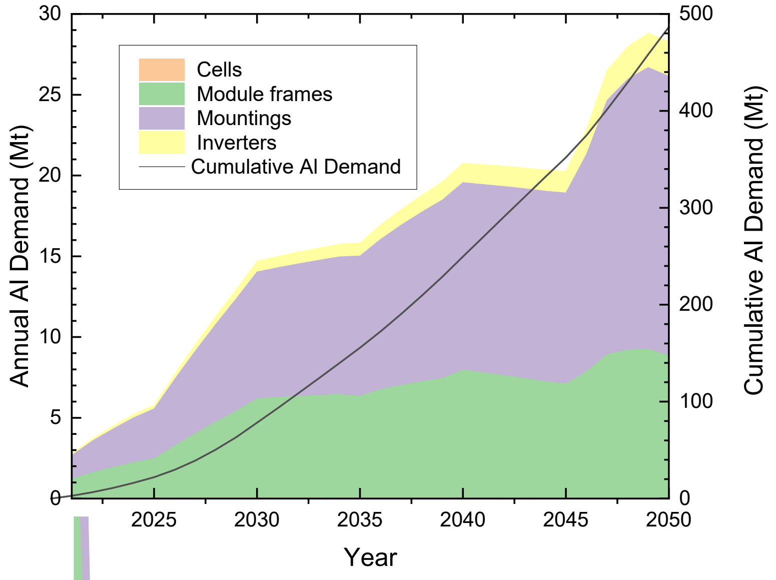


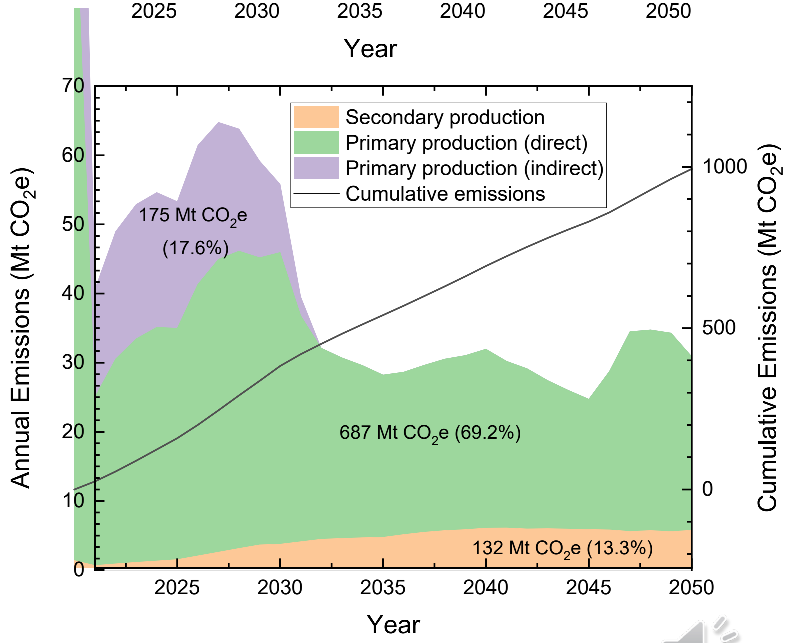
[1] https://www.industry.gov.au/sites/default/files/2020-12/australias-emissions-projections-2020.pdf
[2] H. Hao et al. (2016) GHG emissions from primary aluminium production in China: Regionaldisparity and policy implications, Applied Energy, 166, 264-272
[3] N. Ding et al. (2021) Life cycle greenhouse gas emissions of aluminium based on regional industrial transfer in China, https://doi.org/10.1111/jiec.13146
[4] Australian Industry Energy Intensive: Phase 1 Technical Report, June 2021, https://energytransitionsinitiative.org/wp-content/uploads/2021/06/Phase-1-Technical-Report-June-2021.pdf

Summary

- Achieving targeted PV installed capacities of > 60 TW by 2050 will create a large cumulative demand for Al (486 Mt) due to its use in frames, mountings and inverters of PV systems.
- Producing all the required Al can result in a large GWP (> 1000 Mt CO_2e). We will need:
  - Rapid decarbonisation of electricity (indirect emissions)
  - Process improvements (direct emissions)
- The GWP potential can also be reduced by:
  - Reducing Al usage per GW installed PV (providing suitable alternatives are available);
  - Use of locally manufactured Al to access low emissions electricity and increase the available secondary Al pool.

Al cumulative demand = 486 Mt Al
Peak demand = 28.5 Mt (2050)
Global Al production (2020) = 65 Mt





Australian Government
Australian Research Council

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Australian Renewable Energy Agency

Thank you!

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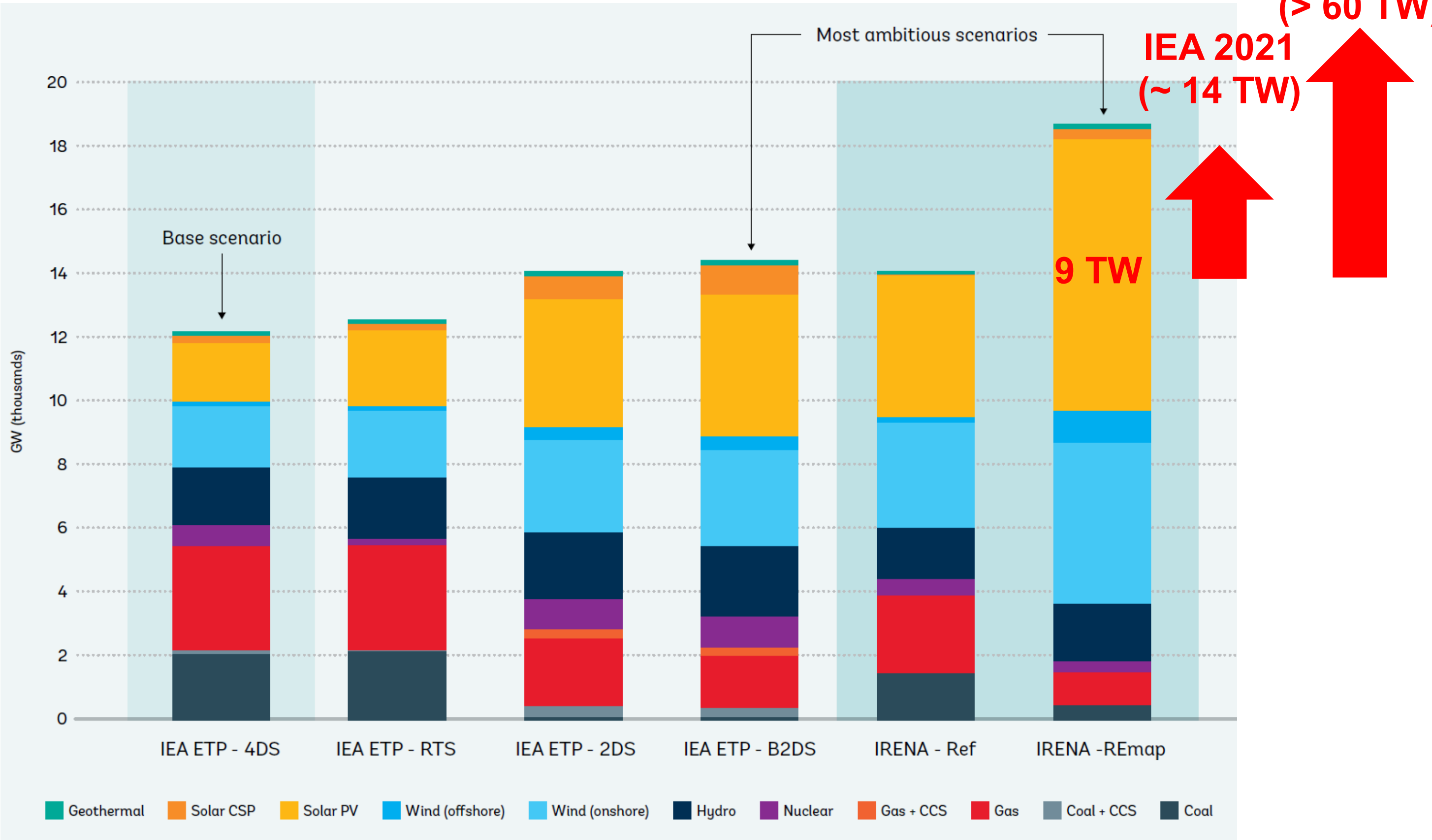
Contribution of PV to NZE 2050

Estimated installed capacity in 2050 across various technology-based mitigation scenarios [1]



- Roadmaps differ in how much PV will be required by 2050.
- IRENA (2019) REmap predicts an installed capacity of 9 TW by 2050 [2].
- IEA's Net Zero Emissions by 2050 target 4 TW installed capacity by 2030 and ~ 14 TW by 2050.
- But that is only 6% of the 2021 ITRPV's broad electrification scenario prediction (> 60 TW by 2050).

[1] World Bank (2020) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf
[2] IRENA (2019) Future of Solar Photovoltaics, November 2019. https://www.irena.org/publications/2019/Nov/Future-of-Solar-Photovoltaic
[3] IEA (2021) Net Zero by 2050: A Roadmap for the Global Energy Sector, May 2021. https://www.iea.org/reports/net-zero-by-2050

Aluminium Demand Placed in Context

- The cumulative predicted Al demand (our ITRPV analysis) was ~486 Mt.
- Despite efficiency improvements leading up to 2050, peak demand of 28.5 Mt is expected at ~ 2050
- Global Al production (primary and secondary) in 2020 was 65 Mt

Scenario	2050 PV Installed Capacity (TWp)	Cumulative Aluminium Demand (Mt)	Peak Aluminium (Mt) (year of peak)
World Bank IEA 2DS (2020)	~4	108 [1]	Not reported
IEA NZE 2050 (2021)	14	121 [3,4]	5.2 (2026)
Broad Electrification of ITRPV (2021)	60	486 [2,3]	28.5 (2050)

- The later peak for the ITRPV broad electrification scenario has implications for reducing emissions to net zero by 2050 (to be discussed later)

[1] World Bank (2020) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf
[2] ITRPV (2021) International Technology Roadmap for Photovoltaics: 2020 Results. https://itrpv.vdma.org/en/
[3] A. Lennon et al. (2021) The Aluminium Demand Risk of Terawatt Photovoltaics for Net Zero Emissions by 2050, Nature Sustainability, in press.
[4] IEA (2021) Net Zero by 2050: A Roadmap for the Global Energy Sector, May 2021. https://www.iea.org/reports/net-zero-by-2050

Emissions of PV Production

- Use of solar PV for low carbon electricity generation is a critical component of most NZE technology mitigation scenarios.
- But the manufacture of PV modules also generates emissions!
- PV manufacturers report the emissions intensity for their PV modules in 'social responsibility' or sustainability reports.

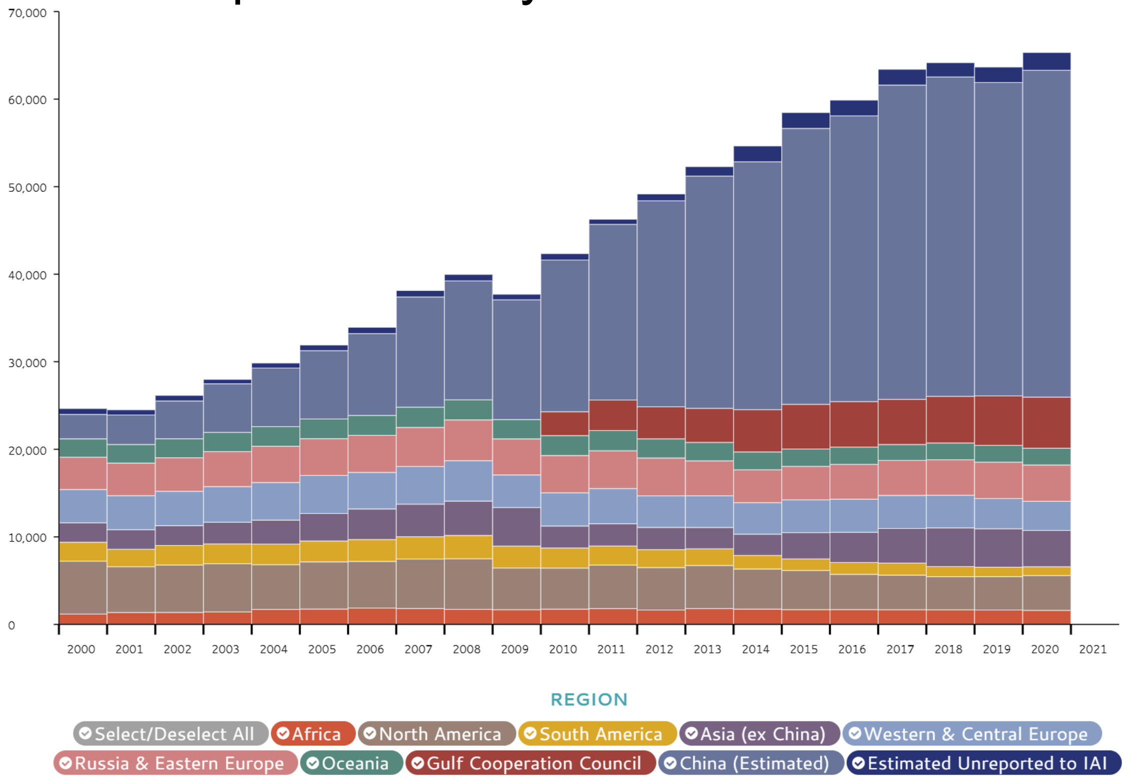
PV Manufacturer	Report Year	Emissions of PV Production (t CO_2e/MW)
Trina Solar	2020	58
Jinko Solar	2018	119
Jinko Solar	2019	113
Jinko Solar	2020	64
Canadian Solar	2021	126
Canadian Solar	2025	92

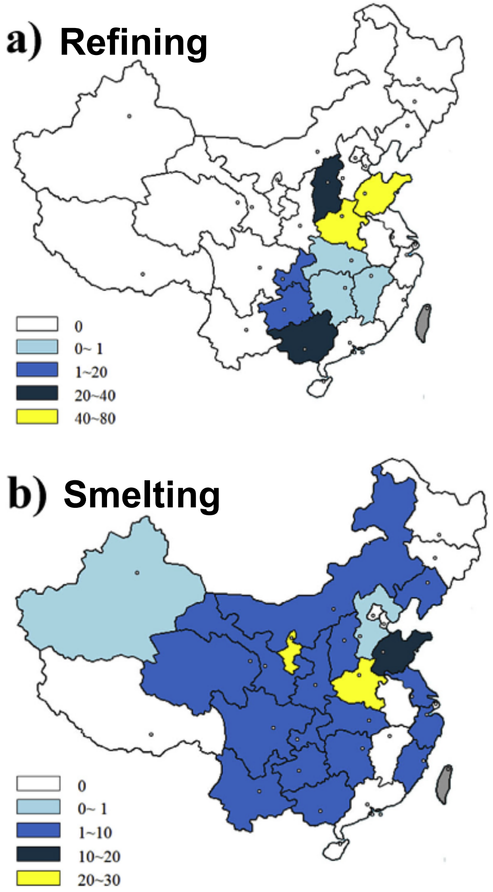
Where is Primary Aluminium Produced?

Since early 2000s, most of the world's primary Al has been produced in China [Statistica]

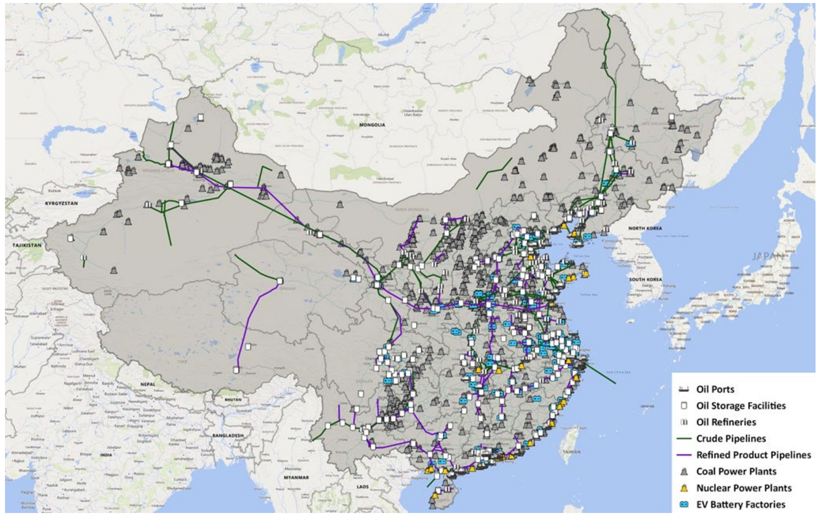
Why?

Cheaper electricity!

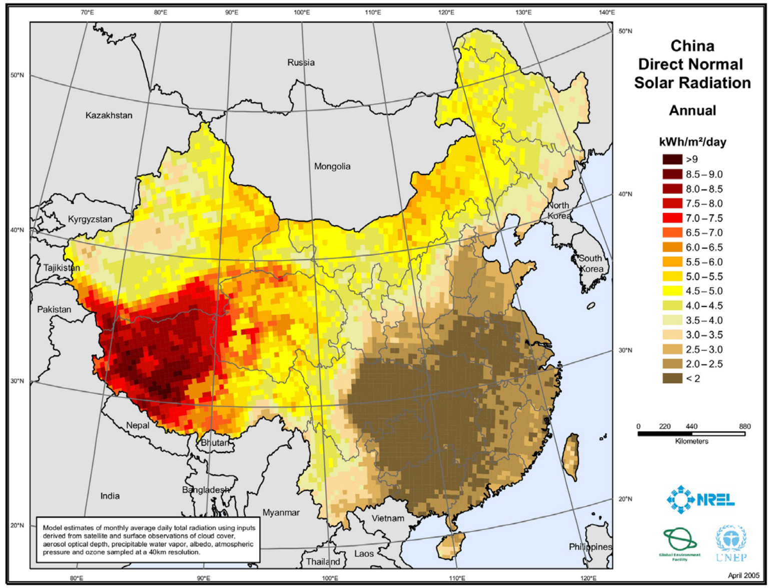




Y. Zhang et al. (2016) *J. of Cleaner Production*, 133,1242-1251



https://www.bakerinstitute.org/opensource-mapping-of-chinas-energy-infrastructure/



J. Wang et al. (2017) *Energy Science & Engineering*, 5 (2), 100-109.

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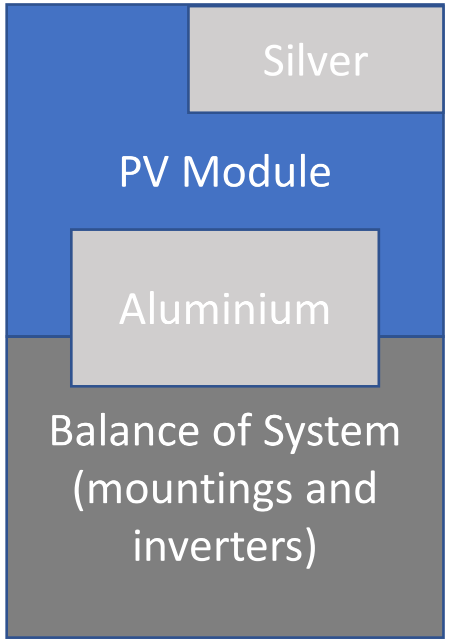
GWP of Metal Demand in Context of PV Emissions (2030)



Annual PV added capacity in 2030	1.4 TW [1]
Emissions intensity of PV production (previous slide)	50 t CO_2e / MW
Emissions from PV module production	70 Mt CO_2e
Annual Al demand in 2030 (our ITRPV 2021 analysis)	15 Mt [3]
Emissions from required Al (assuming most optimistic scenario)	42 Mt CO_2e [3]
Aluminium emissions as a fraction of PV emissions	60%
Annual Ag demand in 2030 (8.5 mg/W PERC [4])	12 kt
Emissions from required Ag (assuming 196 t CO_2e / t Ag [3]*)	2.4 Mt CO_2e

* Ag emissions intensity depends on how it is co-mined, 196 t CO_2e / t Ag is an average, recycled Ag emissions intensity is ~16 t CO_2e / t Ag

Reductions in emissions from primary metal production will be critical for PV to play its anticipated role in NZE by 2050.

[1] ITRPV (2021) International Technology Roadmap for Photovoltaics: 2020 Results. https://itrpv.vdma.org/en/
[2] P. Nuss and M. J. Eckelman (2014) Lifecycle assessment of minerals: A Scientific Synthesis, PLOS One, https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0101298
[3] A. Lennon et al. (2021) The Aluminium Demand Risk of Terawatt Photovoltaics for Net Zero Emissions by 2050, Nature Sustainability, in press.
[4] Y. Zhang et al. (2021) Energy Environ. Sci., https://doi.org/10.1039/D1EE01814K

Alternative Mounting and Inverter Casing Materials

- Replace the Al in the rooftop mountings and inverter casing with stainless steel (SS)
- Comparable GWP if scrap usage is maximised and electricity is decarbonised.

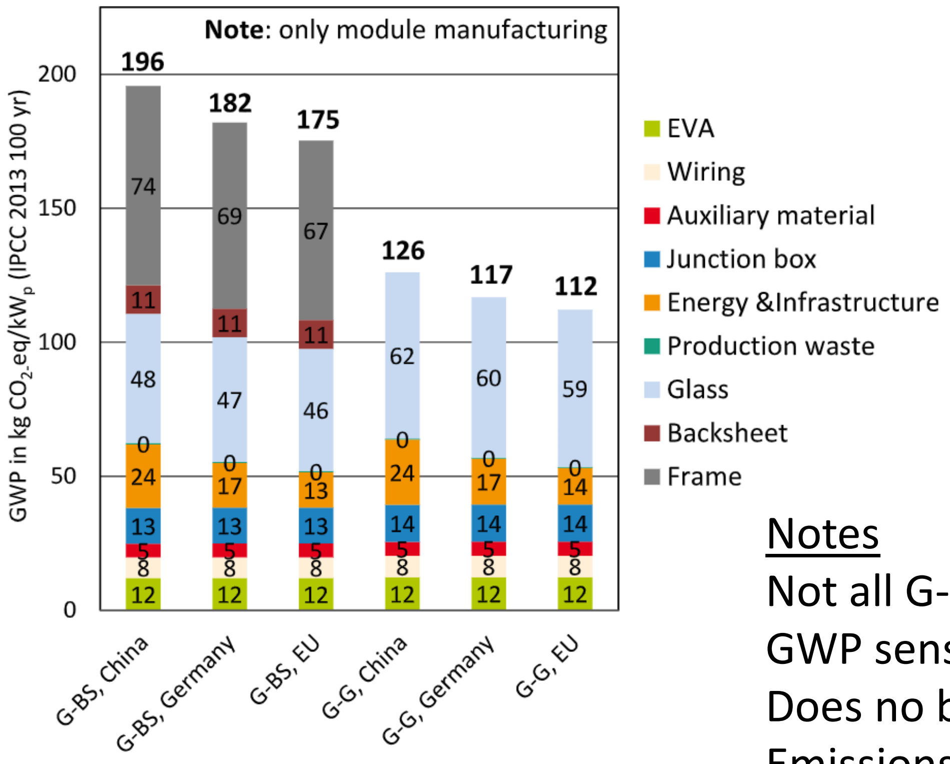
Property	Comparison between Al and SS (Cr)
Strength	SS stronger
Weight	**Al ~ 1/3rd of the weight of SS**
Cost/kg	**Similar, so Al more cost effective**
Corrosion resistance	Good for both SS and Al
Malleability	Al is easier to work with: easier to cut, stretch and manipulate. Can be extruded.

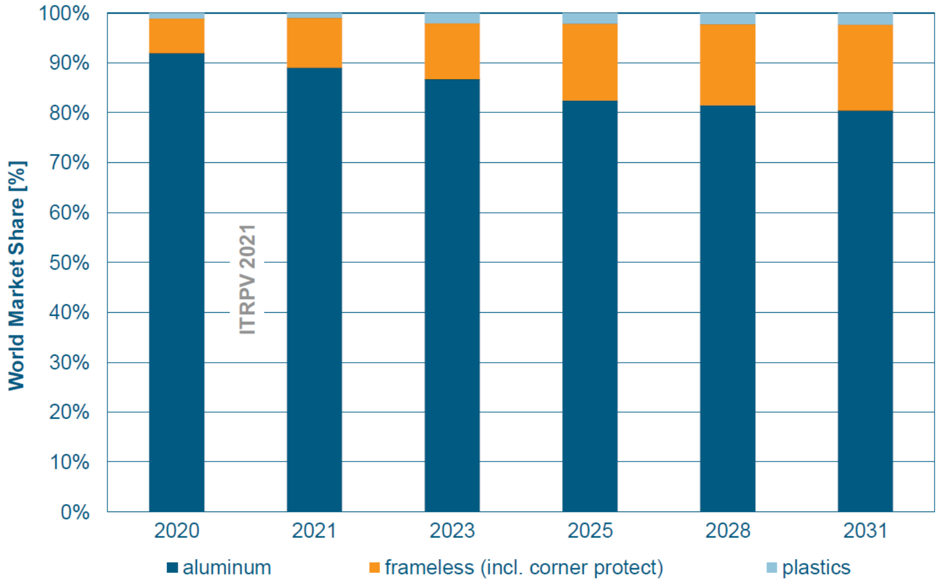
No real value in switch to SS for rooftop mountings and inverters

Metal	Average emissions intensity ($t\ CO_2e$ / t metal)
Aluminium	21 (high carbon electricity 2018)[1] 16.5 World average (2018)[1] 5.5 (low carbon electricity 2018)[1] 14.5 (China, 2017)[2.3]
Copper	4.7 (high carbon electricity)[4] 1.4 (low carbon electricity)[4]
SS (Cr)	6.0[5] (with 50% scrap can be less)

[1] IAI. Aluminium Sector Greenhouse Gas Pathways to 2050, https://www.world-aluminium.org/media/filer_public/2021/03/16/iai_ghg_pathways_position_paper.pdf (2021).
[2] Hao, H., Geng, Y. & Hang, W. GHG emissions from primary aluminum production in China: Regional disparity and policy implications. *Appl. Energy* 166, 264-272, https://doi.org/10.1016/j.apenergy.2015.05.056 (2016).
[3] Ding, N., Liu, N., Lu, B. & Yang, J. Life cycle greenhouse gas emissions of aluminum based on regional industrial transfer in China. *Journal of Industrial Ecology* Online, https://doi.org/10.1111/jiec.13146 (2021).
[4] IEA. The Role of Critical Minerals in Clean Energy Transitions, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions (2021).
[5] ISSF. Stainless Steel and CO2 : Facts and Scientific Observations, https://aceroplatea.es/docs/ISSF_Stainless_Steel_and_CO2.pdf

Faster Uptake of Frameless Modules





<u>Notes</u>

Not all G-G modules produced are frameless

GWP sensitive electricity emissions intensity (EU & Germany – Norwegian Hydo)

Does no breakdown Al production into primary and secondary

Emissions intensity of glass production will also be critical

Only the impact of module manufacturing shown (i.e., excluding cells). Aluminium and glass are produced using regionalized electricity mixes. Glass-backsheet modules: P =366 Wp, η =19.79%. Glass-glass modules: P =359 Wp, η =19.40%

A. Muller et al. (2021) A comparative life cycle assessment of silicon PV modules: Impact of module design,manufacturing location and inventory, SOLMAT, 230, 111277