NREL
Transforming ENERGY

Greener Green Energy Technologies: Reducing Environmental Impacts in Solar Modules

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ASES Solar 2023
Boulder Colorado
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Carbon Budget

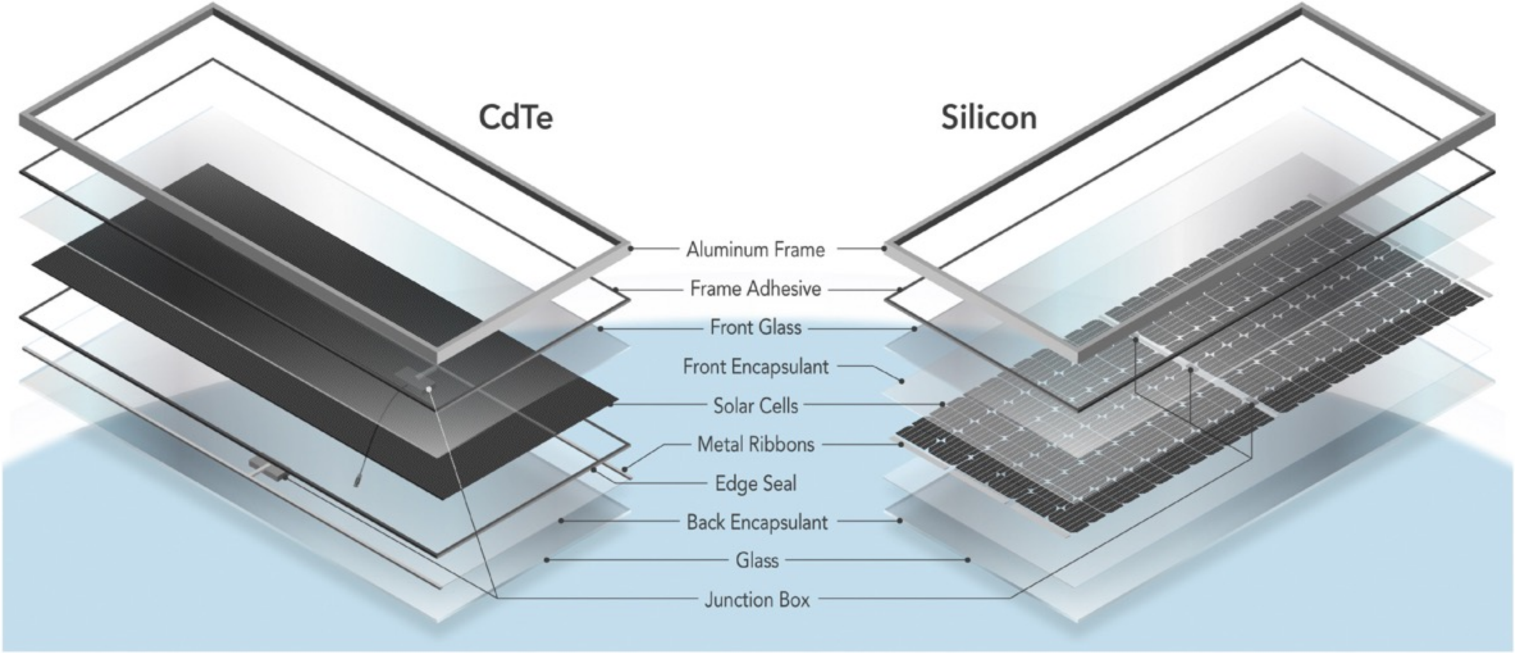
- COP26 and Paris Accords aim to limit temperature rise to 2°C and hopefully 1.5°C
- IPCC Carbon budget to reach the goals
  - 300-900 $GtCO_2e$ (17%-83% confidence).
- Government aims to reduce CO_2e emissions 50% by 2030[1]

Approximate global warming relative to 1850–1900 until temperature limit (°C)	Estimated remaining carbon budgets from the beginning of 2020 ($GtCO_2e$). Likelihood of limiting global warming to temperature limit			
	17%	50%	83%	*Higher or lower reductions in accompanying non-CO2 emissions can increase or decrease the values by 220 $GtCO_2e$ or more*
1.5 ˚C	900	500	300	
2.0 ˚C	2300	1350	900	

https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf

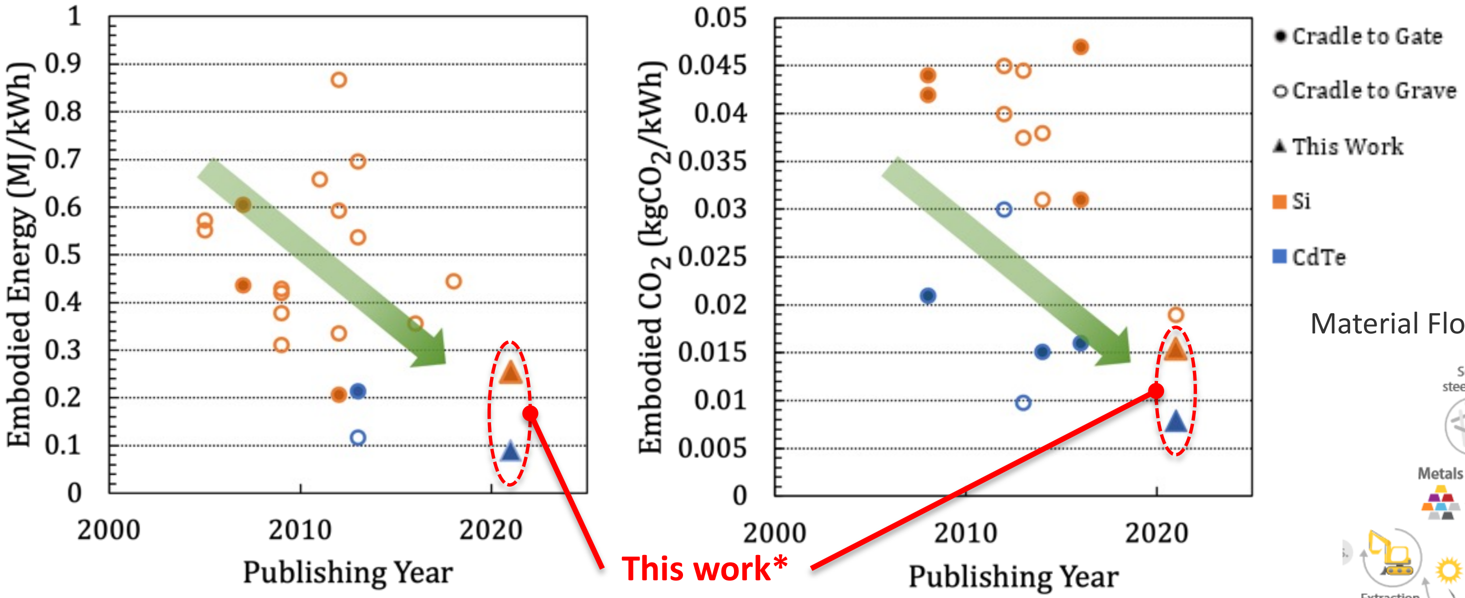
Si and CdTe as "Model" Cases

- Consulting experts determined current state of art "recipes"



[1] Hope M. Wikoff, Samantha B. Reese, Matthew O. Reese, Embodied energy and carbon from the manufacture of cadmium telluride and silicon photovoltaics, Joule, 2022, ISSN 2542-4351, https://doi.org/10.1016/j.joule.2022.06.006.

Methodology



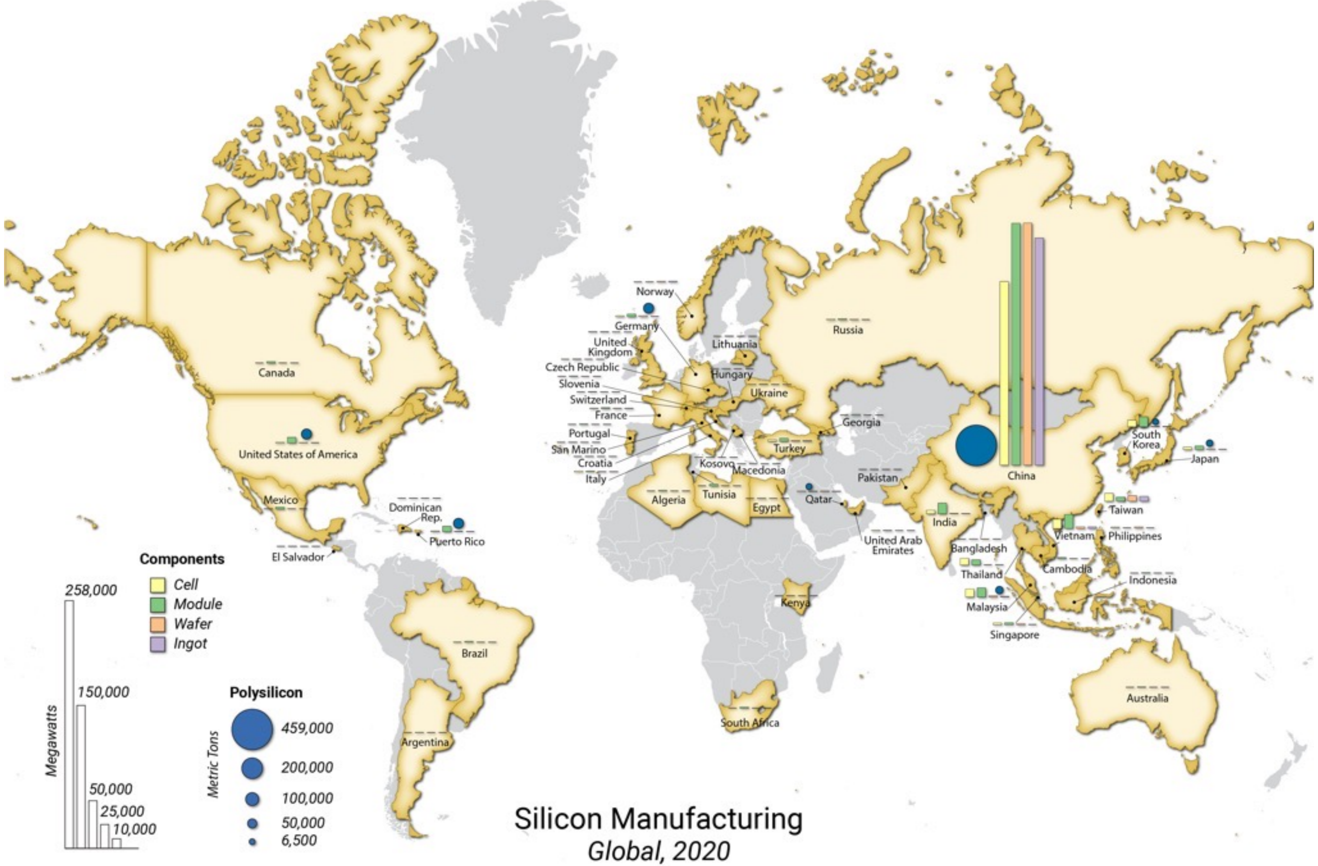
Material Flows through Industry Tool (MFI)

Values for "this work" are cradle-to-gate based on the US energy grid averages

Wikoff, Hope M., Samantha B. Reese, and Matthew O. Reese. 2022. "Embodied Energy and Carbon from the Manufacture of Cadmium Telluride and Silicon Photovoltaics." *Joule*, June. https://doi.org/10.1016/j.joule.2022.06.006.

Illustration by Alfred Hicks, NREL, Photo 63619

Si and CdTe as "Model" Cases



- Silicon based solar cells are most dominant, 90%+ of global market. [1]

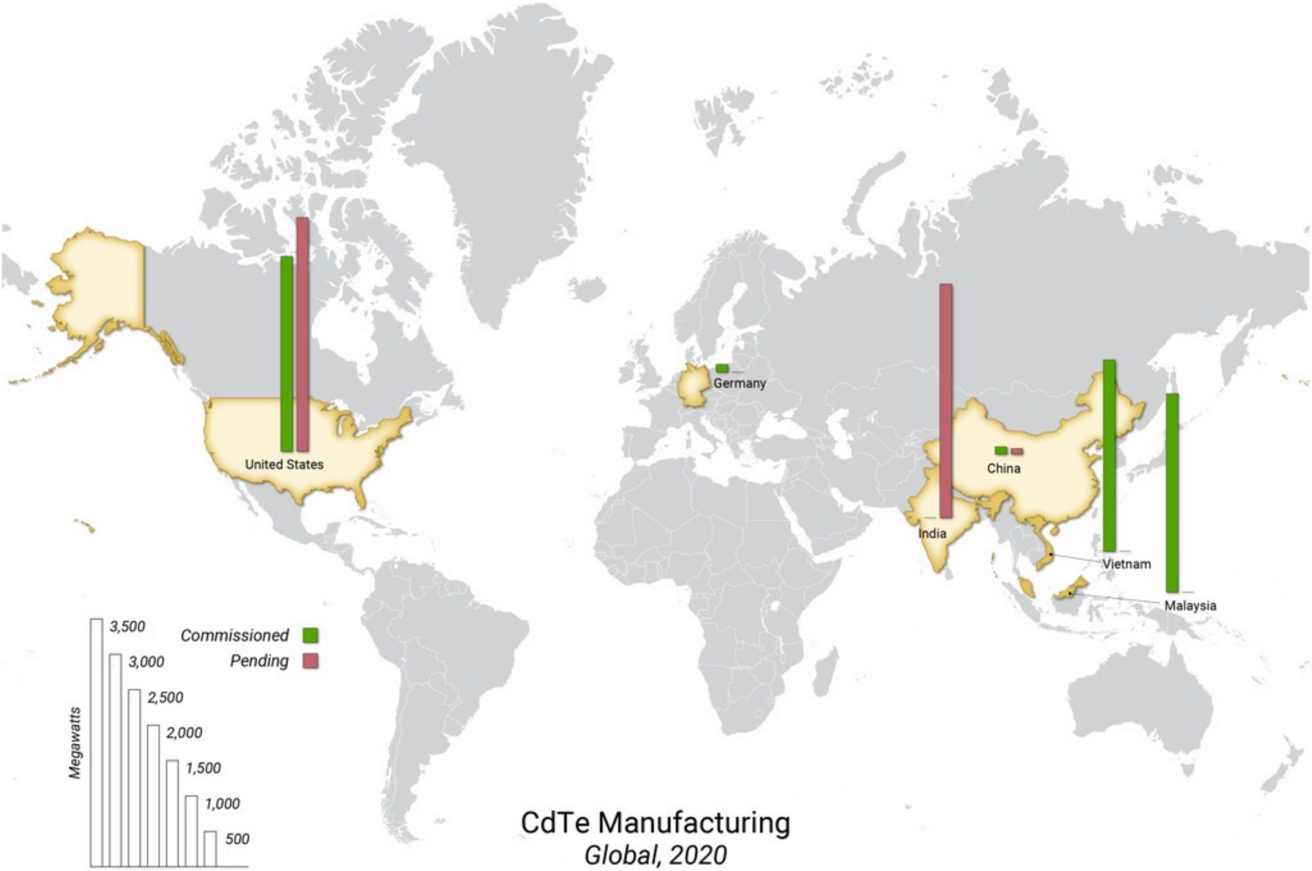
Majority of Si manufacturing in China

[1] Photovoltaic Manufacturer Shipments: Capacity, Price and Revenues 2020/2021 (SPV Market Research, 2021).

[2] Construction cost data for electric generators installed in 2019 (July 14, 2021). EIA. https://www.eia.gov/electricity/generatorcosts/.

[3] Hope M. Wikoff, Samantha B. Reese, Matthew O. Reese, Embodied energy and carbon from the manufacture of cadmium telluride and silicon photovoltaics, Joule, 2022, ISSN 2542-4351, https://doi.org/10.1016/j.joule.2022.06.006.

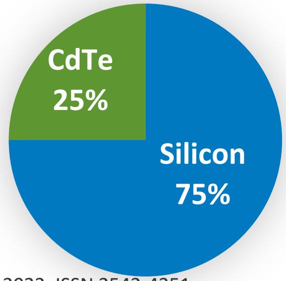
Si and CdTe as “Model” Cases



Major manufacturing of CdTe in USA and southeast Asia.

- Silicon based solar cells are most dominant, 90%+ of global market. [1]
- CdTe is 40% of the U.S. axis-based tracking market, and ~25% of cumulative U.S. installations >1 MW. [2]

US Installations >1MW



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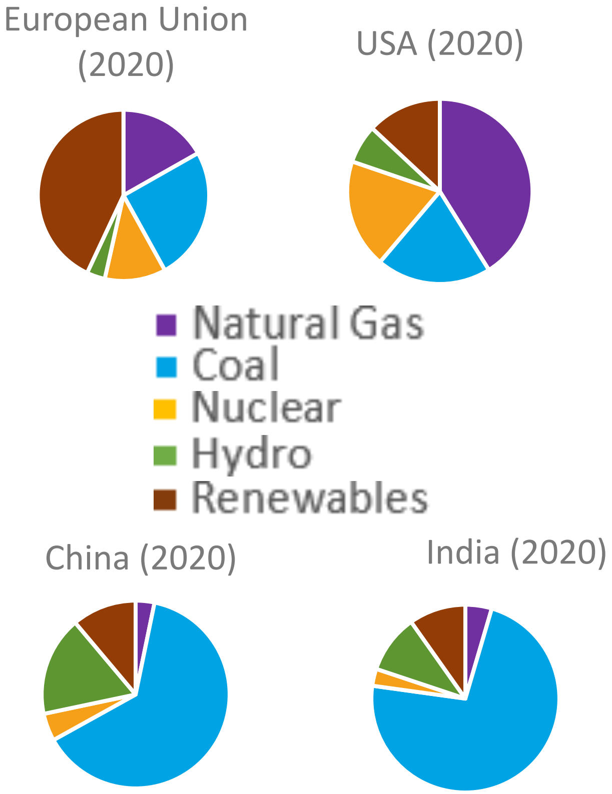
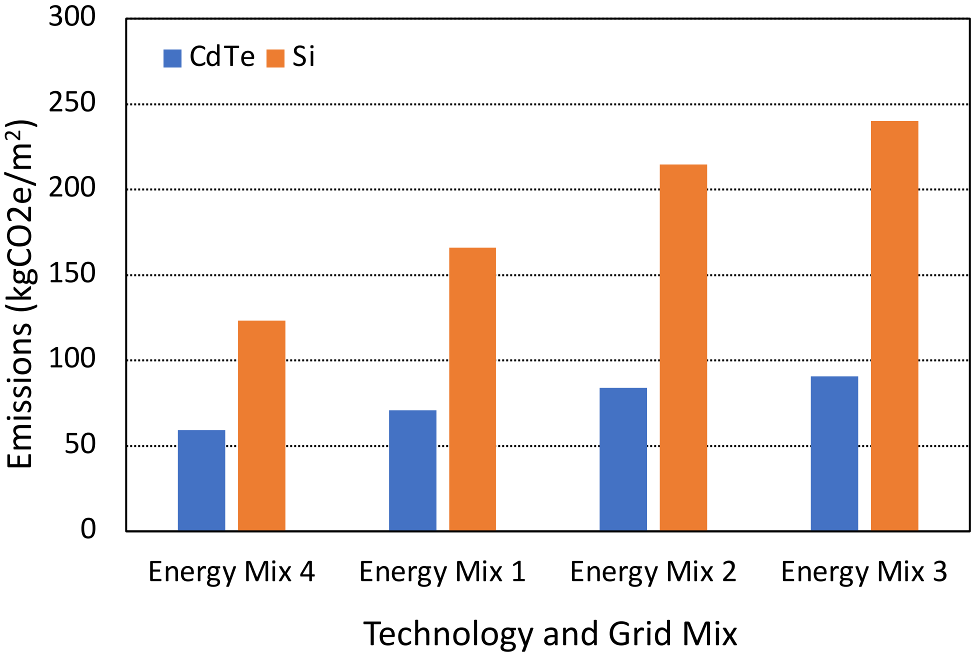
2020 Grid Mixes





- CdTe ~2X lower than Si (same mix)
- Mix can change by amount by ~2X

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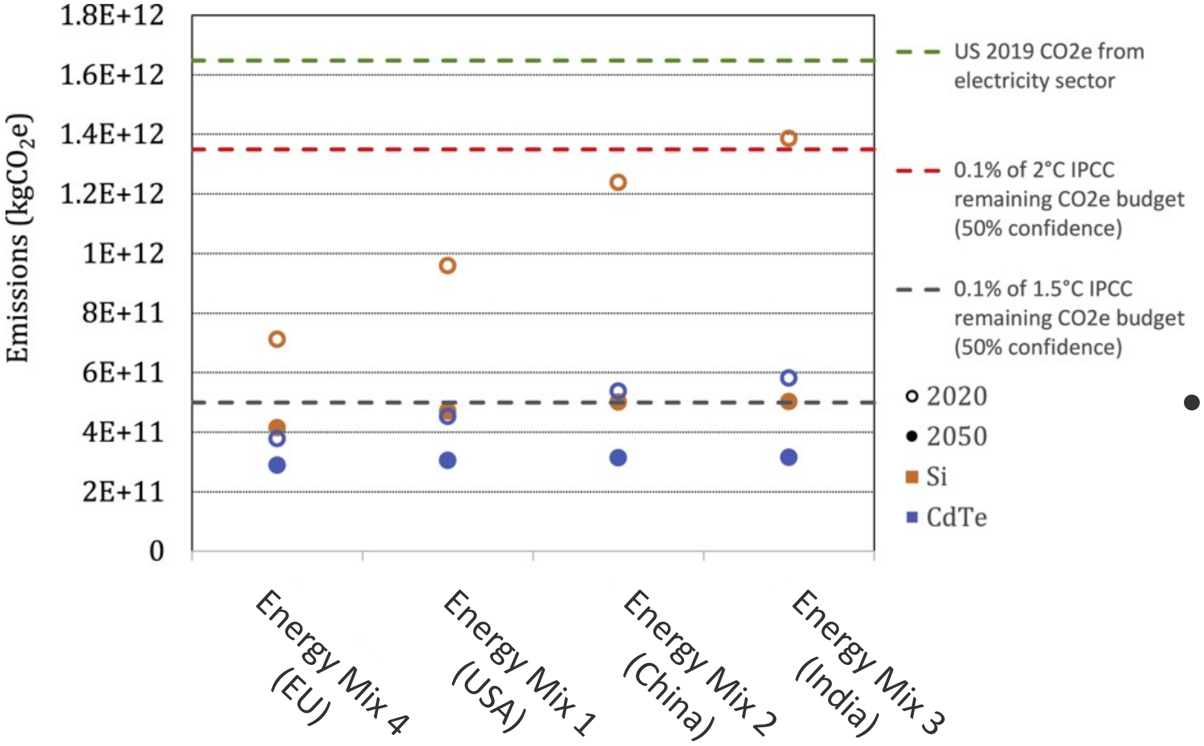
Embodied Carbon for 1 TW



- Each energy mix has ~25% difference as you step up

US manufactured CdTe vs China manufactured SI mitigates over 786Mt CO_2e

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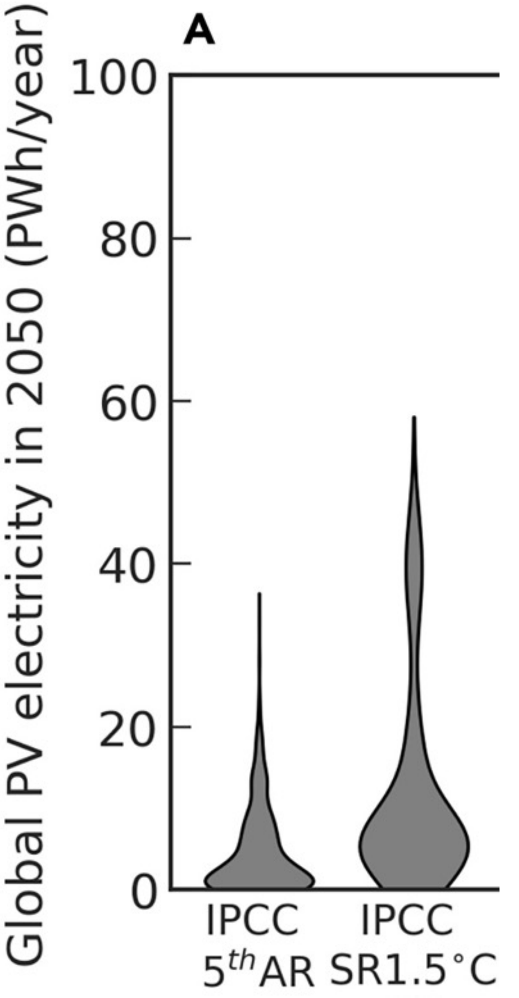
Implications…

- Estimates of installed PV by 2050 vary (~7-70 TW)
- Assuming all Si PV produced on 2020 China grid*
  → ~2-17.5% of IPCC's 1.5˚C ***total remaining budget***
- Assuming all CdTe PV produced on 2020 US grid*
  → ~0.6-6.3% of IPCC's 1.5˚C ***total remaining budget***
- Emerging thin-film PV would be on par with CdTe

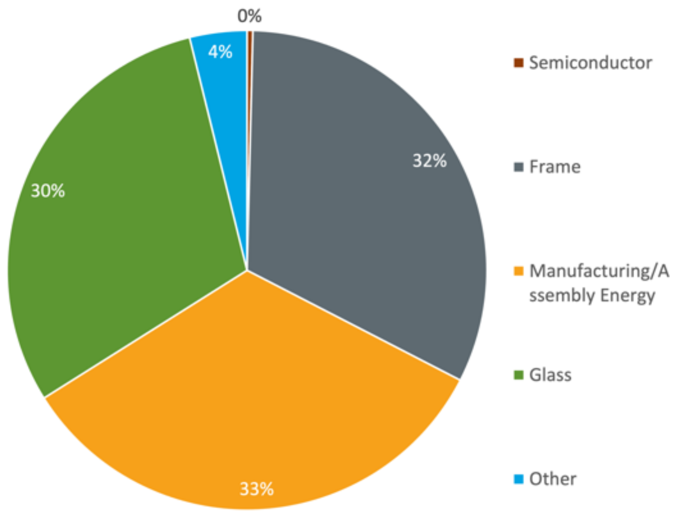


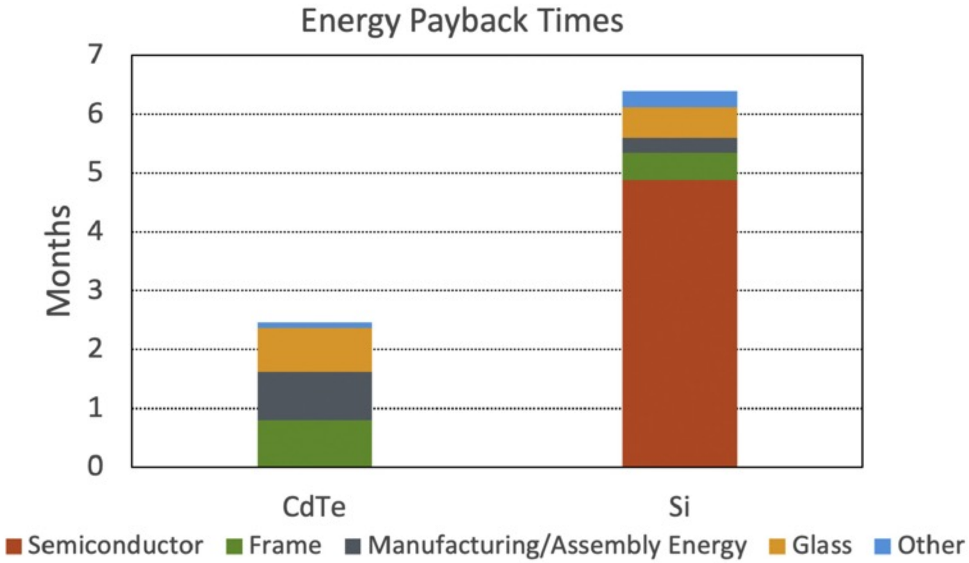
**Doesn't include racking, inverters, or other BOS*

M. Victoria, *et al.* (2021). Solar photovoltaics is ready to power a sustainable future. Joule *5*, 1041-56. https://doi.org/10.1016/j.joule.2021.03.005

Energy Payback Time

- CdTe contributed 0.3% of the material embodied energy
  - Silicon Contributes 76%!
  - CdTe is produced as a byproduct



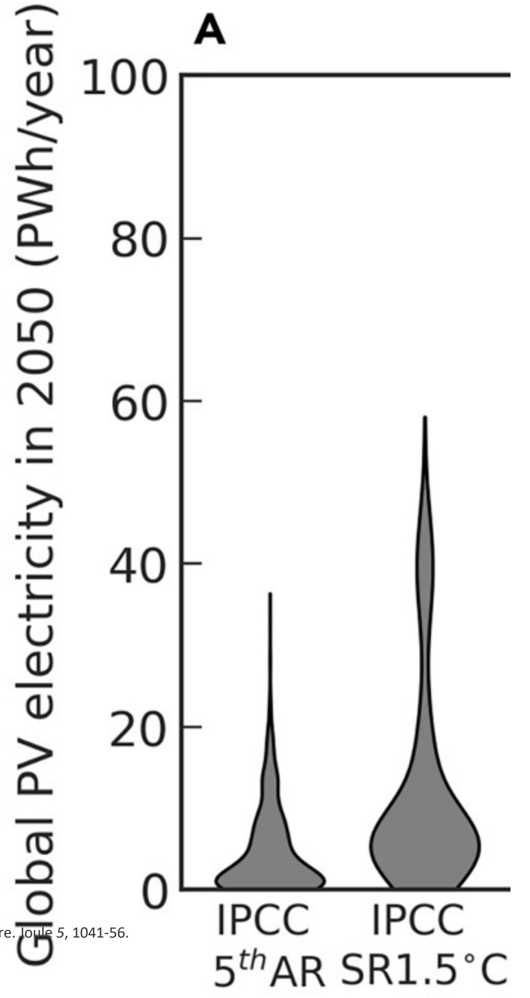


- Reduced Glass and Aluminum in silicon modules due to increased structural support from wafers

World Wide Industrial GHG Contributors

- In 2023 PV could contribute 2% of the World's industrial emissions

Source	% Industrial GHG Contribution Per Year
Ferrous and non ferrous metals	14.3%
Chemicals	10.1%
Cement*	8.8%
231 GW PV in 2023 (Assume SI & China 2020)	1.9%
57 TW PV in 2050, assuming 2TW a year (SI & China 2020)	16%



M. Victoria, N. Haegel, I.M. Peters, R. Sinton, A. Jäger-Waldau, C. del Cañizo, C. Breyer, M. Stocks, A. Blakers, I. Kaizuka, K. Komoto, and A. Smets (2021). Solar photovoltaics is ready to power a sustainable future. Joule 5, 1041-56. https://doi.org/10.1016/j.joule.2021.03.005
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf [page 753]
https://www.nrel.gov/docs/fy22osti/81900.pdf

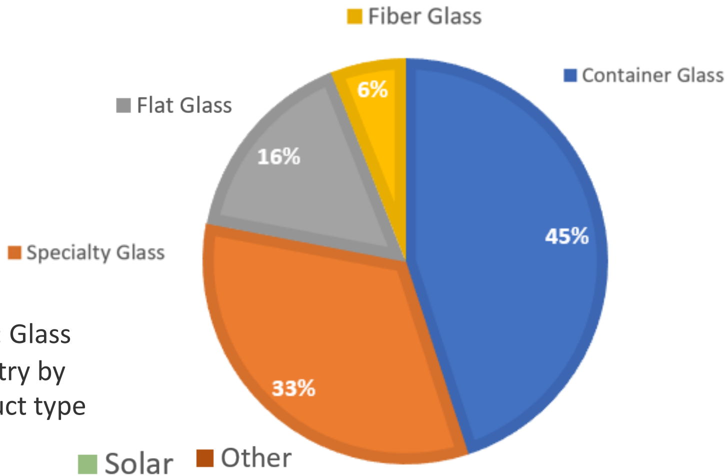
Takeaway

- Manufacturing location and technology choice can mean **3X** GHG difference
- PV manufacturing needs decarbonization
  - Frame
    - New material such as densified wood?
  - Glass
    - 52% of CdTe emissions [90 kgCO_2e]
    - 18% of Si [62.4 kgCO_2e]

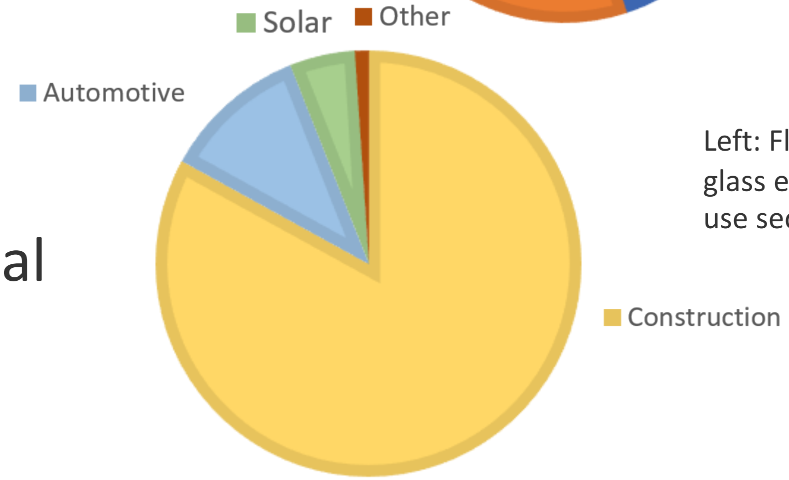
  - Semiconductor
- Carbon tax could mean ~$0.02-0.04/W difference for Si vs. CdTe manufactured in US

Solar Futures Projection

- More than 2.5 billion panels to reach Solar Futures(1TW **in USA** by 2035)
- 77 billion kilograms of glass required
- Nearly 17 years of the entire US flat glass industry to reach this goal
  - without construction, Automotive, and other Flat Glass Products



Right: Glass industry by product type



Left: Flat glass end use sectors

"Flat Glass Market." https://mms.businesswire.com/media/20170907006557/en/611046/5/Flat_Glass_Market.jpg?download=1 (accessed Jun. 29, 2023).
"Glass production global distribution by type 2018," *Statista*. https://www.statista.com/statistics/1059469/distribution-of-glass-production-globally-by-type/ (accessed Jun. 29, 2023).

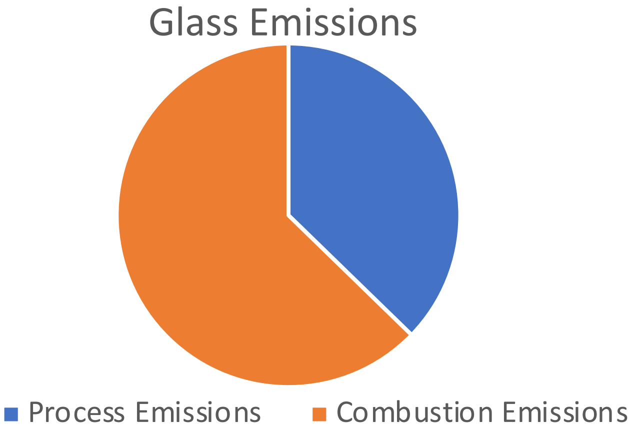
Carbon of Glass

$$Na_2CO_3 + SiO_2 \rightarrow Na_2SiO_3 + CO_2$$

Process Emissions can be a significant part of Glass Manufacturing-which will not be impacted by grid renewable permeation

- CO_2 evolution from chemical reactions can reach up to 36% of overall CO_2 emissions, or 17%wt of input lost as CO_2 [1][2]
- Need for carbon capture will persist, unless entirely closed loop process is implemented

	%	Energy Type
Batching	4-5%	Electricity
Furnace	60-80%	90% Natural Gas
Forming	1%	Electricity
Annealing	>32%	Electricity or Natural Gas



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Cullet Use

Positives

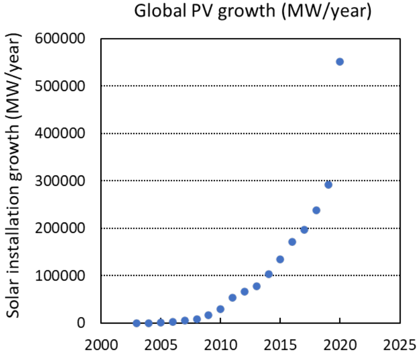
- Approximately 10% of input
  - saves 3% in overall energy[1]
  - 1.2 tons of raw material per ton of cullet [1]
- Due to chemistry no reaction energy required, only energy to melt, and lower melting point

Negatives

- quality issues (glass composition variability, contamination)
  - Transportation distance large impact on carbon savings [1]
- Recycled glass flow too small for ramping solar glass demand

Alter Fritz, 2009 [link]

Pascal Auricht, 2007 [link]



BNEF solar growth
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E. Vieitez, P. Eder, A. Villanueva, and H. Saveyn, “End-of-Waste Criteria for Glass Cullet: Technical Proposals,” European Commission Joint Research Centre, Luxembourg, ISBN 978-92-79-23101-8, 2011. [Online]. Available: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC68281/jrc68281.pdf

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Questions?

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