NREL
Transforming ENERGY

The sustainable decarbonization challenge

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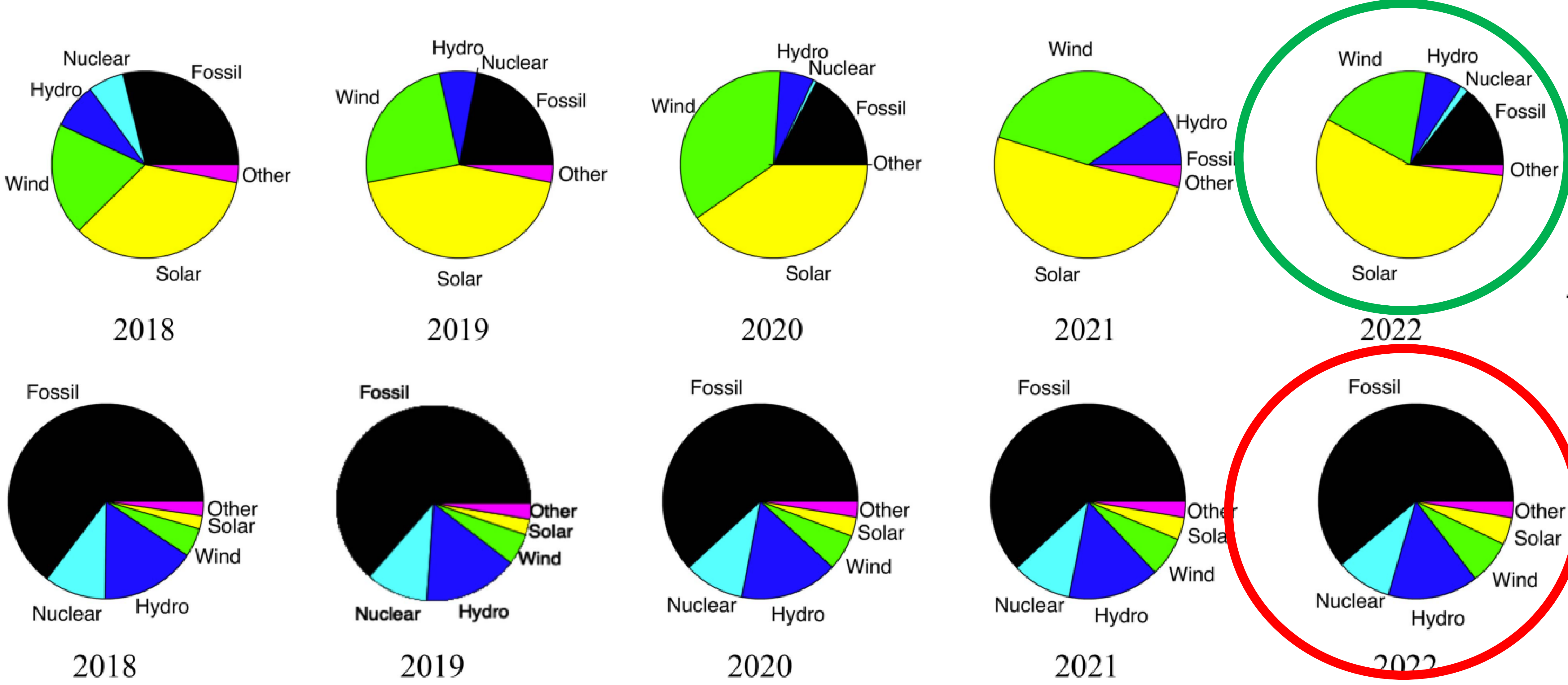
RD20
Research and Development 20 for Clean Energy Technologies
Leaders of G20 R&D Institutes
Meet to Discuss Carbon Neutral
Oct.4-5 @Online

Photo from iStock-627281636

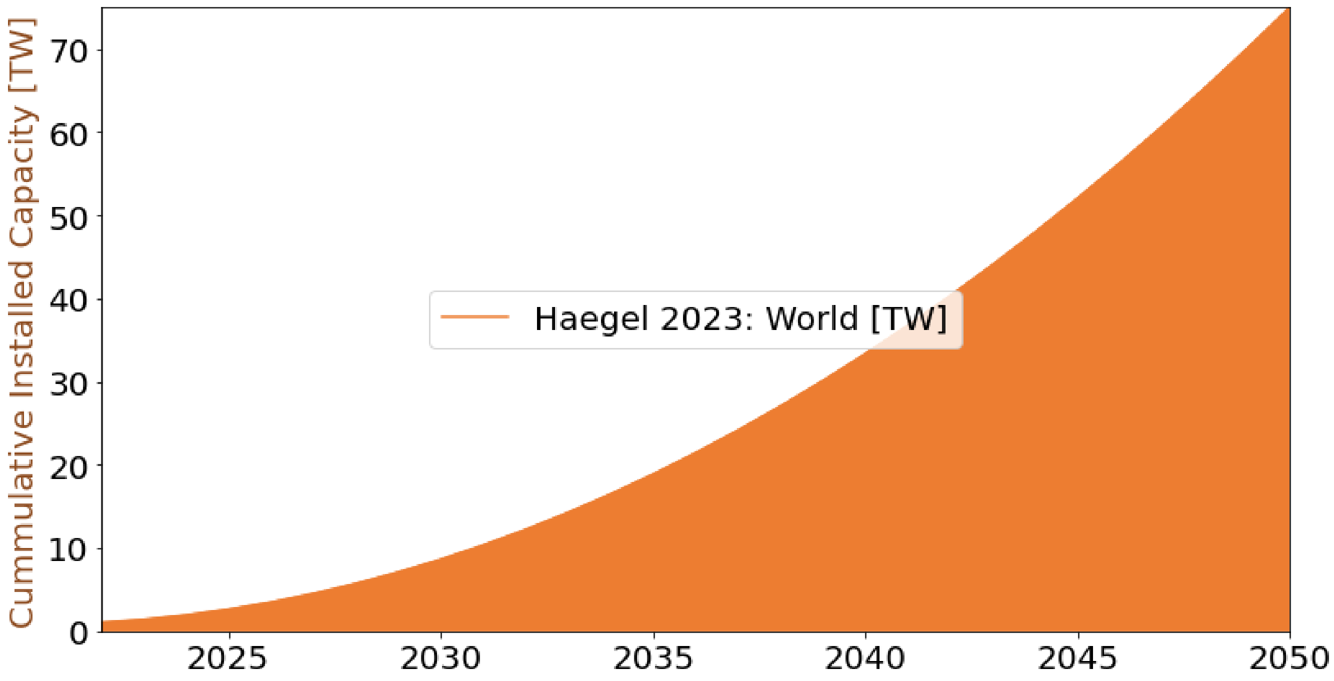
At the cusp of a revolution



Global Progress Toward Renewable Electricity: Tracking the Role of Solar (Version 3)

Haegel and Kurtz, 2023 https://doi.org/10.1109/JPHOTOV.2023.3309922

World Decarbonization Goals and PV Deployment Rates

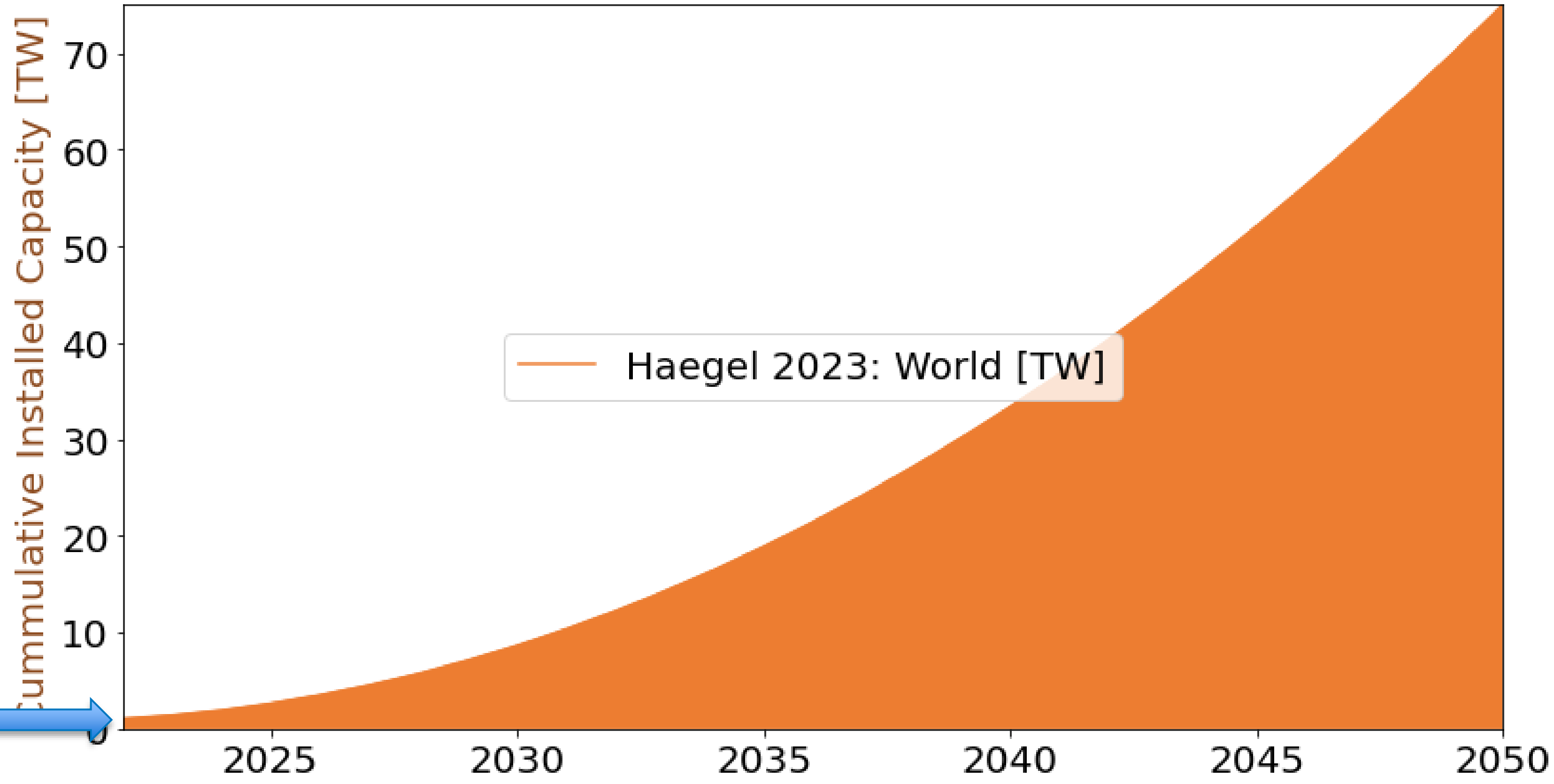


Deployment Goals
75+ TW

Terawatt Workshop
Fraunhofer ISE, AIST and NREL initiative
2016, 2018, 2021, 2022, 2024
~20 countries, ~75 participants

World Decarbonization Goals and PV Deployment Rates

CURRENT: 1.2 TW
Deployment rate
240 GW/yr

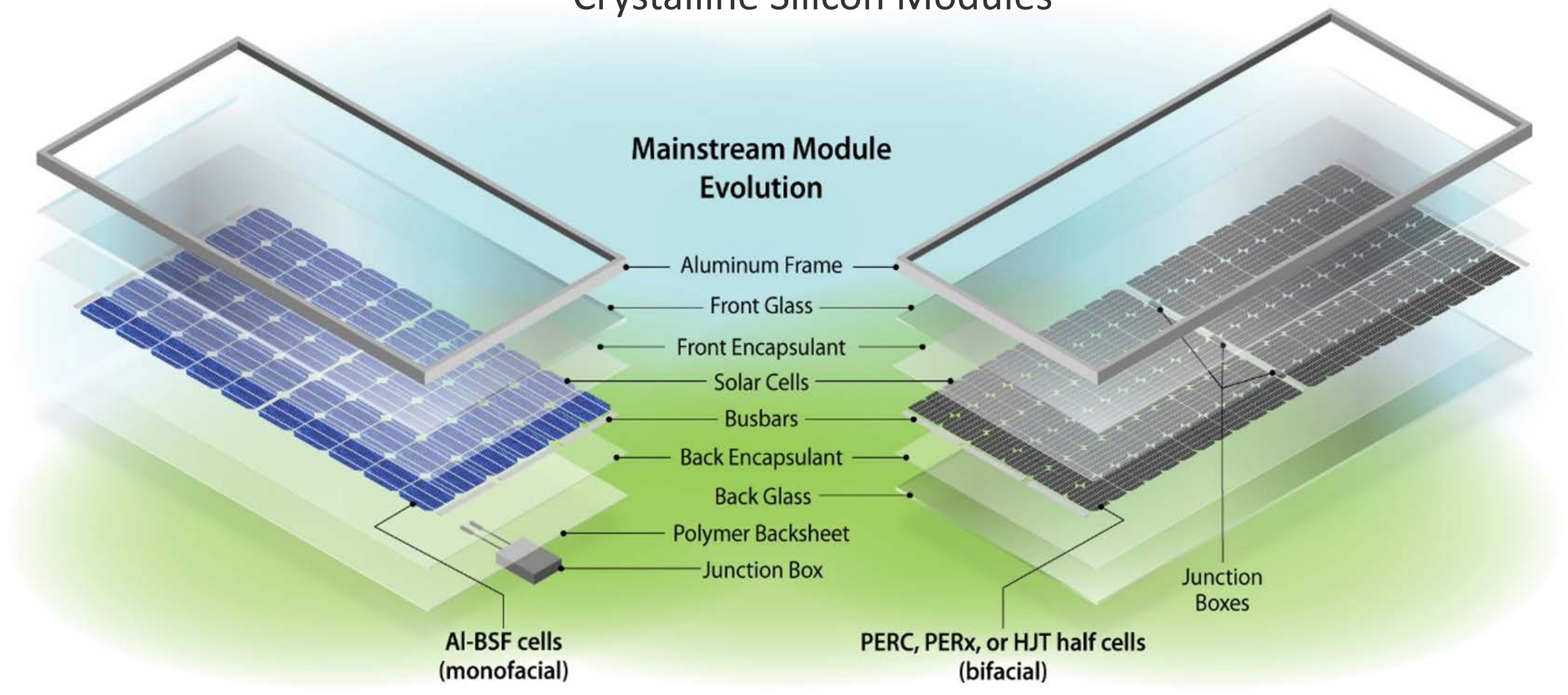


Deployment Goals
75+ TW

Deployment Rate Projected by 2030
3 TW/year
25% manufacturing sustained growth

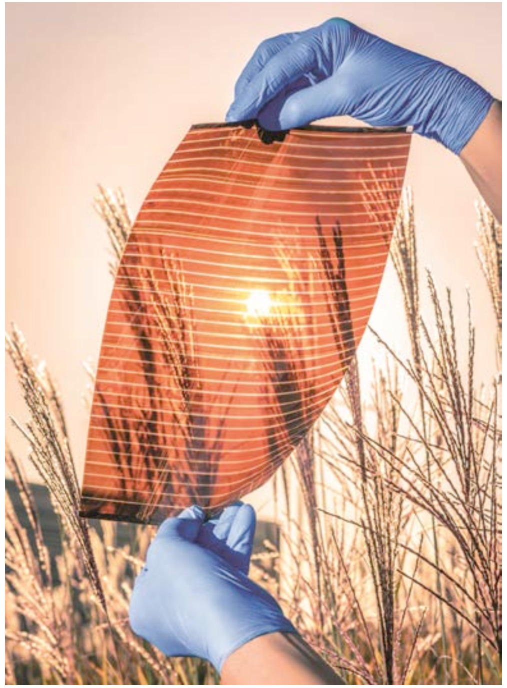
Modules Continuously Evolve

Crystalline Silicon Modules



Pre-2015 module, 20-25 year life

2022 module, 35 year life

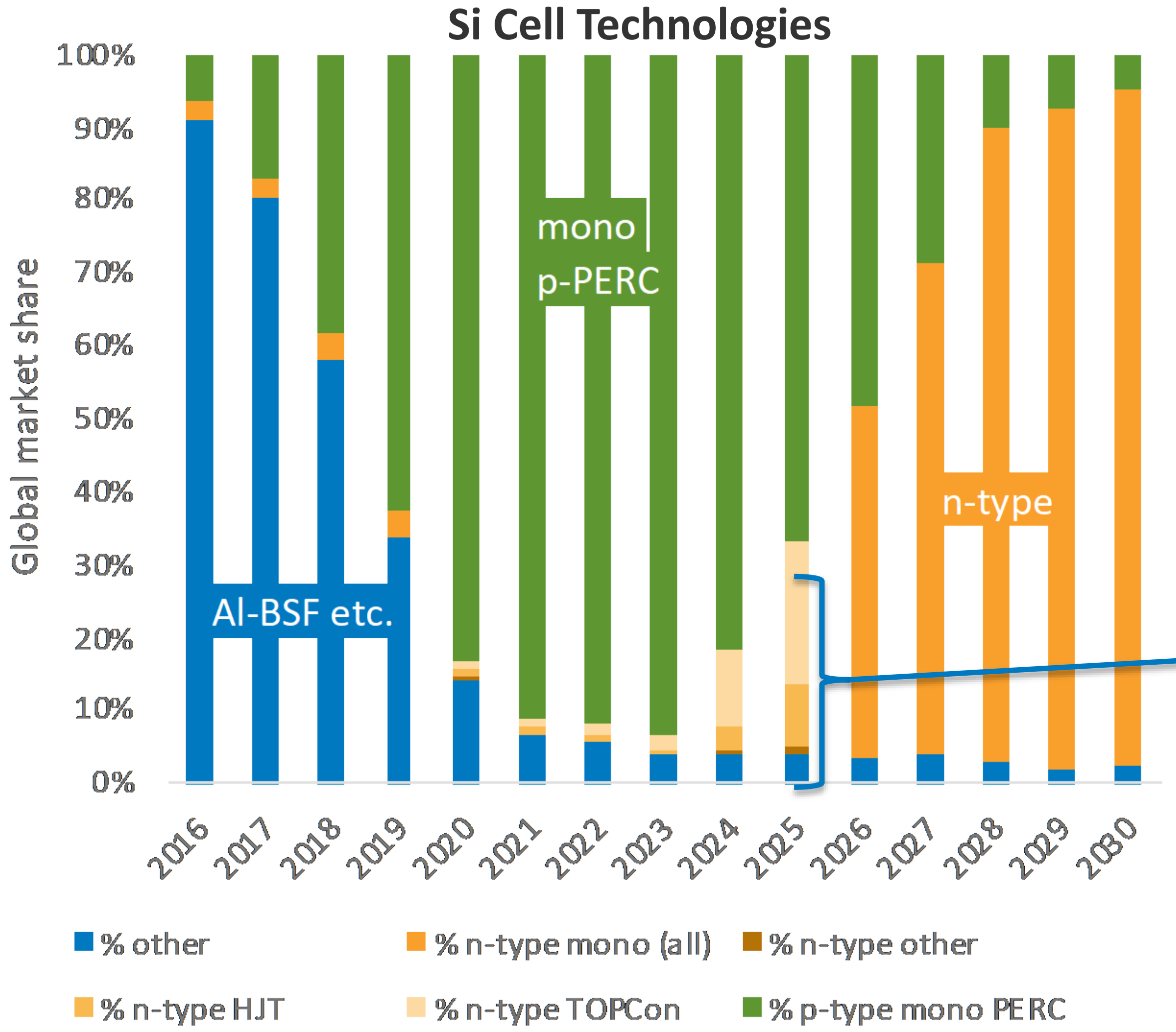


Emerging Products – flexible, non-CdTe thin film, BIPV, Etc.

Ovaitt & Mirletz et al, 2022. “PV in the Circular Economy, A Dynamic Framework Analyzing Technology Evolution and Reliability Impacts.” *ISCIENCE* https://doi.org/10.1016/j.isci.2021.103488.

New Technology + Explosive Growth

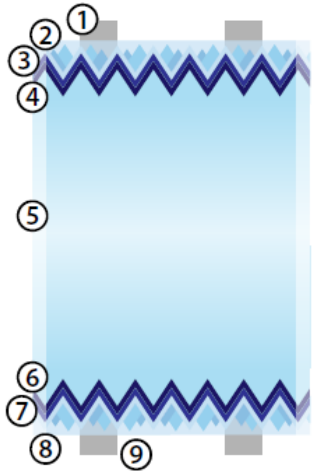
Module bifaciality factor $\phi = \frac{P_{Rear}}{P_{Front}}$



HJT

23-25% cell efficiency

ϕ ~0.85 – 0.95

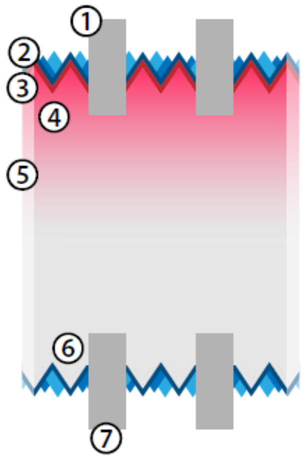


1. Frontside fingers (busbars optional) compromised of low-temperature screen-printed Ag pastes or electroplated Ni/Cu/Sn/Ag
2. TCO by PVD (typically ITO for high optical transmission and low sheet resistance)
3. p^+ doping and full-area emitter formation by PECVD of a-Si:H
4. Intrinsically doped a-Si:H by PECVD
5. High lifetime n-type base wafer
6. Intrinsically doped a-Si:H by PECVD
7. n^+ doping and full-area BSF formation by PECVD of a-Si:H
8. TCO by PVD (typically ITO for high optical transmission and low sheet resistance)
9. Backside fingers (busbars optional)

TOPCon

21-23% by SP, 21-26% by PVD

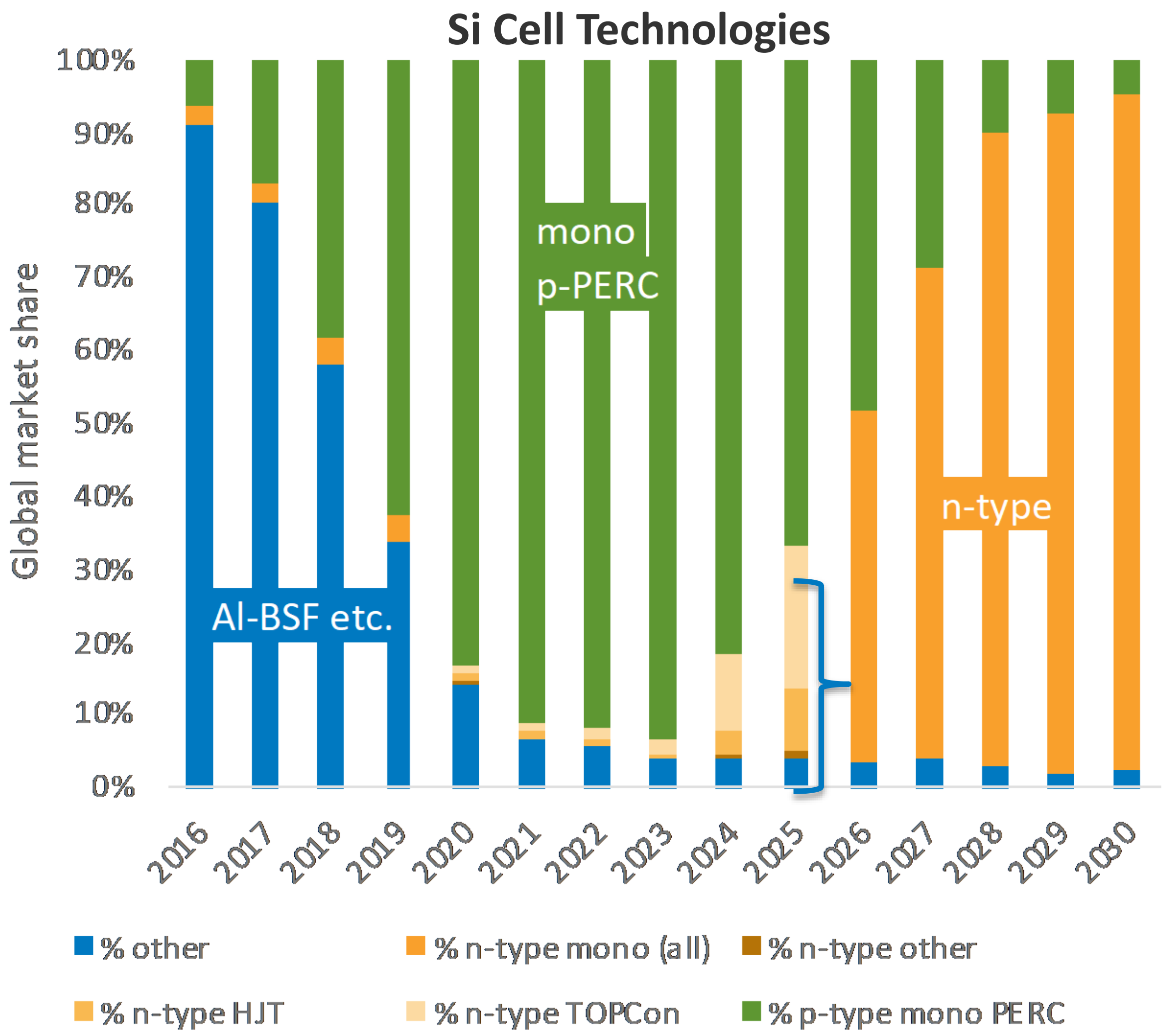
ϕ ~0.8



1. Ag and Al front metallization by screen-printing or PVD
2. SiN_x ARC and passivation layer by PECVD
3. PECVD or ALD of AlO_x surface passivation layer
4. p^+ doping and full-area emitter formation by ion implantation or BBr_3 diffusion
5. High lifetime n-type base wafer
6. Tunnel oxide passivated contact (TOPCon) layer formed by PECVD or LPCVD of doped a-Si or poly-Si layers
7. Ag rear metallization (sometimes full-area) by screen-printing or PVD

Jarett Zuboy. DuraMAT Tech Scouting 2022

New Technology + Explosive Growth



Expect somewhat disruptive technology changes requiring new fabs every few years

Current events illustrate benefits of increased geographic diversity for new plants, and of sustainable planning

Policies (US):

- Uyghur Forced Labor Prevention Act
- Inflation Reduction Act

Market Dynamics

- Supply shortages, i.e. polysilicon price shocks

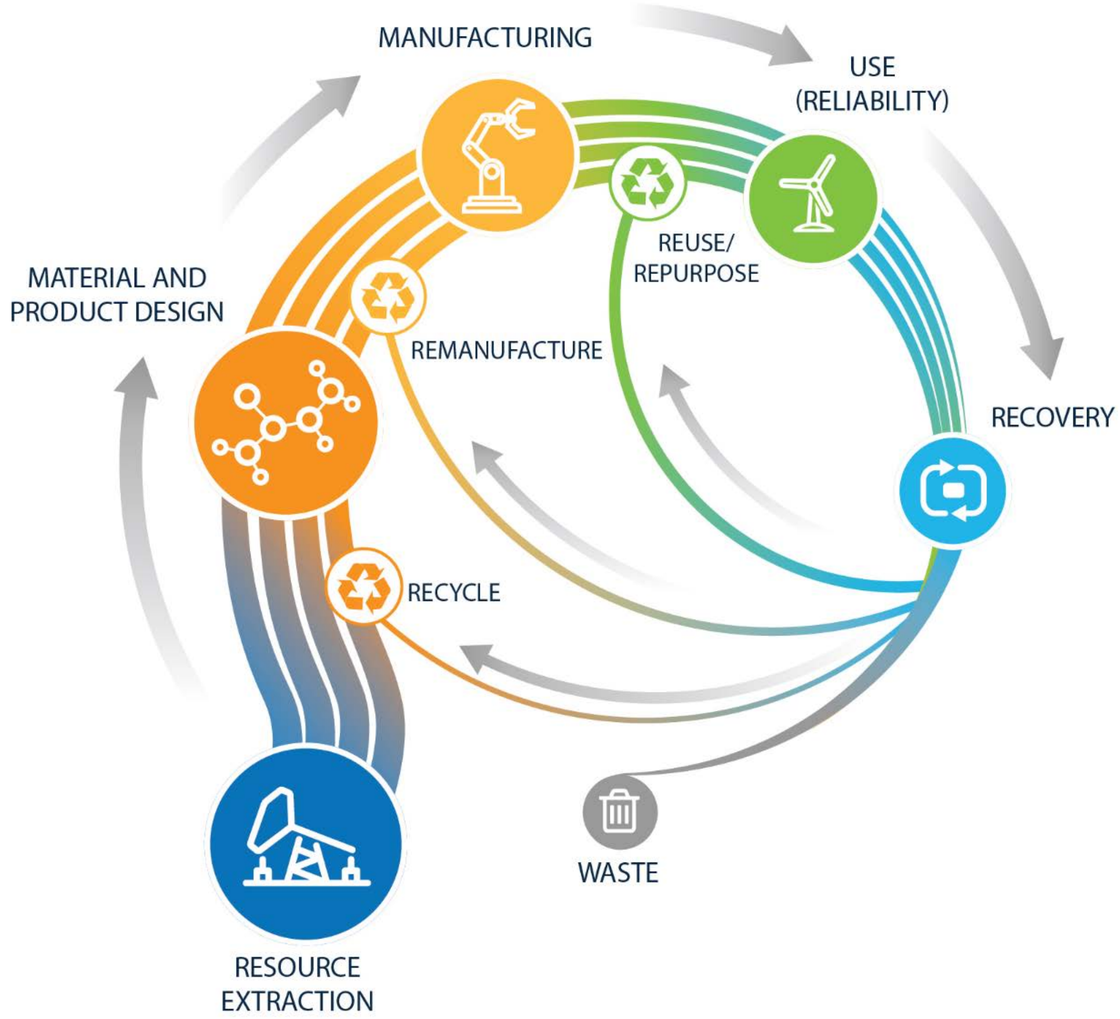
Diversity, Equity, Inclusion & Sustainability

- Reduction of Increased negative environmental and social impacts. i.e. forced labor in polysilicon production, poorly regulated or illegal sand mining

Jarett Zuboy. DuraMAT Tech Scouting 2022

How do we deploy Sustainably?

Circular Economy



$$CI = 1 - \frac{V + W}{2M + \sum_x \frac{W_{F(x)} - W_{R(x)}}{2}}$$

Virgin Material → V

Waste → W

Mass of the product → M

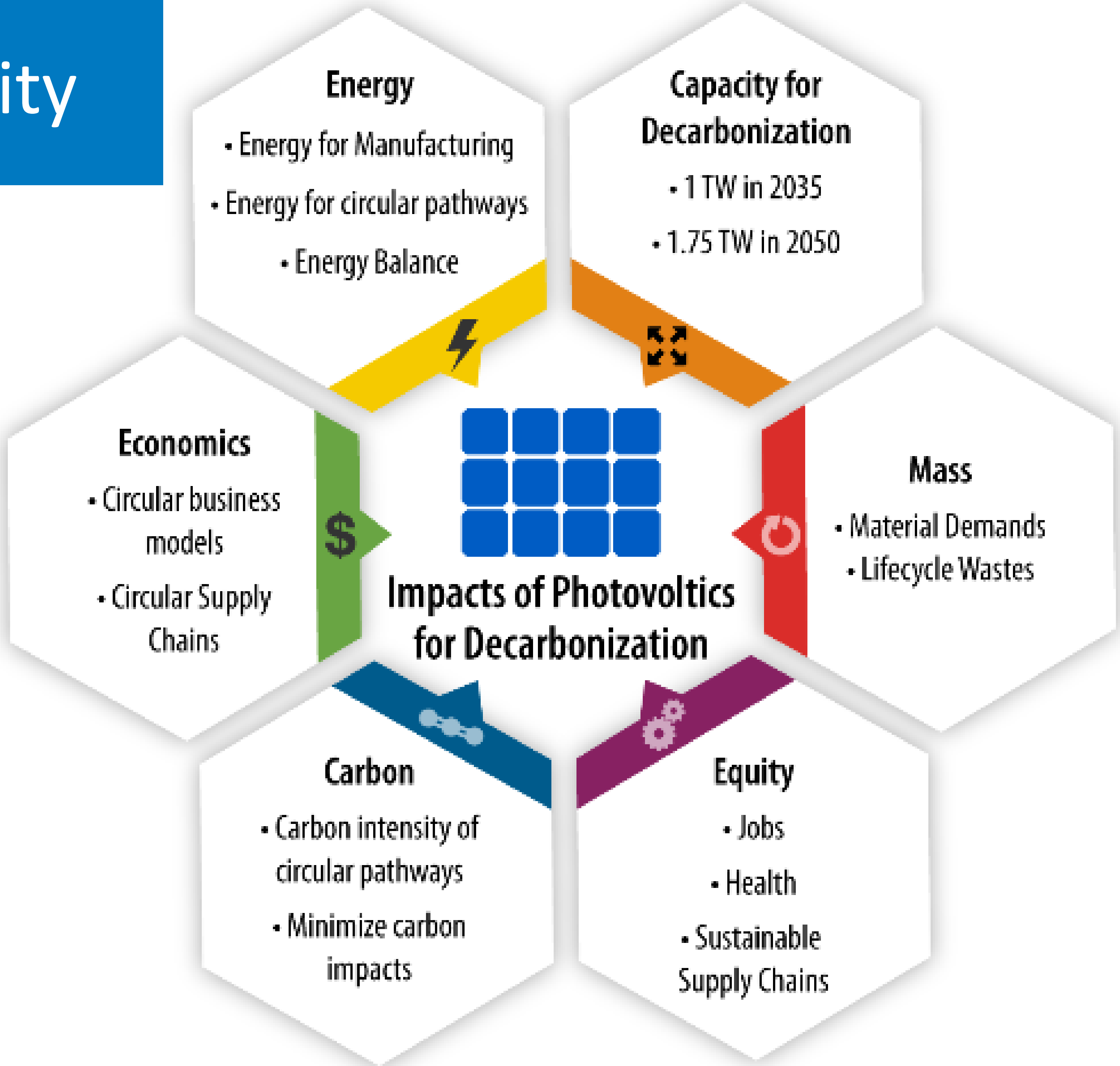
Waste from Feedstock & Manufacturing → $W_{F(x)}$

Waste from recycling process → $W_{R(x)}$

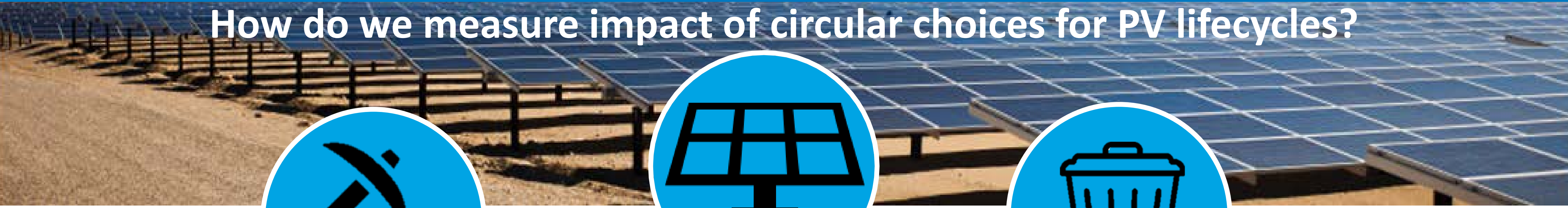
Circularity is not enough

≠

Sustainability



Metrics of Success



How do we measure impact of circular choices for PV lifecycles?

Virgin Material
Reduce Extraction of Virgin Materials

Installed Capacity
Maintain PV Capacity to meet Energy Transition

Waste
Reduce Wastes throughout PV lifecycle

Energy In
Minimize Energy demands of processes and materials

Energy Out
Maximize PV Yield for Energy Transition

Energy Balance
Maximize EROI, EPBT, Net Energy

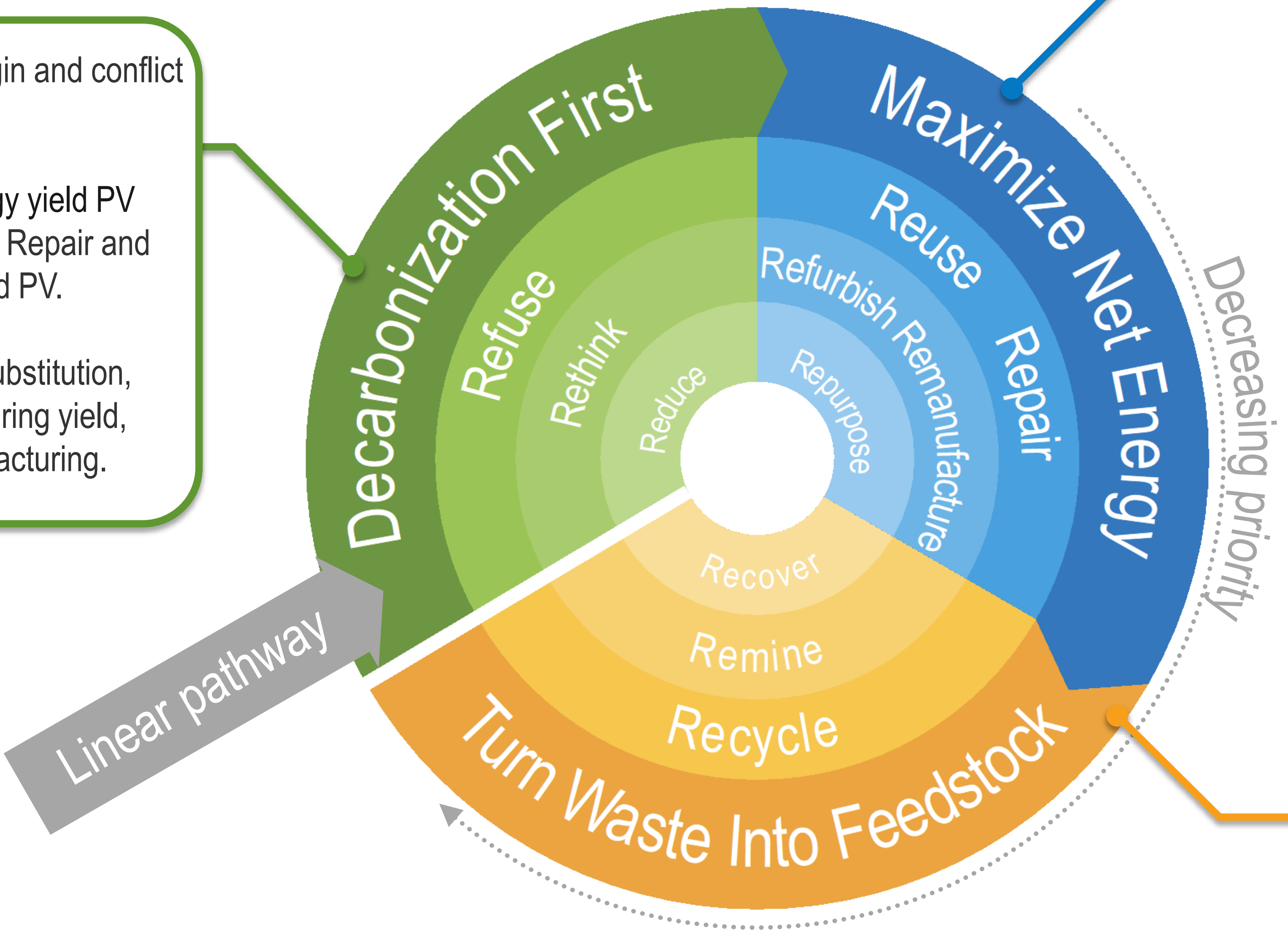
Supply Chain Security
Just and Reliable sourcing of materials

Circular R-strategies for PV in the Energy Transition

Refuse: Refuse virgin and conflict materials.

Rethink: High energy yield PV systems, design for Repair and Reliability Integrated PV.

Reduce: Material substitution, increase manufacturing yield, decarbonize manufacturing.



Reuse: Merchant tail, resell in secondary markets.
Repair: Onsite repair of modules and components.
Refurbish: Demount and transport modules for repairs Replace storm-damaged modules on site .
Remanufacture: Disassemble, replace cells, relaminate.
Repurpose: Repower system with new components

Recycle: Separate modules and components, reclaim materials.

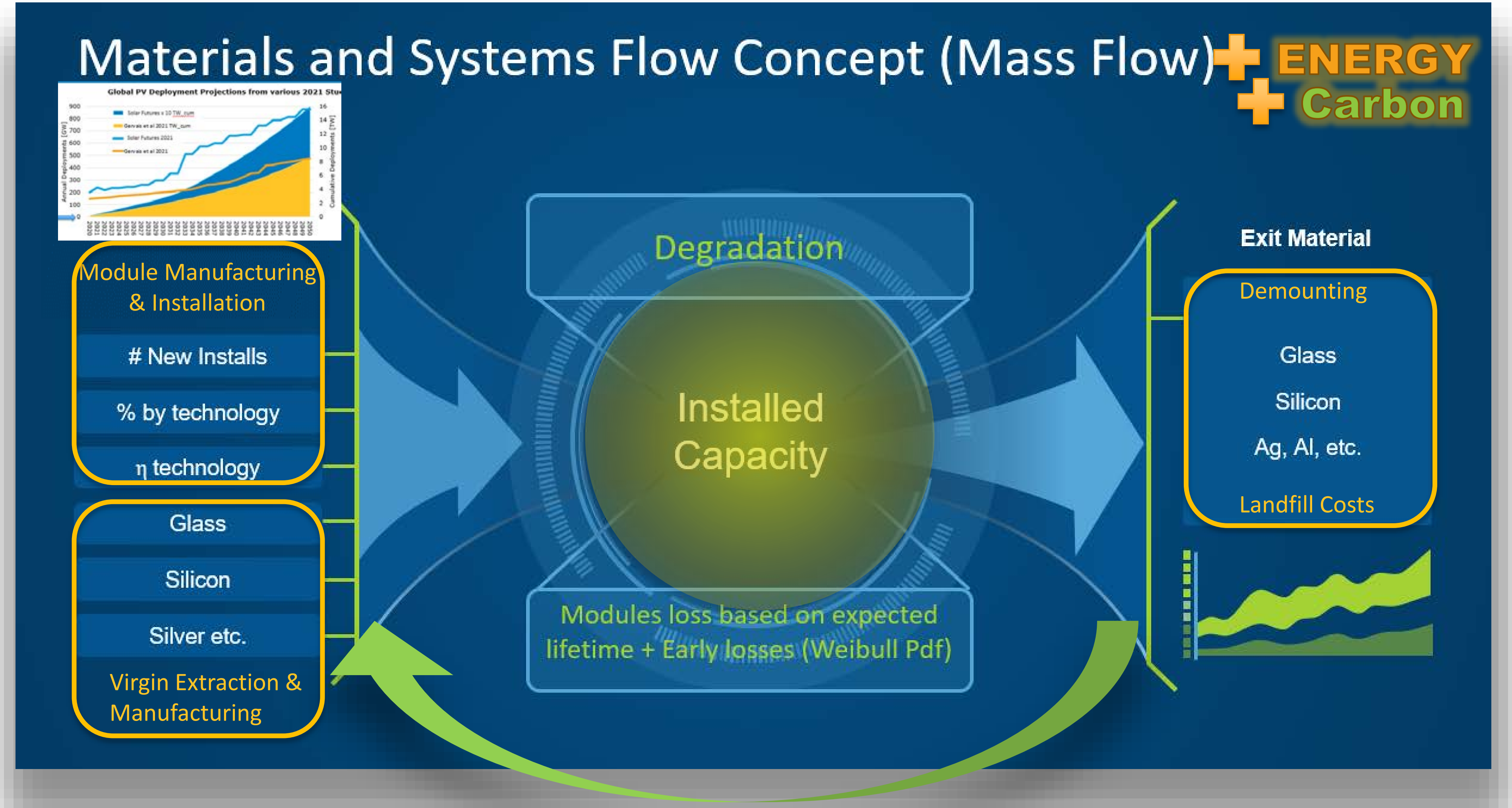
Remine: Mine input materials from landfills, refine.

Recover: Burn component materials for energy generation.

PV ICE

nrel.gov/pv/pv-ice-tool.html

System-dynamics geospatial open-source model, that evaluates the material, energy and carbon viability of the PV manufacturing, deployment, reuse, and recycling industries across the Energy Transition, allowing exploration of supply chains with varying degrees and types of circularities.

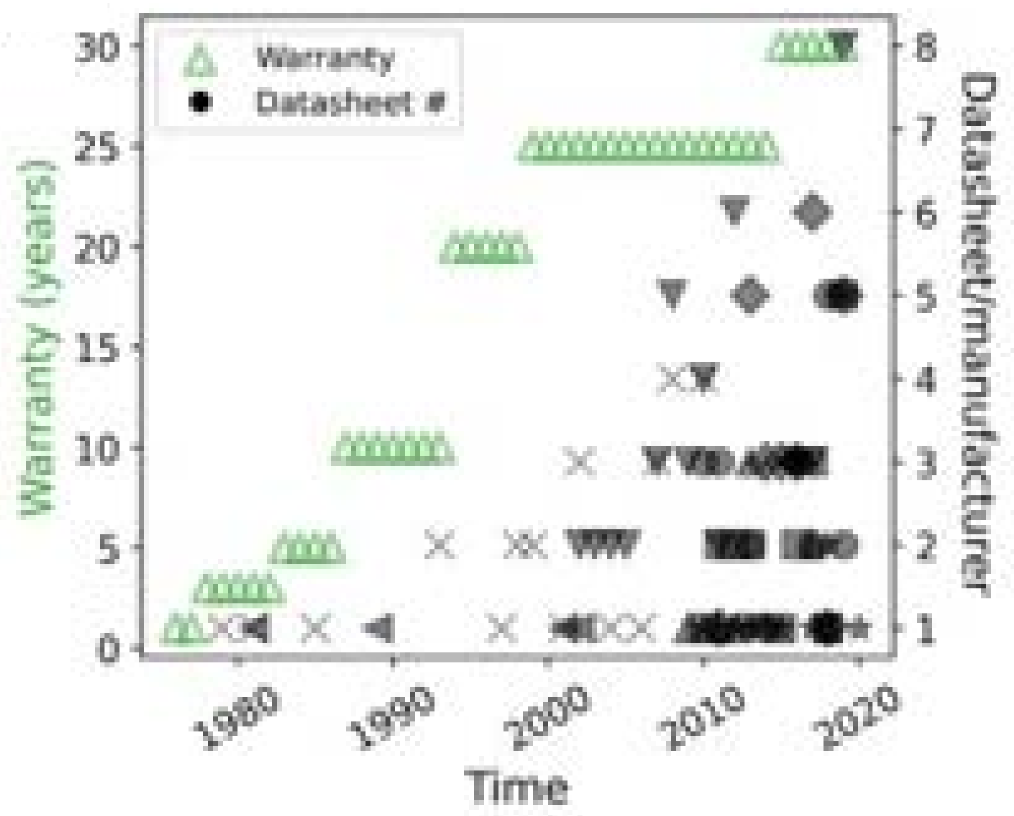


REUSE (RESELL & MERCHANT TAIL), REPAIR, REMANUFACTURE, RECYCLE

PV is closer to construction building waste than to e-waste

- Lifetime
- Solder content
- Plastic content
- Glass content

32 Years
-0.7% Degradation Rate



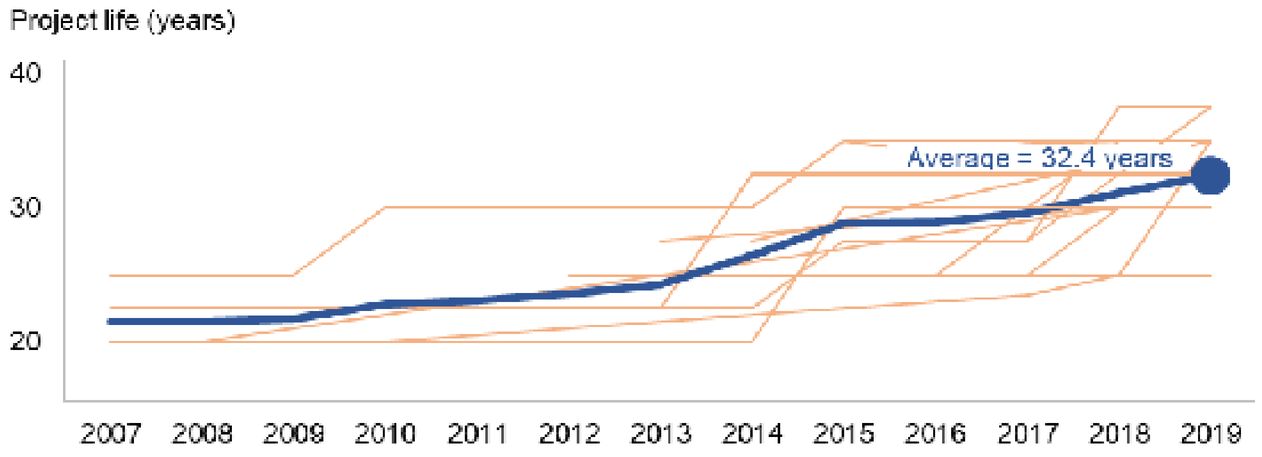


Figure 2. Project Life Expectations for Utility-Scale PV, over Time

[1]D. Jordan, Photovoltaic Module Reliability for the TW Age, Progress in Energy 2022, 10.1088/2516-1083/ac6111
[2] Wiser, LBL, 2020

PV toxicity

U.S. state health department websites:

- Arsenic
- Gallium

} III-Vs for aerospace

- Germanium → Once used in amorphous silicon not at scale
- Hexavalent Chromium → Not used in cells Water heaters?

Others

- Cadmium (CdTe) – Closed-loop recycling success story
- PFAs – **multiple** fluorine atoms

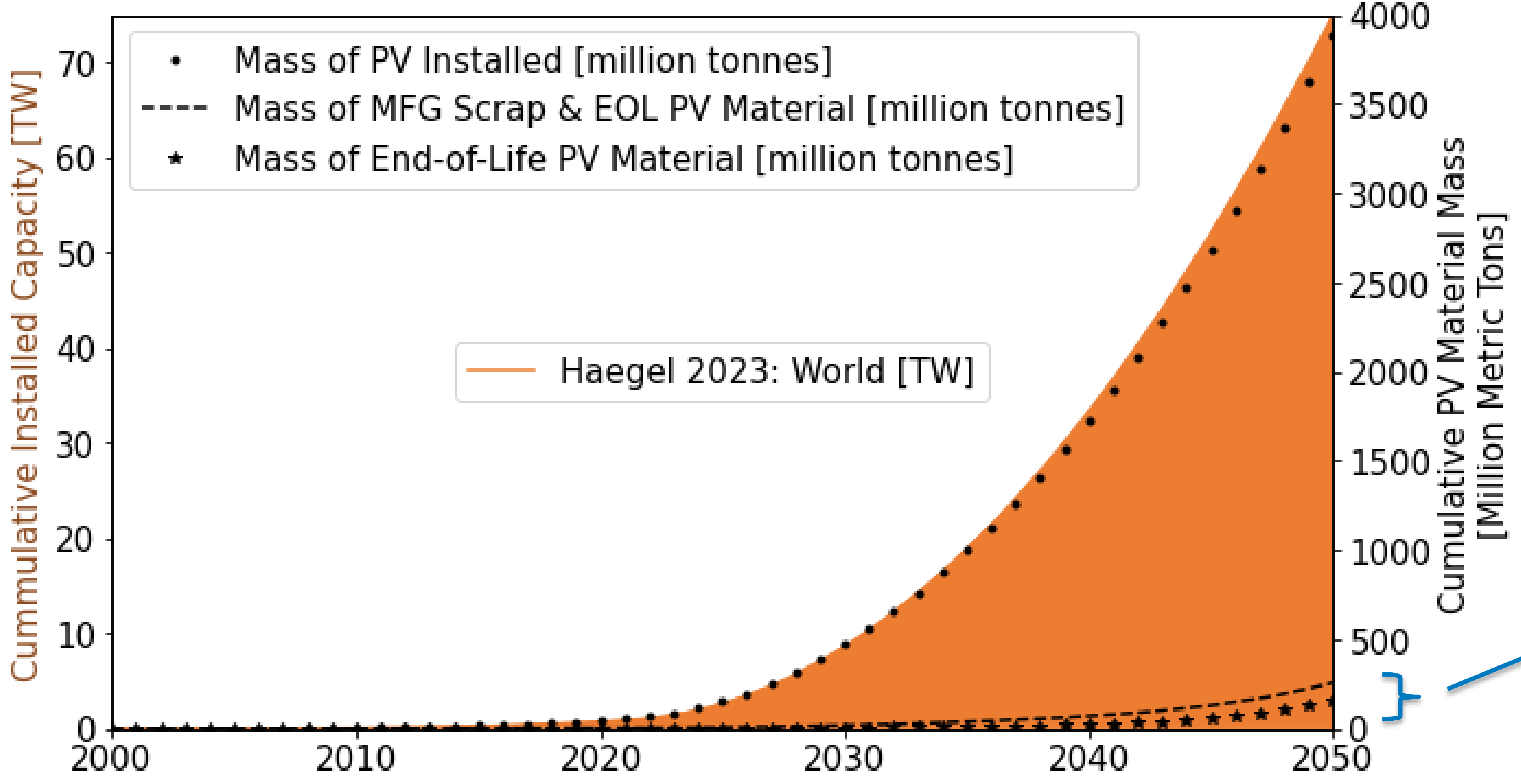
Self cleaning coats? Many non-hazardous silicon chemistry; commercial self-cleaning options (non-solar) contain some.
Adhesives? Solar adhesives based on silicon polymers
Backsheets? Tedlar - weather resistant polymer that is not a PFAS compound itself and makes no use of PFAS during its manufacturing process. Some other have fluorinated compounds, but they are not free PFAs as long as you don't burn.

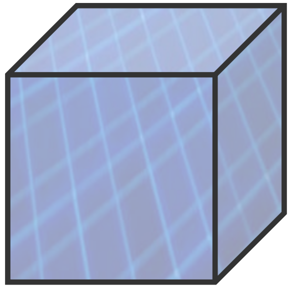
A. Anctil (2023) "Facts about solar panels: PFAS contamination."

Mirletz, Hieslmair, Ovaitt, Curtis, Barnes. **Unfounded concerns about photovoltaic module toxicity and waste are slowing decarbonization**. NATURE, OCTOBER 2023, coming to an internet near you.:

End-of-Life Material

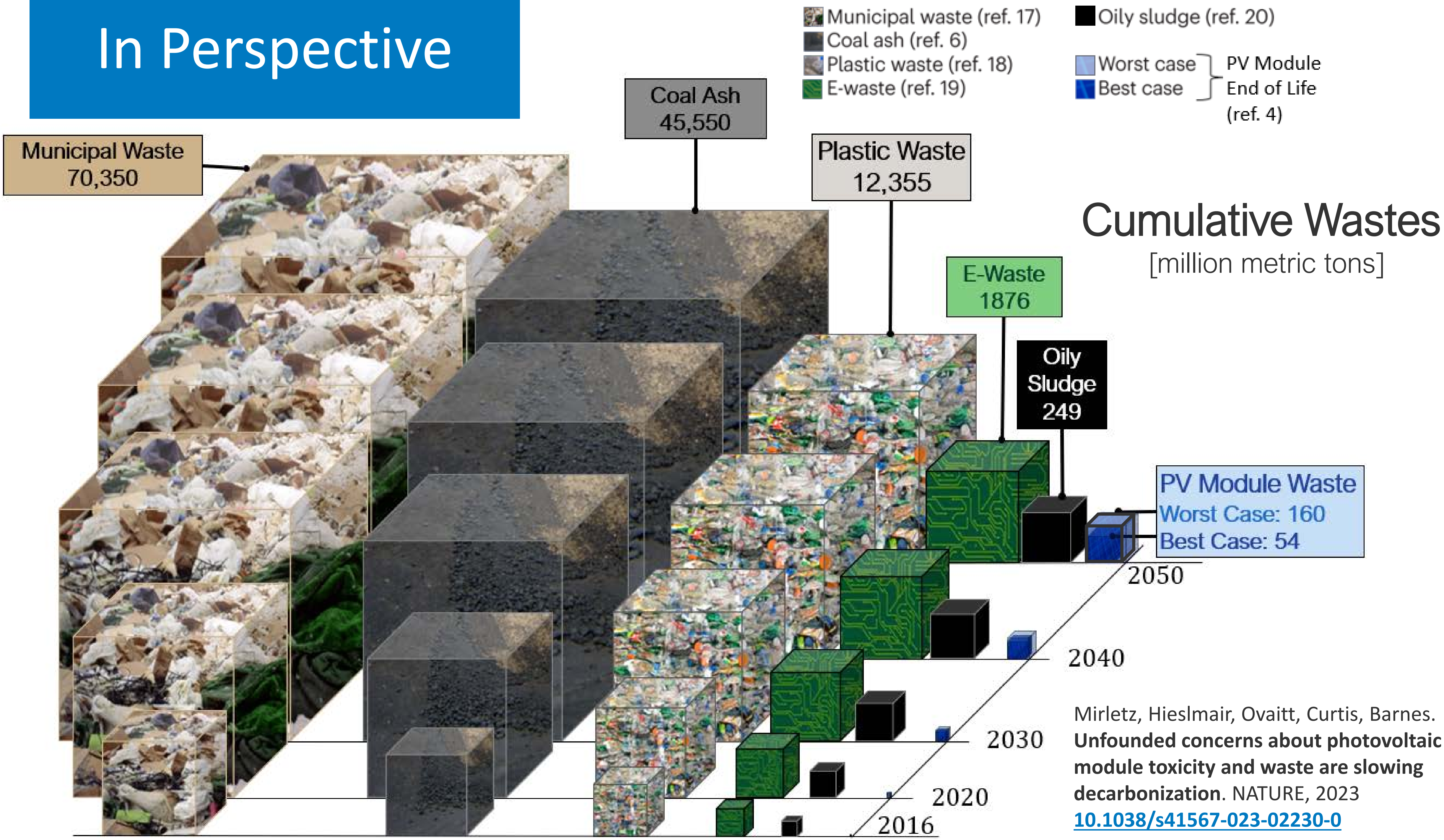
Waste





Mirletz 2023 PVRW

In Perspective



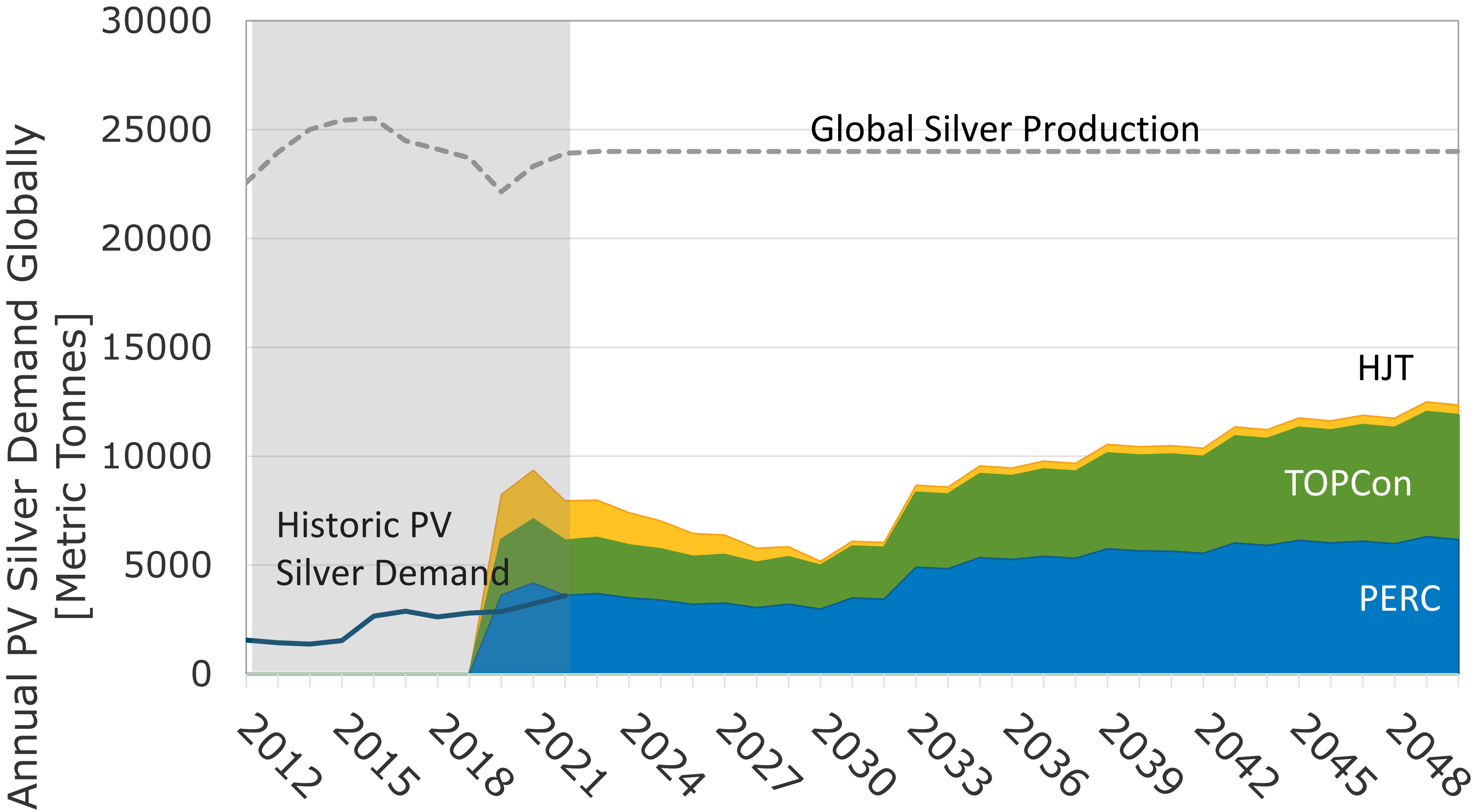
Mirletz, Hieslmair, Ovaitt, Curtis, Barnes. **Unfounded concerns about photovoltaic module toxicity and waste are slowing decarbonization**. NATURE, 2023 [10.1038/s41567-023-02230-0](https://doi.org/10.1038/s41567-023-02230-0)

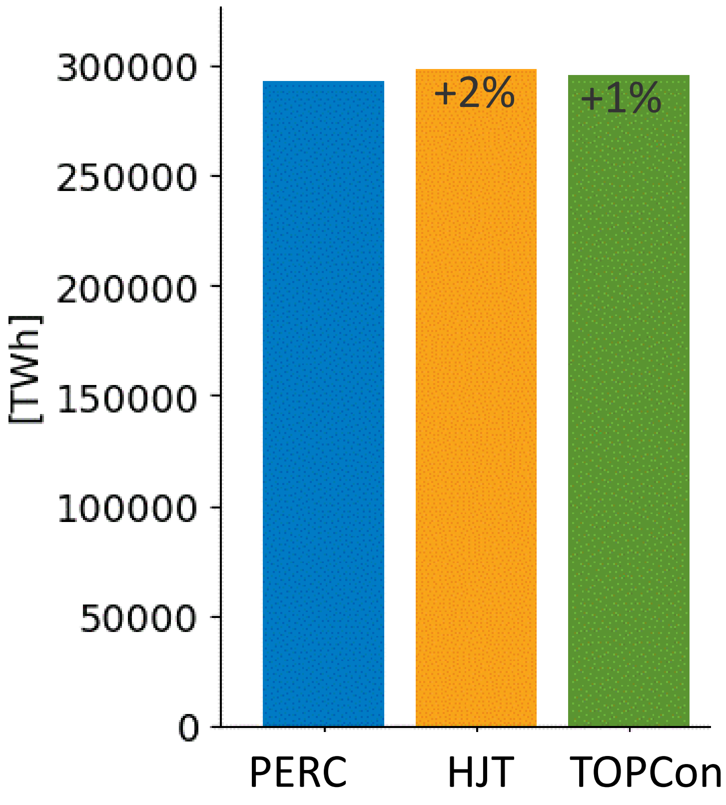
Innovation Can Mitigate Silver Prices

Virgin Material

Energy In

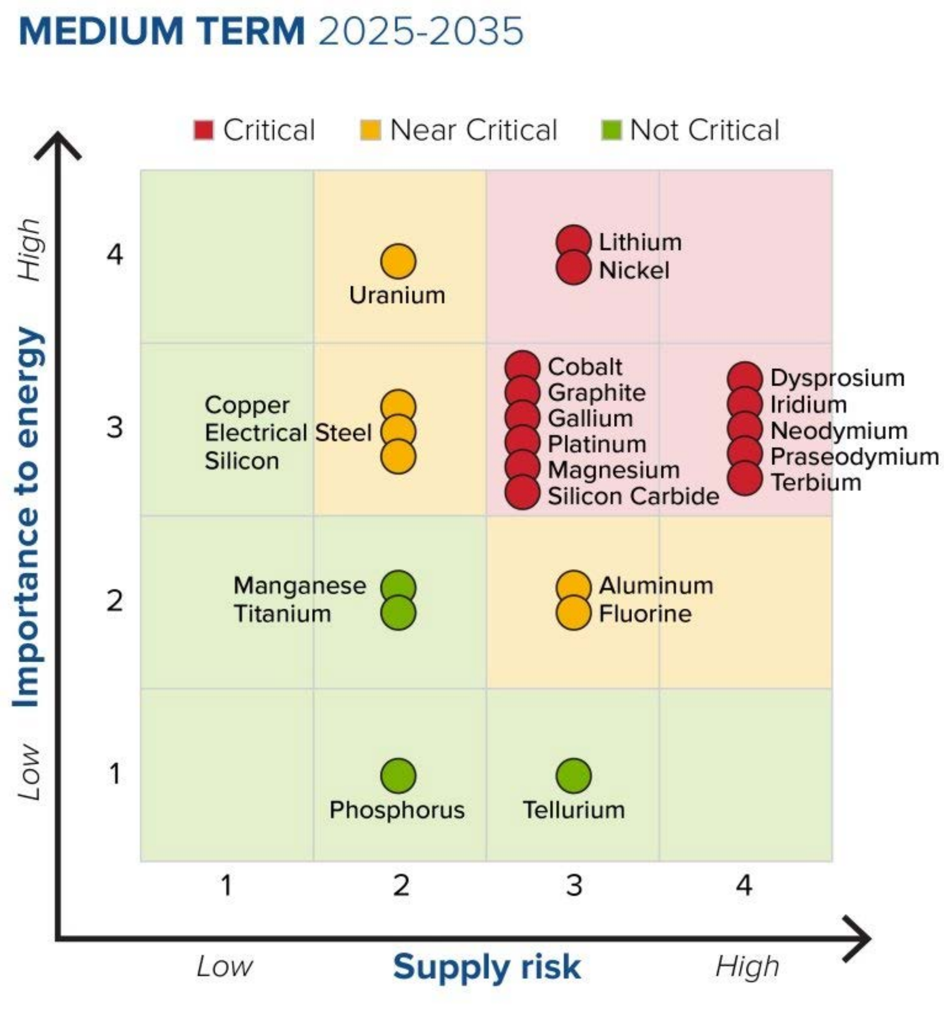
Energy Out





Barnes, et al. 5th International SHJ Workshop, CEA-INES 2022

Mineral and Emission Challenges for Renewables



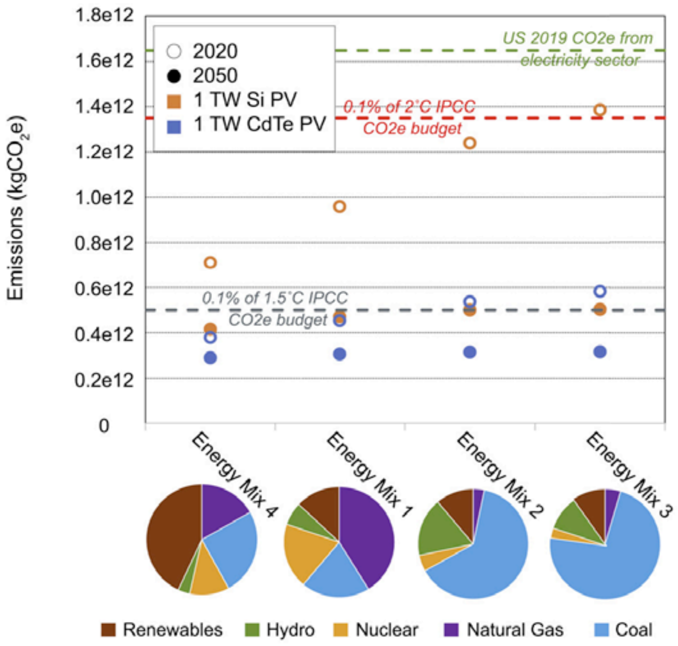
DOE Critical Materials, 2023

Article

Future demand for electricity generation materials under different climate mitigation scenarios

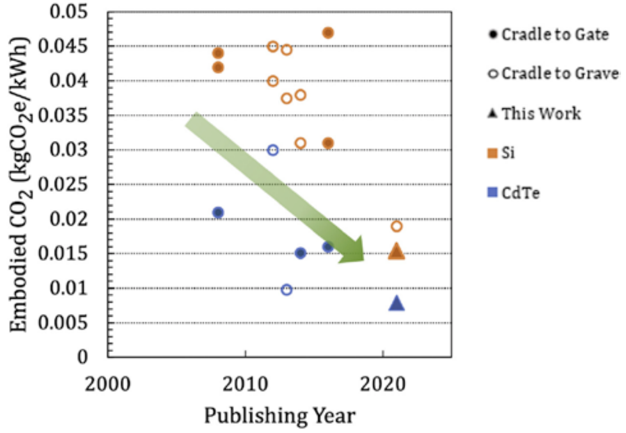
Joule

Wang, Hausfather, et. al, 2023



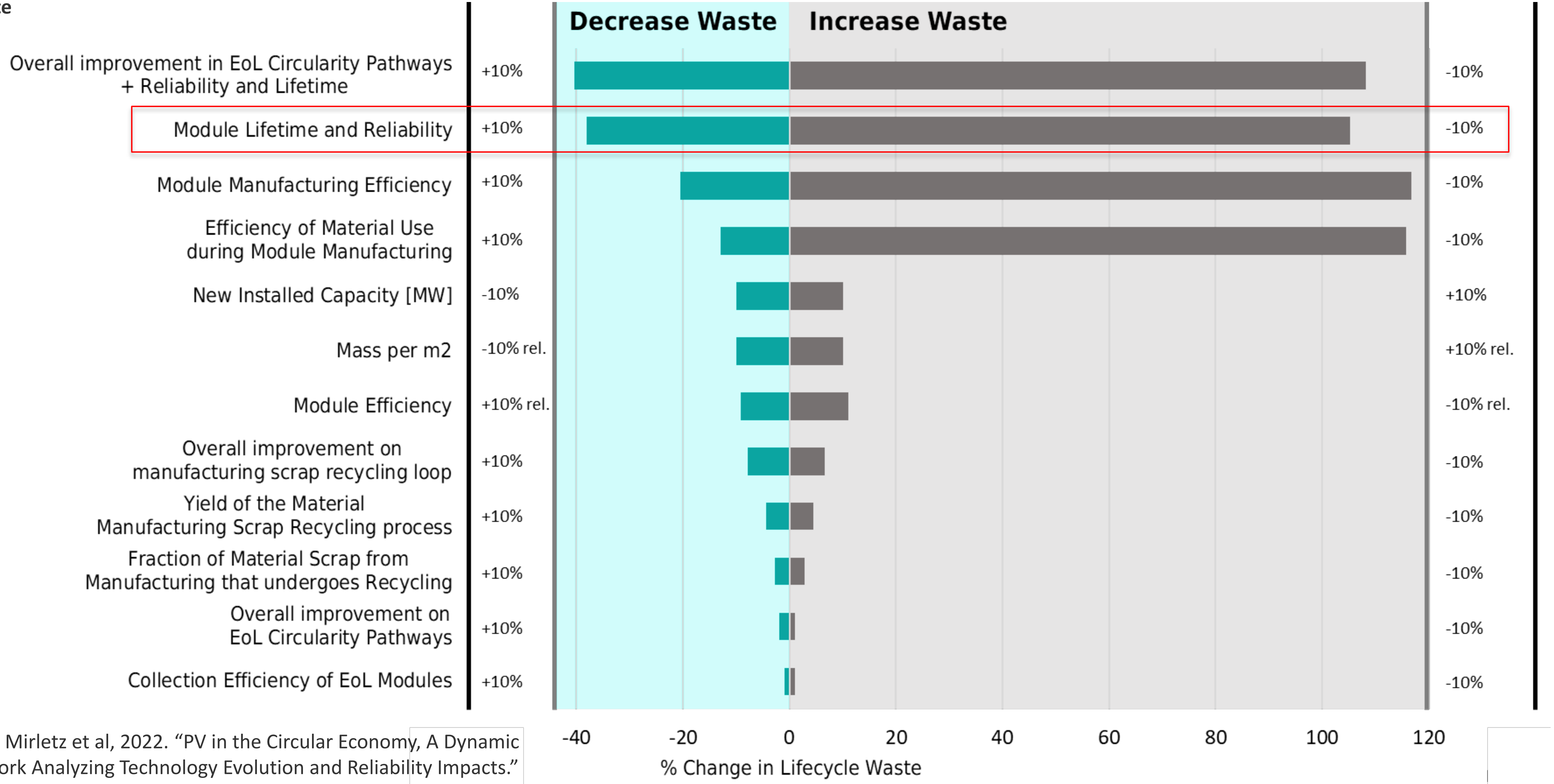
Article

Embodied energy and carbon from the manufacture of cadmium telluride and silicon photovoltaics



Levers to improve mass metrics

Waste



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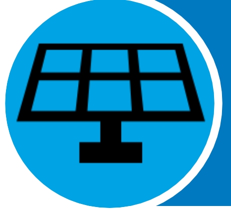
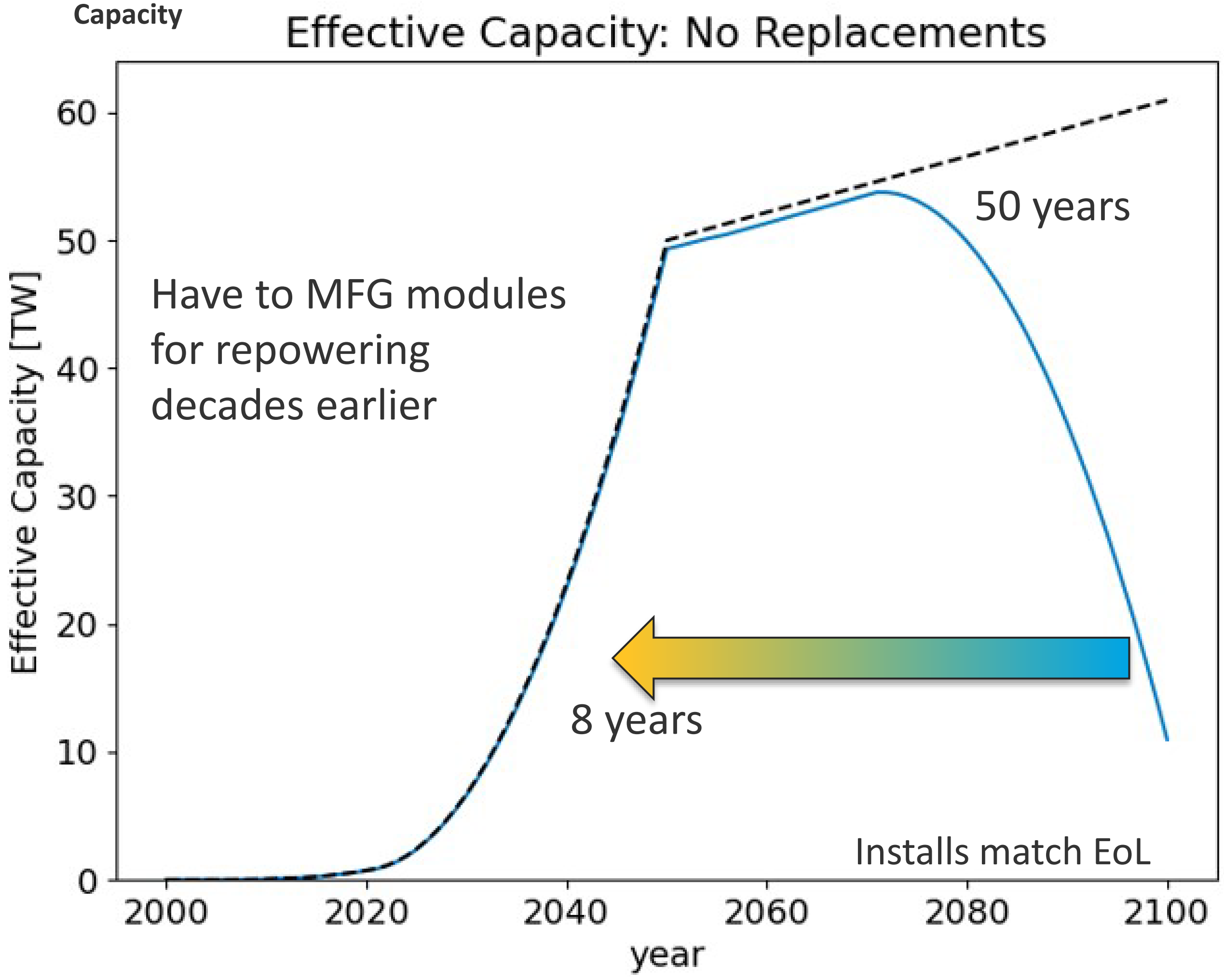
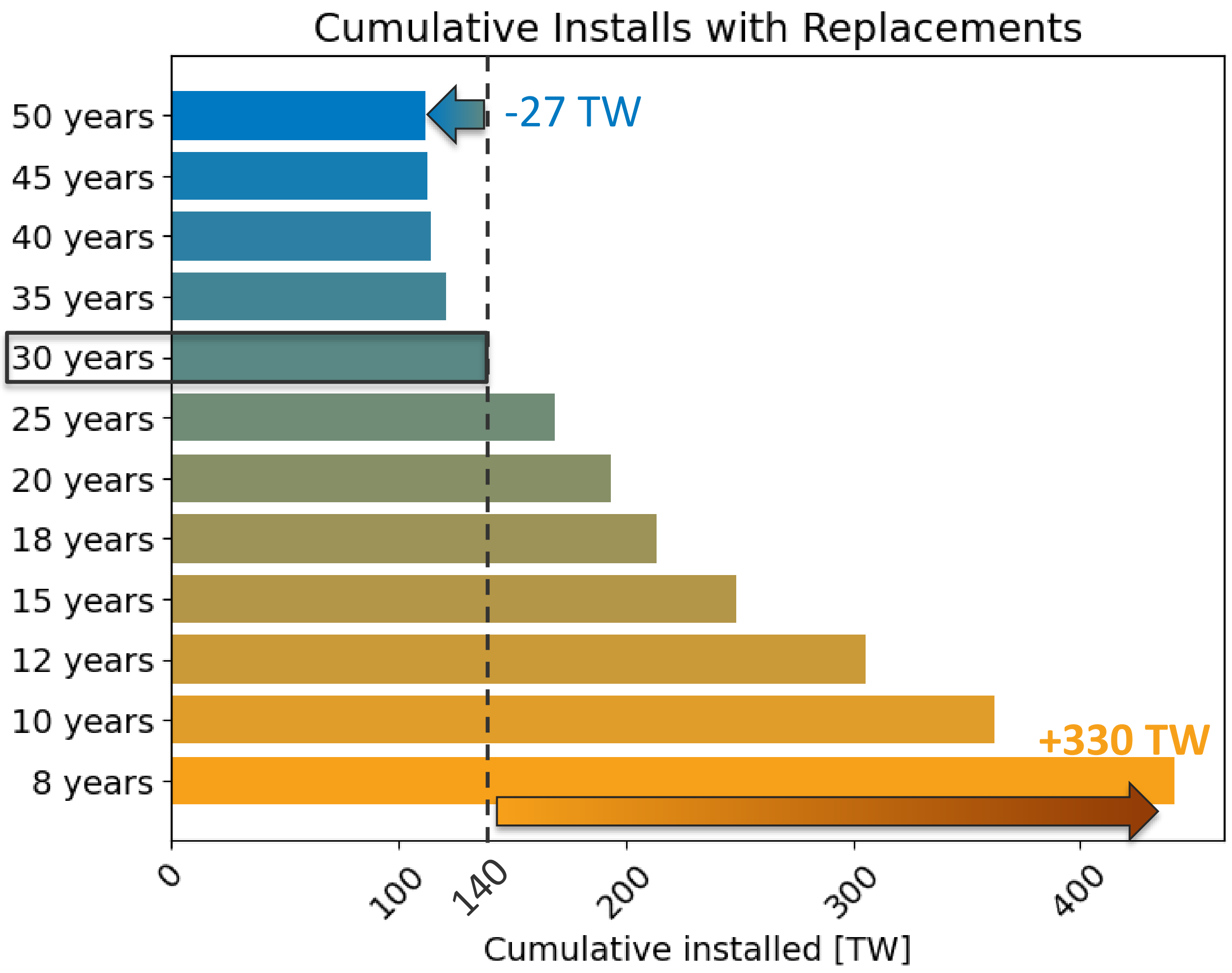


Mass and Energy Improvements by reducing Project Lifetime

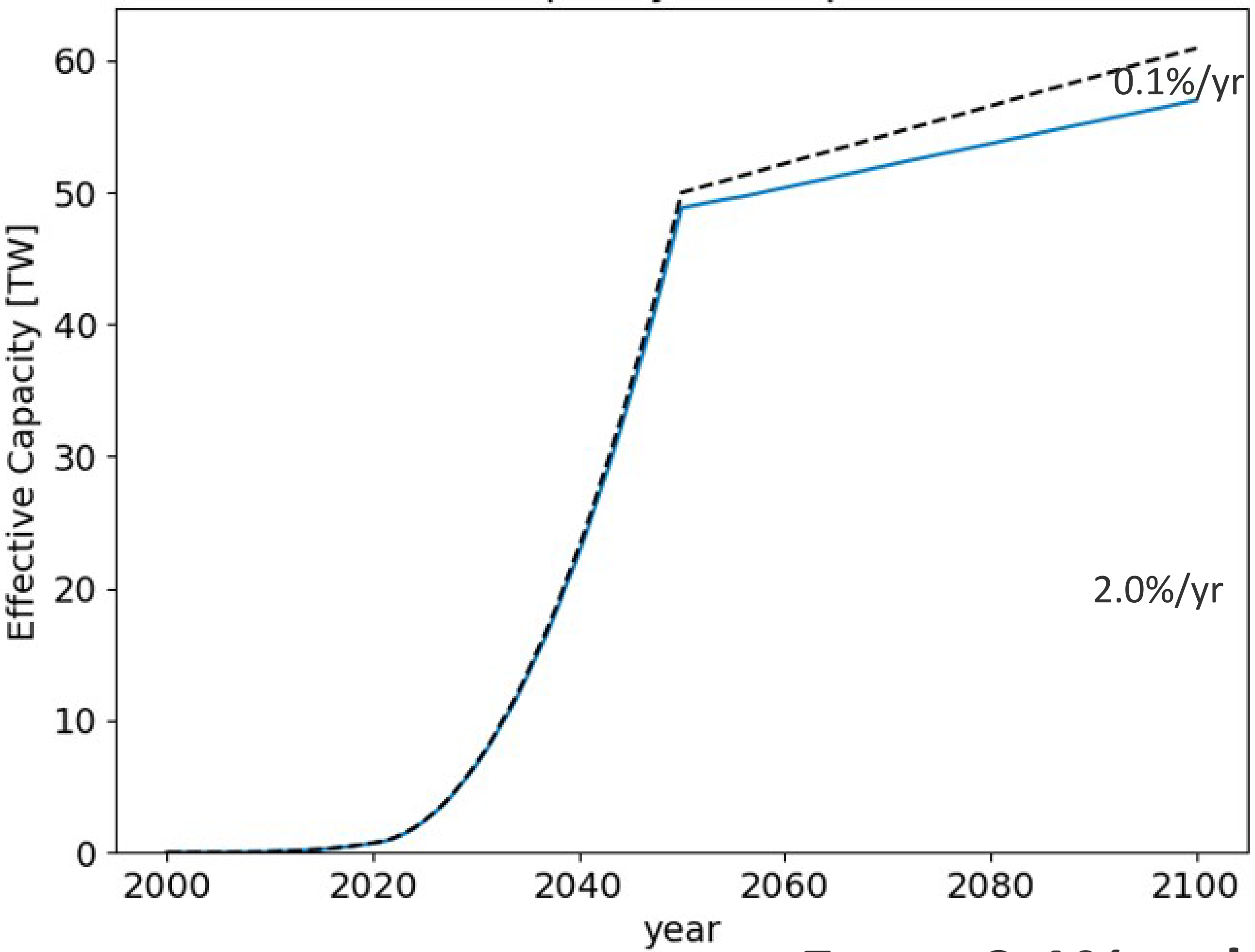


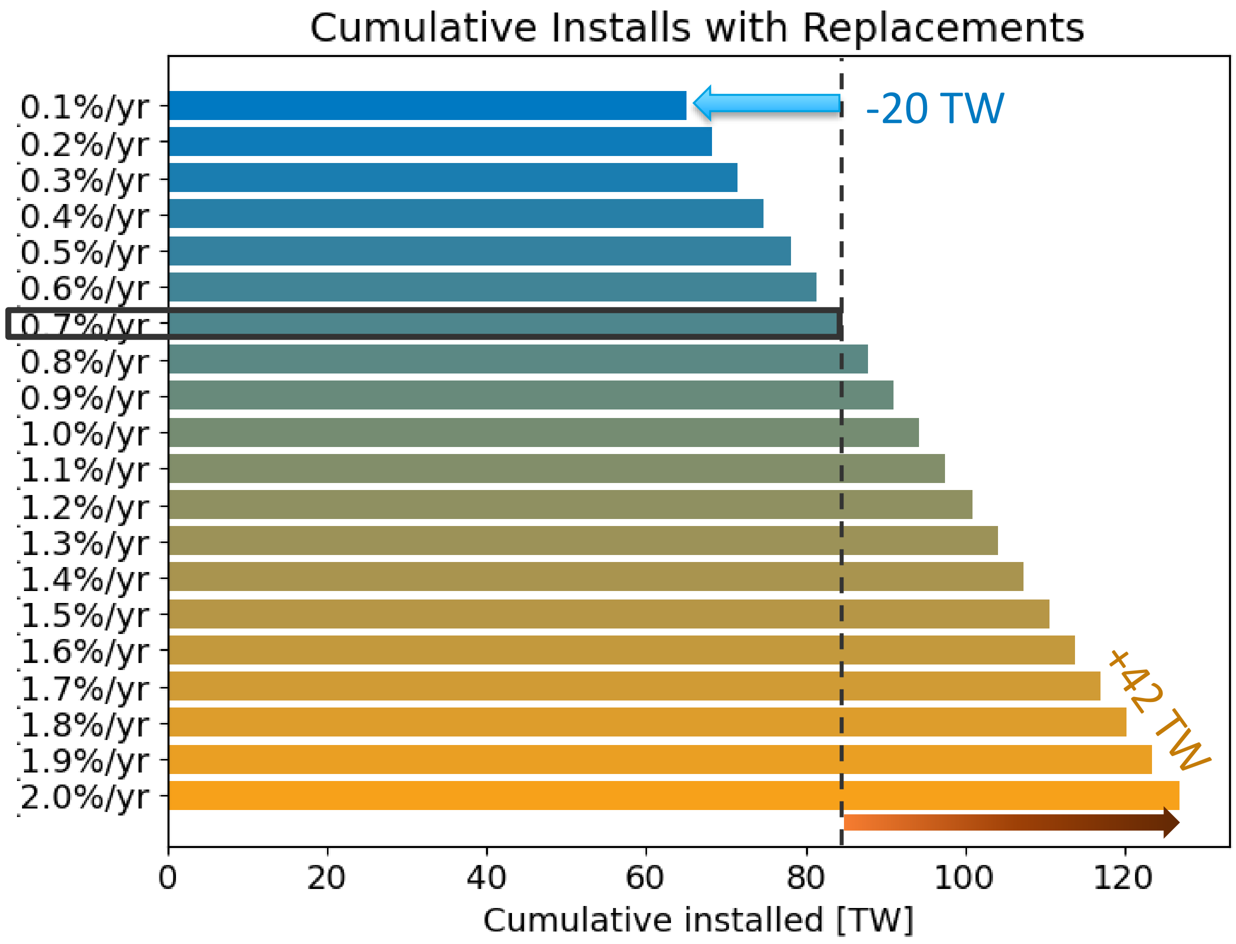


Short project lifetimes require more replacements, sooner

Mass and Energy Improvements by reducing Degradation

Capacity





Every 0.1% reduction in degradation saves ~3 TW of replacements

Threshold: remove at 80% of nameplate

The path forward

Image from:
peakvisor.com

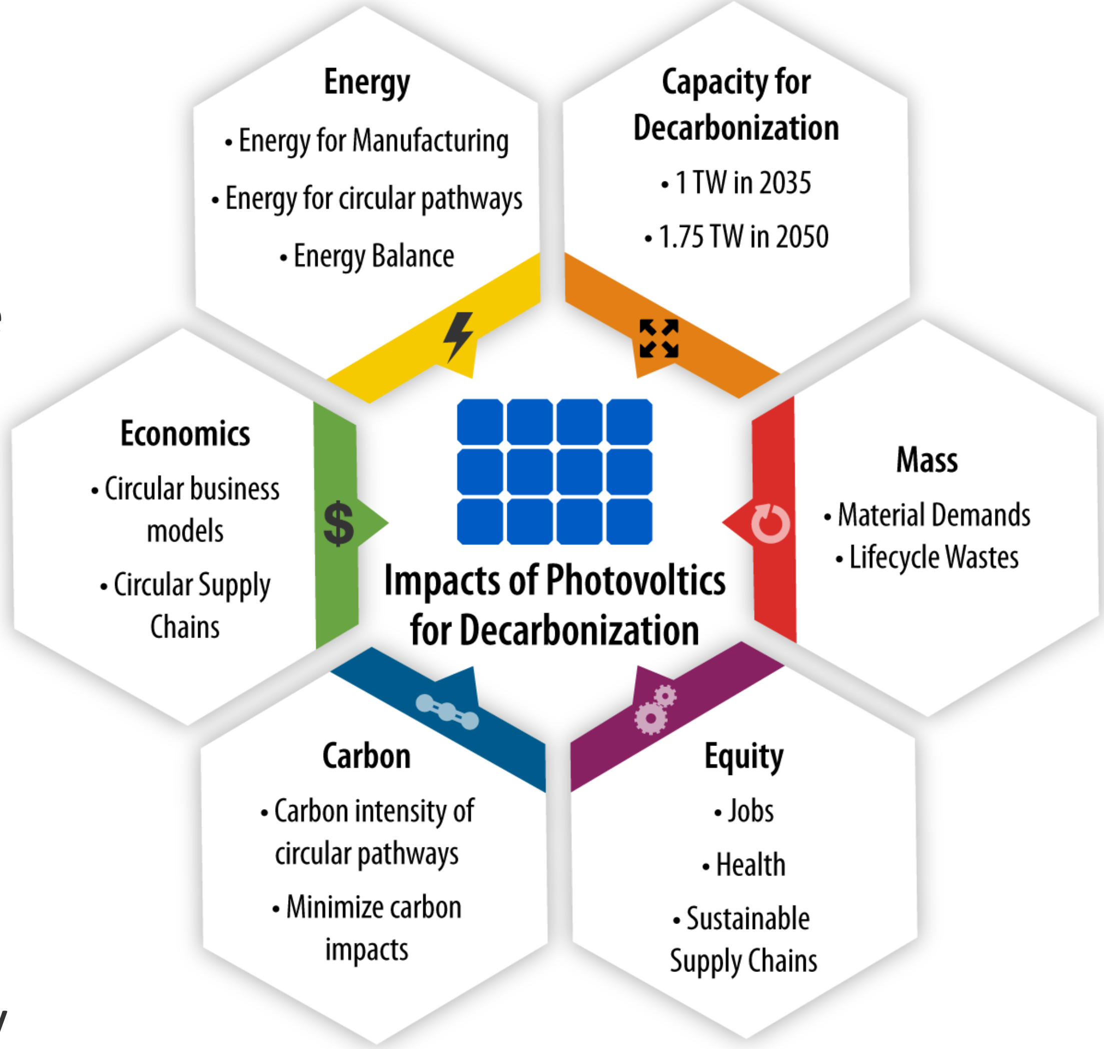
The path forward

Image from:
peakvisor.com

Environment, social and policy aspects

Conclusions

- Reliable, long-life modules AND systems are critical for meeting capacity and decarbonization targets
- Deploy reliable PV as fast as we can, learn faster, and keep getting better – unprecedented speed with little room for error
- **Need a strong scientific and technical foundation**
- Eyes on the prize – we aren't competing between renewable technologies
- More sustainable manufacturing is often more efficient and reduces costs
- End-of-life waste is manageable with steady improvements in technology, policy, and economics.
  - Waste volumes will scale with recycling capacity
  - Circularity opportunities – i.e. glass



Minimize embedded carbon and energy

NREL/PR-5K00-87603

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nrel.gov/pv/pv-ice-tool.html

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