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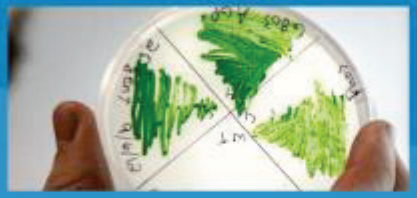



Value of Recycling PV Modules, Market Size and Need for Design for Recycling

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May 22, 2017

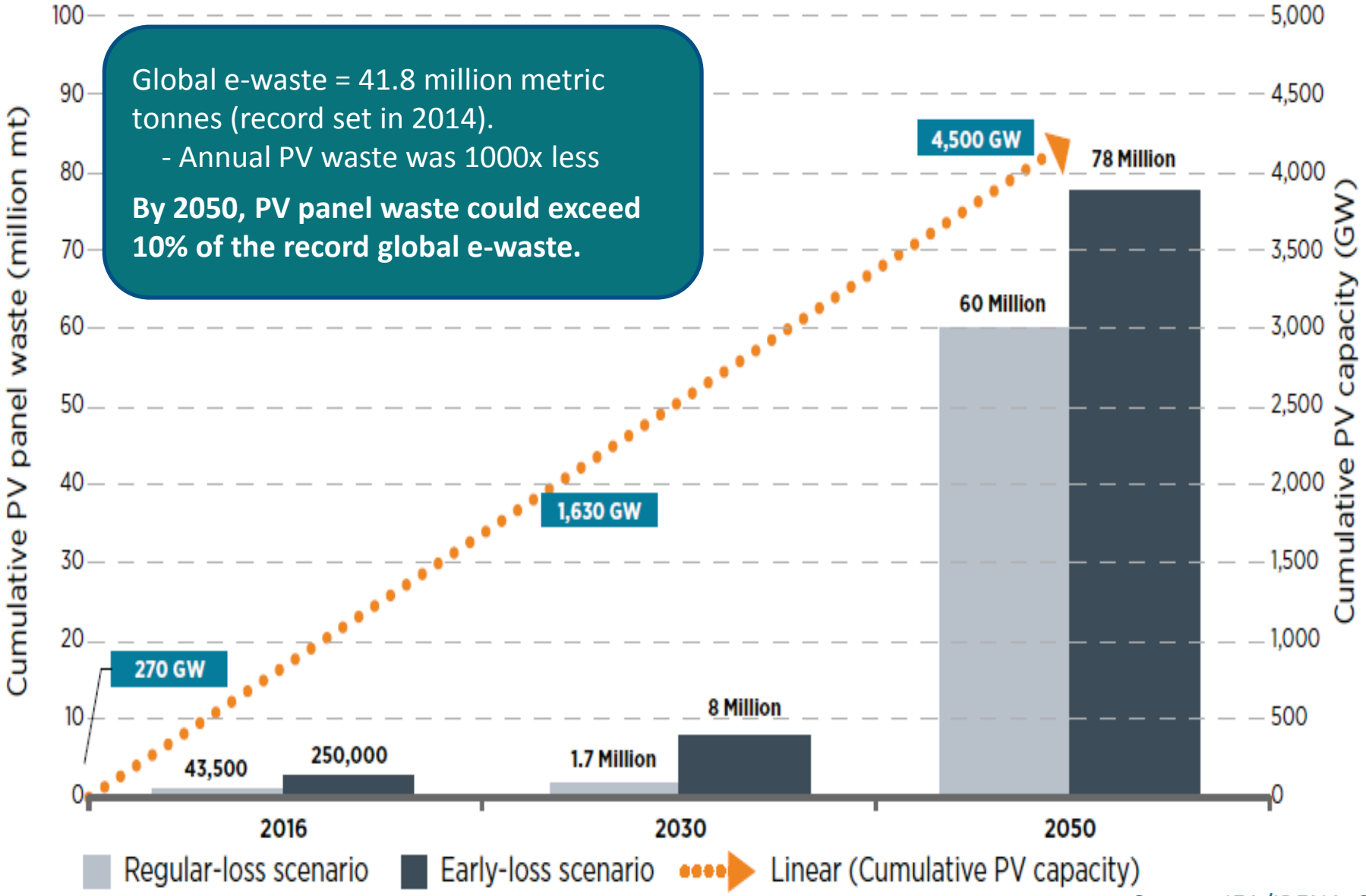
DuraMat workshop

Stanford, CA

Low Volumes Now, PV Waste Will be Significant Challenge in Future

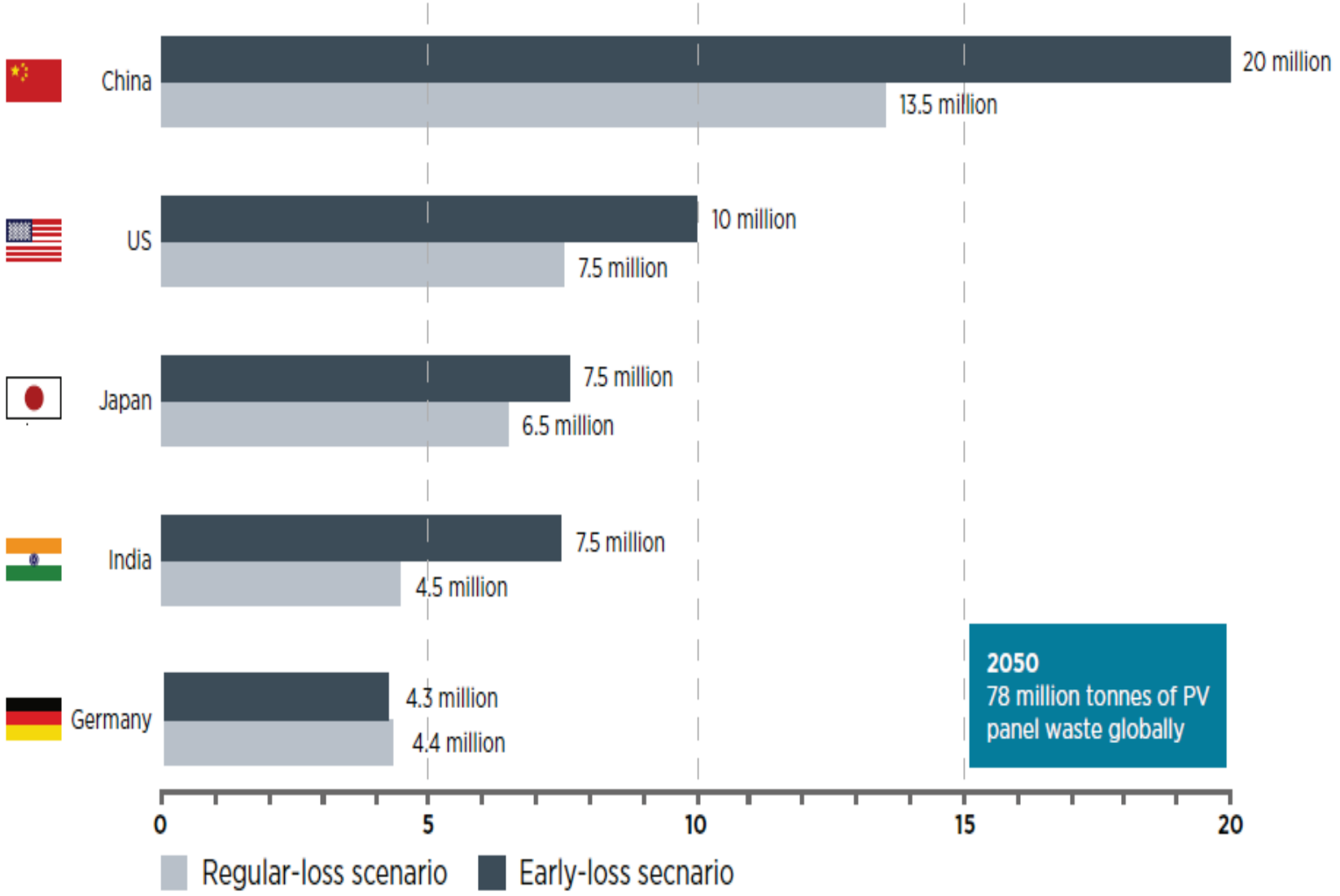
Global e-waste = 41.8 million metric tonnes (record set in 2014).
- Annual PV waste was 1000x less

By 2050, PV panel waste could exceed 10% of the record global e-waste.



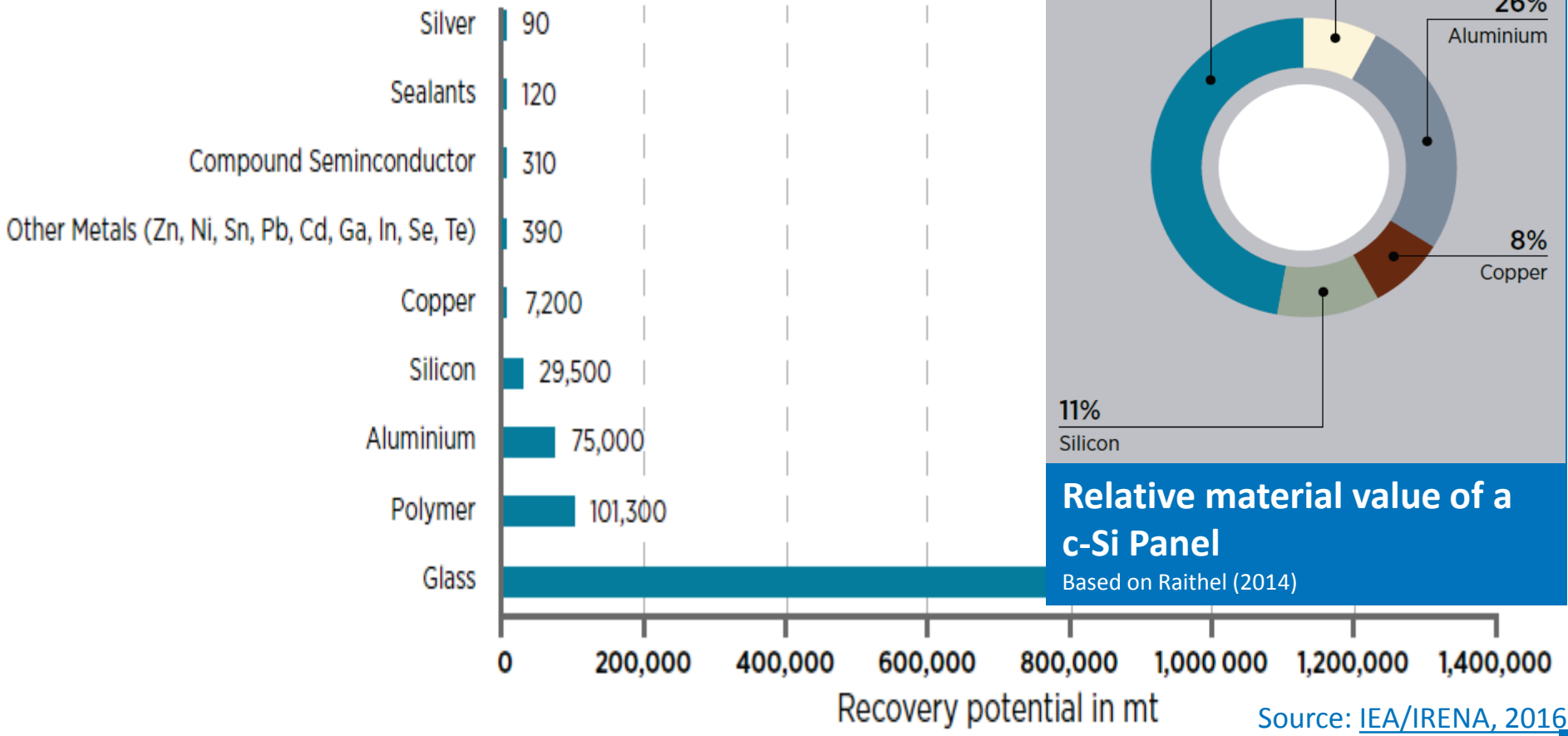
Source: IEA/IRENA, 2016

USA Expected As Second Largest PV Waste Volume – Challenge and Opportunity



Why Recycle Modules?

Cumulative technical potential for end-of-life material recovery (under the regular-loss scenario and considering anticipated changes to module design, like dematerialization)

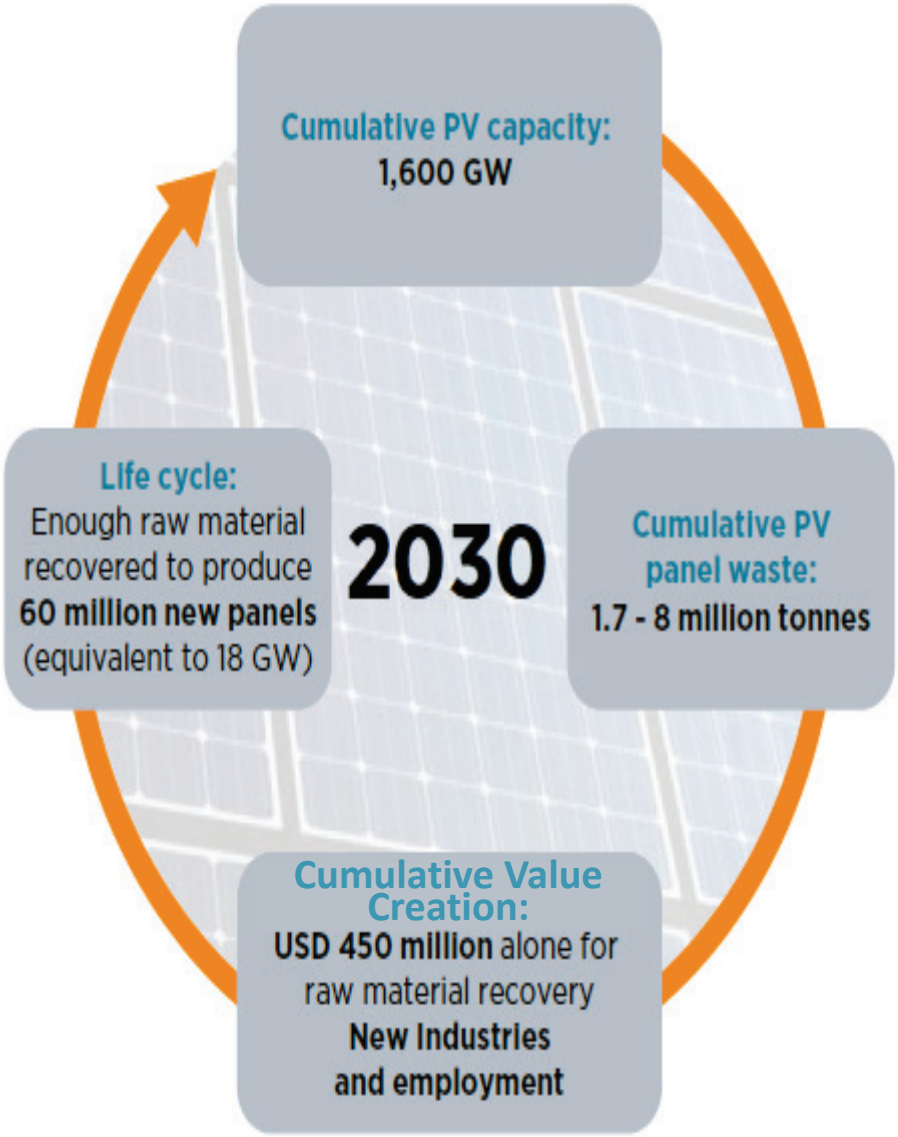


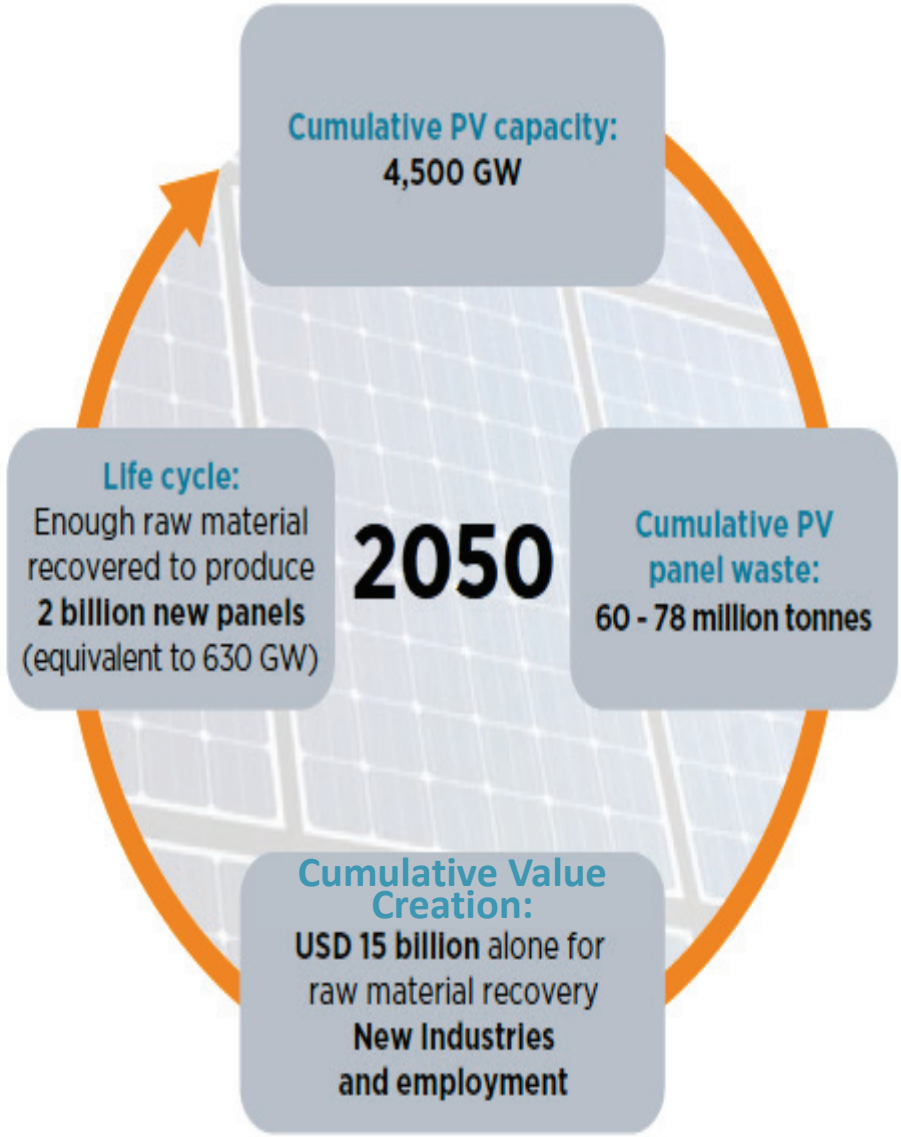
Relative material value of a c-Si Panel

Based on Raithel (2014)

Source: IEA/IRENA, 2016

Potential Value Creation – A Whole New Waste Management Industry?





Challenges

Waste Management and Recycling

The challenge is to prepare the technologies, systems and policies to manage decommissioning and disposal of end-of-life modules that can

- Minimize costs and
- Minimize environmental impacts while
- Maximizing materials recovery.

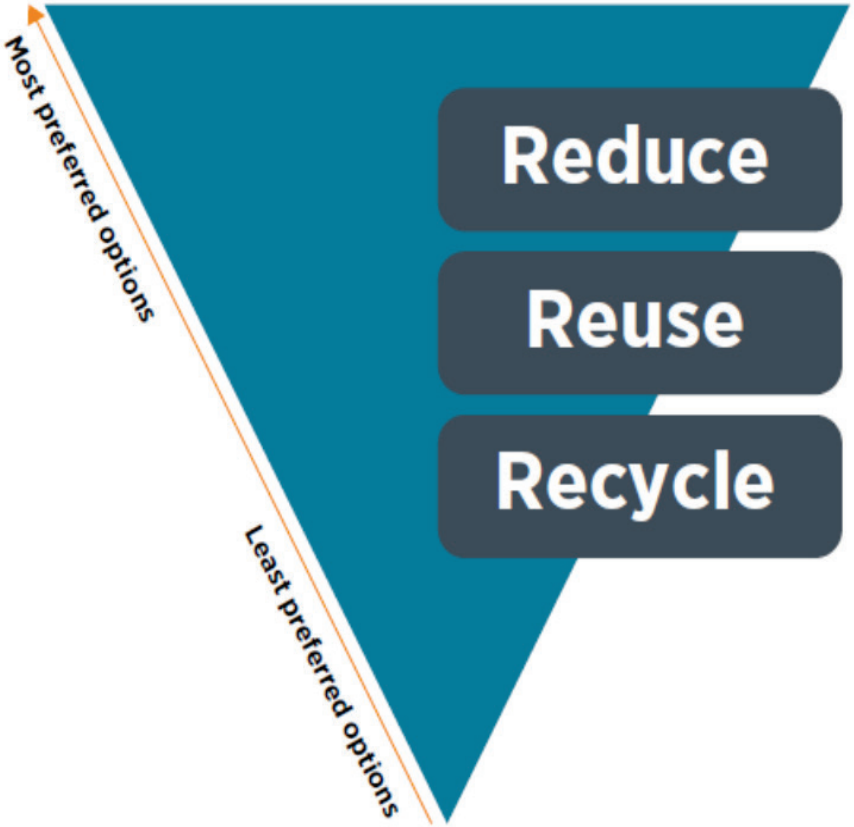
Design for Recycling

Conversely, one way to facilitate economical recycling and maximize material recovery is to design new modules that

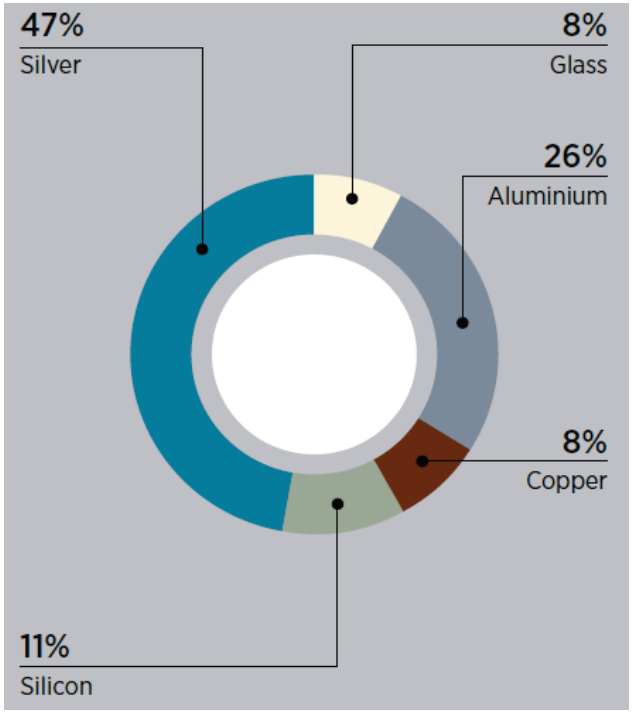
- Increase speed and ease of dismantling,
- Improve rate and purity of recovered materials, and
- Reduce waste.

What Do We Do with PV Waste? The 3 Rs of Waste Management

- PV R&D has set priority topics for material use reduction or substitution for different components commonly used in today's PV panels
- Reusing modules (potentially preceeded by repairing) is conceivable, but practically and economically challenging
- Recycling processes for thin-film and crystalline silicon PV panels have been developed and to some extent implemented on industrial scale, but more development is needed
- Significant recovery potential for different material streams can be realized through ***high-value recycling***



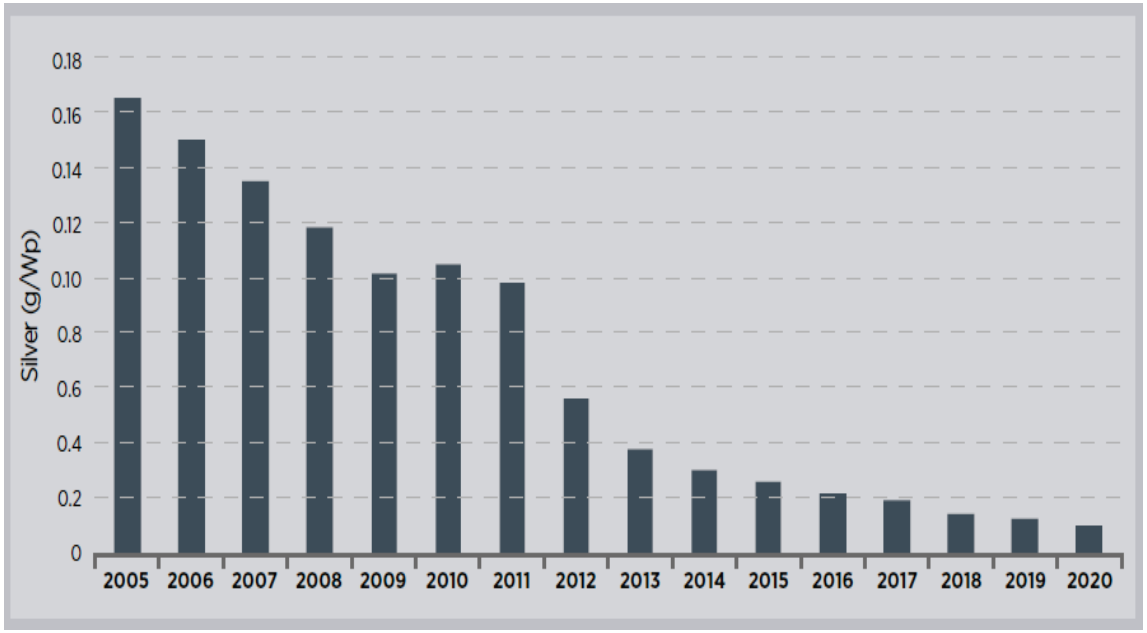
Reduce – Dematerialization



Relative material value of a c-Si Panel

Based on Raithel (2014)

From a value standpoint, silver is by far the most expensive component per unit of mass of a c-Si panel – consuming today about 15% (incl. losses) of the global silver production. Reduction of the use of silver is a clear technology target.

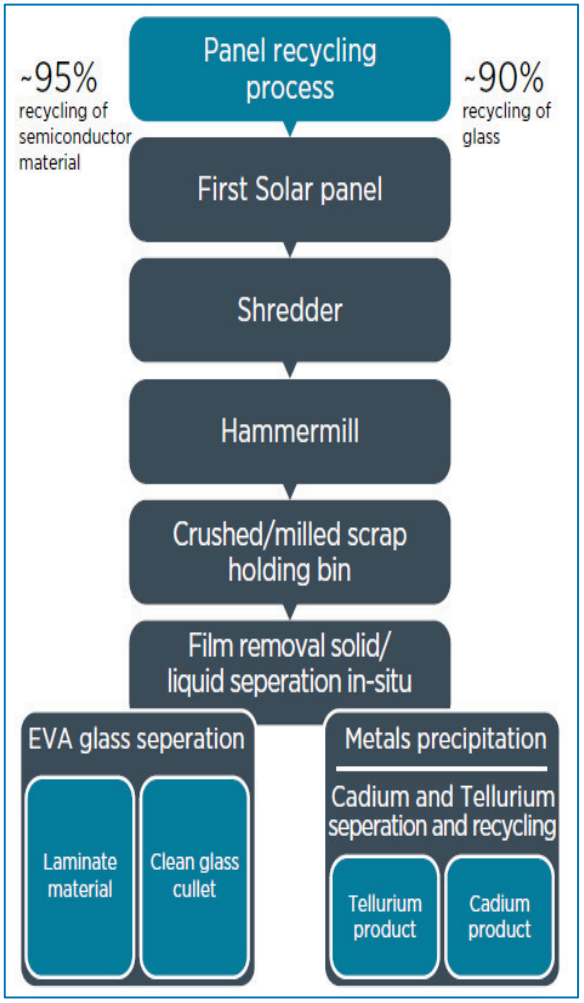


Historic and expected silver consumption per Wp

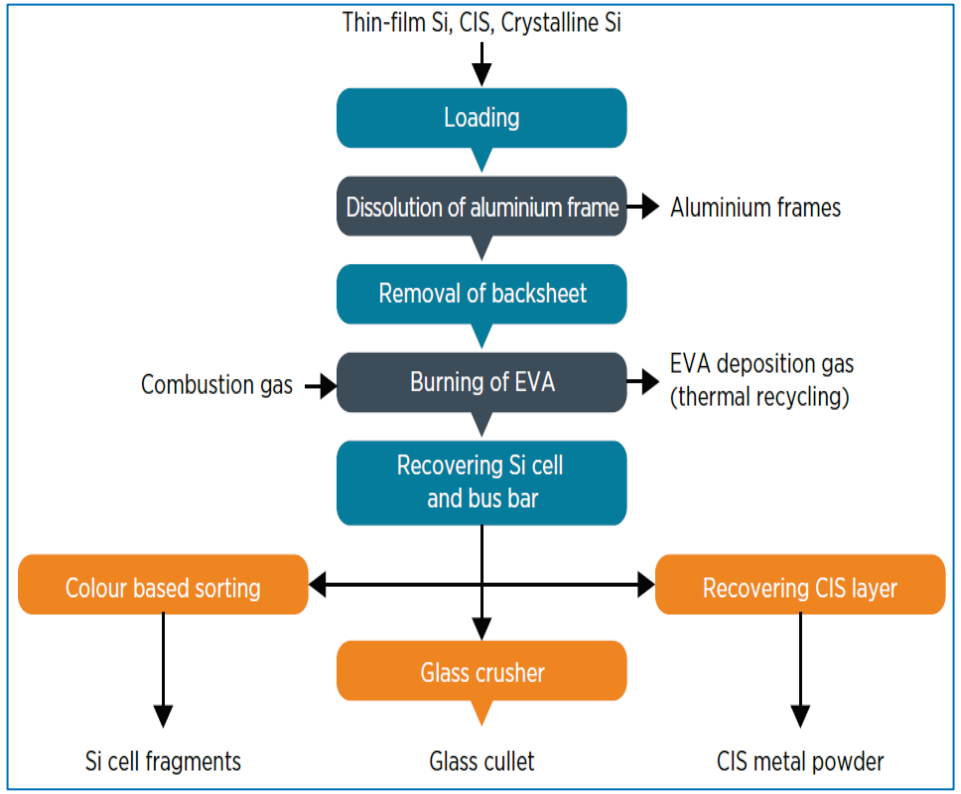
Based on: Perez-Santalla, M. (2013), Silver Use: Changes & Outlook,

Recycle – CdTe and C-Si Examples

Lacking volume for dedicated PV recycling plants, mechanical separation of major components of PV panels is current, first-generation PV recyclers' focus.



CdTe recycling process (First Solar)



Recycling scheme proposed by NEDO/FAIS in Japan

Extending the Value Chain

R&D Organisations

- Public and private institutions
- Producers

Repair/Re-use services industry

- Producers
- Independent services partners
- Producer-dependent contract and service partners (e.g. installation and construction companies
- Waste collectors and companies
- Pre-treatment companies

Recycling treatment industry

- Public waste utilities and regulators
- Waste management companies
- Pre-treatment companies
- Producers

Optimal PV recycling industry will integrate energy and waste sectors

Path Forward – Recycling

- Actions being taken (examples)
  - **IEA-PVPS**: report reviewing global trends in PV recycling technologies based on public sector and private sector (patents) documents (forthcoming)
  - **US Manufacturers**: SEIA voluntary commitment to PV recycling, though recycling network still under development

- Actions needed within broader industry
  - **Technological R&D coupled with prospective techno-economic and environmental analyses** to maximize societal returns, minimize detrimental outcomes and avoid unintended consequences.
  - **Decision support tools** for utility-scale PV owners regarding end-of-life management options, including costs of dismantling, decommissioning, testing and end-of-life treatment
  - **Better empirical understanding of module failure modes** and current disposition of end-of-life PV panels, as well as updated **estimate of market size**
    - Monitoring and reporting system
  - **Analysis of regulatory design options** – collection systems through treatment and disposal
  - **Deeper understanding of structure and experience in the e-waste** management sector to uncover potential lessons for PV

NREL Laboratory-Directed Research and Development Seed Project

- **Developed model framework to perform integrated bottom-up cost modeling and environmental assessment (TEA-LCA) of PV module recycling technologies**
  - LDRD funds did not populate the model
- Why?
  - Once populated, our TEA-LCA framework can **identify key cost drivers and major environmental hot spots** of recycling process designs
    - Data from multiple recycling process designs/recycling companies yields opportunities for industry benchmarking and goal-setting for continuous improvement
  - **Results can inform the development of technology research and development (R&D) roadmaps**

Illustrative Results of Cost Modeling – Which processes contribute most to cost?

September 28, 2016
Conceptual-Only
DRAFT Analysis

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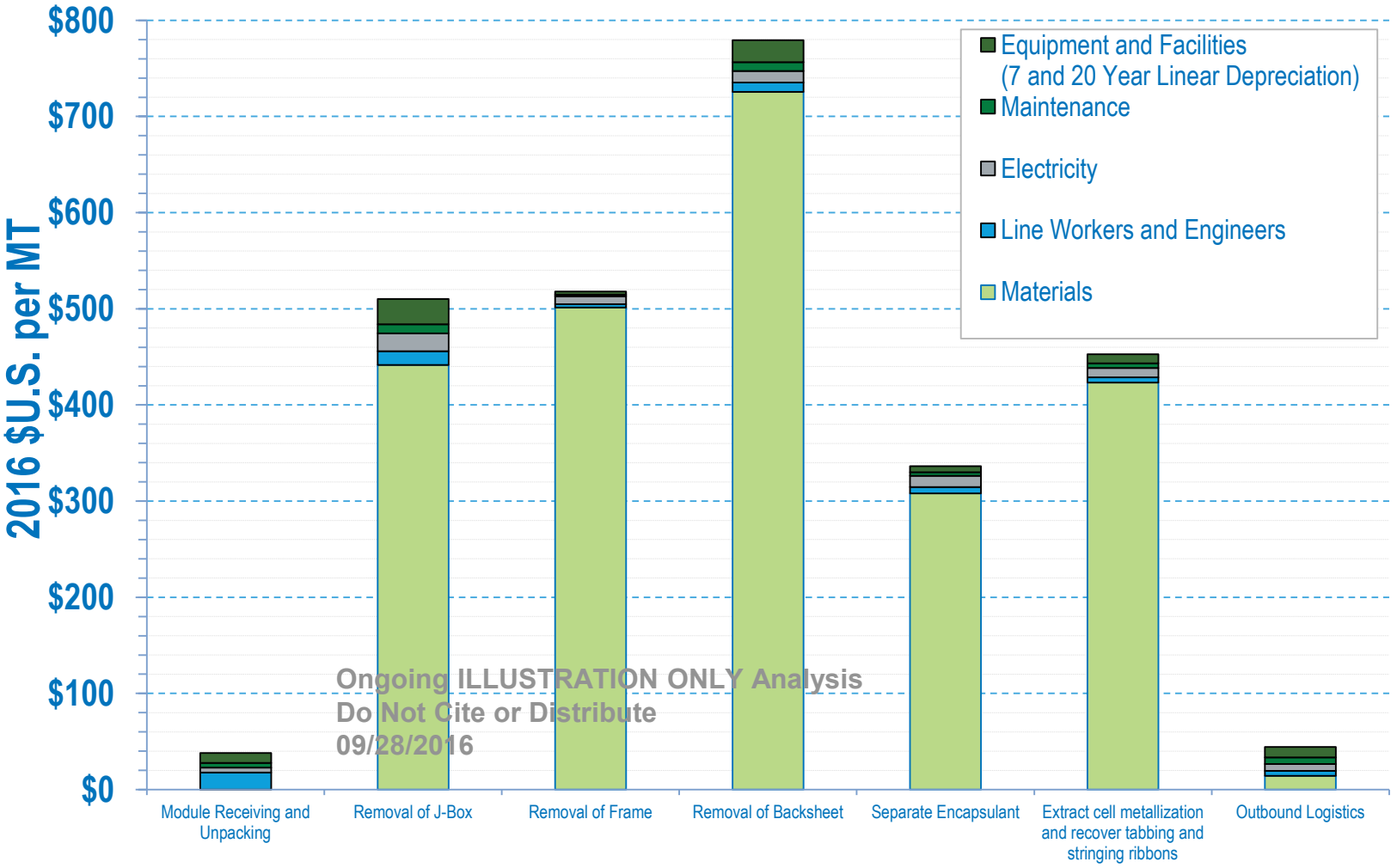
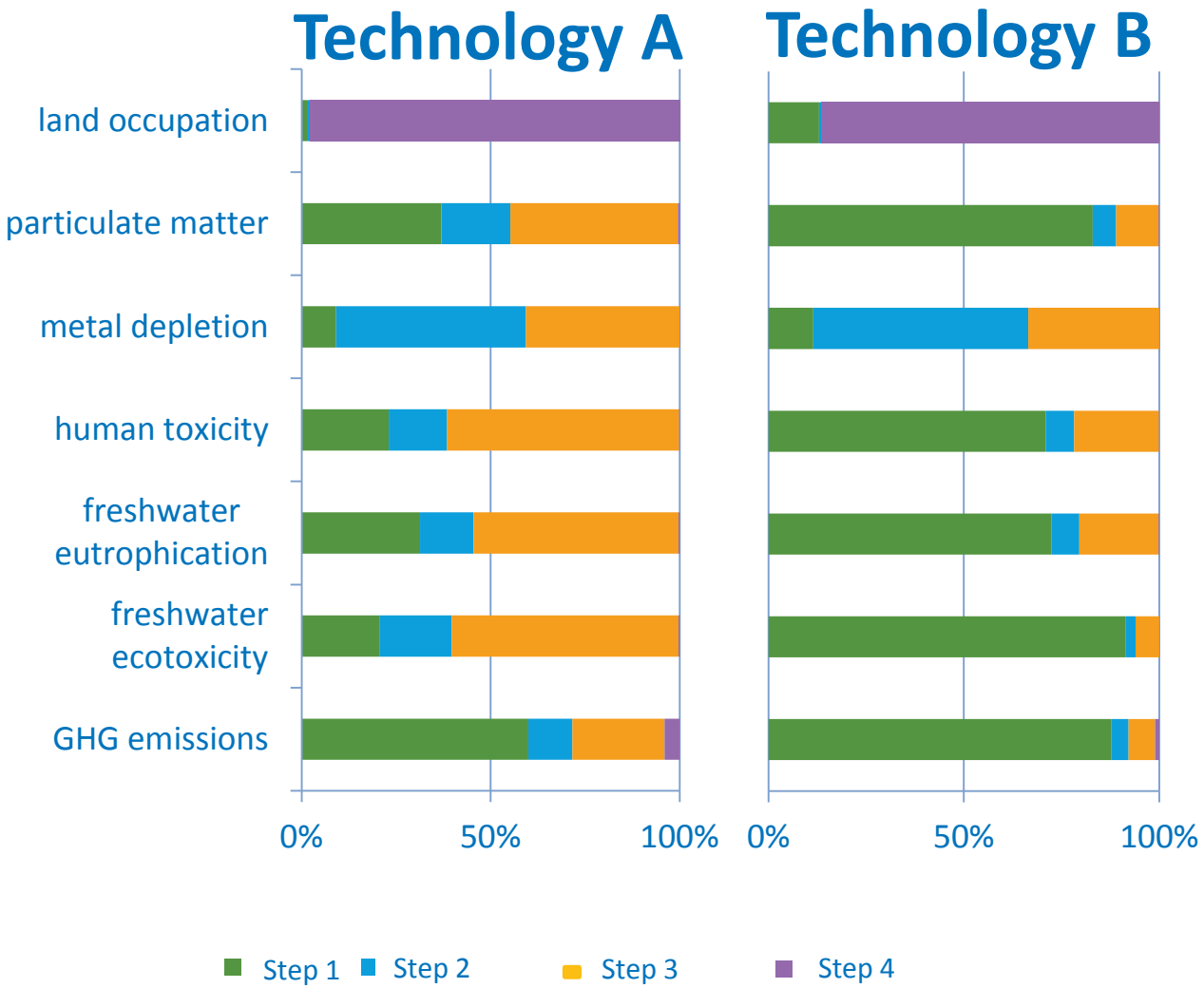
Step-by-Step Costs for Module Recyling

U.S. Recycling Facility, Incoming Modules With 60 (243 cm^2) Cells



Illustrative Environmental Results – Do any process steps contribute disproportionately to certain metrics?



Path Forward – Module Design for Recycling

- Actions being taken (examples)
  - **First Solar**: new models must be approved through recycling team to ensure ability to recycle using their in-house process
  - **IEA-PVPS:** Identification of the principles of the field of design for recycling that are applicable to PV (2018)

- Actions needed within broader industry
  - **Identification of key design features impeding recycling,** starting with generic and moving to model-specific
  - **Alternatives assessment of options to improve recyclability** which should consider feasibility, performance, cost and environmental benefit
  - **Test procedure for recyclability** so that recyclability can be objectively determined in a repeatable fashion.

Thank you!

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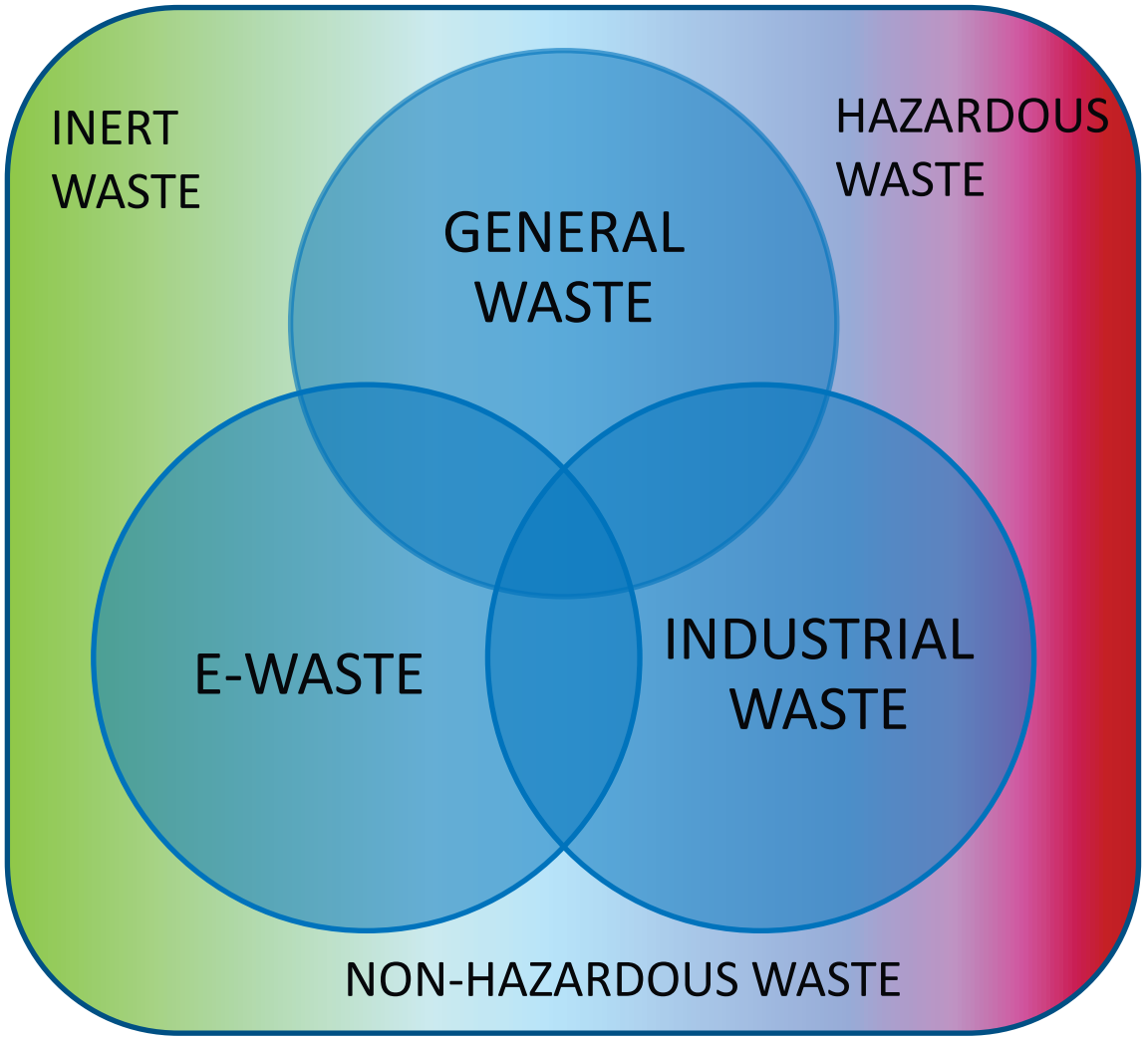
Waste Classification



All PV Panel technologies contain trace amounts of hazardous materials such as lead, tin, zinc, cadmium, selenium, indium, gallium and others.

Depending on the jurisdiction, different waste characterization tests and methods can lead to different classifications of PV panel waste.

Typically, standardized leaching tests and material concentration limits determine the classification and minimum requirements for treatment and disposal.