

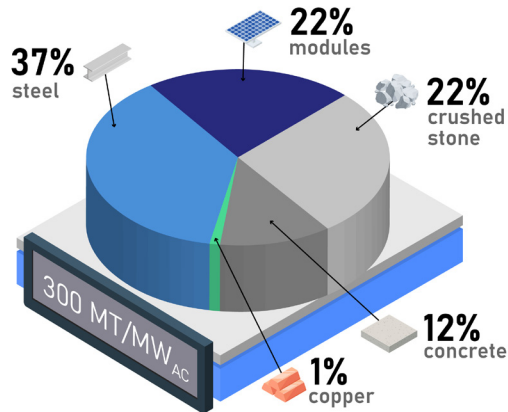


SOLAR PHOTOVOLTAICS

END-OF-LIFE MANAGEMENT



PLANT WEIGHT BREAKDOWN

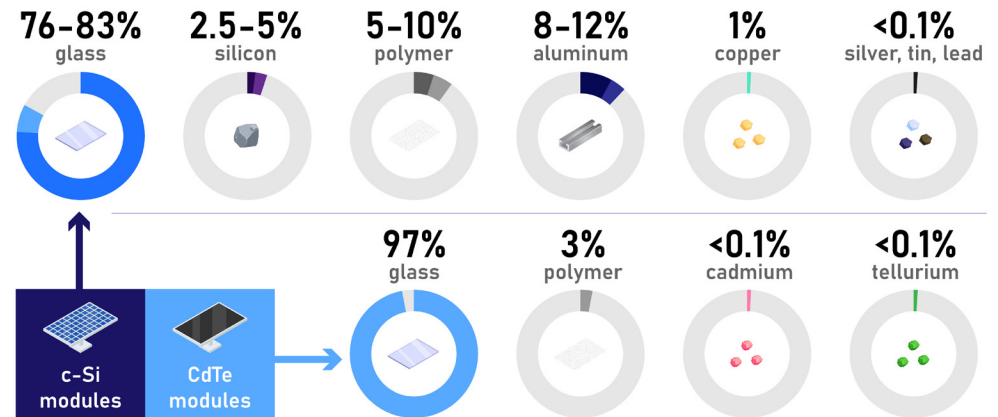


Data Source: EPRI, 2018

Decommissioning solar photovoltaic (PV) plants at end of life (EoL) requires removal and management of a variety of materials. Based on an EPRI study for a conceptual 11 MW_{AC} plant, PV modules represent ~22% of total material by weight. Balance of plant materials include concrete foundations, crushed stone surfacing, fencing, building debris, racking, transformer, inverters, and wiring.



PV MODULE COMPOSITION

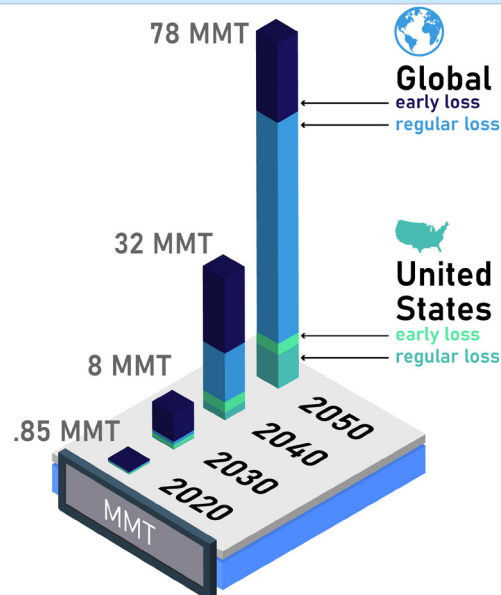


Data Sources: IRENA and IEA, 2016; BloombergNEF, 2020

Crystalline silicon (c-Si) modules currently hold ~95% market share, while the remaining market is mostly served by thin-film cadmium telluride (CdTe) modules. Glass-glass c-Si modules are emerging quickly, with bifacial glass-glass modules expected to hold ~70% market share by 2030. The upper end of the c-Si glass fraction range (83%) reflects glass-glass modules, whereas the lower end (76%) represents conventional c-Si modules with front glass and polymer backsheets. Public data are limited on trace hazardous metals, and module toxicity testing is often required to determine EoL management options.



EoL MODULE PROJECTIONS

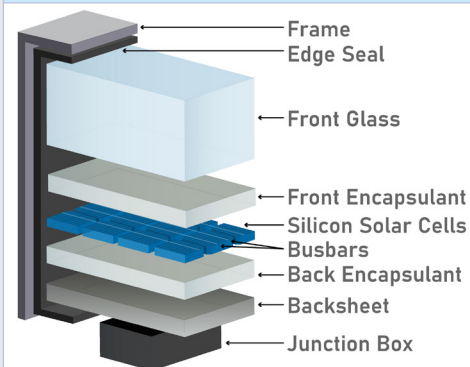


Data Source: IRENA and IEA, 2016

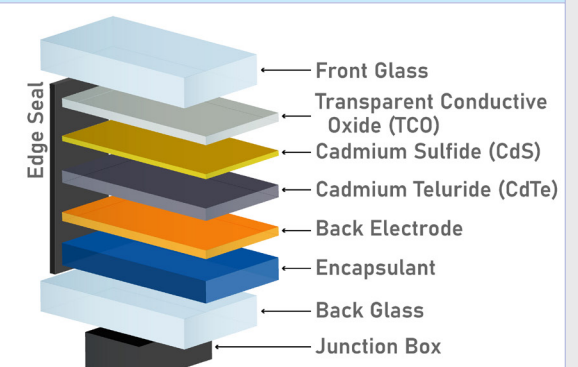
The scale of module EoL management challenges is projected to grow rapidly in the years ahead, mirroring deployment trends around the world but with a time lag consistent with module lifetime of about 20 to 25 years. By 2030, global cumulative EoL PV modules may rise to 8 million metric tons (equivalent to 1.2 million dumpsters). By 2050, those numbers are expected to grow to 78 million metric tons (12 million dumpsters). U.S. EoL module volumes are about 1/8th of the global totals.



c-Si MODULE



CdTe MODULE



Drawings not to scale



MATERIAL RECOVERY VIA RECYCLING

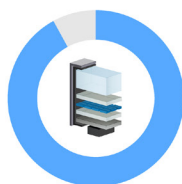
c-Si Modules Recycling Process

current
state-of-the-art



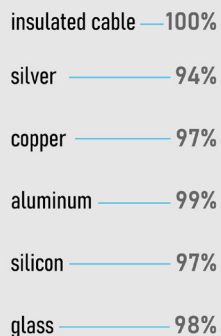
78%
materials
recovered

emerging →



92%
materials
recovered

FREL P material recovery rates



CdTe Modules Recycling Process



90-95%
materials
recovered

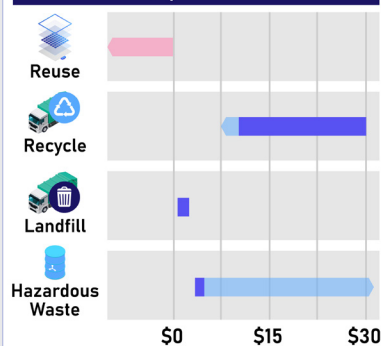
Data Sources: Nature Energy, 2020; EPRI, Alliance for Sustainable Energy, and Wambach-Consulting, 2017; First Solar, 2021

Today, EoL module volumes are low, and most recycling of c-Si modules happens at existing glass recycling facilities on a batch basis. Since the processes aren't customized for PV, only about 78% of materials are recovered by weight. Bulk materials like glass, aluminum frames, and copper wires are recovered for reuse, while high-value materials like silver and silicon are lost. A pilot-scale system, Full Recovery End of Life Photovoltaic (FREL P), that uses a combination of thermal, mechanical, and chemical processes, has achieved 92% recovery. Recycling of CdTe modules is primarily performed by manufacturer First Solar as part of its take-back program. About 90% of glass and up to 95% of Cd and Te is recovered for reuse in new modules.



EoL COSTS

cost per module



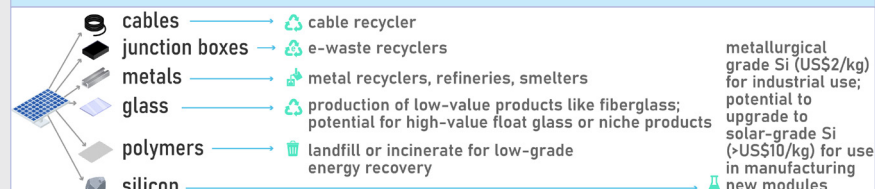
Data Source: EPRI, 2020

Solar decommissioning cost estimates reported in decommissioning plans vary widely, from $-\$70.5/\text{kW}_{\text{DC}}$ to $\$142/\text{kW}_{\text{DC}}$, depending on salvage value assumptions, module management options (reuse, recycling, landfilling, or hazardous waste), and site restoration requirements. Module reuse is by far the most attractive option in the US—economically and environmentally—and may provide the time needed for recycling technology and infrastructure development.

- Reuse provides opportunities for revenue or tax savings
- Recycling for crystalline silicon modules is currently $\sim\$10$ – $\$30$ per module (anecdotal)
- Landfilling modules is cheapest option at $\$0.50$ – $\$1.80$ /module
- Hazardous waste disposal starts at $\$3.60$ /module, and depends on volume and treatment method



MARKETS FOR MATERIALS



Data Sources: Nature Energy, 2020; EPRI, Alliance for Sustainable Energy, and Wambach-Consulting, 2017; BloombergNEF, 2020



R&D NEEDS

- Revise estimates of EoL volumes at country, state, or finer level, including early loss scenarios
- Expand knowledge of EoL management options and costs through documentation of EoL experiences and development of standardized tools for estimating EoL net costs
- Demonstrate high-value recycling technologies customized for PV modules and conduct techno-economic and life-cycle assessments
- Develop processes, such as silicon purification and new glass chemistries, to increase value of recovered materials
- Improve sampling methods for module leach testing to reduce variability in toxicity test results
- Develop PV module collection systems and recycling infrastructure
- Assess second-life opportunities and challenges for PV modules
- Explore opportunities to design PV modules for recycling



ADDITIONAL EPRI RESEARCH



This fact sheet summarizes current and prior EPRI research deliverables on EoL management topics for renewable energy and battery energy storage technologies:

[EPRI Research Activities on Renewable and Battery End-of-Life Management](#).

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Learn more about Environmental Aspects of Solar: www.epri.com/EASolar
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