**Recycling and EOL Waste Management of Solar Panels**

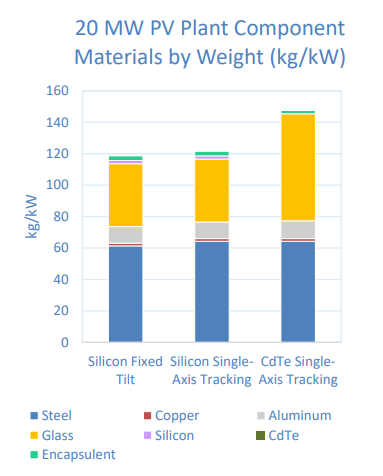
U.S. Department of Energy, (2022) Solar Energy Technologies Office Photovoltaics End-of-Life Action Plan

<https://www.energy.gov/sites/default/files/2022-03/Solar-Energy-Technologies-Office-PV-End-of-Life-Action-Plan_0.pdf>

U.S. Department of Energy Solar Energy Technologies Office, "Request for Information Summary: PV Module Recycling," <https://www.energy.gov/eere/solar/downloads/request-information-summary-pvmodule-recycling>

Solar panels current lifespans are average from 25-35 years, though some components last longer and some components last shorter. What is needed to reduce PV manufacturing’s environmental impact are new materials, designs, and practices, which can serve to minimize waste, energy use, negative effects on human health, and pollution. End-of-life management is the phrase used by the U.S. Department of Energy to describe the process to dispose of solar panels and their components when they are retired from operation. Recycling must be both economically viable and environmentally friendly, and presently recycling solar panels is too expensive, at a cost to waste generators to recycle PV modules of $15-$45 per module, which is significantly higher than the landfill fee, which is $1-$5 per module. Landfilling, recycling, and secondary reuse are the three primary options for PV module EOL, with landfilling currently the lowest cost, with fees ranging from $30/ton to $70/ton depending on geography (Curtis et al., 2021). According to Italian company ERG, secondary reused panels still deliver a significant percentage of their expected power yield and can be redeployed at a relatively low cost (Tripodo, 2024). Social housing programs can benefit from very low-cost, second-life PV modules, provided their performance and safety can be guaranteed after manufacturer warranties are no longer valid (Rüther and Blakers, 2024A). Cumulative end-of-life PV waste in the United States in 2030 is projected to be between 0.17 and 1 million tons, according to the International Renewable Energy Agency. For comparison, the United States produces 200 million tons of solid waste each year, excluding recycled and composted material. The materials in PV modules are 99% non-hazardous and 95% of the materials are recyclable with current technologies. In order for solar cell recycling to enter the supply chain and to become economically viable, safe and low impact EOL material handling tools must be developed, and PV EOL volumes must be handled safely, responsibly, and economically. Weather damage, installation errors, and manufacturing serial defects can lead to early retirement of solar panels, and also technological improvements cause some plant operators and consumers to upgrade before the warranty period expires.[[1]](#footnote-0)

Figure XXX.



*System-level materials breakdown by weight for fixed tilt and single-axis tracking configurations for a Si PV plant, and a single-axis tracking CdTe plant.*

The mechanical recycling processes which dominate the current solar cell recycling market are optimized for compliance with laws based on recycled weight rather than value and economics. Success factors for recycling solar panels include the ability to minimize contamination between different materials, isolate hazardous substances, and recover high-purity fractions of valuable and energy-intensive materials. Today's limited recycling and recovery has typically focused on aluminum frames and glass, not only recovering the precious minerals embedded in the solar panels. Research areas for solar panel recycling include how to handle encapsulation polymers, and how to handle the evolving design of new generations of solar panels, which differ in size, properties, and material composition (Thompson, 2025A).

If new materials and designs can be developed that make PV products longer-lasting, less energy-intensive to produce, easier to recycle, and even less polluting at the end of life, this will reduce end-of-life waste management. Better materials separation and recovery techniques, and designs for recycling plants need to be developed for effective PV EOL recycling.

According to the 2014 SETO PV Recycling Request for Information (RFI), module EOL was defined as the time when a module is operating at 80% (T80) to 50% (T50) of the nameplate power.[[2]](#footnote-1) Assuming a module power degradation rate is constant at around 0.7% per year then a module T80 EOL would be 30 years and a module T50 EOL would be roughly 70 years (Jordan, 2013). According to Lewis (2023), only 10% of solar panels were being recycled as of 2023. He suggests EOL considerations should span the life cycle of a component rather than only at EOL, and that the valuable recyclable materials should be reused to balance the supply chain from mining to finished products. We must reduce our carbon footprint from mining the precious minerals needed for solar panels, and recycling them at EOL is a good start at reducing the carbon footprint. Some helpful data for solar cell recycling include: data on bill of materials, quantity, age, location, cause of EOL, and EOL handling. We need to establish mechanisms for updating quality data on PV EOL, in order to help communities, the solar industry, and EOL industries better understand the current state of EOL and make decisions based on informed analysis (Lewis, 2023). Solar PV adds 50% to the existing glass waste stream (16 kg of solar module waste per person per year compared to 32 kg per person of current glass waste) while avoiding the emission of 900 times greater mass of carbon dioxide. This number for future solar module waste of 16 kg per person per year is only 2% of the 800 kg per person per year of annual solid waste in the U.S. (Rüther and Blakers, 2024B).

Modules, racking structures, and inverters that connect it to the grid all work together to comprise a PV system. Modules contribute about half of the materials by mass of a system, with their composition being 90% glass and aluminum (Al). System materials that comprise the rest of the PV system include steel for racking, piles, and trackers; copper (Cu) and Al for wiring; and plastics for electronics and wire housing. Non-module system components like steel, Al, and Cu can be sold into scrap metal markets, and solar glass can be recycled or used for secondary products, such as reflective paints. The module and inverter, with greater module volumes than inverters, however, are considered electronic waste (e-waste) and do not have established recycling and secondary materials markets. For silicon panels, the embedded silicon is difficult to recover with sufficient purity for reuse. Silicon modules also contain silver (Ag), which is difficult to recover from screen-printed contacts as the silver is embedded in a composite with dielectric materials and engineered to strongly adhere to the silicon wafer. While silver accounts for only 0.3-0.4% of a module by weight, the PV industry has consumed between 8.8% and 9.9% of the global silver supply annually since 2016.[[3]](#footnote-2) This makes The recovered silicon is lower quality than is needed for electronic applications, although it may be useful for metallurgical applications, because other materials are added to the silicon to make it into a solar cell.

Material usage efficiency is the first step to waste management, whereby the amount of materials, especially critical materials, and energy needed to produce system components are reduced. Reuse extends the life of system components when they no longer perform at the levels required for primary use, as developing standards for module size, racking dimensions, and connectors can enable solar modules to be intergenerationally compatible with other manufacturers. Steel, aluminum frames, and glass are easily recovered and recyclable, but are also not hazardous if landfilled. Materials recovery becomes challenging in areas such as recovering silver from the metallization, recycling and separation challenges for polymers and composites such as backsheets, and the semiconductor materials which are difficult to purify for use in solar or electronics applications. The solder used to combine cells in a module is toxic because it contains lead, and this is a concern for landfilling.

Abandoned wind and solar farms result from weak regulations in decommissioning policies, especially for projects left idle before reaching the end of their operational life, according to European researchers. When renewable assets near the end of their operational life, project owners can decommission, repower, renew, operate to failure, or abandon on-site equipment. In a largely decarbonized future, large-scale solar could occupy 0.5% to 2.8% of land in the European Union, but multipurpose land use could potentially ease its footprint. They have determined that their physical footprint can alter land use and aesthetics over the long term. Decommissioning phase planning should be mandatory, even before projects reach the end of their technical operational phase. Regulations should cover the entire life cycle of projects to ensure their true sustainability (Frolova et al., 2025; Molina, 2025).

Mirletz et al. (2023) argues that in the transition away from fossil fuels, we will reduce our waste and carbon emissions, and communities, government agencies and policymakers may be operating under outdated or false assumptions about PV module waste and toxicity hazards resulting in delay or unnecessary impediments to the rapid deployment of PV needed to meet decarbonization goals. PV toxins run the gamut and include such carcinogens as arsenic, gallium, germanium and hexavalent chromium; however, the majority of PV units are composed of crystalline silicon or cadmium telluride. The toxic substances comprise less than 0.1% of the modules, which consist mainly of glass, aluminum and polymers. The International Energy Agency (IEA) claims that the "only potential human health and environmental concern" about PV models are "trace amounts of lead in solder" used in the manufacture of modules. In the IEA’s opinion, cadmium telluride is "extremely stable" and does not pose the same toxicological risk as cadmium (Grad, 2023; Mirletz et al., 2023).

***Silicon and Cadmium Telluride***

To recycle a solar module, first the aluminum frames are mechanically removed, and the junction box is sheared off. When the solar panel is silicon, the module is shredded into small pieces, grinded into fine particles, and then eddy currents and sifting separate the glass, polymers, interconnect ribbons, and cells. Silicon module recycling techniques also use heat to remove the polymers from the glass and chemical treatments to separate the metals from the silicon. When the solar panel is CdTe, mechanical processes are used to remove the frame and junction box, then the laminate is shredded, grinded into small pieces in a hammermill, the glass and laminate pieces are mechanically separated, and then immersed in a series of chemical baths to recover the Cd and Te.

*To recycle silicon from end-of-life photovoltaic panels, Netherlands scientists have created a methodology to help create different wafer categories for recycling silicon for new ingot production, However, most of recycled silicon in the near future will come from p-type products, which will hardly be reutilized in a market now dominated by n-type modules. They investigated how cleaned wafers or wafer fragments recovered from end-of-life (EoL) PV modules could be reused for new crystalline silicon ingot production, and found that gallium-doped wafers could be particularly suitable for this purpose. Silicon from the discarded wafers should be recycled by eliminating any contamination on its surfaces, which would re-include it in the high-purity material category. According to the researchers, the main contaminants are dopant, oxygen, carbon, and nitrogen, analyzed from the perspective of dopant and resistivity control, and to a limited extent also from the perspective of other remaining contaminants (Geerligs et al., 2024; Bellini, 2024A).*

*A wet chemical process to recover silicon with high purity from end-of-life (EoL) solar panels has been developed by Indian researchers, which can be used to make functionalized silica nanoparticles. This wet chemical process for recycling EoL panels focuses on aluminum back surface field (Al-BSF) type panels because most of the current and future EoL panels are this type. To recover silicon-solar cells that are encapsulated between top and bottom ethyl-vinyl acetate (EVA) polymer sheets without incinerating the EVA, solvents can be used for the EVA removal step. However, a challenge is preventing the loss of used medium or solvents and subsequent regeneration for reuse. In their experiment, the Indian researchers exposed recovered cells to successive chemical treatments to selectively etch out various layers, such as the top silver finger contacts, top anti-reflection coatings, and bottom aluminum contact layer. Next, the component materials, such as silicon cells, cover glass, connecting wires, and layers of polymeric were separated to expose the bare silicon wafer. However, the recovered silicon cannot be re-used to manufacture solar silicon, but it can be used to make silica nanoparticles, optical grade hydrophilic silica nanoparticles with optimized functionalization. The team took crushed silicon powder to use as a precursor for the synthesis of the silica nanoparticles, which was processed through chemical functionalization into silica (SNP) and hydrophobic silica (HSNP) nanoparticles in a three-step process. The SNPs and HSNPs were then characterized based on structural, morphological, optical, and spectroscopic techniques. The HSNPs were used as anti-corrosion coatings and outperformed conventional coatings based on both plain polymeric matrix and uncoated nanoparticles-filled polymer composites. HSNP cells performed well and this was attributed to the ability of the nanoparticles to minimize water absorption and effectively prevent corrosive agents from reaching the substrate (Saha et al., 2025; Thompson, 2025B).*

*Australian researchers have developed a process to synthesize freestanding graphene from non-toxic and renewable tangerine peel oil, which they then used to recover silver from waste and end-of-life organic PV material. To demonstrate the quality of the recovered silver and the synthesized graphene, they made a dopamine sensor that reportedly outperformed reference devices. The recycling process resulted in high-quality graphene, and also demonstrated a remarkable ability to selectively recover silver from photovoltaic waste, as one of the most surprising findings was how exceptionally selective the graphene was in targeting silver. The quality of both the recovered and synthesized materials was then demonstrated in a silver-enhanced SPE dopamine sensor device, which outperformed two reference dopamine sensors made without the silver graphene composite (Zafar et al., 2024; Thompson, 2024A).*

*The electrohydraulic shockwave fragmentation (EHF) technique enables the recovery of more than 99.5% of the weight of solar panels, as shockwaves generated by arcing between electrical electrodes suspended in a liquid medium are used to separate and recycle the different materials of a PV module, with chemical processes further used to extract silicon and silver. In this case, electrical electrodes are connected to a power supply of approximately 50 kV, generating shockwaves in water as they interact with the chopped-down PV module that is immersed in the liquid. Before that happens, the aluminum (Al) frame, the external junction box, and the wires are removed by mechanical separation, and the module is cut with a water jet. After the disintegration in the fragmentation unit, individual materials such as glass, backsheet, ethylene vinyl acetate (EVA), copper (Cu) ribbons, and solar cells are separated by filtration, sorting, and binning as they pass through different sieves. The materials can then be used to extract silicon (Si) and silver (Ag) through downstream chemical processes, while the glass, Cu/Al/Ag contacts can be reused post-purification and melting (Padhamnath et al., 2025; Kahana, 2025C).*

*A micro-scale recycling approach involving thermal and chemical processes has been developed to recover silicon and silver from end of life PV panels, with the silicon being pure enough for re-use in silicon carbide-based devices. Micro-recycling enables the selective recovery and transformation of valuable materials at the microscale, and also refers to the microscale characterization techniques used to investigate the recovery mechanisms of valuable metals. The first step is the manual separation of the junction box, cables, and aluminum alloy frame, followed by the module glass delamination via a hydrothermal delamination method. Next, the waste cell material is subjected to a medium-temperature in-situ F-producing heat treatment at 550 C, in order to remove the ethylene vinyl acetate (EVA) encapsulants and polyvinyl fluoride (PVF) backsheets, and eliminate the corrosion resistance imparted by the top layer of the silicon (Si) cell. In the next step, both the heat-treated silicon (HT-Si) and untreated (UT-Si) fragments undergo chemical etching to remove aluminum (Al) using basic 30 wt% potassium hydroxide (KOH) and nitric acidic (20 v% HNO3) media at 80 C. Surface roughness and elemental analyses supported decisions were used to determine the duration of the two-step etching to remove Al impurities, in this experiment at 3 min. The remaining Ag and Sn were extracted using the second etching stage via an acidic media. The team said it was worth noting that the Si purity of the back side of UT-Si fragments remained around 77 wt%, while that of HT-Si fragments exceeded 99 wt%, despite undergoing only 3 minutes of KOH etching (Nekouei et al., 2025; Thompson, 2025K).*

***Perovskite***

With perovskite cells, everything can be recycled, including covering glasses, electrodes, perovskite layers and also the charge transport layer. Perovskite solar cell recycling is efficient and environmentally friendly, although they often contain lead in the perovskite absorber material, and in the lead solder used to connect the cells (Xiao et al., 2025). Current methods for dismantling perovskite solar cells involve using a substance called dimethylformamide, a common ingredient in paint solvents, which is toxic, environmentally hazardous and potentially carcinogenic. Linköping researchers have developed a technology where water can be used as a solvent in dismantling degraded perovskite cells, as high-quality perovskites can be recycled from the water solution (Xiao et al., 2025; Mishra, 2025A). Using advanced recycling processes, it is possible to create a circular economy for photovoltaic systems with lead perovskites.

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