Photovoltaic Circularity: Solar Panel Recycling and End-of-Life Considerations

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Recycling is one of the primary methods used to keep end-of-life solar panels out of landfills and re-circulate various raw materials. However, regulatory and technical challenges, such as a lack of global coordination and limitations in the Harmonized System, have hindered international trade in the industry. This EBOT explores the global state of solar panel recycling and end-of-life opportunities for these products, with a focus on U.S. capabilities and policies that incentivize recycling.

Chinese dominance in the crystalline silicon solar panel supply chain highlights the need for recycling

In 2022, global solar installations totaled over 178 GW, bringing the global cumulative installations to around 1.2 TW. China led the world in installations, with over 105 GW installed in 2022, while the United States installed approximately 21 GW, bringing its total cumulative installations to around 142 GW. Crystalline silicon solar technology makes up the majority of the global solar market, and many of its components can be easily recycled, including the aluminum frame, glass, copper wire, and plastic junction box (together account for about 90 percent of a panel's mass). Solar panels also include other critical minerals (e.g., silicon, tin, tellurium) that could be recycled but present recycling difficulties due to their hazardous nature. Government and industry experts forecast an increase in demand of these critical minerals as global solar power capacity is expected to grow. However, the current supply chain is largely dominated by Chinese presence. For example, China's share of global polysilicon production was 86 percent in 2022 and around 90 percent for solar glass in 2023. Expanding domestic recycling capacity in the United States is thus increasingly seen as an important way to diversify supply chains and reduce Chinese dependence. At the same time, China announced plans to establish an end-of-life recycling mechanism for solar panels by 2025.

Recycling in the United States is limited and inconsistent across states

In the United States, there are processes in place to recycle most of the components that go into a solar panel, including glass which makes up approximately 75 percent of the weight. There are over 20 facilities recycling solar panels and/or components. However, this is not occurring on a large scale, despite established recycling practices of glass, metals, and electronic components. Federal regulations in the United States do not mandate solar panel recycling, but there are certain state-level regulations that do. For example, Washington passed the Solar Incentives Job Bill in 2017 and became the first state to mandate that manufacturers of solar panels recycle their products. In addition, several states, including California, Hawaii, New Jersey, and North Carolina have end-of-life policies regarding waste from solar panels. While elements of solar panel recycling exist in the United States, most of it is only component based, with an emphasis on reusing or refurbishing panels for a second life.

Different approaches exist globally for solar panel recycling, which limits trade in these products

According to IEA's Roadmap to Net Zero Emissions by 2050, systemic recycling of solar panels at end-of-life could meet 20 percent of the global solar industry's demand for aluminum, copper, glass, and silicon, and almost 70 percent for silver. Globally, however, countries and firms vary in their approaches to solar panel recycling. A review by the International Renewable Energy Agency of regulations and guidelines for recycling solar panels shows that the majority of countries do not have specific regulations for end-of-life solar panels, and are therefore treated under the established regulatory frameworks for waste management in a given jurisdiction. The exception is the European Union (EU). Under the Waste from Electrical and Electronic Equipment (WEEE) Directive, the EU mandates that its member states recycle

80 percent of the inputs used in the manufacturing process of solar panels from 2018 onwards. As a result, there are several firms in Europe that specialize in recycling processes that reuse critical materials found in solar panels, including ROSI which opened in 2018 and became the first European plant focused on recycling end-of-life solar panels and is aiming to recycle 10,000 metric tons of end-of-life solar panels in 2025. The global regulatory landscape is changing, however, as some countries like China and Japan consider mandates similar to the EU's WEEE Directive.

Despite updated frameworks and mandates, much of the world's approach to recycling solar panels is fragmented and inconsistent. Although the Basel Convention is intended to regulate transboundary movement of hazardous and non-hazardous waste, classifications for reuse, repair, or recycling still varies from country to country. This is largely due to global inequities in trade infrastructure, access to finance for circularity, and capacity to properly manage such waste. These conditions have hindered trade in these products, according to a framework document for inclusive circular trade developed by a global working group of government and industry experts. According to the document, around 45 percent of the total global value of trade in waste, scrap, and secondary goods and materials occurs entirely between high-income countries in the Global North. Should these conditions persist, they could limit where and to what extent end-of-life solar panels could be recycled and traded. Further, it is likely that a significant proportion of this trade is not captured in official trade statistics, since the Harmonized System often does not distinguish between primary and secondary materials, or between new and recycled/used products. This has the potential to hinder both the measurement and flow of trade.

Recent policy developments encourage solar panel recycling

Current global solar panel recycling capacity is not sufficient to meet expected future demand for these services. Approximately 8 million metric tons of solar panels will reach the end of their useful life by 2030, and that number could reach 80 million metric tons by 2050. One estimate from IRENA/IEA puts the value of recovered materials from end-of-life solar panels at $450 million by 2030 and $15 billion by 2050. These are recovered materials that could be used in the production of domestic solar panels or traded globally. In 2021, the EU launched ReProSolar to develop an industrial method for recycling panels, but its current capacity goal is 5,000 metric tons of panels annually, or approximately 2.7 million panels. In the United States, as part of the Infrastructure Investment and Jobs Act (2021), the federal government is investing in projects that focus on reducing the cost of panel recycling, a major barrier to greater deployment of recycling capacity. The Inflation Reduction Act (2022) also provides tax credits for investing in facilities designed to recycle solar panels. These investments could help reduce reliance on U.S. imports of foreign-made solar panels and increase the security of future raw material supply. Despite these investments, experts point out that the current largely country-by-country approach to recycling will restrict the capacity to manage global end-of-life solar panel recycling demand.

Sources: Chatham House, "Trade for an inclusive circular," 07/2022; EMF, "Circular Economy," accessed 08/22/2024; ROSI, "ReProSolar," accessed 11/14/2024; European Environment Agency, "Recycling materials…" 05/23/2024; IEA, "Special Report on Solar…" 07/2022; IEA PVPS, "Trends in Photovoltaic…" accessed 08/22/2024; IEA PVPS, "2019 Snapshot of Global PV…" accessed 08/22/2024; IRENA, "End-of-Life Management," 06/2016; NREL, "A Circular Economy for Solar…" 04/2021; Nikkei Asia, "Japan eyes recycling…" 06/12/2024; NWPSC, "First solar product stewardship…" 07/18/2017; Orsted, "Orsted commits to reuse…" 06/06/2023; PV Magazine, "US, Canada ramp up solar glass plans," 05/18/2024; PV Tech, "China to build solar recycling…" 04/20/2023; PV Time, "China Urges End-of-Life Management…" 05/31/2023; U.S. DOE, "Biden-Harris Administration Announces $82 Million…" 04/20/2023; U.S. DOE, "Critical Materials Assessment," 07/2023; U.S. DOE, "Federal Tax Credits for Solar Manufacturers," accessed 08/22/2024; U.S. DOE, "Spring 2024 Quarterly…" 05/14/2024; U.S. DOE, "What Are Critical Materials…" accessed 08/22/2024; U.S. EPA, "End-of-Life Management…" 10/26/2023; U.S. EPA, "End-of-Life Solar," 10/23/2023; U.S. EPA, "Solar Panel Recycling," 06/14/2024.