What it takes to realize a circular economy for solar photovoltaic system materials

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Rapidly increasing solar photovoltaic (PV) installations has led to environmental and supply chains concerns. The United States relies on imports of raw materials for solar module manufacturing and imports of PV cells and modules to meet domestic demand. As PV demand increases, so will the need to mine valuable materials—a motivation for domestic reuse and recycling.

Moreover, decommissioned PV modules could total 1 million tons of waste in the United States by 2030, or 1% of the world's e-waste. This presents not only waste management concerns but also opportunities for materials recovery and secondary markets.

"Responsible and cost-effective management of PV system hardware is an important business and environmental consideration," said Taylor Curtis, sustainability analyst at the National Renewable Energy Laboratory (NREL). "Repair, reuse, or recovery of this equipment would reduce negative environmental impacts, reduce resource constraints, and stimulate U.S. economic growth."

Curtis and a team of NREL researchers have been leading ongoing analysis of how to manage retiring PV modules in support of the laboratory's vision of a circular economy for energy materials. The team conducted legal- and literature-based research and interviewed solar industry stakeholders, regulators, and policymakers. They published a series of NREL technical reports, narrowing in on options and opportunities for PV equipment reuse and recycling.

Technical, Economic, and Regulatory Factors for a PV Circular Economy

Today, there is little incentive for private industry to invest in PV recycling, repair, or reuse due to current market conditions and regulatory barriers. In the United States, only one manufacturer has implemented a "takeback" program to reuse or recycle retired PV modules. Although there are a growing number of U.S. third-party recyclers that accept PV modules, most companies only recover bulk material and leave behind high-value materials such as silver, copper, and silicon—according to one report in the study.

In the future, the U.S. industry for recovered PV materials from modules alone could total $60 million by 2030 or $2 billion by 2050. PV equipment recycling could increase supply chain stability and resource security, decrease manufacturing costs, enhance a company's green reputation, provide new revenue streams, add tax benefits, and create American jobs.

To help spur private investment in the early stages of new and expanded PV market opportunities, the analysts recommend government-funded R&D and analysis to help relieve some of the market and regulatory uncertainty associated with the reuse and end-of-life PV options. R&D could focus on designing PV modules to be more easily repaired, reused, or recycled, as well as on the associated cost-effective services and business models.

Policy is also critical to a PV circular economy, ensuring the safe handling, storage, treatment, transport, reuse, recycling, and disposal of PV equipment. However, NREL analysts found that existing interconnection, fire, building, and electrical regulations in the United States could directly prohibit reusing PV modules or inverters for grid-tied applications.

In the United States, PV equipment such as modules that are destined for resource recovery are often regulated the same way as equipment destined for disposal. Therefore, there is no incentive to recycle, especially when disposal costs less. Used PV equipment that is accumulated or stored before recycling or disposal may be regulated as solid waste or hazardous solid waste. U.S. waste laws vary by jurisdiction and mandate specific handling, storage, and transport requirements. Transporters of PV equipment may be subject to U.S. Department of

Transportation hazardous materials regulations with specific packaging, documentation, and other transit-related related requirements. If PV equipment is shipped abroad, it may be subject to international treaty requirements and export regulations.

Based on their analysis, the NREL team recommends a multifaceted regulatory approach that places responsibility across the value chain. Consistent, clearly defined federal, state, and local regulations could mandate and incentivize secondary markets. These laws could prohibit disposing PV modules, provide an exemption from stringent regulation, or require reuse. For example, Washington state has a policy that requires PV manufacturers to take back or recycle modules at no cost to consumers. It also allows modules to be regulated under less-stringent solid waste requirements if they are recycled.

Best Practices for End-of-Life PV Management

In another report in the research effort, NREL analysts dig deeper into alternatives for managing retiring PV systems. The best option for each system that is being decommissioned is determined by estimated costs to refurbish or repower, and the projected revenue from continued operations.

If a system is operational and has not suffered extensive damage, it might be possible to extend the performance period. This involves extending permits and the utility and interconnection agreement. While there is no capital investment with this option, there are higher operation-and-maintenance costs to repair aged equipment.

Refurbishment is an option with detailed physical and electrical inspections and necessary repairs. This could cost about $500 per kilowatt. If a system has suffered storm damage, the cost could exceed $750 per kilowatt. Refurbishment is more difficult because parts of old systems are increasingly hard to find and operation-and-maintenance providers may not have the expertise to work with older systems.

Some older PV systems can be repowered. This entails redesigning the system and installing a new PV array and inverter(s) to rebuild or replace the power source. Repowering often costs 80% of the total plant value. A repowered PV system is new in almost all respects and can leverage existing land-use, permitting, utility interconnections, and power purchase prices.

If it does not make economic sense to repair or refurbish a system, decommissioning might be the right option. This entails removing the PV module and other equipment and restoring the land or roof to the original condition. This ranges from $300 per kilowatt to $440 per kilowatt.

Tax implications can also drive decisions because contracts are often structured so that projects are eligible for tax credits and depreciation.

What Is the Current State of U.S. Policies and Initiatives for PV Recycling?

A final report in the series analyzes federal and state regulations (existing, pending, and historic) that explicitly address PV module recycling in the United States.

The analysts did not find any federal statutes or regulations that explicitly address PV module recycling. However, state- and industry-led policies have started to emerge related to end-of-life PV management concerns. These state- and industry-led policies use their own frameworks tailored to specific options for retiring PV modules and thereby impact different parts of the solar value chain.

Some states, such as New Jersey and North Carolina, passed laws in 2020 to require the study of end-of-life PV management options to help develop options for legislative or regulatory considerations. This research could also provide valuable, publicly available information about the costs and liabilities associated with PV recycling and resource recovery opportunities. In addition, California has enacted universal waste regulations, which address the end-of-life management, transport, storage, accumulation, and treatment of discarded PV modules.

As of May 2020, Hawaii has pending legislation that would require a comprehensive study of issues related to PV module recycling and end-of-life management. Rhode Island has pending legislation that, if enacted, would create a PV module manufacturer stewardship and takeback program. California also has pending legislation to study and recommend policies that would ensure PV module reuse or recycling at end of life.

"A circular economy for solar PV materials will involve everyone across the value chain, from project owners and financiers to manufacturers," Curtis said. "Together, the industry can ensure that liabilities like hazardous materials are avoided and end-of-life management extracts the most economic value and makes the least environmental impact possible."

Provided by National Renewable Energy Laboratory

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