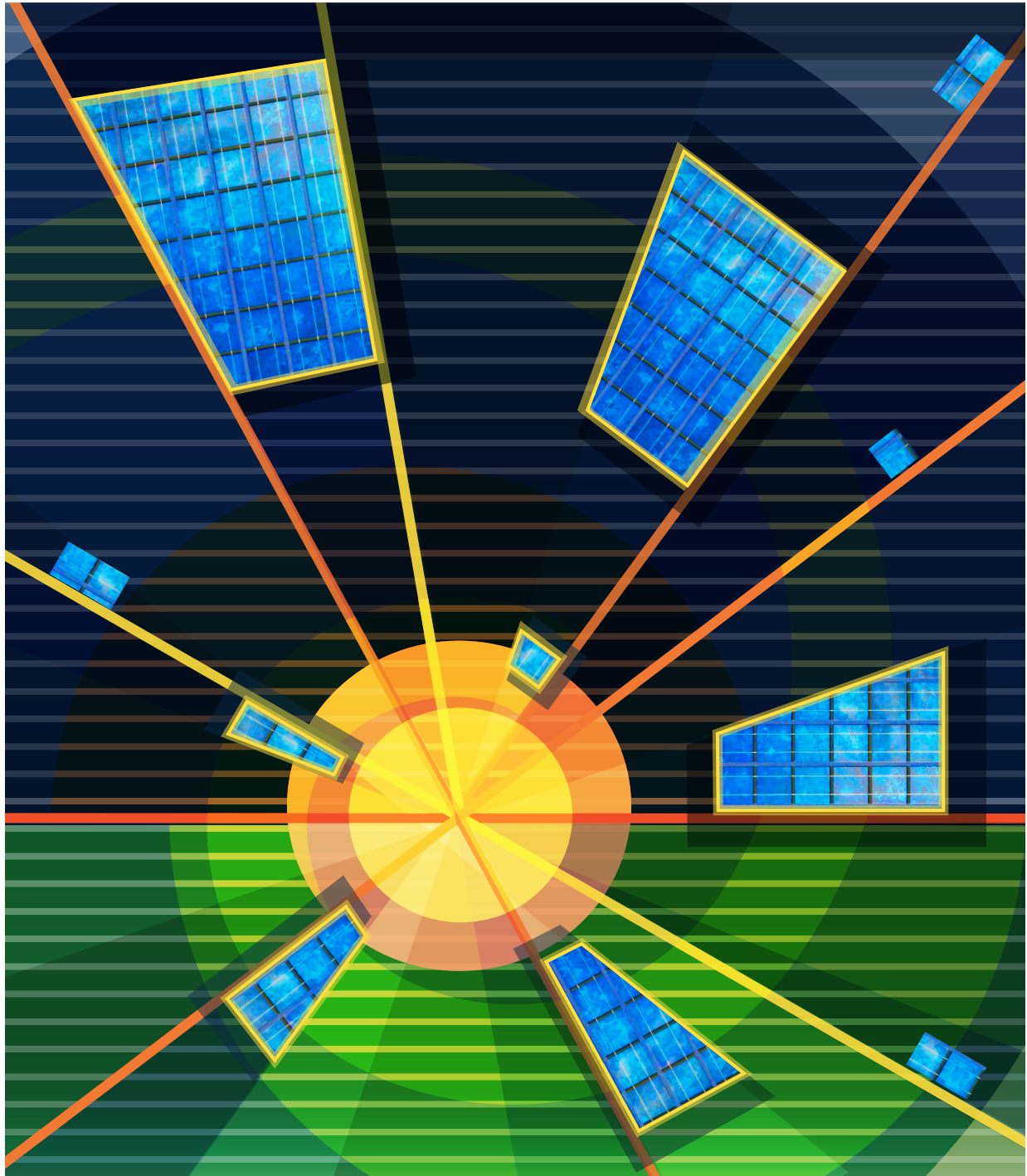


# SOLAR PV MODULE END OF LIFE: OPTIONS AND KNOWLEDGE GAPS FOR UTILITY-SCALE PLANTS

Technical Update Report, December 2018

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**Abstract**

This report provides a snapshot of the present situation in the United States around photovoltaic (PV) module end-of-life (EOL) management. With an expected surge in PV waste volumes in the coming decades, best practices must be established for project decommissioning and for module collection, reuse, recycling, and disposal. The report outlines drivers of existing and future PV waste volumes, currently available EOL options for PV plants and modules, and technologies adopted in mature PV markets such as Europe, where recycling is already mandatory. Key factors that may influence asset management decisions and module recycling and disposal practices are introduced, including performance monitoring, module composition and construction, policy and regulation, emerging recycling technologies, and research and development (R&D) opportunities. The current state of knowledge on PV plant decommissioning practices and EOL costs is presented, based on prior EPRI R&D plus information provided by module recyclers, waste management companies, landfill operators, and utility and PV industry practitioners.

**Keywords**

- Decommissioning
- End-of-life (EOL)
- Environmental impacts
- Life-cycle analysis
- Photovoltaic (PV) recycling
- Photovoltaic (PV) disposal
- Regulations

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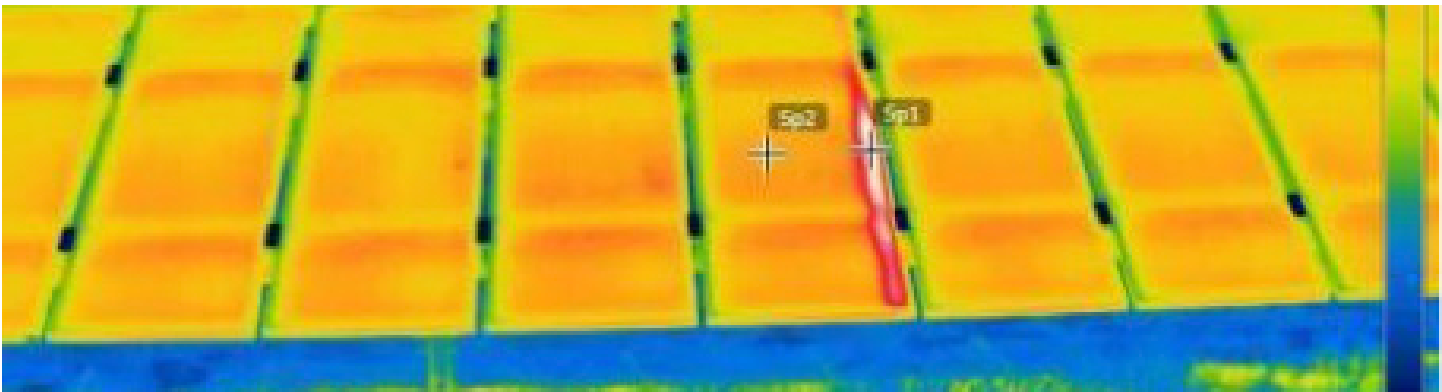
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PV modules reach end of life for a variety of reasons. This infrared image reveals a metal connection failure, likely resulting in performance degradation sufficient to justify module removal and replacement.



## Introduction

Typical utility-scale solar photovoltaic (PV) projects are developed and financed based on an expected lifetime of about 25 years, even though commercial PV modules are capable of generating energy for much longer periods. End-of-life (EOL) considerations are both financial and environmental. While most current solar projects still have many years of useful operation remaining, recent PV deployment will create growing regional and global needs for cost-effective and sustainable EOL practices (Figure 1).<sup>1</sup>

Plant-level options include repowering or full decommissioning, with both entailing module removal and then either reuse, storage, recycling, or disposal. EOL decisions are influenced by factors beyond cost-benefit considerations and the availability of reuse and recycling options. They include site ownership and contract terms;

### Drivers for EOL Management and Innovation

**Spent Module Volumes Are Growing.** At the end of 2018, over 500 gigawatts (GW) of PV capacity are expected to be installed globally, with more than 90% deployed since 2010. Typical PV module lifetimes are between 20 and 30 years. While PV module waste volumes are currently small—at least 43,500 metric tons per year in 2016—they are steadily increasing. The International Energy Agency (IEA) and International Renewable Energy Agency (IRENA) expect annual waste to rise to over 1.7 million metric tons by 2030 and over 60 million metric tons by 2050 (Figure 1). Annual tonnage of spent PV modules could exceed that of new installations by 2050.<sup>1</sup>

**Plant EOL Costs Are Uncertain.** Projects are often required to hold decommissioning bonds to offset the risk associated with the EOL process, but real-world costs are highly uncertain. Contracts may state that a leased site must be returned “back to green” when a project ends, without defining what specific actions are required and conditions must be met. The types and amounts of toxic materials present within a module—and what might leach out—are often unknown, and U.S. recycling and disposal experience is limited.

**Module EOL Options Need to be Safe and Sound.** Safety and environmental impacts are important considerations. Removing and transporting EOL modules—and the recycling and disposal process itself—can be energy intensive. Laboratory testing may be required to determine whether modules or residuals need to be managed as hazardous waste in order to prevent soil and groundwater contamination. During recycling, impurities may reduce

plant vintage and performance; module age, condition, and composition; and code requirements and state and national regulations.

PV plant repowering and decommissioning experience are limited in the United States, and innovation in module recycling technology and development of infrastructure have progressed slowly due to low volumes of EOL feedstock. With examples of economically and technically feasible module take-back and recycling models implemented in the European Union (EU) and elsewhere,<sup>2</sup> there is growing U.S. interest in understanding the economic and environmental potential and challenges of managing EOL modules. This report is intended to cover the U.S. landscape, addressing market drivers, current recycling and disposal practices and costs, and diverse factors that will influence future advances and innovations focused on minimizing the life-cycle environmental impacts of PV technologies.

the value of the product streams, while high-value trace materials like silver may be difficult to isolate in sufficient quantity to compensate for the cost of recovery.

**Regulatory Frameworks Are Evolving.** EOL PV recycling is mandatory in the EU under the 2012 Waste Electrical and Electronic Equipment (WEEE) regulation, which has resulted in greater availability of module collection and recycling programs supported under extended producer responsibility (EPR) requirements.<sup>1,3</sup> California and Washington are the first two states to impose restrictions on module EOL. Elsewhere, the responsibility often falls to PV system owners and operators to determine whether modules should be classified as hazardous waste and to identify the applicable recycling and disposal options.

**Business Implications Are Becoming Clearer.** PV plant developers, owners, and operators need to understand EOL requirements, options, and cost impacts as early as possible in the asset development, acquisition, and/or management process. Decision tools, based on hypothetical or pilot studies and real-world decommissioning experiences, are required to more accurately price decommissioning bonds, reduce risk premiums, or obviate the need for such bonds altogether. Proven collection, reuse, recycling, and disposal methods are essential to lower back-end costs.



**Solar PV Module End of Life: Options and Knowledge Gaps for Utility-Scale Plants**

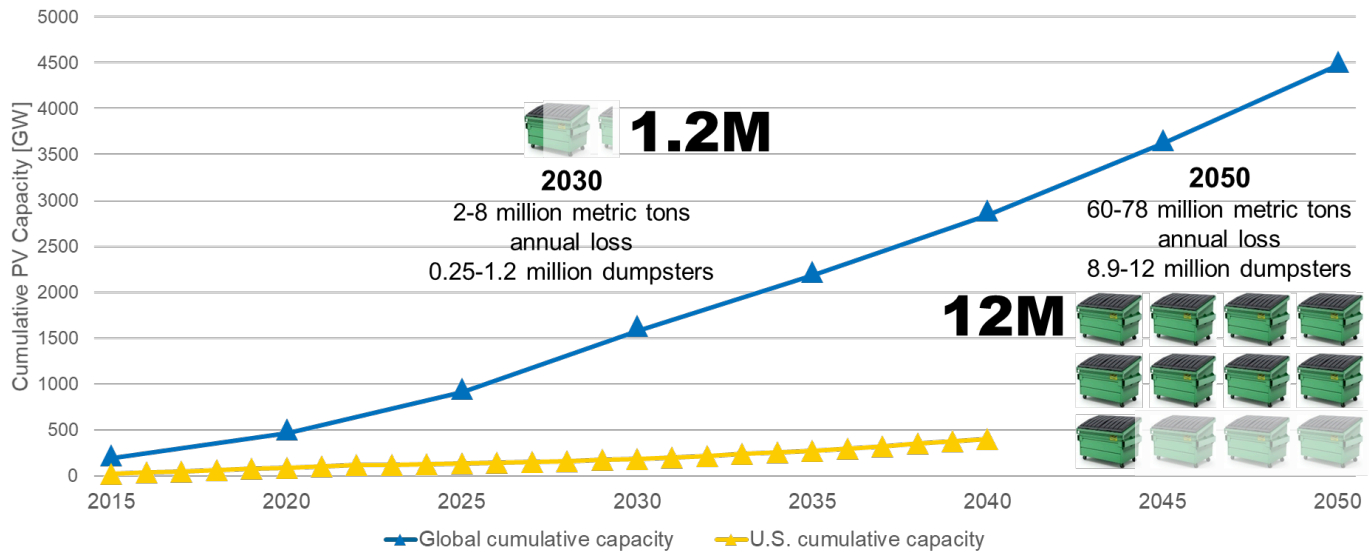


Figure 1 - Cumulative global and U.S. installed PV capacity and global waste projections: In the U.S. market, 170,000 to 1 million metric tons of spent PV modules are expected by 2030, or 25,000 to 150,000 dumpsters (40 cubic yards each). Those numbers are expected to grow roughly 10-fold by 2050.<sup>1</sup> (redrawn by EPRI)

## Plant EOL: Repowering and Decommissioning

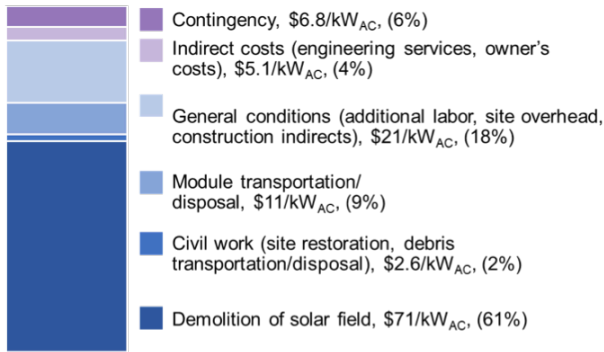
Owners of older or underperforming PV plants can conduct field inspections and analyze historical and ongoing operational and weather data to assess performance and evaluate the options of selective module replacement, repowering, and decommissioning (see “Performance Assessment” box, p. 6). Careful consideration of safety and the latest codes and standards—which can vary by site, host, owner, utility, or contract—is important. The 2011 and 2014 National Electric Code (NEC) cycles made significant safety and performance improvement changes to NEC Article 690 that affect the feasibility of repowering legacy PV plants.<sup>4</sup>

Generally, code changes have transitioned the PV industry toward use of transformer-less inverters and ungrounded systems that offer higher operating voltage, increased efficiency, lower cost, improved safety, and other advantages. For legacy plants, maintaining and replacing isolated inverters pose equipment availability challenges, switching to transformer-less inverters necessitates costly wiring upgrades, and newer and higher-efficiency modules are not compatible with existing grounded wiring. Owners of legacy plants interested in continued solar energy production on the same site do have opportunity to increase capacity within existing footprints by deploying current PV technologies to replace vintage ones. This requires almost complete decommissioning before starting anew.

Full decommissioning of a PV plant includes steps to dismantle, remove, and then salvage, recycle, and/or dispose of foundations, racking, modules, wiring, electrical components, buildings, and fencing. Restoring the site to original or as-specified condition also generally entails grading, seeding, and planting for erosion control, stormwater drainage, and intended future uses.

Publicly available cost data for decommissioning utility-scale PV plants are limited. Major variables include contractual or other obligations, foundation type and size, site restoration requirements, labor rates, machinery costs, and quantity and value of salvageable materials and components such as steel and copper and cables and inverters. The approach to managing ex-service modules also has a significant impact.

EPRI published a 2018 preliminary conceptual cost estimate for decommissioning a representative 11-MWAC PV plant as of December 2017.<sup>5</sup> The estimate relies on numerous assumptions, including landfilling of spent modules. As shown in Figure 2, the negative net value of decommissioning is estimated as \$83/kW<sub>AC</sub>, which corresponds to 4.8% of the system’s installed cost of \$1727/kW. Labor and subcontracting costs associated with dismantling the solar field were the primary contributors to the overall cost estimate, while module transportation and disposal at a conventional landfill accounted for about 10%.



Scrap value of copper and steel: \$34/kW<sub>AC</sub>

Figure 2 - Decommissioning cost breakdown for a 11 MW<sub>AC</sub> power plant, assuming modules are landfilled<sup>5</sup>

The scrap value of recoverable steel and copper reduced the cost of decommissioning by about 25%. Inclusion of salvage value for inverters and other electrical components could provide further cost savings. Selling or donating aged modules into secondary markets, paying to recycle modules, and being required to dispose modules as hazardous waste are among the possibilities that could change this conceptual cost estimate.

### Module EOL: Sources and Causes

Most U.S. utility-scale PV installations fall into the early- or mid-life period of a typical 20- to 30-year operating lifetime. Starting around 2030, these projects will drive growth in decommissioning and the development of a module collection and recycling industry as they reach EOL, just as they once accelerated deployment and the maturation of a supportive chain of PV installers, equipment suppliers, and service providers.

Today, large PV plants hit by extreme weather—hurricanes, hail storms, tornados, and other natural disasters—represent a significant U.S. source of EOL modules. Individual weather events can create the need to manage thousands of damaged modules. Vandalism generates irreparably damaged modules on a scattered and very modest basis. Relatively small U.S. installations from the 1990s that are reaching retirement age are another source of EOL modules. Plants with modules experiencing early failure or significant performance degradation represent a growing source.

Modules can be damaged during transport, handling, and installation and during operations and maintenance (O&M) tasks such as washing and vegetation management. Production losses and failures

### Performance Assessment for Maintenance and EOL Decision-Making

Measured module, string, and plant performance is the best indicator of problems. Module- and string-level degradation can be quantified using current-voltage (I-V) and maximum power point (P<sub>MPP</sub>) curves (Figure 3). Performance measurement of individual modules is not practical for large PV installations, which generally do not employ module-level controllers such as microinverters or DC optimizers.

Infrared imaging by field workers or aerial vehicles is often used to detect potential safety hazards and identify suspect modules. Subsequent measurements can be limited to a subset of modules to monitor and assess degradation or damage. Ideally, the impact of underperforming or damaged modules is also examined at the inverter and plant levels, as shown in Figure 4, to assess the prevalence of performance issues and determine whether targeted maintenance including module replacement is an option to restore power.

All modules that pose a safety concern should be replaced. Some with known damage can continue to operate productively with small string-level performance losses. Ultimately, PV plant owners have the discretion to determine the safety or performance threshold at which to pursue module replacement, repowering, or full decommissioning.

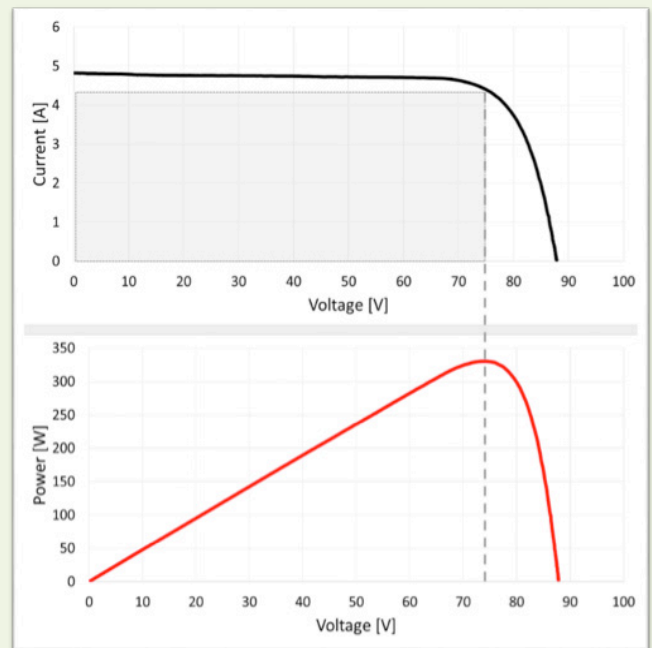


Figure 3 - Characterizing module performance using I-V and P<sub>MPP</sub> curves is essential to diagnosing and mitigating problems.

### Module Replacement: Holding Spares and Avoiding Mismatch

Creating a reserve by purchasing and storing extra modules at the outset of a PV project is a best practice for meeting occasional replacement needs when fielded modules fail. The availability of spare modules can avoid the challenge of identifying suitable non-identical replacements and the possibility of module mismatch leading to performance losses. When swapping out a single module within a string, solar O&M providers recommend choosing a higher-rated module from the same product series, if available. This ensures that the string is not current-limited by the new module. Replacement module selection should also account for possible degradation in string performance since the time the plant was commissioned.<sup>6,7</sup> If another module manufacturer or product must be used, considerations go beyond matching physical dimensions and mechanical properties. Electrical and especially current characteristics are critical. The maximum power point current ( $I_{MPP}$ ) should be within 10% of the existing modules, and the maximum power point voltage ( $V_{MPP}$ ) between strings should be less than 10% to ensure that the inverter stays within limits and continues to operate efficiently.<sup>7</sup>

of varying degrees of severity can occur during normal operation as a result of module defects and damage or service exposures such as thermal cycling. Both visible problems (Figure 4) and hidden damage modes can lead to failures. Additionally, in-service modules experience gradual performance degradation, typically between 0.5% and 1% of rated capacity per year—a rate that accumulates at aging plants even as new modules come to market offering much higher productivity per unit area.

Typically, PV module manufacturers support two kinds of warranties: (1) material defects and workmanship and (2) power and performance. Modules that exhibit defects stemming from manufacture or installation or that fall below an established performance threshold—for example, 1% annual degradation over 25 years—

may be eligible for replacement. Plant insurance policies can provide protection against severe weather or vandalism.

Module replacement costs are often undervalued and can present an unknown performance risk if not mitigated during project planning (see “Module Replacement” box, above). While modules may be eligible for replacement under manufacturer warranty claims, these arrangements typically only cover the cost of the modules. Labor costs to identify and remove failed modules, rearrange existing modules to electrically and physically accommodate new ones, and reinstall and recommission the plant as necessary are often the responsibility of the owner or operator. After weather damage, insurance may cover inspection and all other associated costs once the deductible is met.

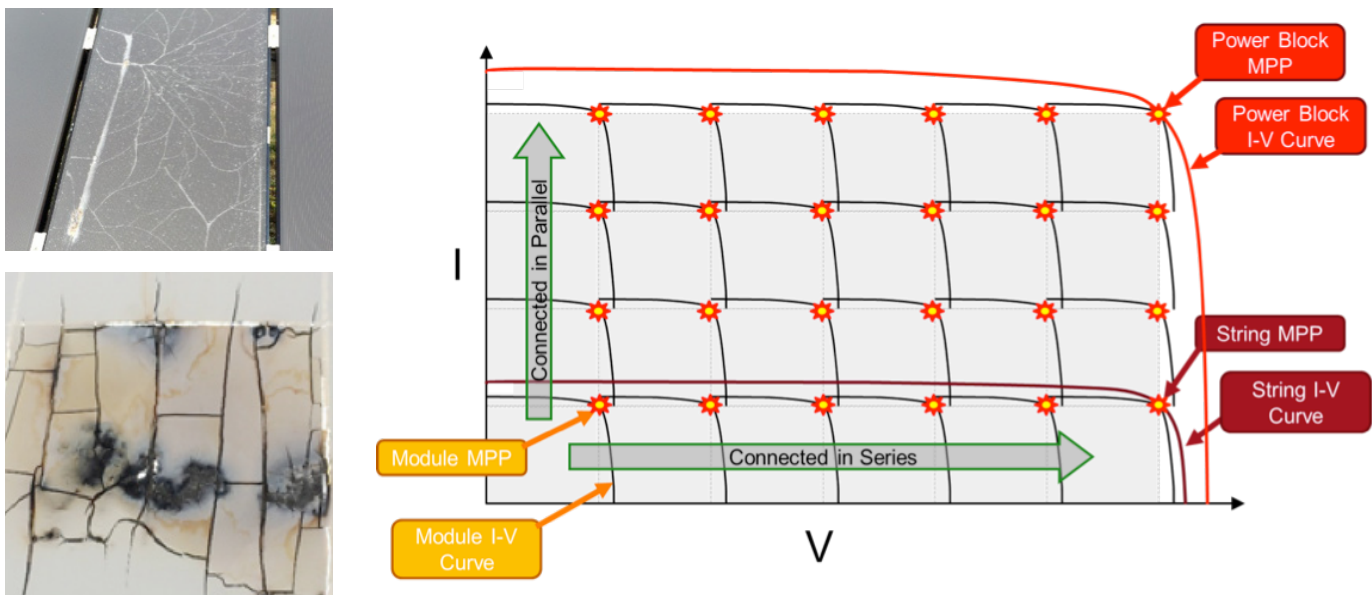


Figure 4 - Structural damage, such as a shattered glass (left, top) and backsheet burning due to a hot spot (left, bottom), provides visual evidence of module failures. The larger impacts of module- and string-level performance issues can be examined by sampling I-V measurement points (right) within a PV plant power block. (Photo Credit (lower left): Southern Company)

## Module EOL: Reuse, Recycling, and Disposal

Figure 5 presents a simple decision tree for ex-service modules. Depending on performance, operable modules may generate revenue or a tax savings if sold or donated for reuse in second-life applications. Manufacturers with take-back programs accept modules regardless of condition, generally at low or no cost. These are the preferred options, both economically and because the PV project owner is freed of EOL responsibility.

Alternatively, module recycling and disposal may impose significant economic and environmental costs. Before accepting modules for processing, U.S. recycling and disposal companies and facilities typically require information about module composition and may request results from waste determination tests such as the US Environmental Protection Agency’s (EPA) Toxicity Characteristic Leaching Procedure (TCLP). Some older modules are known to exceed the TCLP test standard of 5 mg/L for lead (Pb) due to the high levels of solder used.

PV module collection and recycling infrastructure is not well established in the United States, challenging plant owners with responsibility as waste generators. At the time of this writing, module recycling is occurring on a limited basis, and there are no known U.S. reports of PV modules being turned away by recyclers due to TCLP results.

### PV MODULE EOL DECISION TREE

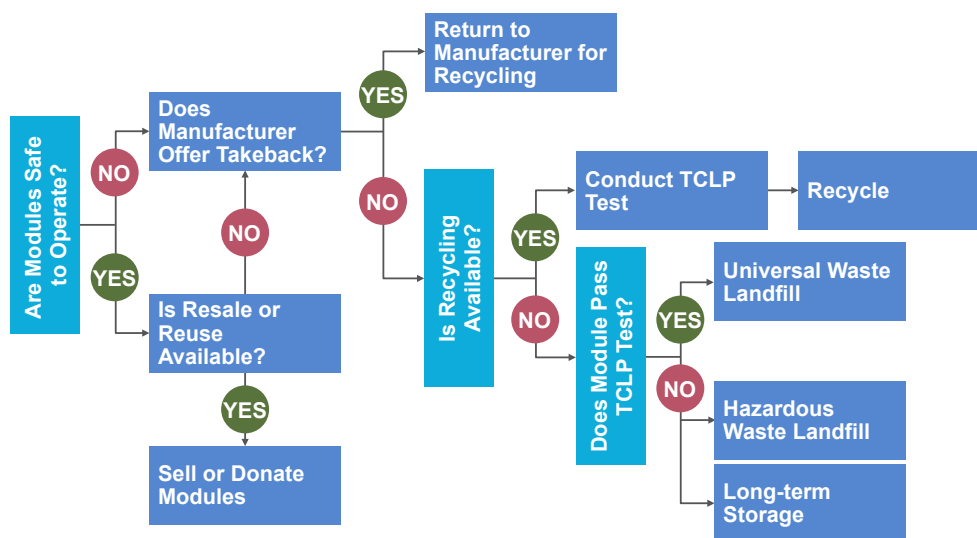


Figure 5 - Decision process for EOL PV modules

If recycling is not available or is not a viable option, test findings determine whether modules are suitable for conventional landfill disposal or must be managed as hazardous waste under the Resource Conservation and Recovery Act (RCRA). EPRI research conducted in 2017-18 indicates that differences in TCLP sampling methods and in locations sampled within the module, as well as lab-to-lab variations, can result in greater than 50% variability in analytical results—an uncertainty with potentially significant implications. U.S. experience includes both conventional landfilling and the management, treatment, and disposal of modules as hazardous waste.

## Effects of Module Composition and Construction

The materials and methods used in fabricating PV modules have important influences on EOL options and impacts. Exact compositions are highly proprietary, and no requirements exist on labeling modules for the presence of any particular set of materials. Installed PV modules typically pose no health risks unless they break and leach toxic materials.<sup>8</sup> Figure 6 provides cross sections of leading module technologies.

For crystalline silicon (c-Si) modules, the typical composition by weight is glass (>75%), aluminum (Al) (about 8%), polymers (about 10%), silicon (Si) semiconductor (3%), and copper (Cu) interconnectors (1%). Lead (Pb) solder content is typically less than 0.1% today. Silver (Ag), the most valuable material, is less than 0.01% by weight. Other trace metals such as tin (Sn), antimony (Sb), and beryllium (Be) may also be present.

Cadmium telluride (CdTe) modules are of frameless construction and offer the intrinsic advantage of employing PV cells deposited as thin semiconductor films. More than 90% of module weight is glass,<sup>9</sup> with polymers representing the largest remaining fraction. The amount of Cd and Te has declined over time with advances in manufacturing driving down semiconductor use and production cost: Older modules may contain

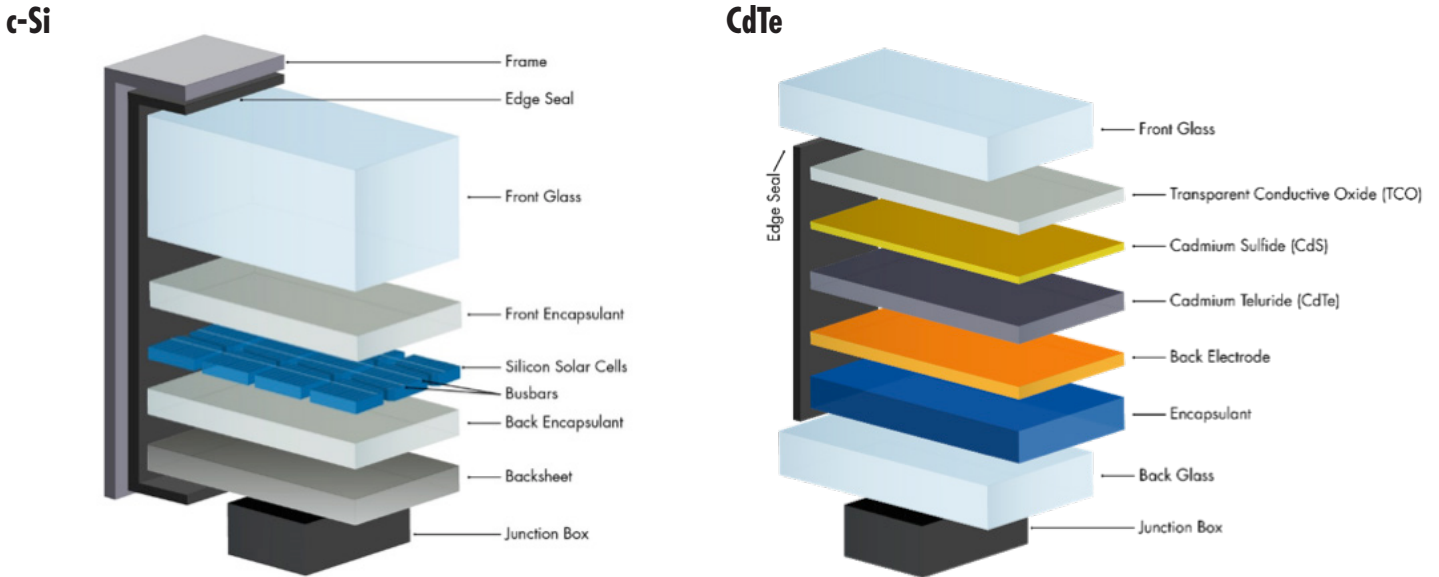


Figure 6 - Heterogeneous cross-sections of c-Si module (left) and CdTe module (right)

about 0.05% Cd and 0.06% Te by weight,<sup>10</sup> but today’s modules may only have 0.004% of each of these constituents.<sup>11</sup>

Some PV modules contain small amounts of hazardous materials other than Pb or Cd, including polybrominated diphenyl ethers (PBDE) and chromium (Cr).<sup>3,8,12</sup> The main environmental concerns associated with module disposal in landfills are (1) leaching of toxic elements from broken modules caused by exposure to rainfall or other liquids, (2) loss of conventional resources such as Al and glass, and (3) loss of rare materials such as Te, Ag, indium (In), gallium (Ga), and germanium (Ge).<sup>13</sup>

In the EU, PV modules currently are exempt from Directive 2011/65/EU, known as the Restriction of Hazardous Substances (RoHS 2), which limits content of Pb and other toxic substances in many electrical products. According to the International Technology Roadmap for Photovoltaic (ITRPV), use of Pb-free pastes is anticipated by 2019-2020 in anticipation of the next RoHS 2 review scheduled for July 2021.<sup>14</sup> Changes like this are critical for managing EOL impacts and risks.

The construction of PV modules that are designed to withstand 30 years of outdoor exposure can make it challenging for recyclers to separate and recover materials with high purity. The frame and junction box typically can be removed cleanly, but module layers are tightly packaged within encapsulant and edge seals that make

complete materials separation difficult. Residuals typically include a blend of polymer film and metal foil materials that may be incinerated for energy recovery.

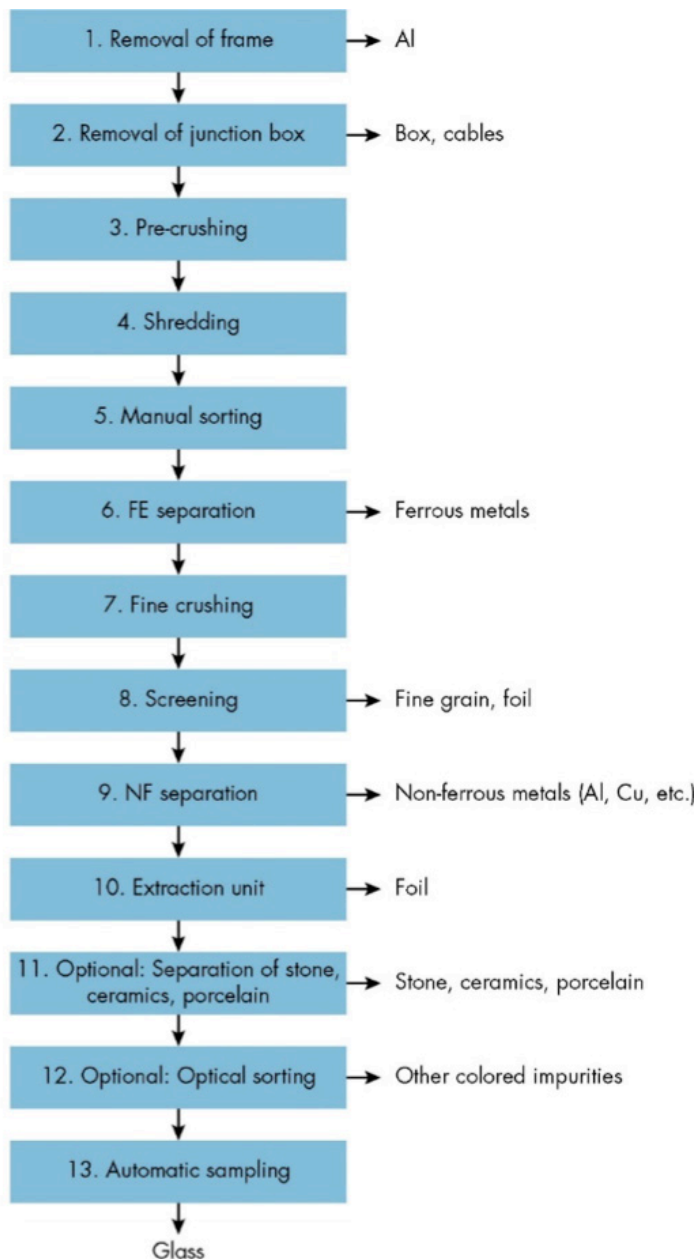
## Recycling Practices in Mature Markets

Manufacturers commonly recycle solar-grade semiconductor materials (see “Recycling” box, p. 10). EOL PV module recycling is primarily available in mature PV markets, such as the EU and Japan. More than 40 recyclers around the world—most of which are located in Europe—claim to process PV modules or subcomponents such as wafers, cells, and junction boxes. However, some recyclers prefer not to process CdTe modules due to concerns about Cd content.

The state-of-the-art process for recycling c-Si modules today is mechanical treatment in laminated glass recycling plants. A survey of European recyclers by EPRI and the U.S. National Renewable Energy Laboratory (NREL) revealed that existing commercial glass and metal recycling plants typically process modules in discrete batches on a periodic basis due to low volumes.<sup>15</sup> Plant capacities are often on the order of 200,000 tons per year, suggesting ability to accommodate rising volumes over time. The equipment used and the process steps can vary somewhat across different plants, as can the yield and the quality of the output.

Laminated glass recycling facilities are typically equipped with crushers, magnets, sieves, eddy-current devices, inductive sorters, optical sorters, and dust collection systems, as indicated by the flow diagram in Figure 7 below. Almost no additional investment in a standard process line is required to separate the module into its main components, as materials are culled from an increasingly pure glass fraction. Metal recycling facilities also can be used to process modules over lines designed to deliver high levels of Al and Cu recovery as shown in Figure 7, below right.

**c-Si Module Processing: Glass Line**



**Recycling by Cell and Module Manufacturers**

Today, only 30 to 50% of solar-grade Si (SoG-Si) feedstock is ultimately used in multicrystalline Si wafers.<sup>16,17</sup> Treatment and reuse of PV waste from cell and module manufacturing processes thus are established practice. Current technology development focuses on increasing the amount of Si that is recovered and recycled as the industry transitions from slurry-based wafer sawing to diamond wire sawing.<sup>14,18</sup>

Larger pieces of scrap SoG-Si from ingot side cutting, along with broken wafers and cells, may be melted and recrystallized into new Si ingots after cleaning and etching processes are applied to remove impurities.<sup>14,19</sup> Advances in this process are applicable for recovering SoG-Si during EOL recycling. However, ingot top-cut scraps that contain metal impurities and Si kerf, the fine powder produced during the wafer sawing process, are usually not reused.

**c-Si Module Processing: Metal Line**

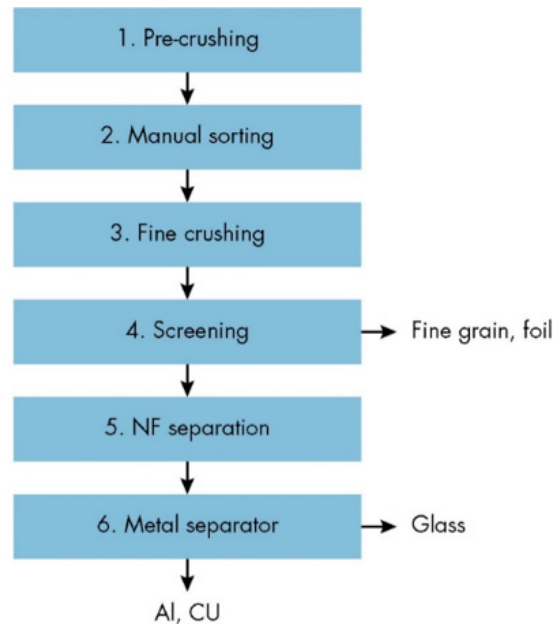


Figure 7 - Current state-of-the-art mechanical recycling processes for c-Si PV modules by glass recycler (left) and metal recycler (right)

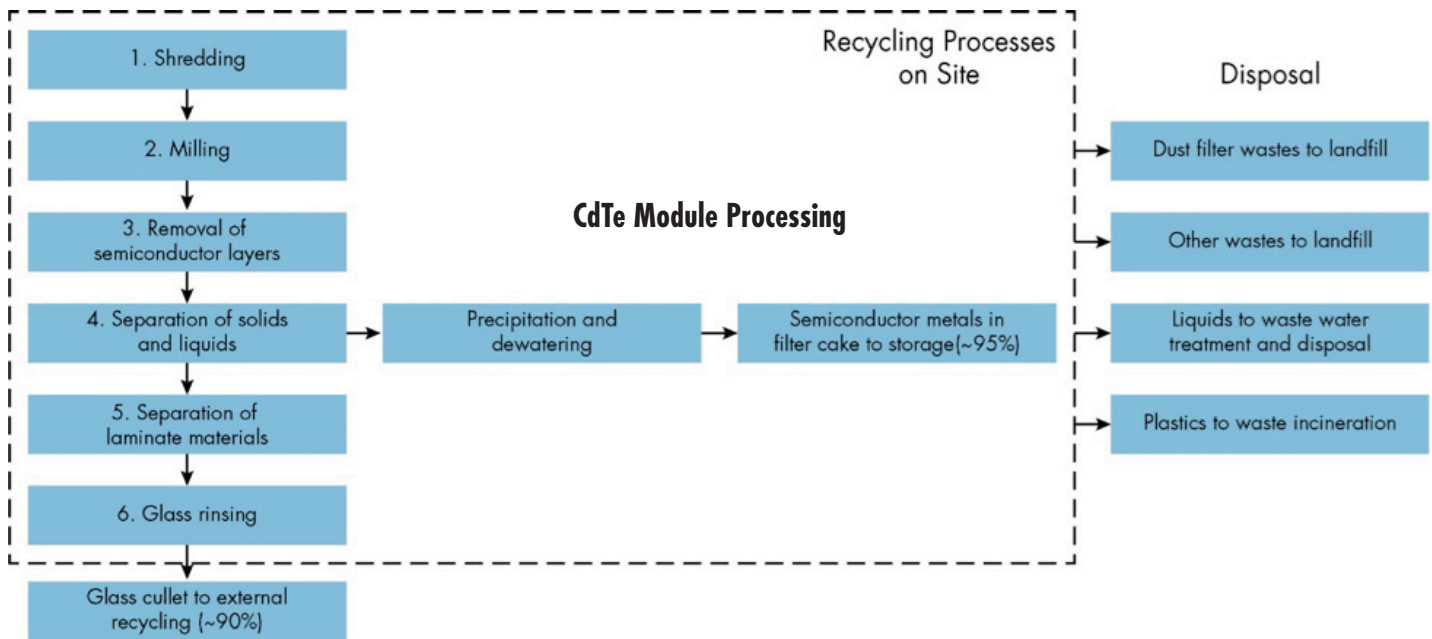


Figure 8 - Current state-of-the-art mechanical recycling process for thin-film CdTe PV modules (redrawn by EPRI)

Commercial glass and metal recycling lines are capable of achieving materials recovery rates by weight of 75 to 90% from c-Si modules.<sup>2</sup> Higher rates of materials recovery generally correspond to higher rates of energy consumption, a process tradeoff illustrated in Figure 8. Glass cullet can be used as a feedstock for foam or fiberglass production, while metals can be sold to smelters for reuse. However, recovered materials are of varying quality, which may or may not be suitable for all secondary markets. Residual foils coated with metal and solar cell materials can be fired for energy recovery or landfilled.

Recycling of CdTe modules is primarily performed by manufacturer First Solar as part of its take-back program. Whereas c-Si recycling typically begins with crushing modules to facilitate the removal of frames and junction boxes, frameless CdTe modules are shredded as a first step (Figure 8). After crushing in a hammermill, chemical processes are used to dissolve and isolate the semiconductor material from the glass fraction. In addition to glass recovery of about 90%, approximately 95% of the Cd and Te is recovered and then stored as a semiconductor-enriched filter cake prior to further processing for reuse in new modules.<sup>9,20</sup>

Recycling processes specifically optimized for module waste will result in more complete and efficient materials recovery but are only beginning to emerge (see “Novel Recycling Processes” box, p. 12). Europe’s first dedicated PV recycling facility, which opened in July

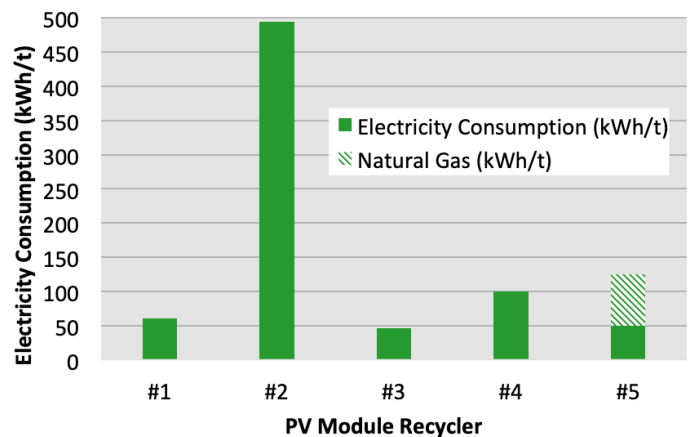


Figure 8 - Energy consumption in recycling: Achieving higher yield and purity in output streams, as reported by Recyclers #2 and #5, corresponds with greater energy inputs.<sup>15</sup>

2018 in southern France, is expected to process 1800 metric tons of c-Si PV waste in 2018 and to increase capacity over time to 4000 metric tons/yr. Owner-operator Veolia claims a materials recovery rate of 95%.<sup>21</sup> In anticipation of increasing waste volumes, several other major resource management companies also are evaluating the PV market, and research- and pilot-stage module recycling activities are being pursued by a range of organizations. At present, the highest reported recycling rate in a demonstration project is 96%.<sup>2</sup>

### Novel Recycling Processes

NREL reported that at least 178 patents have been filed worldwide related to PV recycling,<sup>22</sup> but a recent literature review revealed a much smaller number of organizations actively pursuing commercial technologies. Most innovations are aimed at boosting materials recovery and purity — particularly of Ag and SoG-Si — while reducing cost, achieving low energy consumption, and minimizing the volume and risk of residual materials. Recent innovation scouting by EPRI identified novel mechanical, optical, chemical, and thermal processes — and combinations — at all R&D stages.<sup>23</sup>

### Advanced Recycling Process

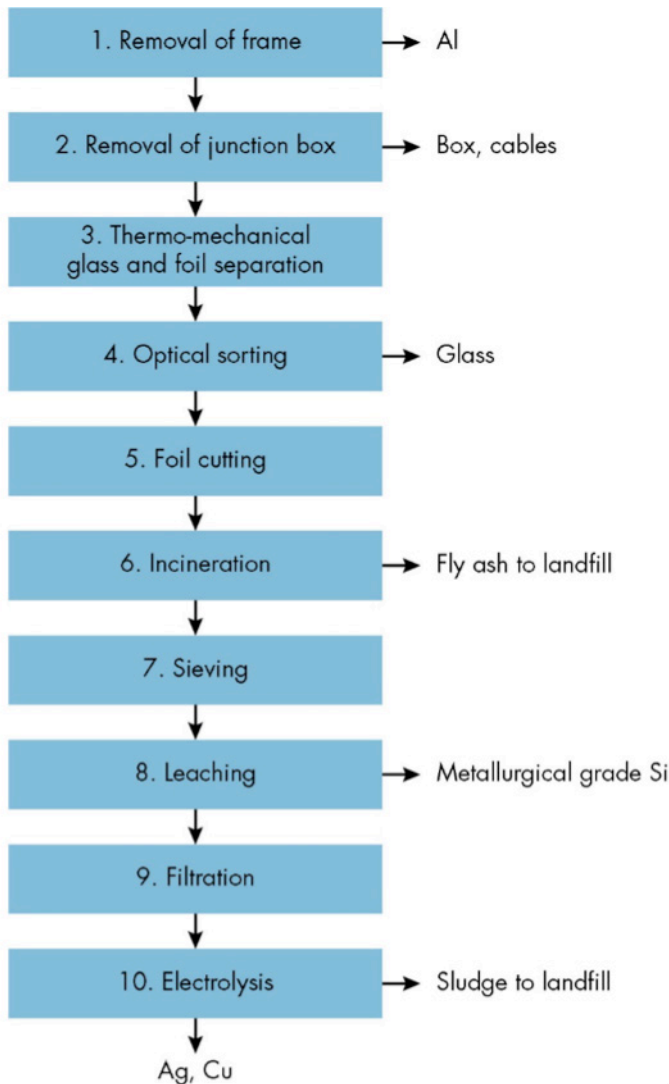


Figure 10 - Pilot-scale recycling system demonstrated by Sasil

Arizona State University (ASU) researchers recently reported the capability to isolate whole PV cells (Figure 9). Many delamination and separation concepts aim to keep the front glass intact. Avoiding breakage slightly increases the recovery value of the glass and dramatically improves the recovery of metals and semiconductor material.

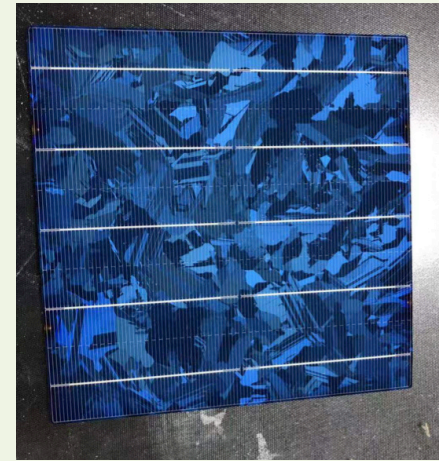


Figure 9 - Whole cell removed via cutting demonstrated by ASU (Photo Credit: TG Companies LLC)

Some innovations apply thermal methods for softening encapsulants or incinerating encapsulant layers at high temperatures (400-600°C). Mechanical means to remove the semiconductor from the top glass after heating include use of suction cups under vacuum and a spinning steel brush that produces a fine semiconductor powder. An alternative delamination approach that does not require preheating wedges a heated blade between the glass and semiconductor layers to drive them apart.

Leaching, filtration, melting, electrowinning, and electrolysis are some of the promising methods being explored specifically to improve the yield and quality of recovered metals. Automating frame removal and other aspects of the recycling process is another active R&D topic, as a means of reducing labor costs.

Sasil S.r.l — one of the respondents to the EPRI-NREL survey — developed and tested a pilot facility in Italy incorporating several innovations.<sup>15</sup> Per Figure 10, the process included an initial thermal stage to soften the encapsulant and applied a vibrating knife to separate polymer material from glass. High-quality glass was recovered via optical sorting, and the remaining material was cut up and then incinerated to eliminate the polymer. The metal/semiconductor fraction was processed via sieving, leaching, filtration, and electrolysis steps to separate out Si and allow high levels of Ag and Cu recovery. Approximately 92% overall materials recovery was demonstrated. Residuals included small amounts of fly ash and metal hydroxide sludge. Glass, Si, and metals (including Ag) were recovered at a rate of 99.8%.

## U.S. EOL Requirements and Developments

The necessary policies and technologies for recycling PV systems are under rapid development in Europe and other maturing PV markets. The best known is the 2012 European WEEE directive (WEEE 2012/19/EU). Take-back and recycling of PV modules are mandatory under WEEE and being performed in small but annually increasing quantities. The PV CYCLE Association was developed to implement this directive, guiding implementation of integrated collection, storage, and recycling infrastructure (Figure 11).

No federal regulatory framework for PV recycling exists in the United States. RCRA regulates disposal of hazardous and non-hazardous waste of all types. Ex-service modules are the responsibility of the project owner as the waste generator. A waste object, such as a PV module, is considered hazardous if it does not meet concentration limits when tested using EPA's TCLP method 1311.

California and Washington are the first states to pass legislation and implement module management programs. California enacted Senate Bill 489, which authorizes the state's Department of Toxic Substances Control (DTSC) to change the classification of EOL modules identified as hazardous waste to universal waste. The intent is to allow modules to be handled and transported within and out of the state in order to facilitate recycling. The legislation will not take effect until the U.S. Environmental Protection Agency (EPA) authorizes hazardous waste modules in California as an additional universal waste category, and the California EPA and DTSC subsequently propose and approve relevant regulations. Until then, ex-service modules in California that do not meet TCLP test limits must be managed as hazardous waste.

The state of Washington passed Senate Bill 5939 in 2017, which directs the state Department of Ecology to create and manage a PV Module Stewardship and Takeback Program. This bill mandates "a convenient, safe, and environmentally sound" system, financed by manufacturers, to recycle all modules purchased for use in the state after July 1, 2017. The take-back program is scheduled to begin in 2020. Other states, including Minnesota and New York, have related regulatory actions pending or are considering actions.

As regulatory mechanisms emerge, tools to support PV module EOL management are becoming available. The new standard NSF/ANSI 457 "Sustainability Leadership Standard for PV Modules," published in December 2017, establishes product performance criteria and corporate performance metrics for the PV module sup-

ply chain.<sup>24</sup> Manufacturers get credit for responsible EOL management, along with other sustainability categories like water use, design for recycling, life-cycle assessment, and energy management.

The Solar Energy Industries Association (SEIA) is sponsoring a PV recycling program designed to bring PV system owners together with manufacturers and vendors to develop an integrated module collection and management infrastructure. The program, open only to SEIA members, promises aggregated pricing from vendors, access to improved recycling processes, and the tracking of waste volumes over time.<sup>25</sup> Participants must report their module waste volumes to SEIA and the other group members.

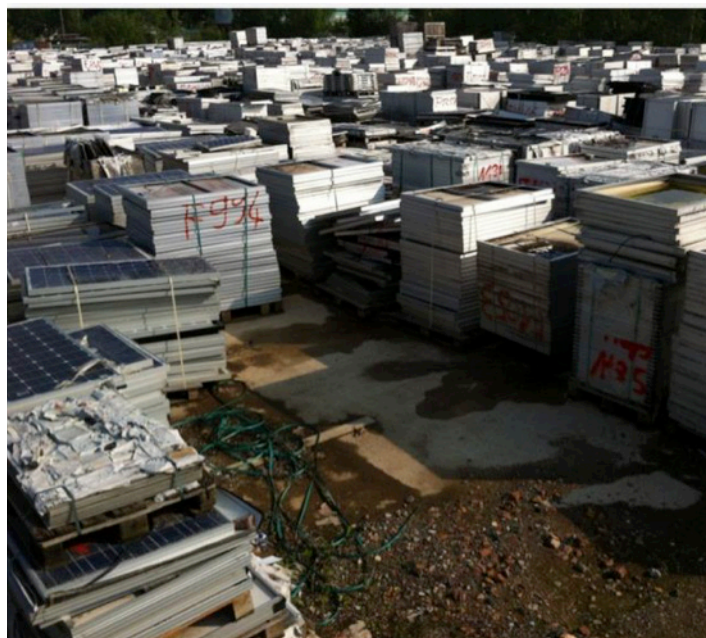


Figure 11 - Spent PV modules stacked on pallets for storage prior to EOL processing<sup>26</sup> (Photo Credit: Wolfram Palitzsch)

## U.S. Module EOL Practices

To assess the current state of the art, EPRI identified almost a dozen companies that claim to accept and recycle PV modules in the United States. These companies, listed in Table 1, were invited to participate in a survey to ascertain details about the types and quantities of modules accepted, recycling processes employed, testing requirements, pricing, and R&D needs. First Solar, leading manufacturer of CdTe modules and early adopter of a corporate EPR policy, is the only company that responded. EPRI also contacted waste management companies, landfill operators, and hazardous

### U.S. Utility Experiences and Insights

- PV plant owners desire module EOL options they can justify based on cost, as well as environmental stewardship. Second-life markets offer a number of opportunities for turning ex-service modules that are still producing into an asset rather than a liability.
- Recycling costs exceed the costs of disposing modules as hazardous waste. Domestic recycling capacity is limited, both in the number of facilities and in the volume of modules that can be handled at a given time. Shipping modules for processing overseas is a recent option offered at lower cost but with uncertain sustainability.
- Outside California and Washington, spent and damaged modules pose an uncertain management challenge. Even in instances where manufacturers say that modules do not even contain lead, TCLP tests can indicate unacceptable levels, especially for older models.
- The lack of standardized sampling methods for module TCLP testing challenges hazardous waste determinations. Samples obtained from the same module can produce very different TCLP results, depending on where the sample is taken, the cutting approach, the amount of crushing, and the laboratory that performs the testing.
- If a given module model fails the TCLP test, entire PV plants could be classified as hazardous waste generators, imposing substantial costs plus challenges and limitations in performing routine O&M tasks.
- Purely on a cost per ton basis, landfilling represents an attractive option for modules that pass the TCLP test. Long-term sustainability is uncertain given the limited space in landfills and current and future levels of PV penetration.
- Utilities want guidance so that they know how to comply and can plan appropriately. For example, federal designation of modules under the scrap metal recycling exemption, as is the case for printed circuit boards, could allow e-waste classification, ensuring recycling while avoiding the need for a universal or hazardous waste designation.
- Ex-service modules from residential and commercial PV systems are likely to end up in landfills unless programs to collect and recycle these materials are put in place.

waste management facilities regarding their experiences, if any, in the handling of PV modules. Interviews addressed waste acceptance, waste characterization and toxicity testing requirements, processing and disposal practices, and transportation costs and tipping fees. In addition, EPRI member utilities with PV projects and fleets were

asked to describe practical experiences with EOL modules, provide business insights, and identify priority needs and concerns regarding planned and operational plants and older facilities approaching the end of their useful lifetime (see “Utility Experiences” box above). Finally, two longtime U.S. installers were interviewed to capture module EOL perspective based on decades of small-scale project development and maintenance experience.

**TABLE 1 - SAMPLE LISTING OF U.S. RECYCLING PROVIDERS**

RECYCLER	LOCATION
Dynamic Lifecycle Innovations	Santa Clara, CA
First Solar	Tempe, AZ
Metal & Catalyst Resources	Houston, TX
Morgen Industries	Secaucus, NJ
Silrec Corporation	Lexington, KY
Solarsilicon Recycling Services	Ventura, CA
Tekoverly	Mount Vernon, NY
WRS Materials	San Jose, CA
Cleanlites Recycling	Spartanburg, SC
Interco Trading Company	Madison, IL
Green Century Electronics Recycling	Portland, OR

Reuse of ex-service modules represents a preferred option for U.S. plant owners, in that decommissioned panels with remaining useful life can be sold or donated to deliver solar energy in new applications while also transferring the waste generator responsibility through a letter of indemnification. Anecdotal reports indicate that decommissioned or damaged c-Si modules—numbering in the thousands from individual plants, often after major storms as shown in Figure 12—also have been recycled or landfilled, while smaller volumes have been managed as hazardous wastes. PV plant owners are challenged by the lack of uniform regulatory guidance, the potential for modules to be designated as hazardous waste, and the limited U.S. capacity for module recycling.

First Solar reports processing 14,000 metric tons of CdTe modules worldwide in 2017 across recycling facilities in Ohio, Germany, Malaysia, and Vietnam, with all providing shredding and recov-

ery of metals, semiconductor, plastics, and glass. TCLP and other applicable testing is performed depending on location. Within the United States and internationally, differences in waste classification pose administrative barriers to cost-effective recycling by complicating transport of EOL modules from the project site (e.g., California) to the recycling facility (e.g., Ohio).

Except in California and Washington, modules that do not fail the TCLP test can be disposed in Subtitle D landfills handling household and other non-hazardous wastes. According to landfill operators, the process typically would involve crushing, blending with other materials, and burial using heavy machinery. Some landfills do not accept wastes like PV modules, based on management plan or site assignment. Before making a decision to handle modules, other landfill operators indicated they would at minimum contact state agencies for guidance and ask the waste generator to provide a safety data sheet from the manufacturer. Individuals interviewed also acknowledged that not all landfills conduct due diligence.

Large waste management companies offering both hauling and landfilling services have rigorous intake procedures when contacted about materials like PV modules not found in typical municipal solid waste or construction and demolition debris. This commonly includes a requirement that the waste generator fill out a form and supply safety data sheets and other detailed information addressing the waste's chemical composition and regulatory status—specifi-

cally, whether it should be managed under RCRA or has known constituents or characteristics requiring special care. Results from TCLP testing, presented in a certified final report from a third-party laboratory, are requested. The form must be certified and signed by an authorized agent of the generator, under federal penalty for submitting false or incomplete information.

One company representative reported accepting a relatively small shipment of modules that passed the TCLP test but profiled as a special waste. Rather than being crushed, intact modules were placed in a trench and buried in a lined monofill area designated for difficult wastes. The modules were accepted—at a premium over the standard tip fee—because the volume was limited, was coming from an individual generator, and could be handled without major interference in routine operations.

If modules failing the TCLP test cannot be recycled, they must be shipped to a hazardous waste management facility under RCRA-prescribed tracking and handling guidelines. One company described shredding several pallets of modules, recovering recyclable metals, and using chemical and other treatment methods to extract Pb and other contaminants for microencapsulation of concentrated waste in polyethylene and disposal in a Subtitle C landfill. Another reported that hazmat modules would be placed in a dedicated pit, covered with a lime-like material for macroencapsulation, and then entombed.



Figure 12 - Hurricanes and other natural disasters are a significant current source of EOL modules. (Photo Credit: Eliza Hotchkiss, NREL)

## U.S. Module EOL Economics

Recyclers and waste management facilities were contacted via email and phone to determine current rates for processing or disposing bulk quantities of modules. Cost data were supplemented by information available in literature, particularly for the recyclers, none of which were willing to disclose their costs for module recycling. Generally, module EOL pricing is by unit or bulk weight, while transport is by volume. Table 2 provides an indication of the scale of the management challenge, depending on project size and module capacity, based on an assumed weight of 18.6 kg (41 lb) per module and transport in 40-cubic-yard (CY) dumpsters or 100-CY containers with an assumed 30% void (modules fill only 70% of volume).

### Disposal

U.S. waste disposal costs vary significantly by region, while module disposal costs depend critically on TCLP test results. Operators of Subtitle D landfills in various regions quoted tipping fees ranging from a low of \$26/ton to a high of \$89/ton for nonhazardous EOL modules comingled with other wastes. Quotes are consistent with regional data shown in Figure 13,<sup>27</sup> which also illustrates anticipated increases in tipping fees in the next several years. These figures do not account for the 2017 collapse in U.S. recycling markets—a factor already resulting in greater volumes of material being landfilled and expected to drive tipping fees even higher. They also do not reflect truck or rail transport costs, which have been on the rise, dampening any savings available from inter-regional waste shipping.

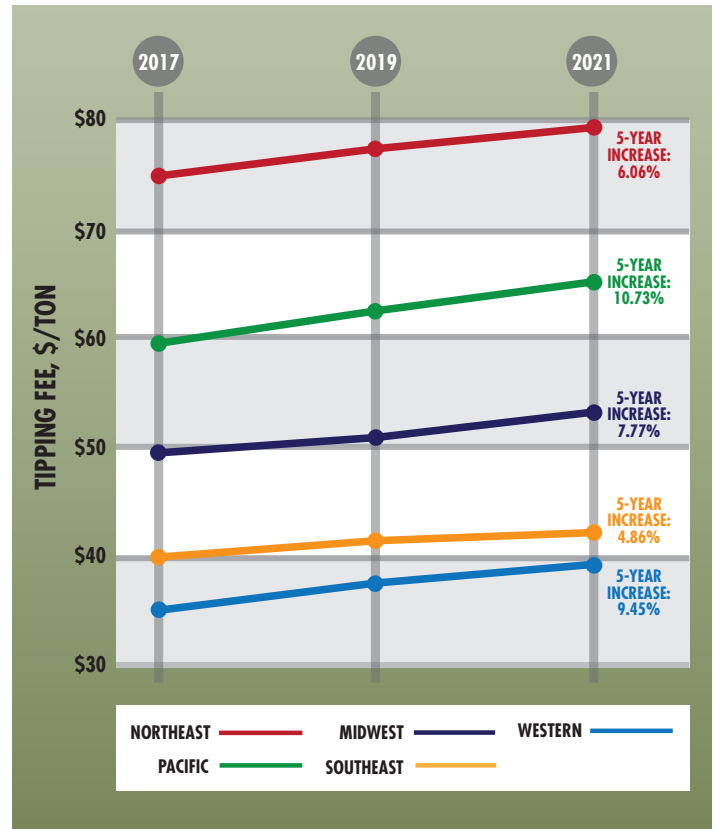


Figure 13 - U.S. waste disposal costs and projections <sup>27</sup> (redrawn by EPRI)

TABLE 2 - PV WASTE DATA

PROJECT SIZE	NUMBER OF MODULES		WEIGHT, US TONS (METRIC TONS)		NUMBER OF DUMPSTERS (40 CY, 30.6 M <sup>3</sup> )		NUMBER OF CONTAINERS (100 CY, 76.5 M <sup>3</sup> )	
	250 W	350 W	250 W	350 W	250 W	350 W	250 W	350 W
10 kW	40	29	0.82 (0.74)	0.59 (0.53)	-	-	-	-
1 MW	4,000	2858	82 (74)	59 (53)	11	8	4	3
10 MW	40,000	28,572	820 (744)	586 (531)	110	78	44	31
50 MW	200,000	142,858	4100 (3719)	2929 (2657)	549	392	220	157

Subtitle C facility operators estimated tipping fees of \$175/ton and up for accepting, treating, and landfilling bulk quantities of EOL modules designated as hazardous wastes, with the minimum tonnage requirement equivalent to hundreds of kilowatts of PV capacity. These figures do not include the significant costs of manifesting and transporting hazardous wastes. Additionally, one operator reported charging a per-module disposal fee of \$500-\$600 to handle and treat a couple pallets of modules containing high levels of lead and other RCRA contaminants, due to the small batch and need for multi-stage treatment.

**Recycling**

Limited information about PV recycling costs has been published. Anecdotal information shared by PV plant owners indicates that the bulk rate charged by U.S. recyclers is on the order of \$25 to \$30 per module. The effects on pricing of factors such as shipping distance and module condition, type, and composition—including both

high-value materials as well as toxic content revealed by TCLP test data—are uncertain.

Figure 14 provides a rough comparison of the relative cost of U.S. EOL options on a per-module basis. Reused modules can generate positive cash flow. Recycling comes at a cost, but recovered materials reduce net impacts. Landfilling is relatively inexpensive, while hazardous waste disposal costs depend strongly on volume.

The price paid to recycle only addresses a portion of module EOL economics, in that processing creates marketable commodities. A literature review revealed a wide range in the potential value of EOL modules, estimated based on the salvage value of recoverable materials. Each recycling approach has a unique recovery rate and purity level for individual materials. Additionally, the bill of module materials is changing over time. Using projections of PV waste growth and assumptions about materials recovery from IEA and IRENA,<sup>1</sup>

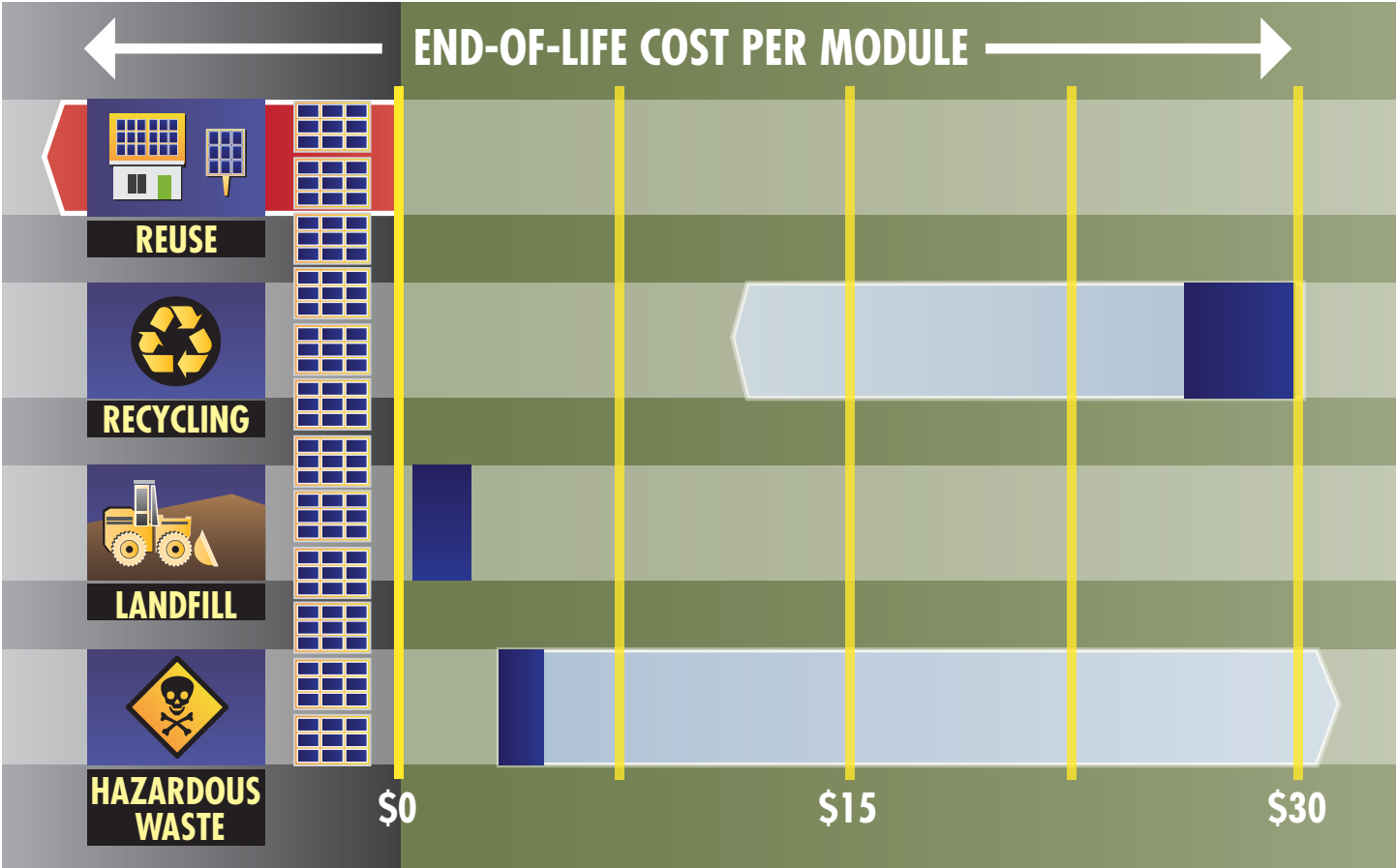


Figure 14 - Reported cost ranges for recycling or landfilling spent modules or disposing of them as hazardous waste are shown in dark blue, while light blue indicates potential to recover value through recycling or to face higher hazardous waste management costs. Reuse has potential to deliver negative costs – and net economic and environmental benefits.

EPRI estimates that the value of raw materials only may be on the order of \$5/module in 2030.

Developers of novel recycling processes at ASU claim to be able to increase this value to \$54/module by achieving higher materials recovery—including intact c-Si cells—and purity above 99%.<sup>28</sup> This projection greatly exceeds estimates developed by the European consortium CABRISS, which focuses on implementation of a circular economy based on recycled, reused, and recovered In, Si, and Ag materials for PV and other applications. The CABRISS estimate is 13.4 euros/module (approximately \$15.50/module), where most of the value is derived from Al, Si, and Ag.<sup>29</sup>

While the economics of PV recycling are expected to improve as waste volumes grow and dedicated processes are employed, evolving module compositions may prove challenging in the longer term. Specifically, as manufacturers drive down costs in new PV modules by reducing the amount of valuable materials, the salvage value of the recyclables will also decline. Fluctuating resale prices of recoverable materials are another source of uncertainty.

## R&D Needs

EPRI has identified a number of R&D needs and opportunities, based on previous studies as well as input from utility, PV, and waste management industry representatives. Ongoing EPRI work is highlighted in the box on p. 20.

**Plant Decommissioning.** Real-world PV plant decommissioning studies are needed to document experiences and costs in order to help reduce risks during the project development process and as existing plants approach the end of their useful lifetime. Work may include time-and-motion studies for multiple PV plant decommissioning events to benchmark current process durations and costs. This could help in identifying opportunities for cost savings and process optimization in task areas such as removing modules, dismantling mounting and racking structures, and stacking and transporting modules.

**Module Design for Recycling.** Module manufacturers have already introduced frameless modules and lowered the use of Ag and Si, which reduces materials loss at EOL, and of Pb and other potentially hazardous contaminants, which lowers EOL risks. To improve recyclability, researchers are developing new module designs that offer easier dismantling and rapid recovery of high-purity materials with less waste. Others are looking at ways to avoid use of encap-



Figure 15 - Water-jet extraction module core samples (top); and strip-cutting sampling process (bottom) (Photo Credits: ASU)

solants. For example, Apollon Solar has developed a vacuum-sealed glass-glass construction for making connections between copper ribbons and cell busbars.<sup>30</sup> Multiple research efforts are investigating use of recycled material in the fabrication of new modules and other products, such as NREL's Circular Economy initiative and the European CABRISS collaborative.

**Recycling Processes.** Automation technologies for removing frames are being developed, and various mechanical, thermal, and chemical recycling processes—and combinations thereof—are being explored and advanced to increase recovery and purity and drive down recycling costs. Demonstrations of PV-specific techniques that can be applied to existing glass and metal recycling lines or demonstrated as standalone processes in dedicated module recycling facilities



Figure 16 - Mechanical coring process setup (Photo Credit: ASU)

are needed to verify materials recovery rates and quantify energy inputs and environmental and human health impacts. For emerging recycling methods, proof-of-concept testing, equipment prototyping, emissions testing, modeling, and other steps may be required before processes can be scaled up and demonstrated. Economic and environmental analyses will then be needed to compare with existing processes.

**Module Toxicity Testing.** Continued research into module leaching characteristics is needed, particularly in understanding how to minimize variation in TCLP results for Pb and other materials that may be present, such as Sn, Zn, Cd, Se, In, Ga, and others. EPRI research indicates that differences in sampling methods—for example, using water jet extraction, strip cutting, or mechanical coring

approaches shown in Figures 15 and 16—and lab-to-lab variations can result in greater than 50% variation in TCLP results. Another challenge is that the leach test methods and protocols used for classifying modules as hazardous or non-hazardous waste were not designed for PV applications. The test environment is not representative of landfill conditions, and leach test analytes (arsenic, barium, Cd, Cr, Pb, mercury, Se, Ag) do not overlap with all potentially hazardous materials in PV modules.

Stakeholders can support research into PV module leach testing through participation in an EPRI supplemental project<sup>31</sup> and/or by providing modules for testing. Development of standards for PV module sampling is a first step toward ensuring spent modules are characterized properly when they are taken out of service. The broader industry need is for manufacturers to have responsibility for ensuring that modules do not contain toxic levels of hazardous materials in the first place. The new ANSI/NSF sustainability standard is a step in that direction.<sup>24</sup>

**Module Replacement Compatibility.** Modeling and field testing is needed to understand options and considerations for reconfiguring plants with replacement modules. EPRI plans 2019 studies to shed light on the following questions:

- Based on the rating of new modules relative to existing ones within a single string, what is the maximum number that can safely be replaced? At what point does it make sense to replace an entire string to avoid module mismatch?
- Can module-level power electronics be installed on replacement modules to avoid electrical mismatch? If so, how would the output of these devices be combined with the rest of the system?
- What is the ideal arrangement of existing and replacement modules? If a system has shading, can higher-power replacement modules be positioned in the shaded area to minimize mismatch?
- What are the long-term effects of module replacement? Does a replacement with a higher power rating experience greater thermal stress, and therefore faster degradation, due to forced under-performance by limiting current? Does the expected higher operating temperature of the replacement have any implications for original modules in the string?

**Module Degradation Research.** More research is needed to quantify how changes in various electrical parameters influence long-term module performance degradation and reliability. In 2018, EPRI is completing a DOE-funded PREDICTS2 project that provides insights into how accelerated aging tests correlate to degrada-

## EPRI R&D on PV EOL Management

**Module Recycling Scouting.** Innovation scouting activities related to PV recycling include primary research, collaborations with technology developers and R&D groups, and pursuit of government and other funding opportunities. In 2019, the anticipated scope includes review of PV modules designed for ease of recycling, novel recycling technologies and processes, and recycling economics, including processing costs and materials recovery values.

**Module Replacement/Repowering Study.** In 2019, EPRI is pursuing a combination of experimental and simulation work to examine specific PV plant retrofit scenarios. The experimental work will likely be performed on one or more arrays deployed at EPRI's test plot at SolarTAC in Aurora, CO (Figure 17). The study may include replacement of one or multiple modules within a single string or multiple strings in parallel, plus use of replacement modules with different power ratings. Modeling will include an investigation of existing PVLIB modeling library offerings to simulate individual module I-V curves and dynamics and validate the output with field data. The expected outcome is a set of best practices for module replacement.

**Module Toxicity Testing.** Initial module TCLP testing was performed at ASU in 2017-2018 through EPRI's Technology Innovation (TI) Program. For a relatively small number of module samples, Pb was the key element of concern. Large variations (>50%) in Pb content were observed, often exceeding thresholds for non-hazardous landfilling. Variations were due to differences in sampling approach—including cylindrical cores, entire cells, and mechanical vs. water-jet cutting—and the portion of the module that was sampled (cell area, non-cell area, and string ribbon). Glass tempering and the degree of sample crushing also impacted results. Additionally, variations in results were observed across laboratories that conducted testing on identical samples. In 2019, a new EPRI supplemental project (3002014825) will further explore PV module sample extraction

and preparation methods and also investigate TCLP result variations due to differences in module manufacturer, manufacturing process, design, model number, and production batch.

**Effect of Cell Cracks on Module Power Loss and Degradation.** In 2018, EPRI was awarded a \$1.1M project, through NREL's DuraMAT Consortium, to investigate the relationship between cracks in PV cells and module power loss and degradation rate. Tasks include finite element modeling, field performance assessment of large-scale PV plants, small-scale outdoor field and accelerated lifetime testing, and the use of multiple advanced imaging techniques, automated image processing, and data analytics. EPRI will work with NREL, LBNL, and Southern Company to produce results that enable:

- Determination of crack thresholds for PV plant commissioning and O&M,
- Improved warranty and insurance contracts to ensure optimal plant performance,
- Relevant qualification test procedures,
- Improved simulation capabilities around module reliability and durability as they relate to cracks and metal fatigue, and
- Enhanced predictive modeling of the propensity for cracks to lead to performance problems in new module designs.

**Review of Regulations and Certification Programs.** EPRI is conducting a review of regulations and certification programs, including a literature review and interviews with key stakeholders. In 2019, a technical brief will be published including information on current federal- and state-level regulations and policies plus relevant certifications from organizations such as the International Organization for Standardization (ISO) and EPA.

tion in an outdoor environment. Results indicate that module bill of materials and specific environmental stressors may determine degradation mechanisms and rates over time. A new project funded through DOE's DuraMAT program will examine the relationship between cracks and power degradation. Continued work in this area is needed to improve predictions of wear-out performance degradation for different PV module designs, for plants of different ages, and for exposure in different climates.

**Module Collection Systems.** Cost-effective recycling requires an efficient system to transport spent PV modules from geographically

dispersed PV projects to recycling facilities. Today's low PV waste volumes present challenges in terms of cost, scheduling, storage, and capacity usage. Based on experiences in Europe and Japan, regulated recycling programs will likely incorporate robust collection systems.<sup>1</sup> Further definition of service needs (collection, consolidation, and transportation), cost modeling, and life-cycle analysis are needed to develop collection systems that optimize costs while minimizing environmental impacts. Monitoring and reporting of module recycling activities are also needed to track PV waste market size by region, failure types, warranty claims, costs, materials recovery rates, compliance rates, and environmental impacts.

**Regulatory Design.** Experience in the EU and Japan points to the need for regulation specific to PV plant decommissioning, module collection and classification, and waste treatment and disposal. To inform proposed regulatory actions and recycling programs, R&D needs include the following:

- Outreach to key regulatory stakeholders to understand their current activities and findings;
- Improved estimates of current U.S. waste volumes;
- Summaries and comparisons of regulations and policies specific to PV EOL;
- Assessment of benefits, challenges, and implications of applying a universal waste classification; and
- Analysis of costs, recovery rates, and environmental benefits of various policy design options addressing residential, commercial, and utility PV deployments.

**EOL Certifications.** Research is needed to confirm available and recommended certifications for PV module EOL processes and guidelines for their use. Specific near-term tasks include comprehensive descriptions of environmental certification programs and metrics, as well as comparative assessments of their effectiveness, ease of use, and costs.

**Environmental Impacts of Recycling.** Based on a life-cycle inventory for PV-derived electricity addressing six indicators (particulate matter; freshwater ecotoxicity; human toxicity non-cancer effects; human toxicity cancer effects; mineral, fossil fuel, and renewable resource depletion; and climate change), the environmental impacts of PV module recycling appear very low relative to those of module manufacturing.<sup>32</sup> Also, compared to the use of raw materials to produce semiconductors, glass, metals, and polymers for new PV modules, recycling was shown to have environmental benefit. While these 2018 results are suggestive, additional investigation of specific recycling technologies and multi-stage processes is needed to characterize energy use, other resource inputs, air emissions, and additional by-products.

### **Collaborative R&D Opportunities: How You Can Inform PV Plant and Module EOL Options**

- Participate in and support the new EPRI supplemental project, *Improving PV Sampling Methods for End-of-Life Leach Testing (3002014825)*. This project will develop an improved technical basis for evaluating the potential toxicity of different types of modules.
- Share PV EOL experiences and data with EPRI for aggregation, analysis, and communication of summary-level information to utility, recycling, waste management, and PV industry stakeholders and regulators. This work will inform development of future EOL management programs and processes.
- Consider partnering with EPRI to conduct a decommissioning and module EOL case study, in the event you own or operate a PV plant that needs to be fully or partially decommissioned due to a weather event, damage, aging, or underperformance of any kind. This work will document the options considered, technical and economic feasibility, decision processes, and experience implementing the solution.



Figure 17 - PV arrays deployed at EPRI's SolarTAC test site may be used to evaluate module replacement scenarios.



Storm-damaged modules (Photo Credit: Eliza Hotchkiss, NREL)

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