U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Solar Energy Technologies Office Photovoltaics End-of-Life Action Plan

March 2022

Executive Summary

To achieve the Biden Administration's goal to decarbonize the electricity grid by 2035, the United States must install 30 gigawatts AC (GW) of solar each year between now and 2025 and ramp up to 60 GW per year from 2025 to 2030. For context, the United States installed 19 GW of solar capacity in 2021 [1]. The installed capacity of photovoltaic (PV) systems in the United States now exceeds 100 GW and approximately 75% of this capacity was deployed in the past five years.

While the lifespan of a PV system is expected to be about 25–35 years, some modules and system components are already entering the waste stream. Modules can reach end-of-life (EOL) due to weather damage, installation errors, or manufacturing serial defects. Annual PV module EOL volumes may reach up to 12% of annual municipal electronic waste volumes in the United States by 2050. PV module materials are 99% non-hazardous and 95% of the materials is recyclable with current technologies. This sets a strong foundation for developing safe and low-impact EOL material handling methods.

Currently the economics of EOL handling are unfavorable to recycling. The cost to waste generators to recycle PV modules is around $15-$45 per module. This is significantly higher than the landfill fee, which is $1-$5 per module. Therefore, it is likely that federal and state policy will have a large impact on how waste is processed.

The U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) aims to reduce the environmental impacts of solar energy [2]. This plan outlines research activities that can enable safe and environmentally sound handling of PV EOL materials. Actions taken now will improve the likelihood that supporting technologies will be developed to handle PV EOL volumes safely, responsibly, and economically, allowing for greater deployment and safe and socially responsible supply chains [3].

SETO plans to address PV EOL issues through stakeholder outreach activities, data gathering, research, and analysis. SETO aims to better understand the state of EOL through the development of a database that tracks the materials, quantity, age, location, cause of EOL, and EOL handling for modules. In addition, it will support hardware research to reduce the environmental impacts of EOL and reduce the cost of module recycling by more than half by 2030.

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Overview

The installed capacity of photovoltaic (PV) systems in the United States now exceeds 100 GW and approximately 75% of this capacity was deployed in the past five years [4] (Figure 1). As described in the DOE Solar Futures Study, achieving a 95% reduction in carbon dioxide emissions in the U.S. electricity grid by 2035 requires an average of 30 GW of solar capacity additions per year from now to 2025 and then 60 GW per year from 2025 to 2030 [1].

Establishing safe, responsible, and economic EOL practices will allow for greater deployment of solar energy. In addition, EOL practices are integral to reducing the environmental impacts of solar energy [2] and supporting a safe and socially responsible supply chain.

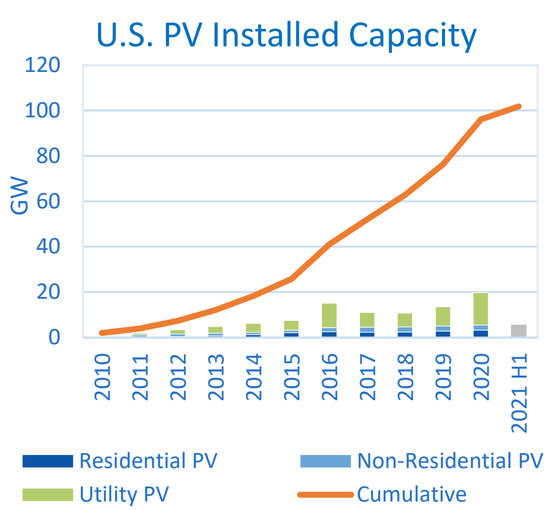

Figure 1. Annual (bars) and cumulative (line) installed capacity of PV in the U.S.

What is PV EOL?

The timescale and variables that determine when PV system components have reached EOL are not well defined. The population of PV systems that have reached their EOL is small compared to the number of systems that have been installed. Additionally, there is little public data on PV EOL, so there is little insight into the state of PV EOL and how PV EOL volumes are processed.

The time to EOL has traditionally been based on what investors use to estimate the operational lifespan of a PV module, which coincides with the module warranty. Currently this range is 25–35 years [5]. However, it is not clear that this method of estimating system lifespan is an appropriate predictor or definition of the useful operational lifespan of a PV system, since the components may reach EOL at different times. Some components may have useful lives longer than the module warranty of 35 years and some components may fail earlier than planned life span. Since most systems in the United States were installed less than 25 years ago, components that have reached EOL have done so earlier than the estimated 25-35 year life span. This is likely due to weather damage, installation errors, or manufacturing serial defects. These components may not be representative of general PV EOL and do not predict the operational lifespan of a PV system that does not experience early failures.

Materials in PV Systems

A PV system is comprised of modules, racking structures, and inverters that connect it to the grid. Modules, which are composed of approximately 90% glass and aluminum

(Al) by mass, contribute about half of the materials by mass of a system. The remainder of the system materials include steel for racking, piles, and trackers; copper (Cu) and Al for wiring; and plastics for electronics and wire housing. The material breakdowns, by mass, of a single-axis tracking silicon (Si) PV plant, a fixed-tilt Si PV plant [8], and single-axis tracking cadmium telluride (CdTe) PV plant are shown in Figure 2. The first three materials of steel, Cu, and Al account for the balance of system components in a system.

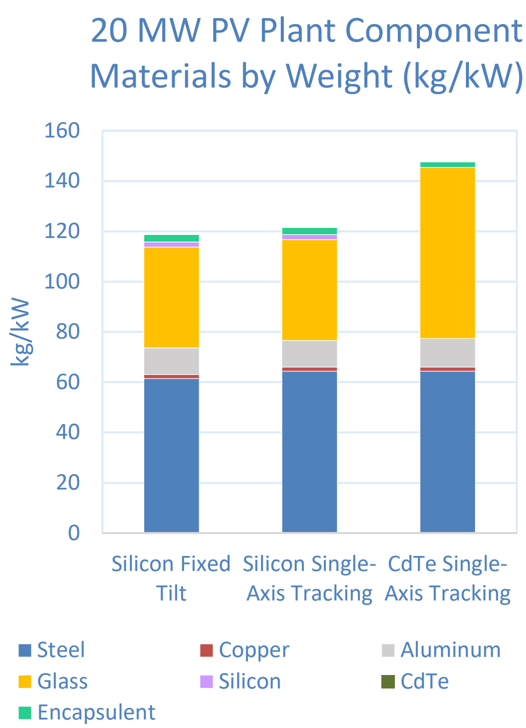

Figure 2. System-level materials breakdown by weight for fixed tilt and single-axis tracking configurations for a Si PV plant, and a single-axis tracking CdTe plant.

The other four materials account for the modules in a system.

The U.S. recycling infrastructure can accommodate future PV system EOL volumes but will need improvements to recycle electronic components efficiently. Steel, Al, and Cu can be sold into scrap metal markets. Solar glass, which is clearer than the majority of glass, can be recycled or used for secondary products, such as reflective paints. However, the glass still needs to be separated from the rest of the module laminate.

The estimated amount of PV materials that will enter the recycling stream in 2050 will be around 2% of the amount of steel, 25% of glass [9], and 6% of Al [10] that was recycled in 2018. Figure 3 compares the 2018 recycled amounts of steel, glass, and Al in the United States along with the 2050 estimated amounts of the same materials from EOL PV systems. While a 25% increase in the glass recycling volume from 2018 to 2050 would be significant, glass recycling in the United States has already experienced this rate of increase when it more than tripled from 750 tons in 1980 to 2,500 tons in 1990. Therefore, it is likely that the current U.S. recycling infrastructure will be able to handle these three materials from PV EOL systems until 2050.

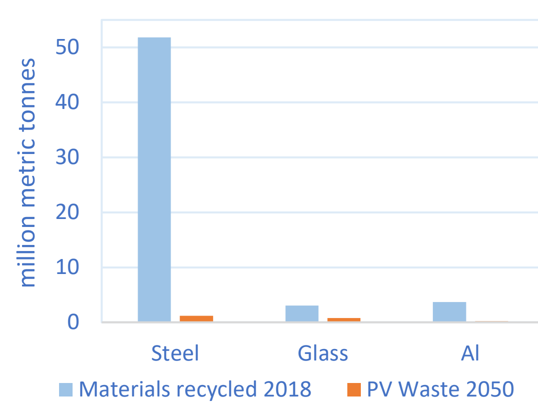

Figure 3. Blue bars show recycled amounts for steel, glass, and aluminum in the United States in 2018. Orange bars show estimated amounts of PV steel, glass, and aluminum waste in 2050.

While the majority of non-module system component materials can be sold to the scrap metal market, the module and inverter are the components that are considered electronic waste (e-waste) and do not have as robust recycling and secondary materials markets as steel, Al, and Cu. However, module EOL volumes will be far larger than inverter EOL volumes due to their respective mass proportions in a system and module recycling will be different from other e-waste recycling due to differences between consumer electronics and module designs. Therefore, module EOL handling will be the main priority.

Materials in PV Modules

A silicon module is made of silicon solar cells, which are electrically connected with silver (Ag), sandwiched between glass and plastic sheets, and framed in Al. These components are shown in Figure 4

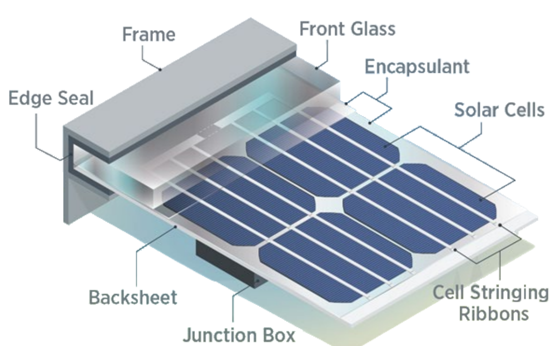

Figure 4. Components of a silicon module.

Modules are categorized as e-waste because they contain electrical components, but more than 90% of a module's mass is made of glass and Al. The material breakdown by mass and recoverable value [9] for a Si module is shown in Figure 5. The breakdown by mass for a CdTe module is shown in Figure 6.

Precious metals, such as silver, are valuable materials in solar modules that could be recovered and reused for multiple purposes.

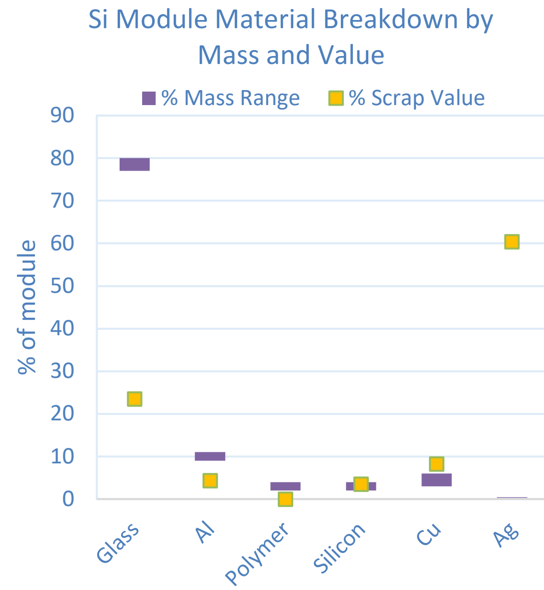

Figure 5. Material breakdown of a PV module by mass and by recoverable value.

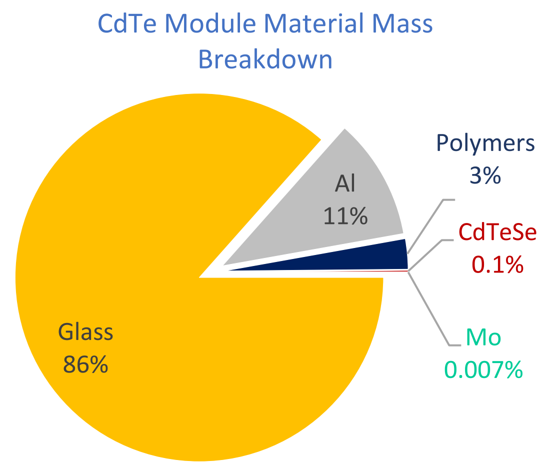

Figure 6. Materials breakdown by mass for a CdTe module.

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 [10]. PV cell and module manufacturers are working to reduce the amount of silver used in each module which reduces silver needs for PV applications. Silver 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.

As with silver, silicon is also difficult to recover with sufficient purity for reuse. While the silicon embodied in a PV cell could be valuable, other materials are intentionally added to the silicon to make it into a solar cell. This makes the recovered silicon lower quality than is needed for electronic applications, although it may be useful for metallurgical applications.

CdTe thin film modules are made by depositing CdTeSe absorber materials directly on the glass of the module, using plastic encapsulant and edge seals, and Al and molybdenum (Mo) contacts, and an Al frame. Tellurium (Te) is a rare element in the earth's crust, with an abundance on par with platinum. The amount of CdTeSe absorber in the module is below 0.1% by mass but an estimated 40% of global Te consumption was used for thin film solar module production in 2020 [13].

EOL Handling Pathways

The three main options for PV module EOL are landfilling, recycling, and secondary use.

Landfilling is currently the lowest cost handling option for PV module EOL generators. Landfilling fees range from $30/ton to $70/ton depending on the geographical location of the landfill. All waste that will be landfilled must follow the U.S. Environmental Protection Agency's (EPA) guidance for determining if a waste stream is hazardous using the Toxicity Characteristic Leaching Procedure. Certain states and municipalities may also have regulations regarding landfilled waste.

The module recycling process starts with mechanically removing the aluminum frames, if applicable, and shearing off the junction box. The commercial process for silicon then shreds the module into small pieces, grinds them into fine particles, and then uses eddy currents and sifting to separate the glass, polymers, interconnect ribbons, and cells. Other silicon module recycling techniques use heat to remove the polymers from the glass and chemical treatments to separate the metals from the silicon [14]. For CdTe modules, after mechanical removal of the frame and junction box the commercial recycling process then proceeds to shred the laminate, grind it into small pieces in a hammermill, mechanical separate the glass and laminate pieces, and then immerse in a series of chemical baths to recover the Cd and Te.

Currently, the cost to recycle PV modules is around $15-$45 per module, which is higher than the landfill fee, which is $1-$5 per module [13], not including transportation costs. Recycling processes that have been developed for CdTe and Si PV modules also cost more than the value of materials obtained at the point of recycling, at least for U.S. recyclers. The PV waste volumes in the short term are likely low and sporadic which further makes building a profitable industry difficult.

The PV module reuse/resale market is currently small but has been established.

Some modules that are decommissioned still output a useful amount of power which can be sold to buyers looking for pre-owned modules or a particular module product. Companies have been established that take care of both these useable decommissioned modules along with EOL modules for system owners.

PV EOL in Context

In the 2014 SETO PV Recycling Request for Information (RFI), respondents defined module EOL to be the time when a module is operating at 80% (T_{80}) to 50% (T_{50}) of the nameplate power [16]. Assuming a module power degradation rate is constant at around 0.7% per year [15] then a module T_{80} EOL would be 30 years and a module T_{50} EOL would be roughly 70 years.

In Figure 7, a 30-year system lifespan is used to estimate the module EOL mass that will be generated per year assuming a module mass range of 13.5-28 kg per module. For reference, the estimated annual municipal-only e-waste that will be generated in the United States for the same time span is plotted as well [16], [19]. The electronics that are included in the e-waste estimates are major appliances, small appliances, TVs, VCRs, DVD players, video cameras, stereo systems, telephones, and computer equipment. The estimated 2050 PV module waste will be between 7% and 12% of total municipal electronic waste.

To put this amount of municipal e-waste in perspective with the overall amount of waste generated in the United States, the volumes for three major sources of waste: municipal waste, construction waste, and industrial

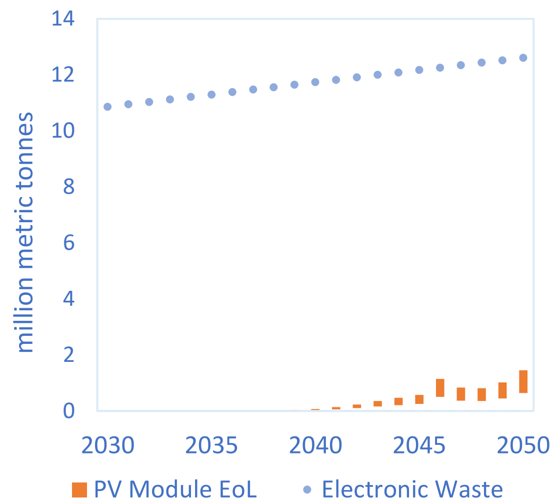

Figure 7. Estimated future annual PV module waste (orange rectangles) and estimated annual consumer e-waste (blue dots).

waste were estimated. In 2018, 255 million metric tonnes of non-electronics U.S. municipal waste was generated. The estimated annual construction waste generated is 540 million metric tonnes [20] and 225 million metric tonnes for non-hazardous solid industrial waste [19]. Figure 8 shows the percentage breakdown of these three waste categories along with the e-waste contribution. 9 million metric tonnes of e-waste was generated in 2018 which accounts for 1% of total waste. The projected amount

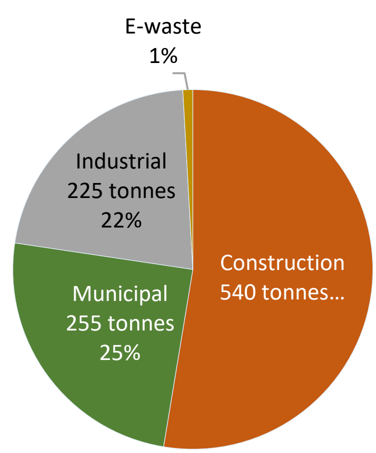

Figure 8. Breakdown of select waste streams generated in the U.S. in 2018.

of PV module waste that would be generated in the year 2050 ranges from 0.8 to 1.5 million metric tonnes. This would be equivalent to 0.1% of the total waste generated in 2018.

PV EOL Policies

Policy has a large impact on how waste is processed. There is currently no U.S. national recycling policy regarding general waste streams to incentivize recycling. However, various state and local policies exist and can play an important role in determining how waste is handled. In terms of Federal policies that apply to PV EOL, the Resource Conservation and Recovery Act managed by the EPA lays out regulations regarding toxicity characteristics of solid waste. A leaching test determines if a solid waste is hazardous [22]. At the state level, California and Hawaii have passed legislation categorizing PV waste as universal waste effective 2021 [23] [24]. CA has more stringent toxicity level requirements for leaching tests than the EPA standards for waste [25]. In 2017, Washington state passed legislation that requires manufacturers or distributors to implement a EOL stewardship plan starting in 2024 [26].

Internationally, European Union member states have been required since 2004 to set targets to recover 85% of e-waste and recycle 80% of the recovered materials under the Waste Electrical and Electronic Equipment Directive. Financial frameworks, information dissemination, and technical strategies to implement the directive are also required from member states [27]. Producers and non-household users are responsible for financing recovery and recycling programs. Photovoltaics were added to the directive in 2017 and commercial processes for module recycling are now available in some member states.

In summary, annual PV EOL volumes may reach 12% of the U.S. annual municipal electronic waste volumes in 2050. This volume would be roughly equivalent to 0.1% of the United States' total solid waste volume in 2018. Most of this volume is made up of recyclable materials such as steel, glass, and aluminum. Currently landfilling of PV modules is lower cost to generators than recycling. The policies that oversee waste volumes and the costs of EOL handling pathways will influence the EOL pathways that will be developed for solar.

Summary of SETO and DOE Projects Related to PV EOL

SETO funds research to improve the performance, lower the cost, and support widespread deployment of PV. Research areas that are relevant to PV EOL include reliability and durability to increase the operating life of PV systems, lowering the resource-intensity of manufacturing, improving PV module recycling processes, and understanding environmental and health impacts of EOL options to provide safe options for handling.

Past SETO Projects:

- From 2018 to 2021, SETO funded various projects, totaling around $450,000, at the National Renewable Energy Laboratory (NREL) to coordinate PV sustainability efforts for the

International Energy Agency Photovoltaic Power Systems (IEA-PVPS).[1] These efforts focused on recycling research and analysis, assessing the life cycle of PV modules, improving environmental safety and health in PV manufacturing, and publishing reports [26] on EOL management for PV modules. NREL published an assessment of worldwide efforts to recycle PV modules [12] and identified the best ways to manage disposal. Other outputs of these agreements included: establishing cost estimates for various module recycling processes, analysis reports on the factors that influence decommissioning of PV plants, a status report on policies related to PV EOL, and investigating a pathway to circularity for PV modules.

- In 2016, SETO awarded $700,000 to EnergyBin, a company that created an online marketplace for solar-industry overstock and hard-to-find components. The marketplace allows decommissioned modules to be reused, in the form of discounted, warrantied solar project components from vetted, reputable sources. This gives new life to old materials while reducing project construction and maintenance costs.

- In 2017, $900,000 was awarded to SRI International, an independent nonprofit research organization, for a project to develop a more efficient process to recycle the silicon waste generated by the wafer-cutting process into PV-grade silicon.

- In 2018, SETO awarded $120,000 to NREL to analyze PV end-of-life management and the effectiveness of efforts to design modules and other equipment for easier reuse.

- In 2018, together with the Energy Department's Advanced Manufacturing Office, SETO funded a $200,000 project at NREL focused on both developing a voluntary eco-label standard to evaluate the environmental impact of modules and to outline design rules for recyclable modules.

Active SETO Projects:

- In 2021, DOE awarded $800,000 to NREL to analyze module end-of-life management such as toxicity tests and to continue to coordinate the IEA-PVPS Task 12 PV sustainability efforts.

- In 2021, two projects that address EOL handling for perovskite module technologies were awarded. One project was supported at $1.5 million includes work to develop a method to seal off lead for damaged and EOL perovskite modules. A second project was awarded $250,000 to develop recycling processes for future perovskite modules.

Other Active DOE Projects:

- In 2021, the Reducing Embodied-energy And Decreasing Emissions (REMADE) Institute, supported by the Advanced Manufacturing Office, selected two projects on PV recycling. A $1,037,733 project at the University of Pittsburgh will design a framework of high-efficiency modules that can be economically recycled, recovered, re-manufactured, and/or reused. A $485,410

[1] The IEA-PVPS is a collaborative research and development agreement within the IEA. Since 1993, participants in the PVPS have been conducting joint projects in the applications of PV conversion of solar energy into electricity. www.iea-pvps.org

project at Arizona State University will develop recycling technologies for improve materials recovery from silicon solar modules.

Targets for PV EOL Research

In June 2021, SETO issued an RFI and held a workshop to solicit feedback from the PV and waste management communities about EOL issues. The responses, along with literature reviews and expert interviews, were used to identify impactful research areas to improve PV EOL practices. Many of the responses emphasized the importance that policy has on EOL handling along with the need for unified EOL policies and standards to increase materials recovery. Many responses also mentioned the importance of improved, low-cost materials recovery through streamlined handling or efficient separation technologies.

To date, the volume and rate of PV EOL generation has been low and sporadic, and information related to PV EOL is scarce. The community has indicated that data on bill of materials, quantity, age, location, cause of EOL, and EOL handling for modules would be most useful. Establishing quality data on PV EOL would help communities, the solar industry, and EOL industries better understand the current state of EOL and make decisions based on informed analysis. By 2000 there was about 50 MW cumulative of PV installed the United States, 10 MW of which was grid tied [28]. While some of these early systems that have been in operation for more than 25 years may continue to output useful power, some will be coming offline in the next few years. There will also be systems that have been in operation for less than 25 years that produced EOL components due to early failures. It may be hard to track the off-grid residential and commercial systems, so only grid tied capacity will be targeted. Therefor SETO intends to establish a database and data standard for PV EOL with the goal of gathering data on more than 10 MW worth of PV EOL system components, including modules, by 2025.

Target: 10 MW of PV EOL data by 2025

In terms of research needs in PV EOL handling, many responses from the community mentioned better materials separation and recovery techniques, and design for recycling. SETO is setting research targets that will result in module design and end-of-life processing that are environmentally and economically favorable. Acknowledging that EOL handling costs will depend on both policy decisions and technology development, SETO aims to decrease the cost of module recycling by a module by more than half by 2030, which would make it \$3/module (or < \$150/ton) by 2030.

Target: Module recycling costs < \$3/module (or < \$150/ton) by 2030.

Action Plan

To reach the targets outlined above, SETO will implement the 5-year plan shown in Figure 9. The plan includes three main areas: outreach with stakeholders, data gathering and analysis, and hardware and processes research.

Outreach

Workshop and RFI – In June 2021, SETO held a PV EOL workshop to elicit stakeholder input on the current state of the art and challenges in hardware design and

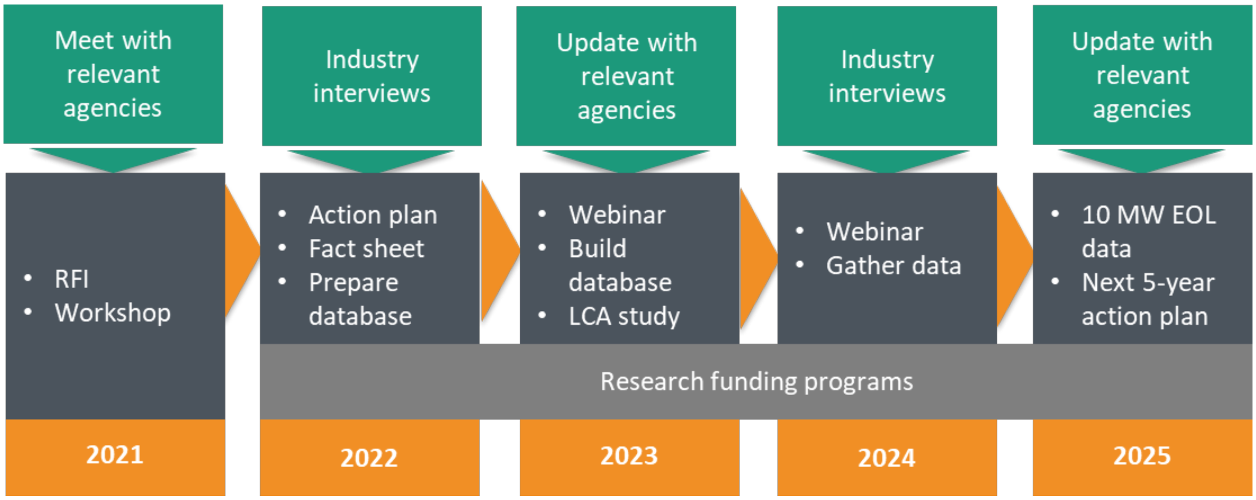

Figure 9. 5-year plan for SETO EOL activities.

data collection and analysis, and to determine DOE's role in addressing EOL management. Workshop attendees included system owners, system operators, resellers, waste management companies, recyclers, policy makers, government agencies, and researchers. Before the workshop, an RFI was posted to gather input from the wider community and help direct the workshop discussion. Both the results of the RFI [31] and the conclusions from the breakout sessions during the workshop [32] have been anonymized, summarized, and published on the DOE website.

Interviews – While gathering information to design research programs for PV EOL, SETO will further contact stakeholders such as EOL generators, waste management firms, and

recyclers on how plant components could be collected, transported, and handled. Other contacts will include the automotive, buildings, e-waste industries that have more experience and history with component recycling initiatives.

Fact Sheet and Webinar – The understanding gained from the workshop, RFI, and data collection effort will be used to create a plain language fact sheet on the state of PV EOL management, as well as hold a webinar highlighting research opportunities and SETO's goals for PV EOL.

Cross-Program Coordination – Within SETO-funded research programs, there are commonalities between EOL, reliability, and resiliency projects. Failure and degradation mechanisms could inform and affect EOL handling. How a module fails or degrades could determine whether it is reusable or recyclable. Designing components for resiliency will also affect lifespans and EOL handling so research in this area should include analysis on the trade-offs between designing for resiliency and EOL reusability or recyclability. Other offices in DOE and other U.S. government agencies also have relevant programs related to PV EOL. These include DOE's Advanced Manufacturing Office, EPA, National Science Foundation, and states. SETO will establish and maintain consistent conversations with these offices to share information on PV EOL learnings, analyses, and activities.

Workforce Support – One of the needs that the community identified in PV EOL is a knowledgeable PV EOL workforce in the EOL industries that understands the technical requirements, technology solutions, and relevant policies to properly and effectively handle EOL. Through the technical assistance program, fact sheet, webinar, and FOA projects SETO will start building a domestic population of experts with technical skills in PV EOL.

Data Gathering and Analysis

PV EOL Database – Discussions about PV EOL and PV EOL research needs have largely been based on modeled estimates of PV EOL volumes and handling, such as the ones projected in the background section. Little is known about the actual state and handling of PV EOL, such as the volumes that are being generated, the reasons behind PV EOL, how owners are decommissioning PV EOL, who handles the PV EOL after removal from the primary solar plant, and transportation logistics.

The establishment of a stand-alone database to which industry and researchers can contribute is targeted for 2024 in order to reach the target 10 MW of PV EOL data collected by 2025. Careful thought is needed to develop comprehensive data standards. Non-confidential aspects of the data will be made publicly accessible to the solar, waste management, and policy communities.

Updated Degradation Rate Analysis – Many estimates of module degradation rate are using rates that were established several years ago [31]. Degradation rates are helpful to estimating module life spans and may have changed with the new Si and CdTe module designs that came into the market in recent years so they will need to be continuously updated for new technologies.

EOL Management Understanding – To better design EOL research programs, a realistic understanding of the trajectory of PV EOL is needed. Waste management technology has not been a focus for the PV community thus far. There are many aspects of PV EOL management that the community could learn from the waste management industry or adjacent industries that have more experience with EOL, such as the automotive or construction industries. This learning can be used to develop PV EOL handling best practices in terms of collection, transportation, sorting, and materials reclamation.

Analysis studies – Analysis will help establish the social, economic, environmental, legislative, regulatory, and technological factors to map out realistic pathways for managing PV EOL. At the national level, EPA oversees regulations on waste classification which applies to all waste including modules. An analysis report on possible legal routes to streamline waste classification of PV that follows EPA guidelines will be explored in FY22. In SETO’s 2021 Multi-Year Program Plan, establishing baseline life cycle analyses of photovoltaics technologies is one of the goals for increasing the sustainability of solar energy. Technoeconomic assessment of EOL processes and life cycle analyses that incorporate EOL will be useful to evaluate projected costs, both monetary and environmental, and the value of recovery for proposed technologies. These analyses can also serve as guides for research strategies as we gain understanding of PV EOL.

Hardware and Process Research Areas

Though waste management practices and recycling processes have been developed for PV, there are still aspects of PV hardware EOL that could be improved.

Material Usage Efficiency – While this document focuses on EOL, material usage efficiency is the first step to waste management. Research to reduce the amount materials, especially critical materials, and energy needed to produce system components will reduce the resources needed to process EOL materials as well. Extending the life span of modules and system components means that the material usage rate will decrease which also alleviate material usage.

Reuse – Reuse extends the life of system components when they no longer perform at the levels required for primary use. PV plant components have not been designed with reuse in mind but with growing demand and markets, designs that consider secondary use for components may be helpful. For example, developing standards for components such as module size, racking dimensions, and connectors could allow for easier intergenerational compatibility and longer useful life spans.

Recycling – At the system level, the steel, aluminum frames, and glass are easily recovered and recyclable. These materials can be saved from the landfill but are not hazardous if they were landfilled. Based on the feedback from the 2021 PV EOL RFI and Workshop, owners mentioned that steel, Al, and Cu can be sold into scrap metal markets at EOL whereas modules are more difficult to recycle. The areas where materials recovery may be challenging include 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. Research into improving the recovery rate and lowering the recovery costs of these materials would help shift the economics of PV recycling.

Landfilling – Safety will be the priority for research in this area. One area of concern is solder used to join cells in a Si module contains lead. This may pose a health and environmental risk depending on the stresses a module experiences in a landfill. Preliminary studies have shown that the amount of lead from modules are below the limits that EPA sets for determining if waste is hazardous. Further studies are needed to establish the environmental impacts of a larger population of PV modules. Another possible area to investigate is the backsheet material that contains fluoropolymers which can release fluorine gases under thermal treatment. Understanding issues in the chemistries needed for CdTe materials recovery and handling of recovered Cd material in CdTe module recycling would be useful to ensure safe handling of these recycled materials.

EOL considerations should span the life cycle of a component rather than only at EOL. The research areas outlined above can cover product design and manufacturing to operations and maintenance of a system to EOL collection and handling.

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