U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Photovoltaic Systems End-of-Life Workshop Summary

October 2021

Solar Energy Technologies Office

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Introduction

The U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) hosted a virtual workshop on June 28, 2021, on photovoltaics system components end-of-life (PV EOL) in order to understand the current state of PV EOL and the technical barriers to sustainable handling of PV EOL. The workshop featured panels and breakout discussion groups with stakeholders from the PV industry, waste management industry, research laboratories, government agencies, and other related organizations, on opportunities and barriers to the development of sustainable practices for PV EOL. You can find the link to the workshop landing page and agenda here.

During the workshop, SETO held two 75-minute breakout sessions – one on EOL issues related to waste management and handling and one on issues with acquiring and analyzing EOL data – with participants broken into small groups that were all answering the same questions. A digital whiteboard was used during the breakout sessions to facilitate discussions where a question was presented, and participants provided their answers via virtual sticky notes. All other participants can see the notes being added in real time. Sticky note responses were saved and anonymized, and those comments, along with the conversations held in each breakout, are summarized in this document.

This document is a summary of the discussions during the workshop's breakout sessions so the public may also benefit from the information received by DOE. DOE is not communicating an opinion or viewpoint about any of the responses.

Breakout Sessions

PV Waste Handling Breakout Sessions

The first breakout session focused on issues related to waste transportation, processing, refurbishment, and reuse of PV EOL. Participants in the breakout sessions included representatives from the US Environmental Protection Agency (EPA); solar plant developers; operations and maintenance (O&M) providers; system asset owners; waste management representatives; and end of life researchers and analysts.

1. What kind of EOL components (modules, inverters, cables, racking, etc.) are you seeing in your operations? How do you define EOL for components? How are you handling and tracking them?

The components that reach EOL most frequently during operations are listed on Figure 1. Modules were identified as reaching EOL most frequently, followed by inverters, racking, cable, and small power electronic components.

For components other than modules, EOL is typically simply defined as when the component is no longer functional. A great deal of the components that waste handlers receive are damaged or obsolete and are not salvageable. Breakout group participants noted that salvageable components can be sent to recycling partners when those relationships are in place.

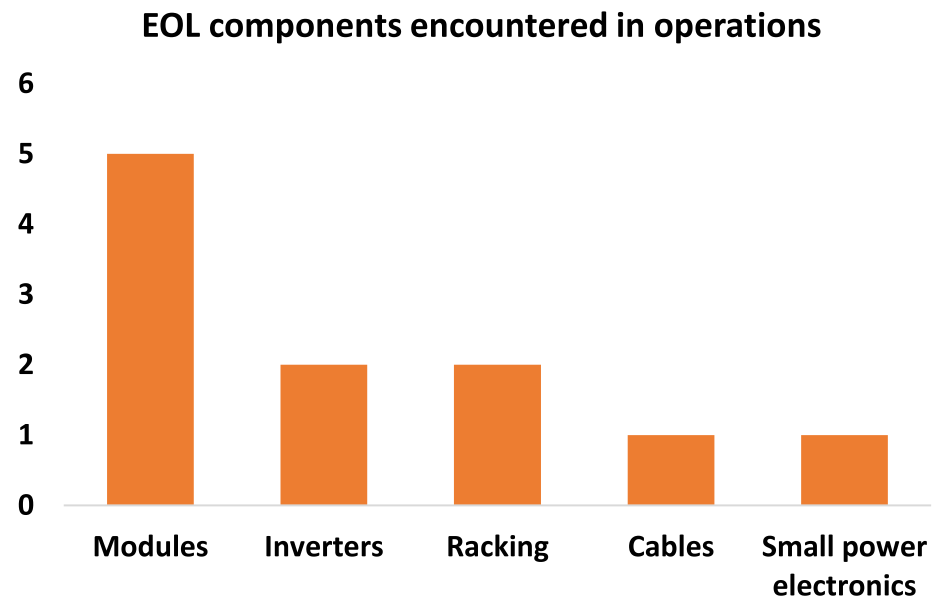

Figure 1: Most frequently seen encountered EOL components by breakout session participants

Although all EOL components are handled and tracked to an extent, stakeholder research objectives and conversations were focused on modules. Modules can be tracked via serial number and damaged modules can be dispositioned by damage type. Undamaged modules can be salvaged and resold profitably, as can steel and aluminum racking. Inverters typically have a lifetime akin to 10-15 years – shorter than that of the rest of the PV system – so they are likely reaching EOL more frequently than some other components in operations. The definitions for PV EOL in Table 1 below mostly refer to solar modules.

Table 1: Photovoltaic material end of life definitions described by breakout session participants

EOL Definition	Details
Economic	Project lifetime/ contract over, no longer profitable to produce power
Discarded	Stops meeting user requirements, no secondary use potential, damaged beyond repair, Resource Conservation and Recovery Act t(RCRA) compliance
Non-functional	Incapable of performing primary function
Below certain percentage of nameplate power output	Typically, 80% of rated power output
Removal from operation	Decommissioned regardless of power output
Damaged	Damaged beyond repair or repair not economic
Obsolete	Decommissioned early in lieu of newer models
Safety	Standards become stricter, components deemed unsafe to use

2. Within your organization, how does EOL of all components factor into your decision-making?

Many of the breakout session participants make decisions in-house to determine how to procure and/or what to do with materials. Utilities may require take-back programs for manufacturers during panel procurement or they may require waste classification data. Sometimes breakage is factored into the budget of a project, or financial assurance for the costs to handle EOL is included; these details may be included, among other things, in a decommissioning plan. Even if manufacturers do not handle waste themselves, EOL factors into the design of the panel or system components and the component's reliability over a promised lifetime. Waste handlers have considered mobile handling facilities to cut down on freight costs associated with transporting waste from large scale PV plants.

3. For EOL handling such as reuse, refurbish, recycle, or disposal, what are the opportunities and technical needs? What are some non-monetary benefits and barriers to reuse, refurbishment, recycling, and sustainable disposal of all PV system components?

Technical needs for reuse, refurbishment, recycling, or disposing of PV EOL are shown in Figure 2 and Table 2 below. The most frequently mentioned need was to streamline identification of PV EOL waste as hazardous or non-hazardous under state or federal regulations.

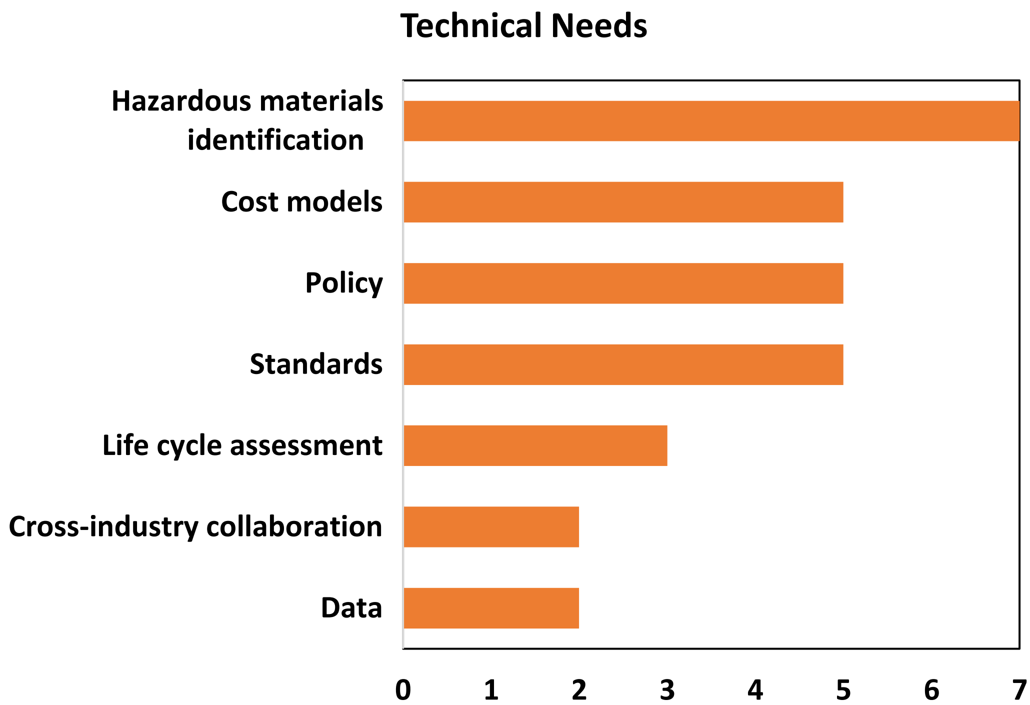

Figure 2: Technical needs identified in breakout sessions and frequency mentioned in Jamboard notes

Table 2: Technical needs for reuse, refurbishment, recycling, or disposing of PV EOL, and descriptions of those technical needs.

Technical Need	Details
Hazardous materials identification	Streamlined classification of hazardous materials, human health assessment, removal of hazardous materials from panel design
Cost models	For technologies, for refurbishment, virgin vs recycled materials
Policy	Tax incentives, guidance on transport and sales, hazardous material testing, reimbursement for transporting waste to a handling facility (offset program for freight)
Standards	Toxicity Characteristic Leaching Procedure (TCLP) test, recycling, trust of re-manufactured products
Life Cycle Assessment	Documented downsides of landfilling
Cross-industry collaboration	Recycled materials markets, recycling collaboration
Data	Secondary markets, refurbishment standards, TCLP results for specified bill of materials (BOM) in modules

Opportunities that stakeholders identified included more accurate methods of waste characterization, more sustainable designs with greener chemistries, and ultimately less waste to landfills. The opportunities and benefits of reuse, refurbishment, recycling, or disposing of PV

EOL are categorized and detailed below in Table 3. Three broad categories – financial, technical, and non-monetary – envelop the opportunities and benefits of reuse, recycling, refurbishment, and disposal of PV EOL.

Table 3: Opportunities and benefits of reuse, recycling, refurbishment, and sustainable disposal of PV EOL.

Opportunities and Benefits of Reuse, Recycling, Refurbishment, and Sustainable Disposal of PV EOL	
Financial	• Value return (Silver recovery and marketability of materials) • Energy and cost savings • Cost-competitiveness • New markets (Use recycled materials rather than re-purifying)
Technical	• Design (perovskites currently difficult to dispose of, reduce lead in modules) • Recycling technology research & development (R&D) • Sustainable packaging • Increase system lifetimes
Non-monetary	• Climate (lower greenhouse gas emissions) • Social (jobs, human health hazards reduced, better public perception) • Diversion from landfill (store until other handling processes are cost effective) • Characterization (efficient ways to characterize waste, starting with manufacturer) • Reduced mining and virgin material use

3c. Are there specific policies or systems that make EOL handling difficult?

Stakeholders identified two issues making EOL handling difficult were: cost and standards. For much of the discussion, the two concepts were intertwined.

EOL policies differ greatly internationally from the U.S, and policies differ greatly between U.S states. In the European Union (EU), the Waste Electrical and Electronic Equipment (WEEE) Directive requires 85% collection and 80% recycling of PV panel materials. In addition, a fee is placed on all modules sold in the EU that goes towards maintaining recycling infrastructure under government discretion. In the U.S, Washington is the only state with a PV material recycling mandate. Recently passed legislation in the state, which will take effect in 2023, will require PV module manufacturers to finance and implement a take-back program to reuse or recycle 85% of PV modules sold into the state. Most other states do not have laws or regulations that directly address EOL recycling.

The systems in some states for classifying PV waste was viewed by some stakeholders as cumbersome. Undue management of waste can occur when a system owner deems all waste hazardous to avoid testing the waste. In California, PV EOL was recently classified as ‘universal waste’, which is a subcategory of hazardous waste. This new classification may reduce the costs and liabilities associated with PV module recycling and disposal in the state.

PV EOL Data Breakout Sessions

The second breakout session asked participants questions about the utility, acquisition, and analysis of data on PV EOL. These questions pertain to both specific handling methods (recycling, reuse, refurbishment, repowering, etc. – the suite of options is sometimes referred to as “re-X”) and the state of the art for U.S. PV EOL practices. Participants in the breakout sessions included representatives from the US Environmental Protection Agency (EPA); solar plant developers; O&M providers; system asset owners; waste management; and end of life researchers and analysts.

1. What data would be useful to your organization for better understanding EOL and why? Where is it available?

Over a dozen different data needs were identified. The types of data and potential sources for the data are listed in Table 4 below, ordered by the number of total responses posted.

Table 4: Data that can help to understand the landscape of U.S PV EOL

Data	Details	Where is this data available?
Volume/mass	Volume of PV EOL going to different re-x streams, mass output, solar installation volume and mass by geographic location, types of materials	Installers, distributors, owners, waste management, resellers
Age	Modules, date when waste was generated	Owners
Costs	Decommissioning, finance models	Engineering, Procurement, and Construction (EPC); insurers
Reason for EOL	Replacement rate, occurrence of extreme weather events	Owners, National Oceanic and Atmospheric Administration (NOAA), insurance companies
Environment	Geographies, site classification (e.g., brownfield)	Owners, satellite data
Hazards	Accuracy of TCLP testing for PV	Recycler, owner, test labs
Processing	Handling method; disaggregated waste by pathway	Recycler, owner
Transportation	Distance and carbon impact for recycle or resale, tracking, waste exports	Owners, exporters, satellite data
Vendor	Location and information	Recyclers, resellers
Reuse	Reused BOS components by site	Owners, O&M
Templates	Sample decommissioning plan	EPC
Bill of Materials	Variability and resiliency of materials, materials flow	Manufacturers, test labs
Specs	Brand and wattage, materials	Manufacturers, installers, O&M
Storage	Modules being stored and for how long	Owners
Reliability	Accelerated testing and field results	Owners, test labs

2. What are the different data needs for utility vs residential systems?

Figure 3 identifies the most important data challenges for the utility and residential systems. This list does not encompass all possible challenges and some overlap exists between the issues in the residential-scale and the utility-scale sectors. Participants spent a significant amount of time discussion each issue in the context of the corresponding system size. For example, logistics of EOL PV waste handling are a challenge for any size system, but a utility-scale system means more waste and therefore the collection and analysis of more data, as well as data that may be more challenging to acquire.

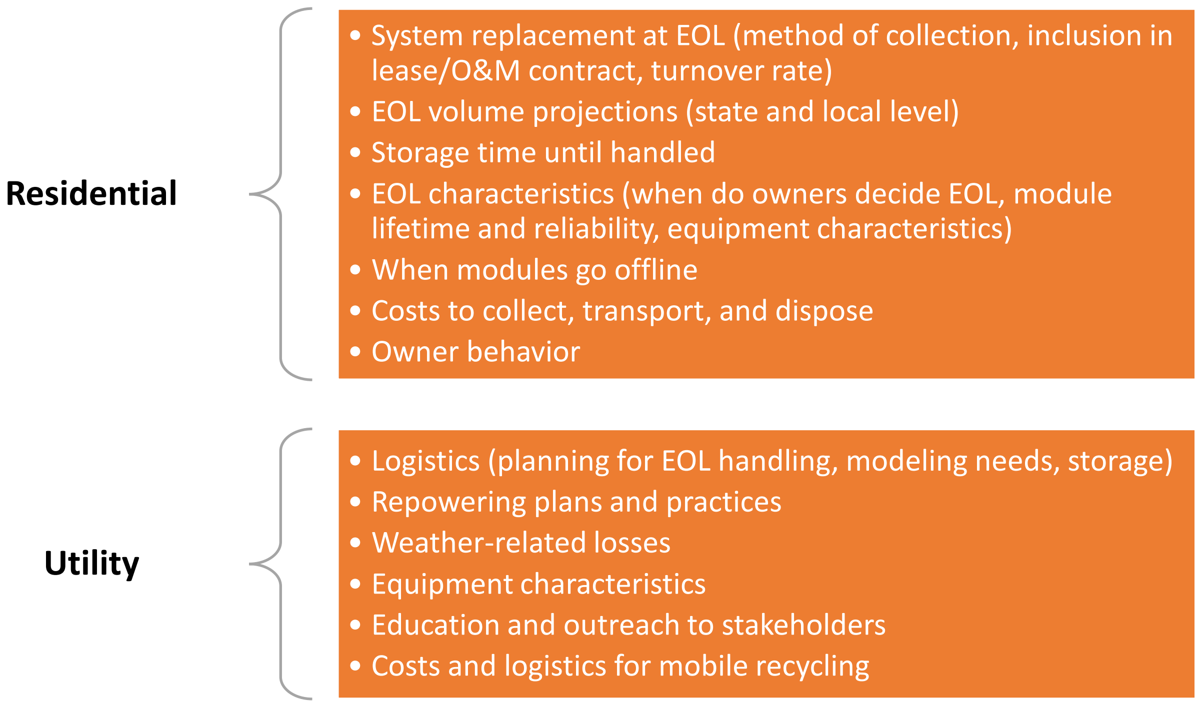

Figure 3: Significant residential and utility data needs identified in breakout sessions

3. What data-driven resources or tools would you find useful for better handling of all PV system EOL?

Several useful tools and improvements to existing tools and resource were proposed during the breakout discussions. Lack of data was identified as a potential limitation for the development of these resources and tools. Table 5 below details the categories of resources or tools that stakeholders would be willing to use.

Table 5: Categories where improvements in data-driven resources or tools would be most useful for better handling of PV system EOL

Resource/Tool	Details
Cost estimation tool	Cost for EOL and repowering, financial models for decommissioning and EOL decisions, economics of EOL handling methods
Equipment characteristics	Module weight by model number for logistics, weather casualties, environmental toxicity
Recycler database	Location of recycler, costs, processes, capacity, materials accepted, regulations by recycler locale
Predictive maps	For where decommissioning will occur, location of all PV systems, solar installation database with info on location, year, size
Survey or report of needs	From industry, of special handling or characteristics or logistics
EOL optimization tool	User optimization for GHG, volume of waste, and/or cost; effect of manufacturer design changes
Materials tracking	Radio-frequency identification (RFID) tags on modules containing module materials info, manufacturer certificate
Best practices	Safety, tools, suppliers, procedures
Non-financial incentives	Scorecards, top performer in sustainability

4. What technical assistance would you find useful?

Many Technical Assistance (TA) needs were identified in the breakout sessions; Table 6 gives more details on each category of TA, ordered from the top by most requested service.

TA on regulations for recycling, reuse, refurbishment, and repower (re-X) methods was identified as the most useful. Subtopics included understanding federal, state, and local incentives; the Toxicity Characteristic Leaching Procedure (TCLP) testing; and refurbishing standards.

Table 6: Useful technical assistance (TA) programs and details respondents provided in breakout sessions, ordered by most requested service

TA Category	Details
Understanding regulation	How to navigate different and changing regulations and standards; which regulations are relevant to which stakeholder group; standards for TCLP; testing and qualification for refurbishing; incentives
Workforce development	Training, best practices, size of existing workforce
EOL processing details	Compare processes based on desired output, standard process for refurbishing (minor frame dent or mildly crushed corner,), mass recycling (at scale)
Logistics	Transportation optimization for GHG, best practices
Outreach	Informing local governments about PV EOL and TCLP, guidance to manufacturers on EOL
EOL re-X (recycle, reuse, refurbish, repower) routes	Mobile units and processes, list of service providers
Analyses	Downsides of landfilling, environmental justice impacts

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