U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Technical Research Opportunities for Photovoltaic System End-of-Life Management Request for Information Summary

October 2021

Solar Energy Technologies Office

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Introduction

On May 19, 2021, the U.S. Department of Energy's Solar Energy Technologies Office (SETO) released the *Technical Research Opportunities for Photovoltaic System End of Life Management Request for Information* (RFI) for public response and comment. The RFI sought feedback from solar and recycling industries, academia, research laboratories, government agencies, and other stakeholders on the current state of PV End of Life (EOL) in the U.S, available data regarding PV EOL, and areas of research needed to reduce the barriers to component reuse and recycling. In the U.S, PV module and component end-of-life practices, such as recovery, reuse, recycling, and disposal, are not well understood since EOL volumes have been low and there are few policies related to PV EOL. To solicit feedback about these challenges, the RFI included questions covering four sections (please refer to the RFI for further background on each topic):

1) Current Status and Available Data;
2) Reuse Practices;
3) Recycling Practices; and
4) Courses of Action.

A total of 24 RFI responses were received and reviewed, including 5 from the manufacturing industry, 4 from national laboratories, 4 from non-profit organizations, 4 from recyclers, 4 from PV generation organizations, and 3 from academia. This document presents aggregated information from all RFI responses, organized by the sections above. **Please note that the Department of Energy (DOE) is not communicating an opinion or particular viewpoint about any of the responses described below, but rather is publishing an RFI response summary so that the public may also benefit from the information received by DOE.**

Current Status and Available Data

1a) What defines ‘end of life’ (EOL) for a solar photovoltaic (PV) component?

The majority of responses defined end of life as the PV component achieving a performance below a minimum threshold, ranging between 80% to 50% of rated power output. This is known as a T_{80} or T_{50} lifetime, with T_{80} denoting a roughly 30-year lifetime for solar panels if an average degradation of 0.6% of rated power output per year is assumed. Other responses similarly defined EOL of a panel as no longer producing power “economically” or “efficiently”, or no longer producing power at all. EOL was also defined as the end of the warranty or financial contract period for the system, when the component reaches a landfill, or when the component arrives at a recycling center.

1b) What are the common causes of PV EOL?

Components most frequently reach EOL prematurely due to physical damages from a variety of factors. Every response identified component physical damage but did not always specify the reason. Severe weather events, namely fires, hurricanes, and hail, were the most common reasons for irreparable or unacceptable physical damage. Water damage was also often mentioned. The percentage of respondents who identified at least one of the 6 most frequent causes is shown in Figure 2.

The second most frequent response (65%) was component performance degradation. Performance degradation is the result of various factors and is included in all solar system performance analyses. Different components degrade at different rates. The encapsulant tends to have a lower life span than most other system components. Even if severe weather events do not directly cause end of life, damage from them can lower the component’s lifespan via performance degradation.

Panel and component obsolescence is another reason for end of life. Component lifetimes are shortened when system owners see financial or aesthetic value in newer, more efficient technologies and replace the older versions of those components. For residential systems, a new system owner who inherited the system may not desire solar and therefore decommission the system.

Some respondents mentioned a ‘bathtub curve’ to describe the failure rates of PV panels throughout a standard panel lifetime. The bathtub shape refers to many failures occurring at the beginning or the end of the PV panel lifecycle, rather than in the middle. “Infant mortalities” can be due to poor shipping and handling practices, manufacturing defects, or problems during installation. The components with the highest failure rates include: **encapsulants**, **inverters**, **backsheets**, **diodes**, **busbars**, **cables**, and **connectors**. Causes for degradation addressed in the RFI responses are shown in Table 1.

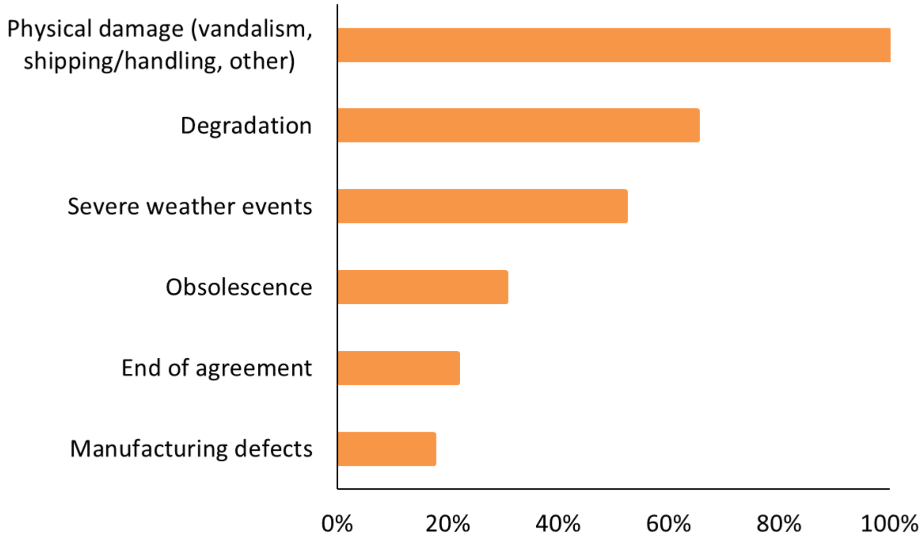

Figure 1: Percent of respondents addressing each of the categories listed related to causes for end of life

Table 1: Common causes for degradation addressed in RFI responses and brief descriptions.

Causes of Degradation	Description
Improper bill of materials	Inaccurate list of materials may affect performance and safety qualities of the PV system
Improper installations	Common mistakes include poor wiring; insufficient inverter ventilation; no lighting protection; and roof perforation without adequate sealing methods
Hot spots	A disproportionate heating of a single solar cell compared to surrounding ones; caused by shading, manufacturing defects, and mechanical damage
EVA Discoloration	Ethyl vinyl acetate (EVA) encapsulant browns as a result of continued UV exposure; this will significantly reduce the performance of solar cells
Thermal cycling	Mechanical stress on components from temperature cycling of day/night and varied solar radiation exposure
Backsheet cracking	Formation of cracks in backsheets from seasonal temperature changes, producing plastic deformation of the backsheet
Water leakage	Reduced performance of component as a result of water ingress
UV Exposure	Exposure to UV rays causes a variety of component performance degradation mechanisms or failures
PID (Potential Induced Degradation)	Existence of stray currents within a PV system, accelerated by high system voltages, temperatures, and external humidity levels
Electromigration	Current-induced transport of activated ions in a semiconductor that can cause short circuits in a module.
Pinholes	Tiny holes in the top layer of a perovskite solar cell that create pathways for water and other gas molecules in air to diffuse through the thin film and degrade the perovskite

1c. How is PV EOL currently handled?

Methods for handling PV EOL mentioned by respondents in the RFI, as well as reasons for performing those methods, are described in Table 2. RFI respondents indicated that most PV panels and components are sent to landfills – some estimates were as high as 90% of decommissioned panels. Reasons for disposal of panels in landfills included convenience, cheap tipping fees, concerns related to hazardous waste classification, and a lack of regulations requiring handling methods other than landfilling.

Table 2. Methods of handling PV EOL waste categorized by frequency of methodology in the U.S, reasoning, and any issues with the method described in RFI responses.

Method	Category	Description
Landfill	Frequency	United States rate up to 90%
	Reasons	Low tipping fees; convenience
	Issues	Materials can no longer be used
Storage	Reasons	Unsure what to do with waste; hazardous/non-hazardous assessment not yet performed; storing until preferred handling method is cost-effective
	Issues	Materials not being used
Shipping Overseas	Frequency	Up to 10%
	Reasons	Convenience; land space limitations
	Issues	Unregulated; may still be landfilled anyway
Recycling	Frequency	10% of global PV materials
	Techniques	Mounting and racking recycled as industrial metals; eddy current separation for nonferrous metals; dry shredding and sorting of glass; inverters and junction boxes recycled as e-waste
	Issues	Low %; seldom cost effective; lack of infrastructure
Recovery from recycling	Frequency	%s unknown: glass, aluminum, and steel recovery are common; precious metal, such as silver, and silicon recovery is rare
	Issues	Low amounts of material recovered; seldom cost effective; lack of infrastructure; Use of nitric acid to recover metals can create waste issues. Materials like antimony, chromium, calcium fluoride, and silicon are not recovered at the amounts needed to support a PV circular economy

Recycling of components is less common than landfilling and recycling rates differ depending on the type of component. Some components are more easily or frequently recycled or recovered than others when they are sent to recycling facilities. Mounting and racking components are valuable in the scrap steel market. Though it can be expensive, recycling glass is simple. Precious metals can be recovered with chemical treatments, though it is not common to do so. Silver would be valuable to recover, but because less silver is used in newer system models, there is less financial incentive to do so.

A few other less-common methods were mentioned. Components that are not immediately landfilled are sometimes stored indefinitely by system owners or handlers. Components may also be donated if they are taken offline but can still perform their primary function. Components are sometimes shipped overseas to be resold, repaired, or landfilled; estimates can be as high as 10% of EOL components, though the actual amount is unknown.

1d. What data would be useful to understand and track the PV system EOL landscape? Where is this data available?

Respondents most often pointed to information on manufacturer bill of materials as useful data. Many respondents also mentioned tracking the quantity and age of panels taken offline at a site and the reasons for taking them offline. Cost of shipping waste can be ambiguous and expensive, so the location of and distance between offline panels or components and nearby handling facilities was cited as potentially useful for calculating costs. Ecotoxicity data from industry may be useful when classifying EOL waste. Responses to Question 1d are summarized in Table 3 below:

Table 3. List of common responses to what data would be useful grouped by potential sources, as well as potential sources for that data

What data would be useful to understand PV EOL?	Where is this data available?
Bill of materials; expected productive life cycle of equipment	Manufacturers
Quantity of panels removed; maximum power when panels were removed	System owner
Why panels come offline and what damages	System owner, weather data, O&M providers
Locations of recycling centers relative to offline modules; cost of freight; geographic concentrations of PV waste	Geographic Information System (GIS) data
Date of system installation and yearly performance of panels; forecasted EOL time	System owner (field performance data)
Material ecotoxicity data; chemical products and treatment times for recovery	Industry, government regulatory bodies
Quantity of components landfilled	Waste management
Quantity of EOL modules being stored	Distributors, installers, developers, and system owners
Distribution of components sent to landfill, recycling center, or other from a site	Various
Examples of decommissioning plans	IRENA, national labs

Reuse Practices

What are barriers to PV component reuse at EOL for both PV and other applications, and how can the rate of PV EOL reused be increased?

Responses can be divided into roughly 4 barriers: financial, regulatory, social, and technological. The most common ones are shown below in Figure 2. In Figure 2, the barriers are in red boxes and potential solutions to these barriers are in green boxes.

Figure 2. List of barriers (red text) and potential remedies to these barriers (blue text) divided into 4 categories

Financial

- Landfilling is cheap
- Logistics of handling
- Cost of freight
- Cost of recovery

- Develop methods to calculate true potential value of recovered materials
- Financial incentive not to landfill

Regulatory

- Lack of enforced standards or obligation to collect for reuse or recycle
- No market connecting supply and demand
- Poor market confidence
- Increasingly strict fire, building, and electrical code requirements

- Remove option to landfill for decommissioning contractors
- Regulatory framework to ease collection
- Credits for guaranteed extended lifetimes
- Resource Conservation and Recovery Act adherence or other environmental regulations

Safety

- Misunderstanding of financial opportunities
- Awareness and location of reuse opportunities
- 'Assorted' reused/recycled panels for large scale projects increases safety and reliability risks
- Lack of service providers / infrastructure
- Little social pressure for change

- Knowledge dissemination
- Technical assistance for resource recovery and handling
- Stakeholder convenings

Technological

- Landfilling is simpler than other options
- Lack of good separation techniques; Polymers, gels, pottants, and encapsulants complicated and energy intensive to remove
- Silver recovery via smelting is energy intensive
- Process of reusing silicon wafers involves disposal of acidic liquids; physical and mechanical processes generate toxic dusts

- High innovation rate of PV; Changing designs
- Research & development into novel separation techniques
- Component standardization

Recycling Practices

What areas of PV component design could be improved to increase material recycling rates at component EOL without sacrificing performance, cost, or reliability and why?

The concept of designing for recycling (DfR) was brought up by multiple respondents. Subtopics within DfR discussed included: easier module disassembly and separation; adherence to Institute of Scrap Recycling Industries (ISRI) principles; and simpler removal of frames. Materials that can be problematic for recycling and that can be addressed with proper DfR include backsheets, particularly the fluoropolymers within bifacial systems; ethyl vinyl acetate (EVA) encapsulants; racking materials, which could be made with sustainable materials; lead and rare earth metals, which can cause modules to fail hazardous waste tests; and polymer material chemistries (Figure 3a)

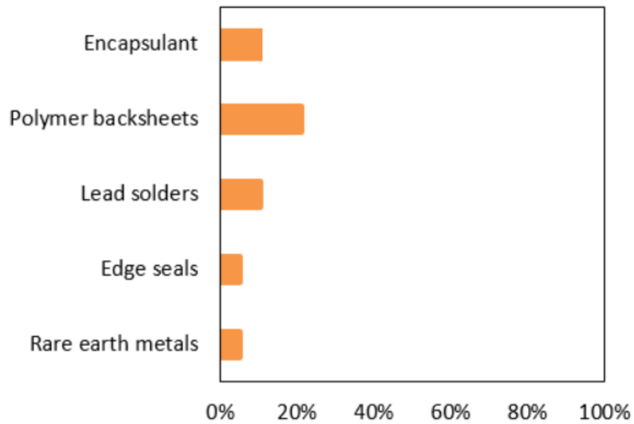

Figure 3a: Commonly referenced problematic components to recycle

Respondents also identified PV recycling practices that could be improved (Figure 3b).

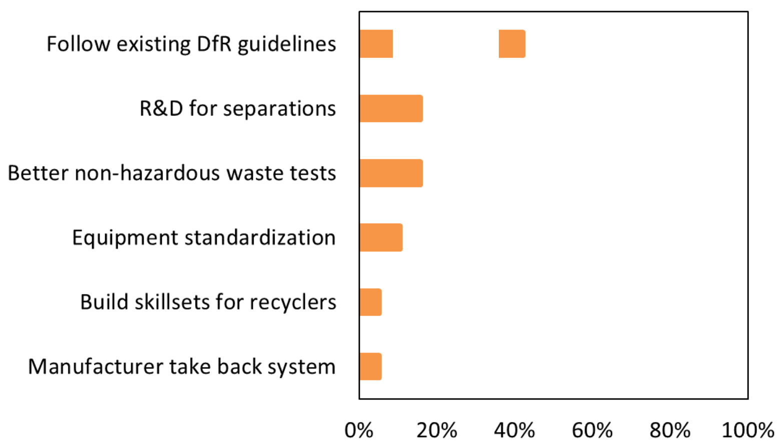

Figure 3b: Potential improvements to the current state of U.S. PV recycling practices.

Courses of Action

What actions can PV module manufacturers, distributors, developers, owners, waste management, or recyclers take to increase the fraction of PV components reused or recycled?

38% of responses mentioned convenings and collaboratives between stakeholder groups as a necessary action to increase reuse or recycling of PV components. Cost-sharing recycling infrastructure and process development was mentioned in 19% of the responses. Answers to who is responsible for paying and when varied. Many responses cited previous work on developing standards and regulations in the sector through programs like Waste from Electrical and Electronic Equipment (WEEE) directive and International Energy Administration Photovoltaic Power System Programme (IEA PVPS). Actions directed that could be taken by specific stakeholder groups are shown below in Table 4:

Table 4: Suggested actions that can be taken by stakeholders to increase PV component recycling

Stakeholder	Action #1	Action #2	Action #3	Action #4	Additional Actions
Manufacturer	Provide bill of materials or transparency in component manufacturing	Extend manufacturing warranty for used panels	Adhere to existing voluntary standards (NSF 457, others)	Use more easily recyclable materials	Standardize panel size; Secure a domestic supply chain
Distributor	Favor durable and easily recyclable products	Connect service providers and consumers	Collect EOL materials	Cost share with other stakeholders	
Developers and/or Installers	Require decommissioning costs in project financial plans	Cost share with other stakeholders	Favor durable and easily recyclable products	Inform individual consumers and state/local governments of alternate handling opportunities	Participate in convenings
System Owners	In-field diagnostics to identify glass type	Partner with recyclers to ensure responsible output for systems at EOL	Cost share with other stakeholders	Make plans for recycling / reuse publicly available	Collect and publicize data, such as # of panels at EOL and reasons for EOL
Recyclers / Waste Management	Reject PV EOL at landfills	Create a network of locations that panel owners can use	Invest in efficient handling technology and processes	Cost share with other stakeholders	Participate in convenings

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