PV Module Management Across the Value Chain

SOLAR
Securing critical material supply chains by enabling phOtovoltaic circuLARity

Key Takeaways from NSF SOLAR Module Management Working Group

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Abstract

Battelle Memorial Institute is leading a research study, **S**ecuring critical material supply chains by enabling ph**O**tovoltaic circu**LAR**ity (SOLAR), through a National Science Foundation (NSF) grant in partnership with the National Renewable Energy Laboratory (NREL), EPRI, and Texas A&M University's Energy Institute. The project is dedicated to creating a collaborative ecosystem to enable full circularity of photovoltaic (PV) materials.

Phase 1 activities were designed to engage all stakeholders across the solar PV supply chain, relevant research disciplines, and all affected communities to synthesize equitable and sustainable solutions to this complex and transboundary materials circularity problem. Working Group 1 (WG1), led by EPRI with support from NREL and Battelle, focused on PV end-of-life (EoL) decision-making and PV module management applicable to PV plant owners, operators, recyclers, and reuse providers.

Through a series of 10 virtual WG1 meetings, the project team discerned knowledge gaps and barriers to solar PV circularity that could be addressed in Phase 2 of the project. Participating WG1 stakeholders included: utility companies, solar PV developers, PV module manufacturers, recyclers, and reuse providers; federal and state regulators and policymakers; university professors and students, technical staff from national laboratories, and members of national and international standards committees. The highly engaging discussions were typically attended by ~35 stakeholders per session with over 100 stakeholders engaged in total. The focus of each webcast rotated between three topics: 1) Module condition assessment and sorting for reuse and recycling, 2) Module management policies, and 3) Voluntary sustainability and environmental quality standards. This report provides key takeaways related to these three central topics as informed by stakeholders throughout the PV module value chain.

Keywords

Circular economy
End-of-life management
Hazardous waste determination
PV module management
Solar photovoltaic (PV) module
Workforce development

Executive Summary

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Primary Audience: Stakeholders within the PV module value chain, including manufacturers, policymakers, reuse and recycling service providers; solar PV researchers involved in circular economy and module management research; solar PV system asset owners and operators; and utility integrated resource planners.

KEY RESEARCH QUESTION

Solar energy generation is expected to play an important role in achieving deep electric grid decarbonization with projected U.S. capacity growth from approximately 150 GW in mid-2023 to 1 TW by 2050. In the U.S., most end-of-life (EOL) PV modules are landfilled today. This project identifies barriers to circular economy options like lifetime extension, repair, reuse, and recycling and develops solutions to enable greater PV module circularity.

RESEARCH OVERVIEW

In Phase 1 of the NSF Convergence Accelerator's Securing critical material supply chains by enabling phOtovoltaic circuLARity (SOLAR) project, Working Group 1 (WG1) focused on PV plant EOL decision-making applicable to PV plant owners, operators, recyclers, and reuse providers and PV module management. Through a series of ten virtual WG1 meetings, the project team discerned knowledge gaps and barriers to solar PV circularity that could be addressed in Phase 2 of the project. The highly engaging discussions were typically attended by ~35 stakeholders per session with over 100 stakeholders engaged in total. The focus of each webcast rotated between three topics: 1) Module condition assessment and sorting for reuse and recycling; 2) Module management policies; and 3) Voluntary sustainability and environmental quality standards. This report provides key takeaways related to these three central topics as informed by PV value chain stakeholders.

Executive Summary

KEY FINDINGS

- PV value chain WG1 stakeholders identified needs for:
  - A more standardized approach for plant-level EoL decision-making
  - Tools and guidance to perform PV module condition assessments
  - Worker training to enable efficient module sorting for reuse and recycling
  - Guidance on hazardous waste regulatory requirements for PV modules
  - Guidance, data, and procedures for legally sufficient knowledge-based hazardous waste determinations
  - Guidance on the advantages and disadvantages of different policy frameworks to enable PV module reuse and recycling

WHY THIS MATTERS

PV module stakeholders are vital to advancing PV module circularity. The experience and insights shared by WG1 stakeholders related to PV module management and end-of-life decision-making informed the knowledge gaps and circularity barriers identified in this study. This report can help inform PV EoL decision making and module management practices. It provides a collection of insights from across the PV module value chain for decision-makers to consider as they undergo PV module management processes.

HOW TO APPLY RESULTS

The findings of this project can inform PV plant and module management decision-making and offer strategies to increase circularity. Targeted information on the various topics covered in WG1 may be useful to value chain stakeholders, including 1) module condition assessments and sorting for reuse and recycling; 2) module management policies; and 3) voluntary sustainability and environmental quality standards. While EPRI understands the information in this report to reflect the current trends, the nature of the study is such that these findings are not intended to be used for the explicit purpose of informing public regulatory discussions or policy arguments.

Executive Summary

LEARNING AND ENGAGEMENT OPPORTUNITIES

- **EPRI** Program 252: Environmental Aspects of Solar Supplemental Program | Program Home (epri.com)
- **NREL** Photovoltaics in the Circular Economy | Photovoltaic Research | NREL

EPRI CONTACTS: Cara Libby, Principal Technical Leader, clibby@epri.com

PROGRAM: Environmental Aspects of Solar (P252).

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Introduction to NSF SOLAR

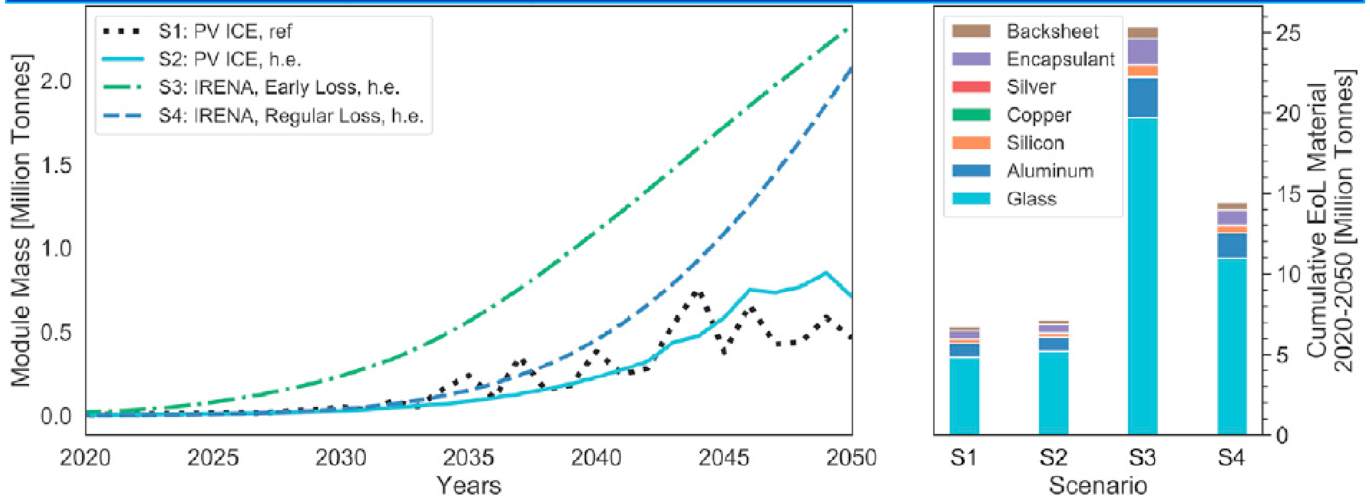
Opportunity for Circularity

Solar energy is expected to play a key role in achieving decarbonization goals. U.S. PV capacity is expected to grow from about 150 GW in mid-2023 to over 1 TW by 2050. There are several motivating factors to proactively establish materials circularity for PV.

- Utility-scale PV systems are just starting to reach end of life, but cumulative U.S. volumes could reach 7 to 25 Mt by 2050.
- Solar PV manufacturing demand for silver in 2030 may exceed 30% of global 2020-level silver production.
- Circular materials economy can reduce solar PV GHG emissions 30-50%.
- It costs $1-5 to landfill a PV module, but $15-45 to recycle.

U.S. Yearly End-of-Life PV Module Material by Scenario

Scenario variables include different levels of electrification and different lifetime, degradation, and failure assumptions

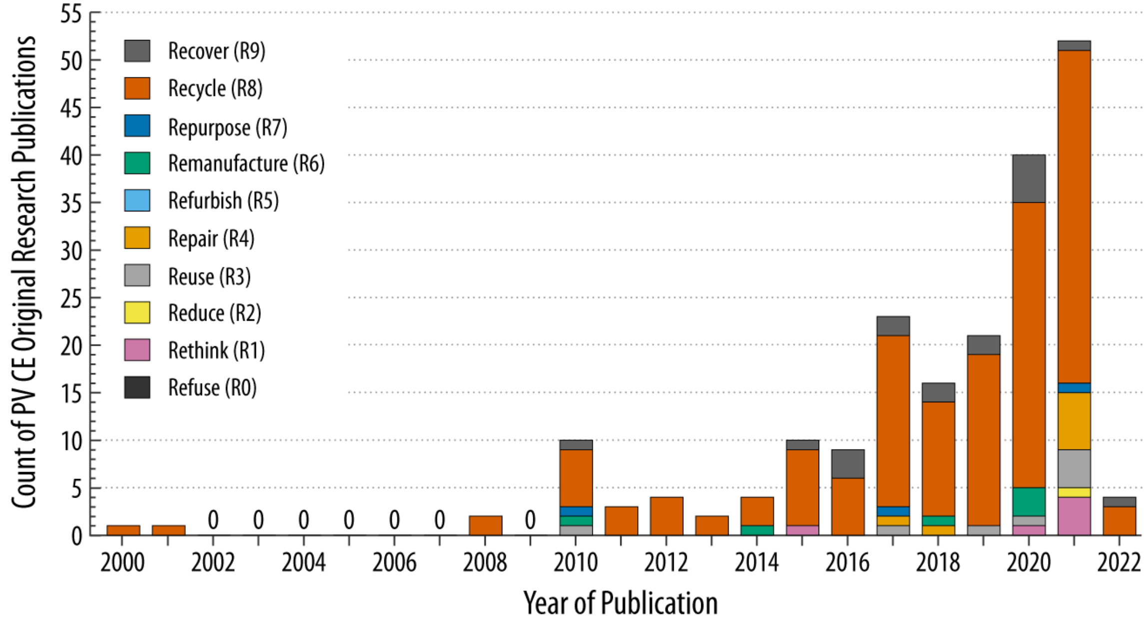


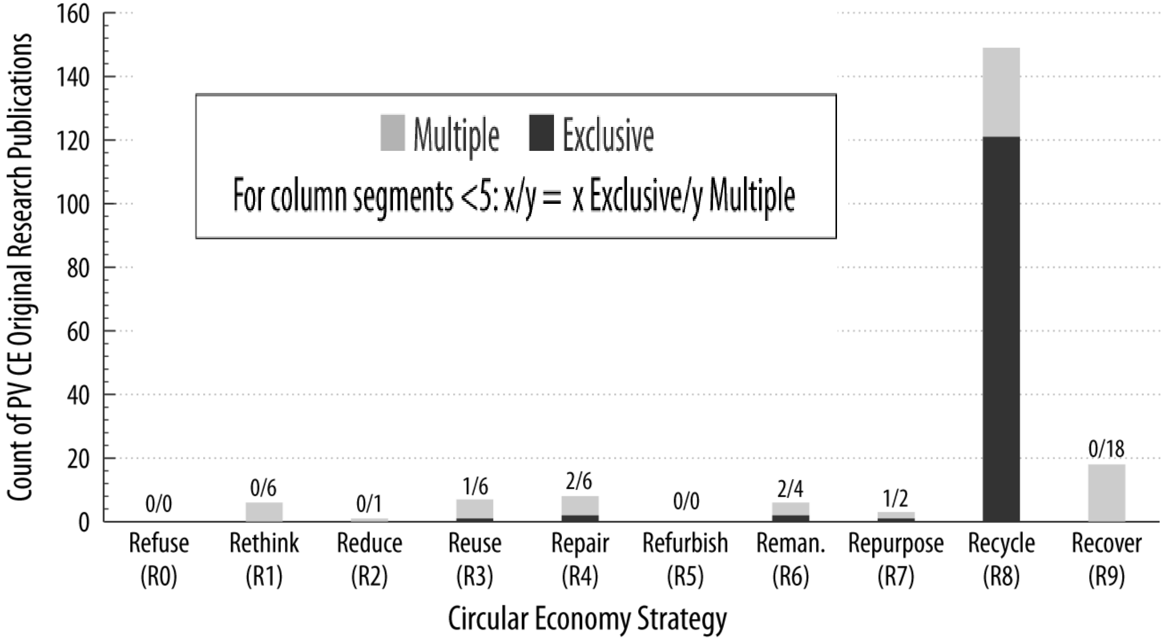
Source: Ovaitt, et *al*., 2021.

Source: IEA 2023; Curtis et al. 2021a; Curtis et al. 2021b; Wikoff et al. 2022

PV Circularity Research is Growing to Address this Opportunity…

Large amount of research on PV module recycling, but lower amounts of research on other aspects of circularity.





- 1,757 publications reviewed
  - 181 passed screens
- 70 classifications

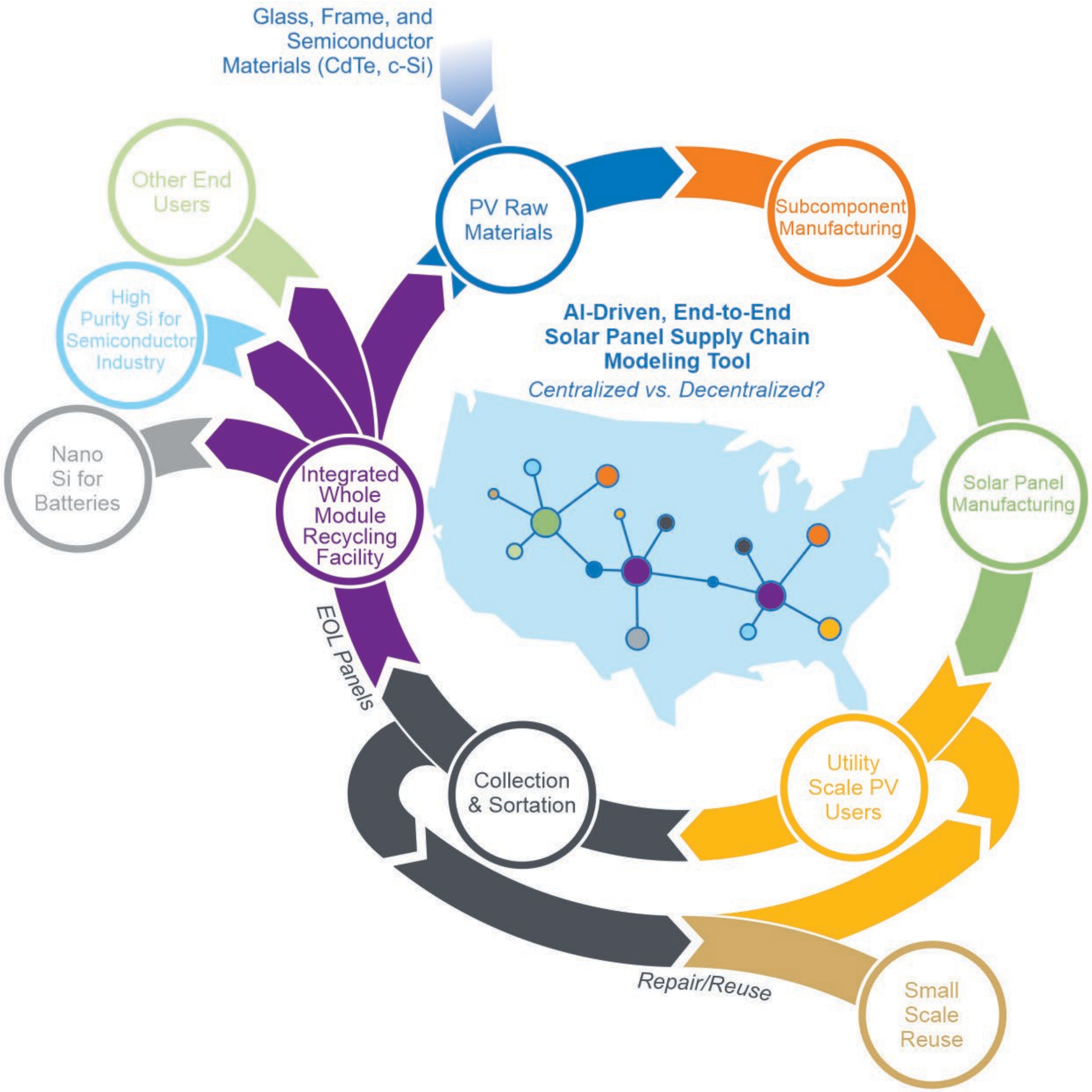
Source: A critical review of the circular economy for lithium-ion batteries and photovoltaic modules – status, challenges, and opportunities by Garvin Heath, Dwarakanath Ravikumar, Brianna Hansen, and Elaine Kupets taken from Journal of the Air & Waste Management Association © 2022 Alliance for Sustainable Energy, LLC. Published with license by Taylor & Francis Group, LLC.

3 Topics of Focus for SOLAR

1. **End of Life/Module Management**
   - Module condition assessment and sorting for reuse and recycling
   - Module management policies
   - Voluntary sustainability and environmental quality standards

2. **Converging Advances in Recycling and Upcycling**
   - Scale, optimization and demonstration
   - End markets

3. **Next-Generation Supply Chain and Logistics**
   - Transportation
   - Centralized vs. decentralized processes
   - Waste classification policies



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NSF Convergence Accelerator

- **Phase 1**
  - One-year planning effort
  - Apply multidisciplinary approach to develop initial ideas and identify new team members and partners
- **Phase 2**
  - Two-year effort focused on developing sustainable and impactful project deliverables at scale

Phase 1 Key Takeaways for Working Group 1:
End-of-Life Decision-Making and PV Module Management

WG1 End-of-Life Decision-Making and PV Module Management

NSF SOLAR Working Group 1 hosted 10 stakeholder engagement sessions dedicated to 3 topics:

1. Module condition assessment and sorting for reuse and recycling
2. Module management policies
3. Voluntary sustainability and environmental quality standards

- On average ~35 PV module value chain stakeholders joined each of the working group sessions:
  - PV module manufacturers and recyclers
  - R&D and academia thought leaders
  - Federal and state regulators
  - Electric utilities
  - Industry professionals

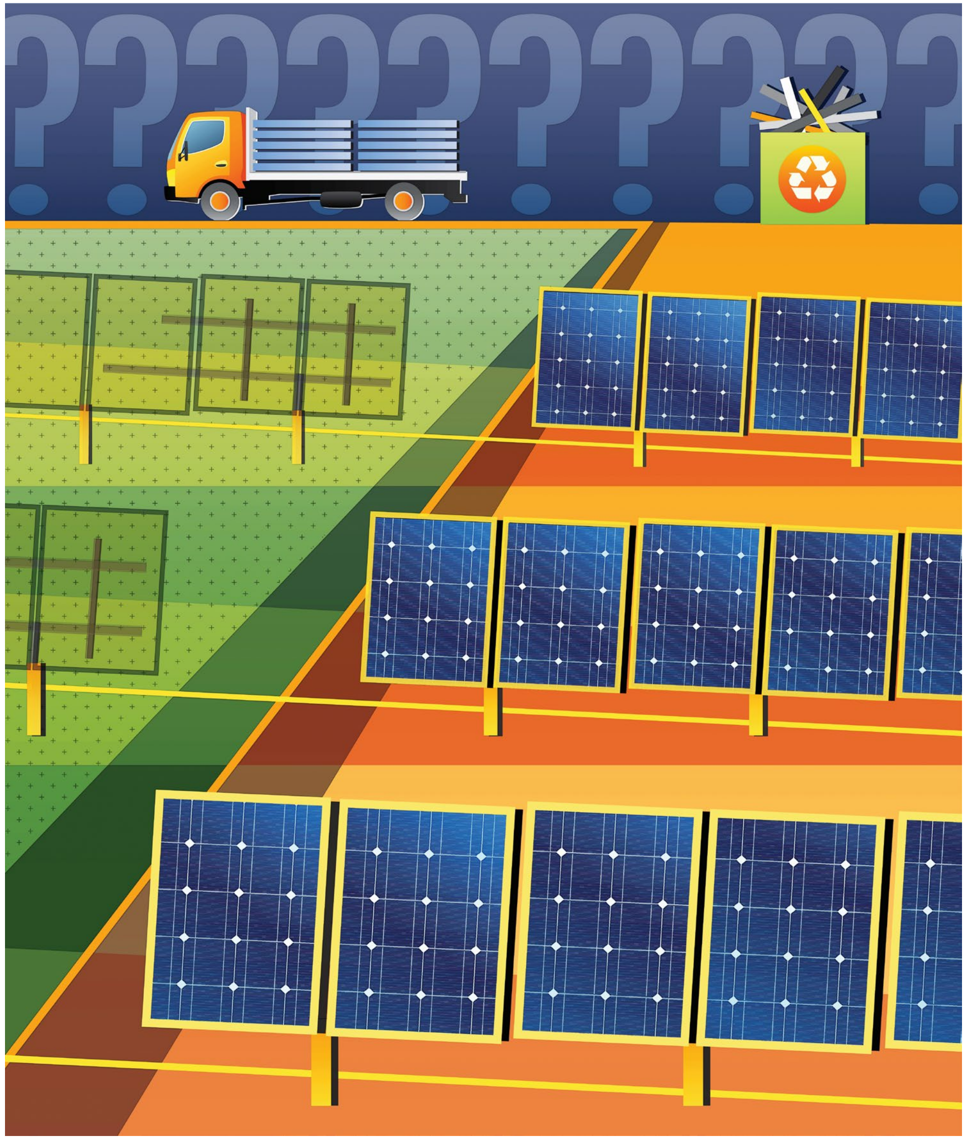
Topic 1: Module Condition Assessment and Sorting for Reuse and Recycling

- Phase 1 discussions included:
  - Level-setting discussions on approaches for PV module diagnostic testing, e.g., in-field vs. central indoor facility
  - Module performance and safety assessment techniques
  - Standards to address module repair and reuse, such as:
    - International Electrotechnical Commission (IEC 82) TR 63525 ED1 – Reuse of PV modules and circular economy
    - International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) Task 13 – Reliability and Performance of PV Systems, Subtask 1.2
    - International PV Quality Assurance Task Force (PVQAT) Task Group 15 – Repair, Reuse, Recertification, and Recycling of PV
- Stakeholders identified needs for:
  - Guidance on PV plant management decisions
    - Maintenance vs. refurbishment vs. repower vs. decommissioning?
    - When to take modules out of first-life service?
  - Improved tools and methods for efficient module condition assessment and sortation
    - Standardized approach to module management decision-making
    - Technology to quickly detect module defects and damage, such as cell cracks
  - Workforce development training for workers to assess module condition

Topic 1

Proof of concept prototype photoluminescence (PL) PLatypus imaging system to detect cell cracks in field-mounted modules (Credit: NREL)

Plant Management Decisions



Topic 1

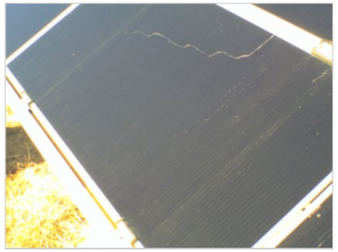
- Plant owners are often legally responsible for the management of retired modules and their disposition
- Typical module warranty provisions guarantee performance for 25 to 30 years, but early losses due to damage, degradation, or failure drive the need for near-term management options
- Decisions may be influenced by
  - Performance and safety
  - Economics
  - Policy/regulations
  - Environmental responsibility practices, e.g., corporate sustainability goals
  - Availability of module management services

PV Module Condition Assessment

Topic 1

In-Field Diagnostic Techniques

- Visual inspection and infrared (IR) scans are commonly used for detecting hot spots and other problems
- Current-voltage (I-V) curve traces of strings and modules indicate performance
- Ultraviolet fluorescence (UVF) imaging can detect and characterize cell cracks but only works with specific module bill of materials, namely glass/backsheet packages with certain encapsulant formulations
- Electroluminescence (EL) imaging is used for detection of cracks and other defects, but requires electrical connection to each module



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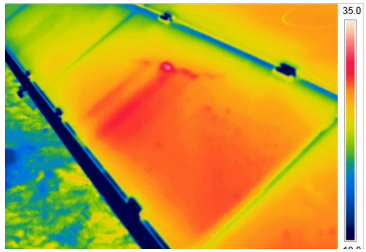
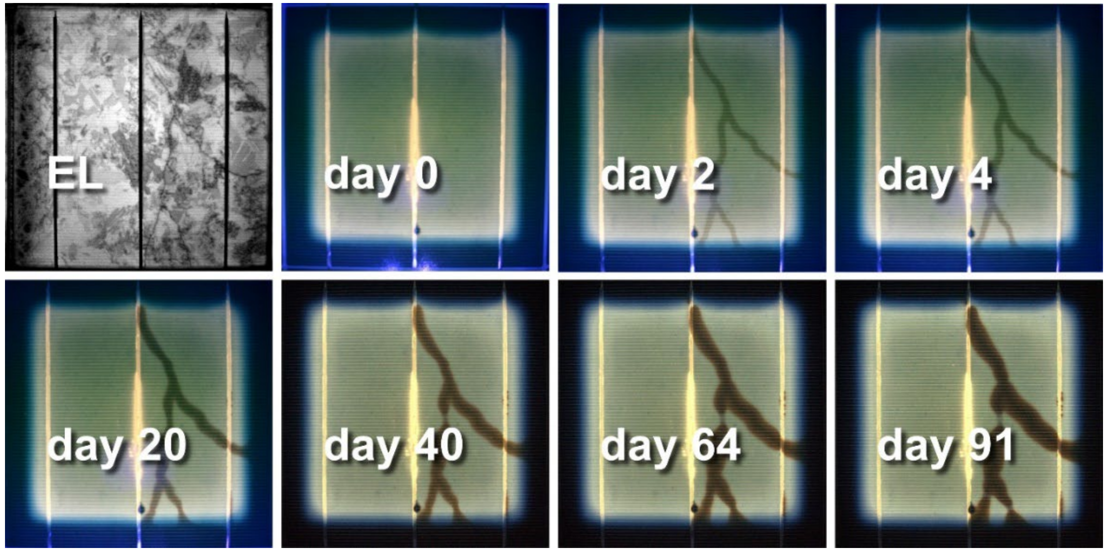
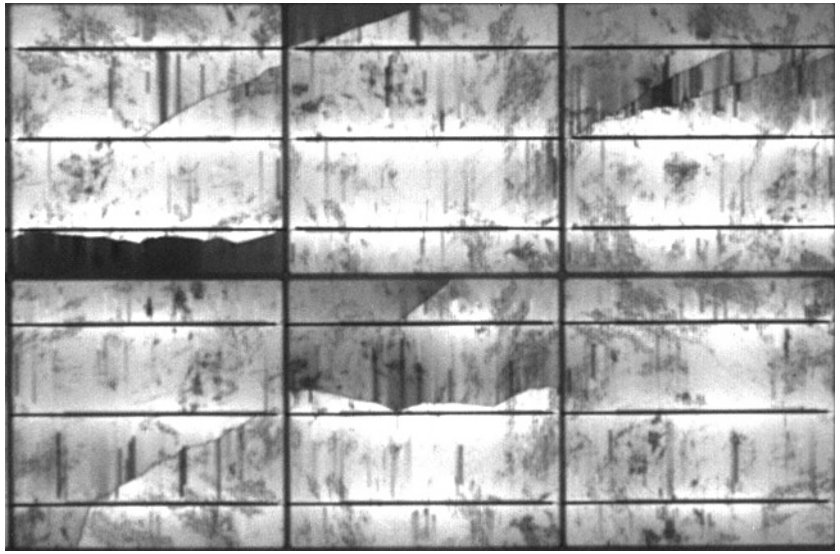


IR Image



Images provided by Will Hobbs (Southern Company) and Steve Johnston (NREL)

UVF Images of Crack Growth vs. EL Image (top left)



EL Image

Source: W. Hobbs, et al. 2020; EPRI 2018; EPRI 2019

Module Decision Making Considerations

Topic 1

- Potential for module damage during handling/re-handling for module-level electrical testing
- Efficiency of visual and/or thermal testing while modules are installed outdoors
- Logistics of assessing and sorting in or near solar PV field vs. central indoor facility
- Risk of failure-prone modules being sold for reuse based on current condition without considering experience of other modules in the system, e.g., modules prone to hot spots
- Feasibility of process control for repair/refurbishment
- Applicable test protocols and sorting criteria, e.g., thresholds for cell crack characteristics, based on intended future use

EPRI

Insights Provided by WG1 Stakeholders

Topic 1

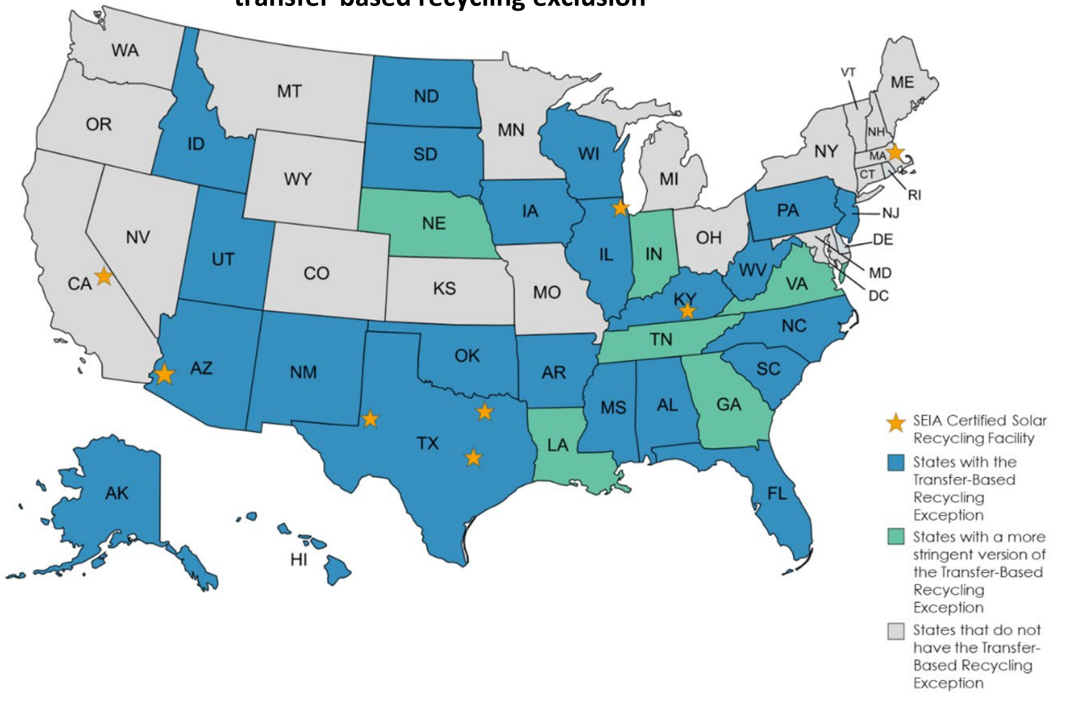
- Individual PV plant owners typically develop their own decision trees and approaches to considering plant management options, such as decommissioning, repowering, maintenance, and refurbishment
- Similarly, there is no standard guidance on module management decision-making
  - Existing processes to characterize module condition are highly manual
  - Service providers use different approaches and tools to assess causes of module performance issues and failures
  - Stakeholders are split on the merits of assessing every single module v. batch testing for potential reuse
- A standardized approach to module management decision-making is needed
  - There is a need for more efficient tools and methods to assess module condition and sort for repair, reuse (resale or donation), or recycling
  - Technology to quickly detect module defects and damage, such as cell cracks, is needed
- Field technicians that dismantle solar PV facilities typically do not have the skills to assess module condition and sort them
- Workforce development training is needed for workers to learn how to assess module condition, including the sequence of inspections and testing

Topic 2: Module Management Policies

- Phase 1 discussions included:
  - regulatory requirements for reuse, repair, decommissioning, handling, transport and storage of PV modules prior to recycling
  - hazardous waste determinations for PV modules
  - policy frameworks, including extended producer responsibility (EPR), universal waste, transfer-based recycling exclusion, and alternative regulatory schemes for recycling
- Stakeholders identified needs for:
  - guidance on federal and state regulatory requirements for for reuse, repair, decommissioning, handling, transport and storage of PV modules
  - solutions to accurately and efficiently determine bill of materials for PV modules
  - improved hazardous waste determination procedure
  - guidance on policy options for increased circularity

- There are several regulatory federal exclusions or exemptions that may apply to PV module recycling that may make it "easier" in terms of the requirements mandated by law – including no requirement to make a hazardous waste determination
- But there is uncertainty as to whether these exclusions and exemptions apply (and if so, under what circumstances)
  - Ex. Household hazardous waste exclusion may apply to residential PV modules in some jurisdictions
  - Ex. Reclamation exclusion may apply to PV module manufacturers that have an on-site recycling facility
- Limited legal analysis on application to PV modules and patchwork adoption of federal exclusions and exemptions has led to uncertainty and concerns of legal liability and potential over management of PV modules as hazardous

Map of U.S. states that have adopted the transfer-based recycling exclusion



Source: Maps modified from Curtis et al. 2021; Curtis et al. 2024 forthcoming

Regulatory Requirements for PV Modules

Topic 2

Hazardous Waste Determinations

- A hazardous waste determination is required as a pre-requisite to PV module recycling in most states
- Resource Conservation and Recovery Act (RCRA) – federally enforced presumption that PV modules are hazardous until proven otherwise
- Manufacturing data (e.g., safety data sheets, bill of materials) today typically do not include detailed concentrations of material less than 1% by module weight
- Toxicity Characteristic Leaching Procedure (TCLP) – primary Environmental Protection Agency (EPA) test to determine if PV modules should be regulated and managed as hazardous waste prior to recycling
- Other EPA-approved test methods like California's Waste Extraction Test (WET) may be required in lieu or in addition to TCLP
- Using "knowledge" in lieu of EPA-approved test methods is an existing regulatory option but is relatively unknown

Hazardous Waste Management

- If PV modules are regulated as hazardous, stringent federal and state hazardous waste requirements for on-site accumulation, storage, handling, transport, and treatment may apply
  - Ex. Limit the # of PV modules and # days PV modules can be stored prior to recycling
  - Ex. May need a RCRA permit, and need to comply with specific training, notice, documentation, record keeping, reporting, packing and labeling requirements
- PV module recyclers that store and treat PV modules regulated as hazardous may also have to comply with stringent and costly federal, state and local solid waste requirements, e.g., hazardous waste facility permit, record keeping, reporting, liability insurance
- Transporters and handlers may also need to comply with U.S. Department of Transportation hazardous material requirements to transport PV modules regulated as hazardous offsite
- Noncompliance with federal and state regulatory requirements may result in civil and criminal penalties

Source: Curtis et al. 2021a; Curtis et al. 2024 forthcoming

PV Module Toxicity

Topic 2

- Installed PV modules and some new modules deployed today may contain trace amounts of heavy metals (e.g., lead)
- PV modules being recycled or landfilled that exceed any of the regulatory limits for toxic metals (e.g., 5 mg/L of Pb) must be regulated and managed as hazardous waste
- Today toxicity labeling is not required for PV modules, and manufacturing data typically do not include precise concentrations of heavy metals
- There are limited studies to inform the potential for toxic metals to leach from a PV module under different conditions (e.g., cracked) and management scenarios prior to recycling

Regulatory Limits for Toxic Metals in Leachate

	EPA TCLP Method 1311 (mg/L)[1]	California WET Method (mg/L)[2]
Lead (Pb)	5	5
Copper (Cu)	–	25
Zinc (Zn)	–	250
Silver (Ag)	5	5
Nickel (Ni)	–	20
Cadmium (Cd)	1	1
Selenium (Se)	1	1
Molybdenum (Mo)	–	350
Arsenic (As)	5	5
Barium (Ba)	100	100
Chromium (Cr)	5	5
Mercury (Hg)	0.2	0.2

[1] EPA

[2] CA EPA Department of Toxic Substances Control (DTSC)

Source: F. Li, et al. 2022

Acceptable Knowledge as an Alternative to TCLP

Topic 2

Knowledge can be used in lieu of an EPA-approved test method, such as TCLP, to determine whether a PV module must be regulated as hazardous waste (40 C.F.R. §§262.11, 261.24).

- Knowledge is an existing regulatory option but is relatively unknown

Acceptable Knowledge can include:

- **process knowledge** (e.g., information about chemical feedstocks and other inputs to the production process)
- **knowledge of products**…by the manufacturing process
- **chemical or physical characterization** of wastes
- **information on the chemical and physical properties**
- **testing other than TCLP** (e.g., total waste analysis)
- **other reliable information** (40 C.F.R. §§261.11(d)(1); RO13647)

"**process knowledge is a substitute for physical testing** that may be gleaned from **data and records produced at some point when there was reliable knowledge**" (*U.S. v. Hoffman,* 154 Wash. 2d 730 [Wash. 2005]).

EPA may allow **test data on wastes very similar to other wastes to be used in place of testing and may allow previous analytical data from similar wastes as acceptable knowledge** (RO13506; RO11829).

"Waste" here is a regulatory term that can include recyclable products/products destined for recycling (not yet processed)

Source: Curtis et al. 2021a; Curtis et al. 2024 forthcoming

Using Knowledge for PV Module Hazardous Waste Determinations

Topic 2

What ***forms***, and ***sources*** of information/data could be used to make an accurate, and legally sufficient knowledge-based hazardous waste determination for PV modules?

Forms of Information *examples*

- Product documentation, including bill of materials, safety data sheets, product labels
- Studies, analyses, and/or test data
- Online databases

Sources of Information *examples*

- PV module manufacturers
- Government and/or independent laboratories and testing facilities
- Recyclers
- Asset owners

Does the ***timing*** at which information is generated and then used to make a knowledge-based hazardous waste determination impact accuracy/legal sufficiency? *What **level of detail*** is required?

- Ex. Information/data generated prior to the point of sale/first use and used sometime after the point of sale (e.g., 10 years, 20 years later)
- Ex. List of all constituents in a particular PV module model and the exact quantity of those materials (percentage by weight) v. List of only the metals of concern and the quantity of those metals (percentage by weight)

Hypothesis

Knowledge can be used in lieu of an EPA-approved test method, such as TCLP, to make a legally sufficient hazardous waste determination for PV panels.

A wide range of forms and sources of information can be used to make an accurate and legally sufficient knowledge-based hazardous waste determination for PV panels.

Information generated sometime before the PV panel is used could be legally sufficient to make an accurate knowledge-based hazardous waste determination for PV panels.

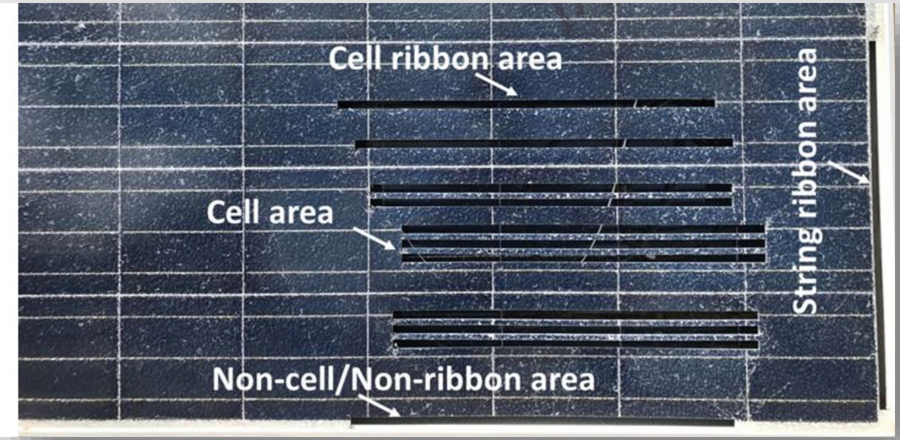
Information used to make a hazardous waste determination for one PV panel may be applied to make an accurate and legally sufficient knowledge-based hazardous waste determination for another PV panel so long as the information is relevant.

Source: Curtis et al. 2024 forthcoming

Topic 2

ASTM Standard Practice (E3325-21): *Sampling of Solar PV Modules for Toxicity Testing*

- Standard sampling practice was developed to reduce variability in TCLP pass/fail test results
- Procedure based on a waterjet cutting method that uses proportional sampling
  - Square pieces obtained from cell ribbon and cell areas
  - Rectangular pieces from non-cell/non-ribbon and string ribbon areas
- Instructions for both c-Si and CdTe technologies and 60- and 72-cell modules



Credit: Arizona State University

Proportionally representative TCLP test samples are extracted from different areas within the module laminate

Credit: EPRI

Waterjet cutting

Credit: EPRI

Samples sent to TCLP lab

5. Summary of Practice

5.1 This practice presents a representative and repeatable methodology to remove sample pieces from PV modules for later use in the TCLP testing. This practice refers to the extraction and preparation of PV module sample pieces complying to the EPA Method 1311 for later testing to eight (8) distinct metals – mercury (by Method 7470A), arsenic, barium, cadmium, chromium, lead, selenium and silver (by Method 6010C) as well as the analysis and interpretation of the TCLP test results on a module level.

5.2 Sample pieces must be 9.3 by 9.3 – 9.5 by 9.5 mm square.

5.3 The total weight of all sample pieces must be a minimum of 100 g for TCLP testing, plus 5–10 g for pH testing.

5.4 For both module types (crystalline silicon and cadmium telluride), the following step-wise procedure is used:

5.4.1 Measure the required areas of the module; these differ for crystalline-Si (four areas) and CdTe (three areas) modules.

5.4.2 Calculate the percentage of the total laminate area for each required area.

5.4.3 Estimate the number of samples needed from the total weight of samples needed divided by the average weight of a sample piece.

5.4.4 Remove samples using the waterjet cutting approach.

5.4.5 Rinse and dry samples.

5.4.6 Group samples according to the areas from which they were removed.

5.4.7 Weigh all samples in each area group.

5.4.8 Calculate the number of samples needed for each area group.

5.4.9 Verify that the samples meet the total weight in 5.3.

5.4.10 Submit the samples for TCLP testing.

Source: ASTM 2021; F. Li, et *al.* 2022

Insights Provided by WG1 Stakeholders

Topic 2

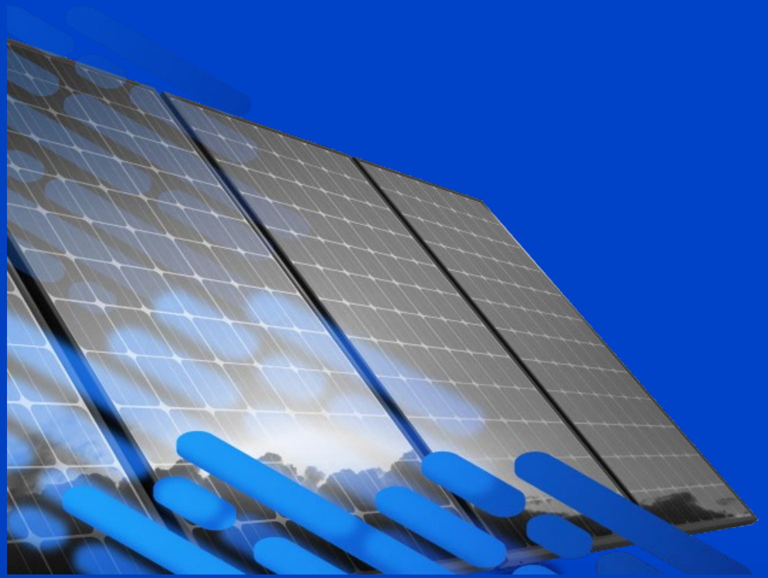
- Stakeholders voiced challenges with predominant hazardous waste determination methods
  - TCLP test result variability evidenced at greater than 50%
  - Differences in cutting approach, location of samples within the module laminate, crushing of the sample, and other factors can generate different TCLP results, and in the worst case allow people to “game the system”
- ASTM E3325-21 sampling standard reduces variability in TCLP results but may be time and cost prohibitive
- Uncertainty associated with TCLP test results is creating liability concerns/impacting recycling
  - Conflation of sampling modules and toxicity testing – such as obtaining representative samples (ASTM E3325-21) and running a toxicity test procedure (TCLP testing) – has caused confusion in PV module recycling discussions
  - Fear of noncompliance due to untrustworthy test results leads to PV module disposal in hazardous waste landfills by asset owners who would otherwise be willing to pay higher costs for recycling
- Scalable solution is needed to efficiently and accurately determine whether PV modules must be regulated as hazardous waste
- Acceptable knowledge is an existing legal pathway that allows for information/data and other tests (if approved) as an alternative to TCLP
- Requirements/restrictions for PV modules regulated as hazardous waste make it more costly and challenging to recycle
  - Obstacles in transporting PV modules between states, counties, and districts with varying hazardous waste requirements/restrictions
- Exportation of modules marketed as reuse in bad-faith to avoid regulation
- Lack of consensus around effective PV module circularity policies and a need for policy analysis on advantages and challenges of policy options. Debates around efficacy of universal waste (UW) hazardous waste alternative regulatory option, transfer-based recycling exclusion, EPR, voluntary take-back programs, and other policy frameworks to promote circularity

Topic 3: Voluntary Sustainability and Environmental Quality Standards

- Phase 1 discussions included:
  - National and international voluntary sustainability and environmental quality industry standards application to PV modules and solar PV industry
- Stakeholders identified needs for:
  - Guidance on voluntary industry standards application to PV modules and solar PV industry (e.g., benefits analysis)
  - Gap analysis of current industry standards and need for modifications or additions to promote PV circularity

There are several standards under development for PV modules that address sustainable design, module management, and business practices of industry actors (e.g., manufacturers and recyclers)

Topic 3



Current Voluntary Standards that Apply to PV Modules

Topic 3

Current Voluntary Standards that Apply to PV Modules	Applicability	Description
EPEAT Ecolabel for PV Modules and Inverters (based on NSF/ ANSI (American National Standards Institute) 457 Sustainability Leadership Standard for PV Modules and Inverters)	International	Provides information to consumers about sustainable business practices of solar PV manufacturers; framework and standardized sustainability criteria for manufacturers
SERI (Sustainable Electronics Recycling International) Responsible Recycling (R2) Standard	International	Provides a framework and standardized criteria to aid electronic recyclers in sustainable business practices
Silicon Valley Toxics Coalition (SVTC) Solar Scorecard	United States	Provides information to consumers about the business practices of solar PV manufacturers
China Photovoltaic Industry Association Standard TCPIA 0002-2017	China	Provides guidance on collecting, transporting, storing, dismantling, processing, and recycling thin-film PV modules including compliance with national/federal regulatory requirements
ISO 14001 Environmental Management Systems Standard	International	Provides a framework and standardized criteria for an organization/company to develop an effective environmental management system to demonstrate compliance with environmental, health and safety (EH&S) requirements
Recycling Industry Operating Standard (RIOS™)	International	Provides a framework for recyclers to achieve measurable environmentally responsible and efficient performance objectives and demonstrate compliance with EH&S requirements
Ethical and Responsible Reuse, Recycling and Disposition of Electronic Equipment and Information Technology (e-Stewards)	International	Provides a framework and set of criteria for an organization/company to ensure environmentally responsible electronics reuse and recycling practices and incorporates ISO 14001 Standard requirements

Source: Curtis et al. 2021b

Updates to Voluntary Industry Standards during NSF SOLAR WG1 Stakeholder Engagement Sessions

Topic 3

- SERI R2 Standard – currently adding PV modules to existing standards through editing appendices to make PV modules applicable to existing equipment standards
  - Establishes a hierarchy of reuse, repair, recycling
- EPEAT – global label to identify more sustainable electronics with a new product category for solar PV
  - Criteria around recycled content, product takeback and responsible recycling
  - Primarily a procurement standard – remanufacturing over recycling and a criterion for reuse and remanufacturing achievement increase clarity
  - Seeking improvements to these processes in 2024

EPRI

Insights Provided by WG1 Stakeholders

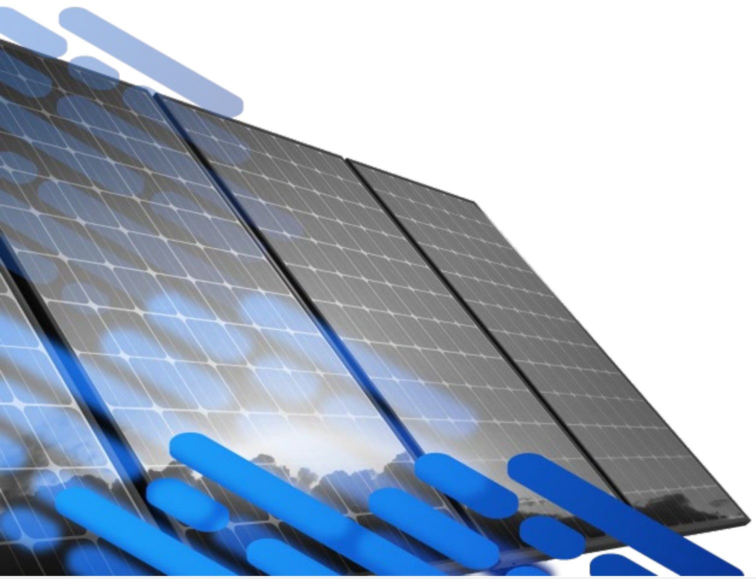
Topic 3

- Lack of data on if and how voluntary industry standards promote reuse and repair above recycling
  - Efforts are underway through IEC 82 TR 63525 ED1 and IEA PVPS Task 13 Subtask 1.2 to develop testing specifications and screening protocols to assess potential for module reuse
- There is a range of specifications for different PV modules and the variance of component make up – challenges with BOM verification
- The U.S. national electric code requires that you follow installation instructions for second life PV modules, yet there are no instructions on how to remove and transport PV modules
- If a used module does not meet specifications for utility installation, could it still be used for residential, industrial or research uses?
  - There are no guidelines or agreement between installers on reuse practices
- There is a need for more study on standards for reuse and repair or refurbishment; stakeholders have a lot of questions about warranties for second-life modules
- Standards such as EPEAT that focus on sustainability requirements for PV module design can ease later module management actions, such as repair, reuse, and recycling
- End users can send demand signals to promote recycling and modules designed with enhanced sustainability by referencing standards such as R2 and EPEAT, asking suppliers about the environmental attributes, e.g., lower embodied carbon, and establishing stringent supply chain requirements for procurement

Looking Ahead
Next Steps and Proposed Tasks for Ongoing Research

Phase 2 Plans

SOLAR proposes to develop a consortium and technology toolkits to close solar PV circularity gaps. Based on input from WG1 stakeholders in Phase 1, the project team defined knowledge gaps and barriers. In Phase 2, EPRI would lead development of an EoL Management Toolkit (Activity 1), in partnership with NREL, to support WG1 stakeholder needs.



SOLAR

Activity 1: EoL Management Toolkit Development

1. PV plant management decisions
2. PV module condition assessment and sortation methods
3. Workforce development for in-field module condition assessment and sortation
4. Addressing PV module toxicity concerns and hazardous waste determination challenges
5. Policies and standards to progress PV module circularity

#1 Need for Guidance on PV Plant Management Decisions

Phase 1 WG1 Impressions

- Plant management decisions may include continuing to operate and maintain by extending the period of performance often with partial or full system refurbishment (e.g., replacements, upgrades), or repowering, or decommissioning the system.
- There is limited guidance regarding system refurbishment, repowering or decommissioning.
- There is also limited guidance about when to retire system equipment (e.g., PV modules), or best practices for handling, storing and transporting equipment prior to final disposition or about disposition options including reuse and recycling.
- The cost (or salvage value) of managing PV modules is an important financial factor in evaluating PV plant management decisions, along with other economic, performance, safety, and social considerations.

Phase 2, Task 1: PV plant management decisions

- Interview utilities and third-party owners (i.e., power purchase agreements) about PV plant management decision-making practices
- Create a decision tree and accompanying guidance to support PV plant owners and operators that are facing PV plant management decisions

#2 Need for Improved Tools and Methods for Module Condition Assessment and Sortation

Phase 1 WG1 Impressions

- A standardized approach to decision making would be helpful
  - Module assessment methods for reuse vs. recycling vary
  - Testing individual modules is time consuming and expensive
- Knowledge of performance history, environmental exposure, type of defect, safety risk, etc. is important in decision making

Phase 2, Task 2: PV module condition assessment and sortation methods

- Develop a flow chart and accompanying field guide for in-field module condition assessment and sortation
- Develop in-field photoluminescence (PL) imaging to rapidly detect cell cracks
- Define path for automated decision making
- Pilot test in-field PV module assessment and sortation techniques at a commercial PV plant
- Compare/contrast testing options in-field vs. central indoor facility and hybrid approaches, e.g., mobile laboratory

#3 Workforce Development

Phase 1 WG1 Impressions

- Sorting for reuse vs. recycling typically happens in central recycling/EOL management facilities at least in part because field personnel do not have the skills to inspect modules and sort them.
- There is a lack of experience decommissioning or repowering large-scale PV plants.
- There is a need for training on how to assess PV module condition in the field and sort modules efficiently prior to shipping.

Phase 2, Task 3: Workforce development for in-field module condition assessment and sortation

- Develop training for workers in disadvantaged communities on how to assess module condition in the field and sort modules prior to shipping
- Publish classroom “simulation” training materials and an online, on-demand EPRI|U training program

#4 Challenges with Predominant Hazardous Waste Determination Methods

Phase 1 WG1 Impressions

- TCLP test result variability evidenced at greater than 50%
- ASTM standard reduces variability but may be time and cost prohibitive
- Uncertainty associated with TCLP test results is creating liability concerns/impacting recycling
- Scalable solution is needed to efficiently and accurately determine whether PV modules must be regulated as hazardous

Phase 2, Task 4: Addressing PV Module Toxicity Concerns

- Investigate using knowledge to make an accurate and legally sufficient hazardous waste determination
- Create management scenario mapping and best management practices
- Conduct toxicity testing to generate knowledge of health and environmental risks at EoL

#5 Regulatory Barriers and Policy/Standards to Progress PV Module Circularity

Phase 1 WG1 Impressions

- Requirements/restrictions for PV modules regulated as hazardous waste are barriers to recycling
- Obstacles in transporting PV modules between states, counties, and districts with varying hazardous waste requirements/restrictions
- Lack of consensus around effective PV module circularity policies
  - Debates around efficacy of universal waste, transfer-based recycling exclusion, EPR, voluntary take-back programs, etc. to promote circularity
- Current sustainability and environmental quality standards for PV modules are in development
  - A need for expert commentary or recommendations for relevant standards

Phase 2, Task 5: Policies and Standards to Progress PV Module Circularity

- Review and analyze policy options
- Inform and track activities of international standards development for PV circularity
- Working Group continuation and expansion to underrepresented groups

Further Engagement Opportunities

If awarded, Phase 2 work would start in 2024. Plans include continuation of WG1 and expansion to engage underrepresented groups in regions where large-scale solar PV projects have been developed and PV EoL materials may be managed.

EPRI's solar PV circular economy research is primarily conducted through the Environmental Aspects of Solar Program (P252) and Circular Economy for Energy Technologies Interest Group

NREL resources can be found at NREL Photovoltaics in the Circular Economy

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