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MANAGING END-OF-LIFE RISK FOR SOLAR PV:

A Systems Approach to Circularity in the United States

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UNIVERSITY OF MICHIGAN

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Abstract

As solar capacity grows in the United States, there are increasing concerns about managing End-of-Life (EoL) photovoltaic (PV) modules. Circularity through reuse and recycling aims to reduce EoL management costs, toxicity concerns, liability concerns, and raw material procurement. This study aimed to analyze the current state of PV circularity and identify potential strategies for improving PV circularity outcomes in the United States, focusing on four areas of circularity concern: (1) the current state of EoL management and toxicity characterization, including end-of-life management pathways and PV toxicity risks; (2) community concerns about solar development and how governance and project-level decisions are made; (3) industry-level circularity concerns using a comparative study of the lead acid battery industry; and (4) understanding the current state of PV end of life policy in the United States, and how those policies are affecting circularity in the industry. The identified drivers and barriers to circularity are critical information in the effort to develop strategies promoting circularity.

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Introduction

Rapid acceleration of solar photovoltaic (PV) deployment in the United States has presented a critical emerging challenge: the systematic management of PV modules at end-of-life (EoL). Even with solar power being a cornerstone of national decarbonization, the infrastructure and regulatory frameworks required to capture and reintegrate material flows remain fragmented and economically infeasible at scale (Masson et al., 2024). This disconnect creates a paradoxical pipeline in which low-carbon technology generates a high-volume waste stream (Li et al., 2024). By bridging quantitative material flow analysis with qualitative stakeholder and community insights, this study seeks to resolve this by transforming EoL liability into a resilient, circular supply chain that supports the long-term sustainability of the American energy transition.

This study presents a mixed-methods analysis to identify the structural conditions necessary to enable a robust circular economy for PV in the United States. Rather than treating recycling as just a downstream technical and economic hurdle, circularity is an emergent property of interacting policy, industry, community, and regulatory-technical systems. To examine these dynamics, we investigated raw material extraction, manufacturing, installation, and operations, and EoL processes of the PV lifecycle, beginning with the evolving policy landscape. Although there has been an increase in legislative activity, the current policy environment has had limited market impact. While state-level initiatives proliferate, many remain non-binding or lack the clear liability structures and financial mechanisms required to incentivize circular outcomes at scale.

The industrial architecture of PV must be benchmarked against established models to understand the drivers of material recovery and circularity. By comparing the emerging PV sector to the mature lead-acid battery (LAB) system, this analysis demonstrates that circularity is driven by reinforcing economic value, logistics, regulations, and technology. Currently, the PV industry faces significant characteristic barriers, including low intrinsic material recovery value and highly decentralized, delayed waste streams that challenge traditional economic viability.

Beyond technical and economic factors, the community dimension plays a decisive role in system design. Local concerns regarding toxicity and long-term waste management are increasingly shaping public opposition and land-use governance, suggesting that social acceptance is a critical, yet under-integrated, component of project viability. Finally, a persistent regulatory-technical mismatch complicates the transition to a circular model. Current testing methods, such as the Toxicity Characteristic Leaching Procedure (TCLP), introduce significant classification uncertainty, increasing operational costs and discouraging recycling by framing compliance through risk mitigation rather than resource recovery.

Altogether, this work shows that PV circularity depends on aligning economic incentives, regulatory clarity, logistical systems, and community trust. By integrating quantitative material flow analysis with qualitative stakeholder perspectives, this study proposes a systems-level approach to diagnose structural barriers and identify the reinforcing conditions necessary to enable sustained circular outcomes. PV EoL management can turn from a cost-intensive liability into a potential value-retaining industrial system by improving investment certainty, guiding infrastructure development, and informing more effective policy design. The results provide actionable insight for key stakeholders, including policy makers, developers, recyclers, and utilities, by highlighting high-leverage interventions such as stewardship-based financing mechanisms and standardized and accessible collection networks, by clarifying the liability regime, and by promoting the development of a secondary market.

Future work should focus on implementing and testing some of the proposed strategies. This includes developing scenario-based models to evaluate economic feasibility under varying policy and market conditions, designing and deploying pilot programs to assess logistical and operational performance, and refining regulatory instruments to better align incentives across the value chain. Digital tracking systems, harmonization of federal and state regulatory frameworks, and the maturation of secondary material markets through procurement incentives and quality standardization should be prioritized to enable a scalable and resilient circular economy for PV in the United States.

Scope of Study

This study analyzes four dimensions that drive the progress of EoL PV module circularity in the United States. The dimensions are community, technology, industry, and policy regulation. To understand how community dynamics drive circularity, we analyzed community behaviors and beliefs surrounding PV, including toxicity concerns. To better understand technological barriers and drivers, we assessed how hazardous waste testing protocols affect classification and regulatory outcomes. To understand circularity in the PV industry as a whole, we analyzed the lead acid battery industry, which has similar characteristics to the PV industry but has achieved a much higher rate of circularity. Finally, we investigated statewide PV decommissioning policies to understand political drivers and barriers to circularity.

Policy Landscape Analysis

A systematic survey of state PV decommissioning and EoL policies was conducted to map the United States regulatory environment. These policies were categorized by mechanism type, the effect on government and market actors, and the specific market barriers they target. This categorization enabled identification of policy trends and an analysis of the strengths and weaknesses of different policy types that are necessary for promoting circularity.

Industrial Benchmarking and Material Flow Assessment.

To assess industry conditions, we conducted a comparative analysis between emerging PV EoL systems and the long-established LAB system. This analysis focused on four reinforcing pillars of success: material value and recyclability, established collection infrastructure, market pull and downstream stability, and industrial coordination. By quantifying the gap in intrinsic material value and the decentralization of waste streams between these two systems, we identify the structural thresholds required for a PV recycling market to achieve economic viability without perpetual subsidy.

Socio-Technical Community Dynamics.

Recognizing that system design is constrained by social acceptance, we examined community dynamics through qualitative analysis of recent case studies and datasets on opposition to renewable energy. We specifically interrogated how perceived PV module toxicity concerns and EoL management influence local governance decisions and siting outcomes. This component of the study analyzes social acceptance not as a statistical variable, but as a critical feedback loop that shapes both policy formation and the physical trajectory of project deployment.

Regulatory-Technical Alignment Evaluation.

The study evaluates the alignment between hazardous waste testing protocols and PV module design. Focusing on the TCLP, we developed a semi-quantitative framework to assess common EoL processes across two dimensions: relative sensitivity and operational practicality. Sensitivity was parameterized by extraction conditions, particle size requirements, and duration. This framework facilitated a systemic comparison of leaching-based, compositional, and screening methods. Furthermore, the analysis investigated how sampling procedures, material heterogeneity, and experimental conditions drive variability in classification, which in turn influences regulatory outcomes, compliance costs, and EoL management pathways.

Synthesis

Findings across these four dimensions were used to identify systemic barriers and catalysts for PV circularity. Policy taxonomies, material bottlenecks, community patterns, and classification uncertainty were mapped onto five interacting system dimensions: (i) policy signals and liability structures; (ii) material value and recovery limitations; (iii) logistical and infrastructure constraints; (iv) regulatory classifications and uncertainty; (v) community perception and governance response. Dependencies and feedback loops exist between these dimensions. For example, regulatory ambiguity elevates compliance risk, disincentivizing infrastructure investment, and reinforcing landfilling as the default pathway. Finally, a gap analysis using the LAB benchmark was conducted to define the structural thresholds required for circularity, including clearer liability frameworks, improved material recovery pathways, more accessible collection infrastructure, and stronger alignment between technical standards and regulatory objectives.

Community Landscape

Growing opposition and community concerns

Opposition to renewable energy has increased across the United States since 2021 (Eisenson et al. 2025). Most of the opposition comes from project host communities, which are often in rural areas characterized by minimal high-rise infrastructures, making them desirable to host renewable projects, because of higher electricity generation potential than in urban areas.

The Sabin Center for Climate Change Law, affiliated with Columbia Law School, keeps a record of communities that oppose solar projects. They published a 2025 report that highlights a 16% annual increase in local restrictions to utility-scale solar and wind energy projects, from 395 counties in the U.S.to 459 counties (Eisenson et al. 2025). Of the total number of counties restricting renewable energy projects, 248 counties restrict solar projects, in particular, utility-scale solar energy systems.

Reasons for restrictions reflect unresolved community concerns about using land to install and operate solar PV modules, along with the management of PV modules that have reached end-of-life (EoL) (Curtis, Smith, and Townsend 2026). Concerns transform into opposition when communities learn that PV modules pose a potential risk to public health due to toxic elements that they contain, e.g., cadmium.

How concerns shape project outcomes

Out of 248 counties that impose restrictions on utility-scale solar projects, we were able to identify 44 (using triangulation of social media, local news, public hearings, and local ordinances) that have restrictions specific to PV modules. Of these counties, 54% of view PV modules as a risk to public health. For example, San Bernardino County, California, enacted a ban on large-scale solar and wind projects 2019 to address local concerns of PV module toxicity and impact on water supply for farming. The ban removed “more than one million acres (~1600 square miles) of land” from potentially being utilized for large-scale solar and wind development projects (“San Bernardino County Bans Large-Scale Solar, Wind in Some Areas”

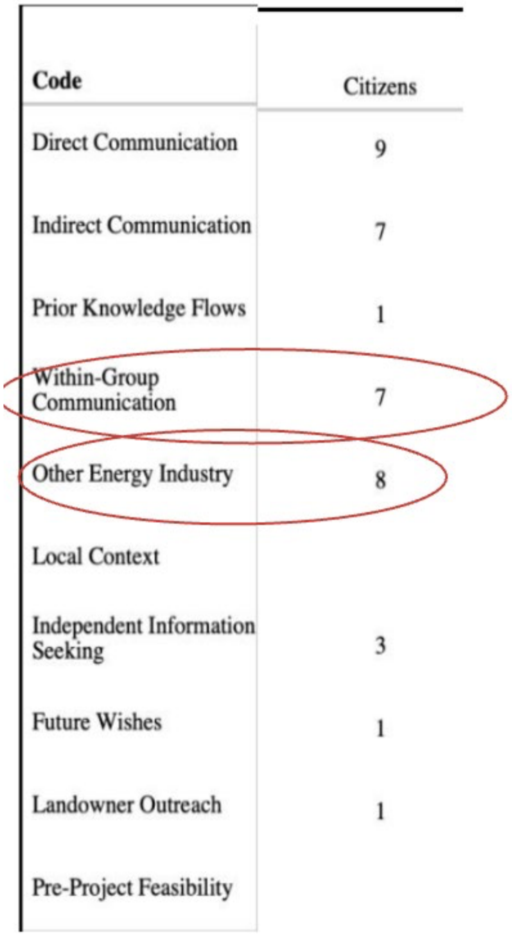
2019). While San Bernardino County justifies restrictions against renewable energy projects based on a combination of agricultural and health risks, several counties have imposed restrictions solely due to the health hazards of utilizing renewable energy technologies. In Bethany Beach, Delaware, the township enacted bans specifically for utility-scale PV modules (Curtis, Smith, and Townsend 2026) in 2010 to address local concerns about perceived PV module toxicity. One resident stated that, “Living in proximity to solar farms may cause cancer and other potential effects on the nervous system” (Metzner, 2023). This concern reflects a perception of PV module toxicity that is not informed by scientific or technical knowledge.

Though California and Delaware have located a sitting approval authority at the local level (Breckel and Falkenburg 2025), not all states’ sitting authority is given primarily to local regulators. Renewable energy project siting decision-making varies by state - some states allocate more sitting power to specific governance levels, and some distribute power equally between state and county-level regulators. But state siting governance is not static; it is continuously shaped by community concerns. For instance, Ohio’s SB 52 (Ohio General Assembly 2021) was created because of community pressure to acquire more sitting authority at the county level. This act allows Ohio counties to veto both solar and wind projects at specific scales, despite projects receiving approval from the Ohio Power Siting Board (Eisenson et al. 2025). Community concerns get codified into regulatory action through two main steps. The first is entering concerns into public records through public hearings and comments, and the second is using public records as inputs to create or revamp existing ordinances or laws. In states where local regulators are given more authority, community voices hold more weight in designing community regulation.

Knowledge flow in communities

Where project approval authority is local, as in Virginia, Ohio, and Indiana (Breckel and Falkenburg 2025), communities seek to get educated about renewable energy from neighboring communities that have had previous experience hosting projects. Figure 1 (Michaud et al. 2024) provides the total counts of specific channels and methods that community residents used to acquire renewable energy projects information from a study that examines knowledge flows in rural communities across Michigan, Minnesota, Wisconsin, Illinois, Indiana, and Ohio. “Within-Group Communication” and “Other Energy Industry” had highest counts as knowledge acquisition methods while “Direct communication” was the most common knowledge-sharing channel. This is consistent with the study results, which suggests that except for landowners who get direct engagement from project developers, rural community residents mostly rely on informal ways of acquiring information through “word-of-mouth” and “interpersonal stories” (Michaud et al. 2024). Trust in information is further built on the knowledge that the source originates from the same stakeholder group. The only community stakeholder groups that get direct engagement from project developers are landowners and local officials, whereas local regulators receive contact once developers submit a bid for the project. Regulators in the study characterized the developer’s outreach as “business-driven and minimally communicative,” which is not in agreement with the solar developer interviewees’ perception that the engagement intended to establish interpersonal relationship with the communities.

NLR reported in 2024 that 8.5% of U.S counties had local ordinances for utility-scale solar projects indicating that the deployment of solar projects is a relatively new concept amongst communities (National Renewable Energy Laboratory 2024). Local regulators in the study, however, sense a disingenuous approach from project developers; this negative perception, combined with word-of-mouth knowledge sources, could lead to community opposition to renewable energy projects (Michaud et al. 2024).



Code	Citizens
Direct Communication	9
Indirect Communication	7
Prior Knowledge Flows	1
Within-Group Communication	7
Other Energy Industry	8
Local Context	
Independent Information Seeking	3
Future Wishes	1
Landowner Outreach	1
Pre-Project Feasibility	

Figure 1. Counts of knowledge-sharing channel and methods rural community citizens use to learn about renewable energy projects (from Michaud et al. 2024)

Case Study: Amherst County, Virginia

The Piney River Solar project, a 50-MW solar facility proposed by Energix Renewables on 180 acres in Amherst County, Virginia, was slated to generate more than $10M in tax revenue over 45 years of operation (Hunziker 2023). The Amherst County Planning Commission was authorized to approve the project as Virginia's solar siting governance is predominantly local (Breckel and Falkenburg 2025). Amherst residents received a letter from the Virginia Coalition for Human Rights (VCHR), a grassroots organization specifically targeting Energix due to the developer's use of cadmium telluride (CdTe) solar modules, encouraging them to reject the proposal. The letter defined cadmium telluride as a "toxic heavy metal that has the potential to leak into soil and water," and that "four Virginia counties forbid its use" (VCHR 2023a). VCHR also claimed that multiple U.S. Government agencies list CdTe as a toxic substance (VCHR 2023a). This claim, however, was misleading as the letter did not differentiate the characteristics of working solar modules and module waste. In fact, the Environmental Protection Agency (EPA), which was mentioned in the letter classifying CdTe as toxic, highlighted in its website that "working solar panels do not leach those (cadmium, silver, or lead,) toxic metals" because of the encapsulant properties of solar modules ("Solar Panel Frequent Questions" 2021).

As a result of this type of misinformation, the Piney Solar Project was denied twice by the county commission board, stating that the project proposal did not contribute to the county's economic growth and development plans, before Energix withdrew the project. Furthermore, Amherst County also restricted utility-scale solar farms, establishing a 50-acre cap (Faulconer 2024) after the project denial.

Counties in Virginia with restrictions and community concerns against CdTe PV modules are located in proximity to one another Figure 2), suggesting that communities are susceptible to the infectious nature of misinformation flow as they put in a lot of trust on word-of-mouth knowledge when they develop solar ordinances (VCHR 2023b) (Curtis, Smith, and Townsend 2026) (Madison County Planning Commission and Board of Supervisors 2025) (Allen 2025).

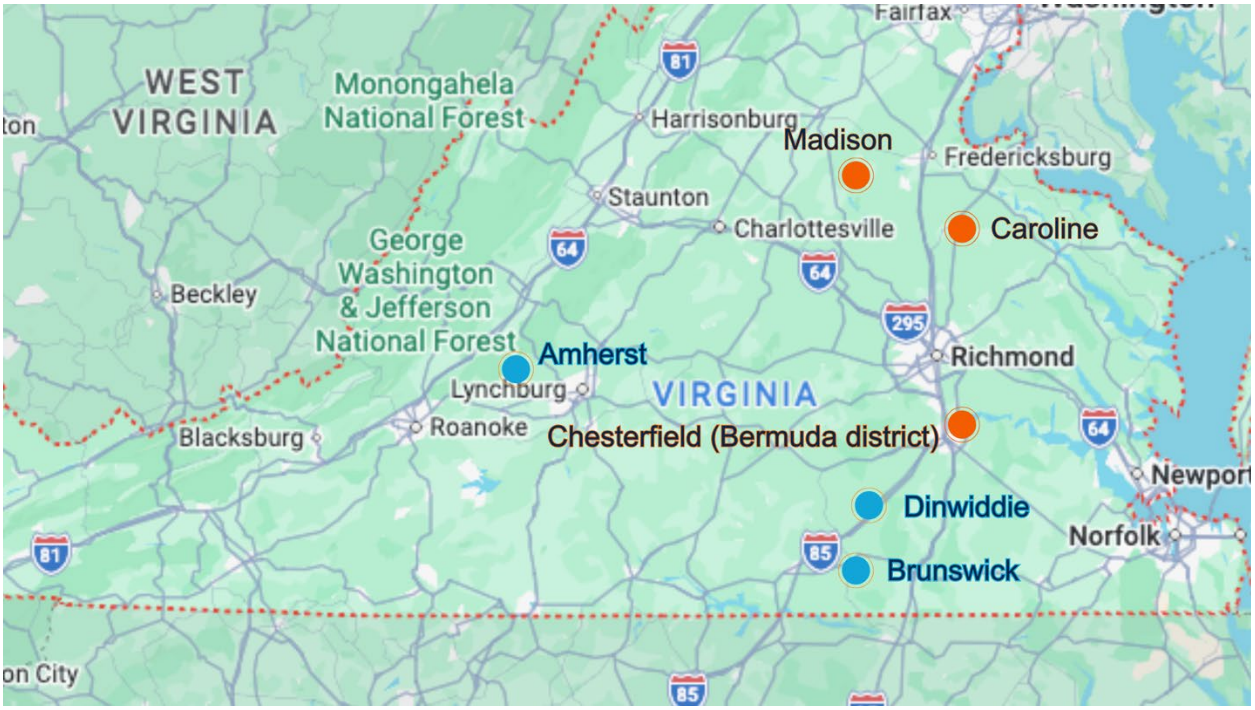


Figure 2. Counties in Virginia with bans on PV modules. Counties with local prohibition specific to CdTe panels are marked in red and opposition in blue.

Tools to address concerns beyond bans and moratorium

Without relying on local bans, local communities have policy and regulatory levers to address concerns of PV module toxicity and waste management. There are 24 state legislatures that have passed or considered a bill dedicated to decommissioning rules for solar systems, including mandating financial assurance and recycling of facility materials. (Linderman, 2025). Figure 3 illustrates PV module decommissioning status for U.S. states (Linderman, 2025).

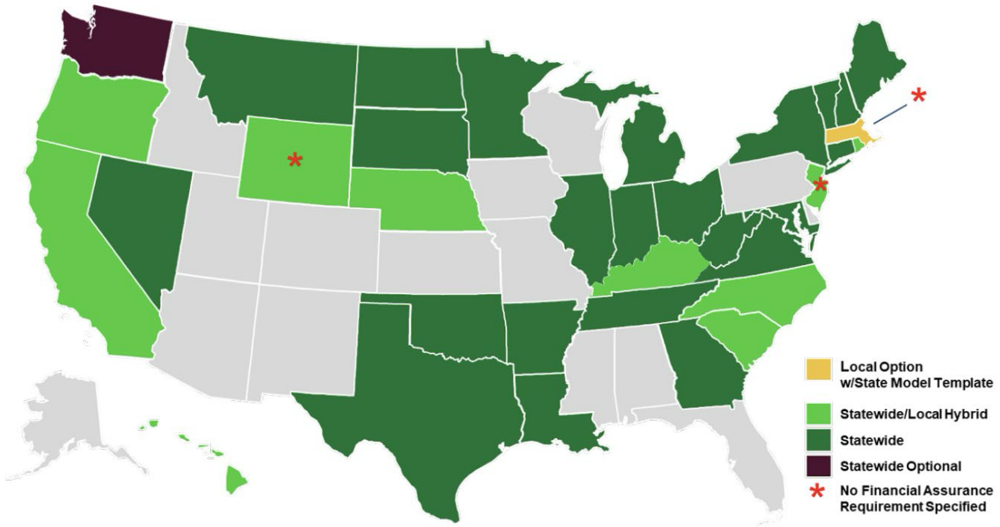


Figure 3. PV Decommissioning polices across U.S. states (from Linderman, 2025)

While not every state is considering implementing PV module decommissioning regulations, local counties can either establish a local zoning ordinance or a Host Community Agreement (HCA). Since local zoning ordinances are a regulatory mechanism, they are an effective and more robust approach for communities to manage zoning sites for solar. HCA is a legally binding agreement between local governments and project developers, but both mechanisms allow communities to use legal guardrails against potential PV module toxicity and waste issues by requiring developers to provide preventive assurance measures (Eisenson et al. 2025). HCA and local ordinances can complement each other, especially if HCA is used to fill the gaps that local solar regulations miss.

While local communities are encouraged to be proactive in deploying policy and regulatory guardrails to address local concerns, project developers should demonstrate project transparency through early and direct community-wide engagement to create long-lasting trust between both parties. The advantage of direct developer-community communication can also prevent misinformation (Michaud et al. 2024). Project developers can leverage a community's word-of-mouth knowledge mechanism to disseminate accurate solar information across communities. On the other hand, state energy agencies and regulatory organizations must ensure that they provide correct information about PV module technologies. NLR’s 2026 report found inaccurate information about commercially available silicon and CdTe PV modules in multiple U.S. state regulatory agency guidelines from Florida, Ohio, California, and Iowa (Curtis, Smith, and Townsend 2026).

While imposing permanent PV project bans or moratoriums (temporary bans) have become the two most common methods to address community concerns, in particular PV module toxicity and waste challenges, they do not guarantee that future projects will be unchallenged. This is particularly relevant in states where solar siting governance is split between the state and local communities. In response to local module bans, some states, such as Nevada, New York, and Illinois, have also imposed a state policy guardrail to override local solar restrictions (Eisenson et al. 2025).

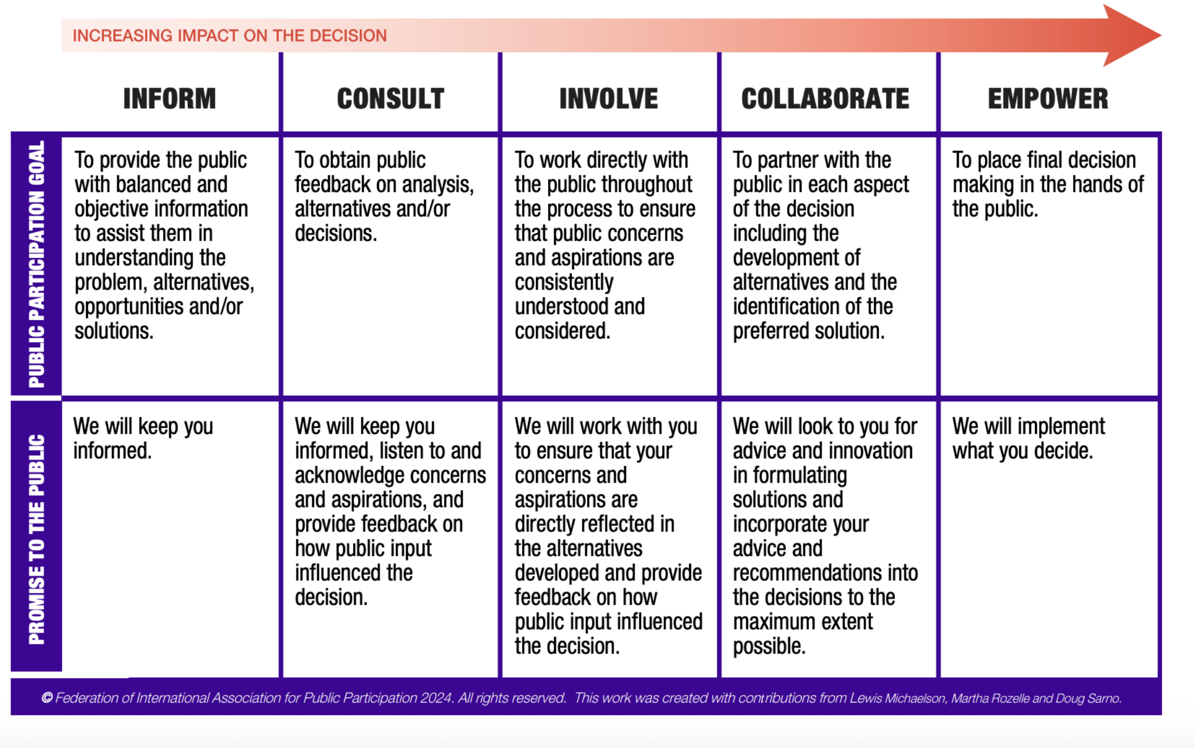
Case study: Niagara County, New York

Niagara County, New York, which splits solar siting governance between the state (Office of Renewable Energy Siting and Electric Transmission (ORES)) and county-level (Breckel and Falkenburg 2025), takes a unique approach to address local concerns by mandating a module recycling law, which also fosters PV module circularity.

The county enacted a law (Local Law No. 4 of 2021) that requires any solar manufacturer, installer, or developer of projects in the county to be responsible for financing a module recycling program (Niagara County 2022). The county did not oppose solar projects and explicitly announced that it expects PV modules to “proliferate to meet New York’s Clean Energy goals.” In December 2024, New York approved a 125 MW solar project in the Town of Somerset, Niagara County, through the Office of Renewable Energy Siting and Electric Transmission (ORES). This project became the first state-permitted utility-scale solar project in Niagara County, given that the project developer (AEC) has complied with the local recycling law and has included community engagement as part of the project process (Orleans Hub 2024).

This case demonstrates a pathway to leverage PV module toxicity concerns into a module recycling opportunity without running into New York’s local restriction guardrail policy. However, local concerns regarding AEC’s Somerset project persisted as the proposed project site is primarily on farmland (WGRZ-TV 2025) - a grassroots issue that was unaccounted for by ORES due to state priority to meet energy transition targets, which often overlooks the local consequences that accompany utility-scale clean energy projects.

Although this is a classic challenge that local counties face in states with split solar siting governance, it also illustrates the challenges of relying only on regulation to build renewable energy projects. The AEC community engagement process was a form of compliance to get project approval, not to engage with host communities for project decision-making involvement. According to the International Association for Public Participation (IAP2) community engagement framework, AEC's community involvement in its Somerset solar project belongs to "Consult" in Figure 4 (IAP2 International Federation 2018). Project developers conforming to this level are expected to obtain public feedback on project analysis and decisions but are not required to incorporate it into project final decisions. Community concerns that did not become a mandate, like the module recycling law, were not addressed, which initiated local dissatisfaction and transformed into opposition (Rounds 2026). Long-term community openness to renewable energy projects would require developers to increase community involvement in project decision-making. In the IAP2 framework, this progresses beyond "Consult."



INCREASING IMPACT ON THE DECISION

	INFORM	CONSULT	INVOLVE	COLLABORATE	EMPOWER
PUBLIC PARTICIPATION GOAL	To provide the public with balanced and objective information to assist them in understanding the problem, alternatives, opportunities and/or solutions.	To obtain public feedback on analysis, alternatives and/or decisions.	To work directly with the public throughout the process to ensure that public concerns and aspirations are consistently understood and considered.	To partner with the public in each aspect of the decision including the development of alternatives and the identification of the preferred solution.	To place final decision making in the hands of the public.
PROMISE TO THE PUBLIC	We will keep you informed.	We will keep you informed, listen to and acknowledge concerns and aspirations, and provide feedback on how public input influenced the decision.	We will work with you to ensure that your concerns and aspirations are directly reflected in the alternatives developed and provide feedback on how public input influenced the decision.	We will look to you for advice and innovation in formulating solutions and incorporate your advice and recommendations into the decisions to the maximum extent possible.	We will implement what you decide.

Figure 4. Community involvement framework, with “Inform” as the lowest level of engagement and “Empower” as the highest level (from IAP2 International Federation 2018)

Synthesis of Socio-Technical Drivers

As local restrictions on utility-scale solar projects continue to rise, the underlying concerns driving opposition, particularly around perceived PV module toxicity and EoL module management, will not be resolved by bans and moratoriums. The cases of Amherst and Niagara counties illustrate two diverging trajectories, yet both show how community perception and knowledge of PV modules directly shape project outcomes. Niagara’s case further reveals that regulatory compliance is necessary but insufficient for prolonged community trust without genuine engagement with host communities. Effective solar deployment in host communities requires both regulatory and relational compliance - progressing beyond collecting public feedback toward incorporating it into final decision-making. Together, these tenets form a more durable foundation for long-term community acceptance of solar projects.

Method – Material Mismatch

Regulatory-Technical Mismatch in PV EoL Classification

Within the U.S. currently, hazardous-waste determination functions as a gatekeeper: once classification is triggered, downstream decisions (site handling, transportation, recycler access, insurance posture, recordkeeping, and contractual allocation of risk) become constrained. This is also consistent with NRL findings (Curtis, Heath, and Sinha, 2026) that method selection shapes regulatory outcomes: the test is not just reporting risk; it can create compliance outcomes through how samples are prepared and how extraction conditions are defined.

PV modules are complex, multilayered engineered products composed of glass, polymers, metals, and semiconductor materials. These include base metals (e.g., Cu, Pb, Al), rare or valuable metals (e.g., Ag, In, Ga), and in some cases toxic elements such as cadmium (Cd) or lead (Pb)(Li et al., 2024). For example, lead is typically localized in solder connections, while cadmium is present in thin-film CdTe modules, generally at low weight fractions (Li et al., 2025). In addition, PV modules are engineered for durability, with operational lifetimes of 25–40 years under environmental stressors such as UV radiation, rain and snow, and temperature cycling (Li et al., 2025).

PV modules have three components that matter for leaching/characterization:

1. Layered laminates (e.g., glass + encapsulant)
2. Cell stack
3. Backsheet

The module structure, which behaves unlike uniform bulk waste when intact, is shown in Figure 5, This structure exhibits heterogeneity across depth and regions (e.g., cell area, non-cell area, and interconnect ribbon areas), which makes measured outcomes highly dependent on sampling location and representation. The encapsulated structure of PV modules is designed to resist moisture ingress; real-world release is governed by encapsulation integrity, degradation state, and exposure conditions, instead of simply presence of regulated elements.

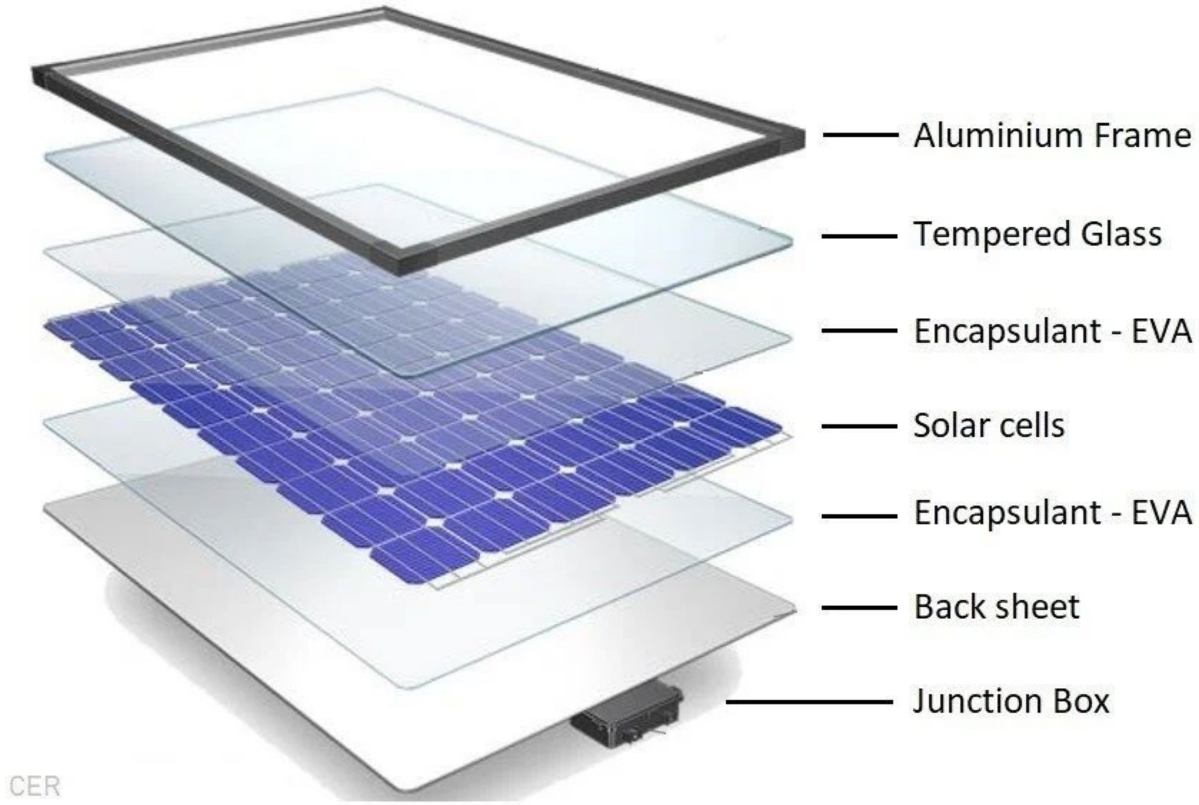


Figure 5. Laminated structure of a PV module. (Svarc, 2022)

The "method-material mismatch" described here is structural. The Toxicity Characteristic Leaching Procedure (TCLP, EPA Method 1311) was designed to simulate leaching from crushed, heterogeneous municipal solid waste (MSW) disposal conditions, whereas PV modules are engineered laminates built to resist ingress and release (Masson, 2022).

The mismatch between TCLP and PV module structure becomes consequential because TCLP outputs can yield inconsistent results even for identical or comparable modules, increasing compliance uncertainty for asset owners and creating pressure toward over-management (e.g., defaulting to more restrictive handling) to manage classification risk.

This section examines how method-material mismatch in PV module testing affects hazardous-waste classification outcomes. Specifically, it asks:

To what extent do commonly used testing methods (e.g., TCLP) produce variable or non-representative results for PV modules;

How does test method selection influence regulatory classification and downstream compliance decisions; and

What implications does this have for risk, cost, and circularity pathways (reuse, recycling, disposal) in PV EoL management?

Mechanisms of Method-Material Mismatch

The methods included in this analysis were selected to represent the major categories of PV EoL characterization approaches (i.e., analytical methods used to identify and quantify material composition and leaching behavior) currently used in regulatory and industrial contexts. Specifically, this section tried to form a framework that include leaching-based tests including the U.S. EPA Toxicity Characteristic Leaching Procedure (TCLP), California Waste Extraction Test (WET), and Japan's JLT-13 standard, which simulate different chemical conditions to assess potential metal leaching, which are directly linked to hazardous-waste classification; compositional analysis methods (e.g., RoHS digestion), which quantify total elemental content; and screening tools (e.g., XRF, LIBS, Raman), which are increasingly used for rapid, field-based material identification.

This selection is intended to capture the diversity of measurement objectives—ranging from regulatory compliance to material screening—rather than to provide an exhaustive inventory of all available techniques. As such, the comparison emphasizes structural differences between method types that are most relevant to EoL decision-making.

The TCLP Assessment was originally designed to simulate leaching behavior of waste materials under landfill conditions, assuming test samples are representative, and that size reduction does not fundamentally alter material behavior (Li et al., 2024). These assumptions are not well aligned with PV modules. To perform TCLP testing, PV modules must be physically processed into smaller pieces. Research shows that particle size strongly influences leaching results: smaller particles increase surface area and can artificially elevate metal release concentrations (Li et al., 2025). TCLP Testing conditions, such as acidic extraction fluids and crushed samples, may not reflect real-world disposal scenarios. In practice, PV modules are often disposed of as intact or partially damaged units, were encapsulation layers limit exposure of internal materials. Thus, TCLP may simulate conditions closer to material processing than to actual landfill behavior, potentially overestimating environmental risk.

Additionally, sampling methods introduce variability. Mechanical cutting techniques can produce inconsistent results in measured concentrations, while alternative methods such as waterjet cutting reduce this variability slightly (Królicka et al., 2025; Li et al., 2025). This reveals a fundamental mismatch between the testing procedure modifying the material system, thus affecting the outcome. The methods included in this analysis were selected to represent the major categories of PV EoL characterization approaches currently used in regulatory and industrial contexts. Specifically, the framework incorporates leaching-based tests (TCLP, WET, JLT-13), which are directly linked to hazardous-waste classification; compositional analysis methods (e.g., RoHS digestion), which quantify total elemental content; and screening tools (e.g., XRF, LIBS, Raman), which are increasingly used for rapid, field-based material identification.

To systematically compare different PV end-of-life (EoL) assessment methods, this study develops a semi-quantitative analytical framework that evaluates each method along two dimensions: relative sensitivity and practicality. These dimensions are designed to capture both the technical rigor of material characterization and the operational feasibility of implementation in real-world EoL decision-making contexts.

Relative Sensitivity

Relative sensitivity represents the extent to which a method is capable of extracting or detecting regulated substances under defined conditions. For leaching-based methods (e.g., TCLP, WET, JLT-13), sensitivity is conceptualized as a function of three primary parameters that govern dissolution behavior:

1. Acidity (pH) — lower pH corresponds to more aggressive chemical conditions and greater potential for metal mobilization;
2. Particle size requirement — smaller particle sizes increase surface area and promote

leaching;

3. Extraction duration — longer contact times allow for greater dissolution.

These parameters are weighted (50%, 30%, and 20%, respectively) and combined to generate a normalized measure of leaching test aggressiveness (on a scale of 0–100), which will be referred to as a sensitivity score. The weighting scheme was selected to reflect the relative influence of each parameter on leaching behavior, based on established priciples of dissolution kinetics and regulatory test design. Acidity (pH) was assigned the highest weight (50%) because it is the primary driver of metal solubility and mobilization under leaching conditions and is explicitly controlled in all regulatory leaching protocols. Particle size was assigned a secondary weight (30%), reflecting its effect on surface area and solid-liquid interaction, which influences the rate and extent of dissolution. Extraction duration was assigned a lower weight (20%), as its influence is conditional on the chemical environment and tends to produce diminishing returns beyond standard test durations.

For non-leaching methods, adjustments are applied to account for differences in measurement intent. Compositional methods (e.g., RoHS digestion) are assigned an intermediate sensitivity. While chemically aggressive due to strong acid digestion and fine sample size, they are discounted in comparison with other methods because they measure total elemental composition rather than leachable release under disposal conditions. Screening methods (e.g., XRF, LIBS, Raman) are assigned lower sensitivity scores, reflecting their role in rapid identification of material presence rather than quantitative assessment of leaching behavior. Differentiation among screening tools is based on their interaction with material structure (e.g., surface vs. micro-destructive access).

The score assignment logic is that the pH score was normalized relative to neutral conditions using pH 7 as the low aggressiveness reference and pH 2.8 (lowest amongst all methods) as the high aggressiveness reference. Particle size scores were normalized on a logarithmic scale to reflect the non-linear effect of particle size. Duration scores were normalized to a 24-hour extraction period.

For example, the pH score is 49 for TCLP, which uses solvent with a pH of 4.93, and the pH score is 98 for WET, which uses solvent with a pH of 2.80. The particle size score is calculated as log (10/particle size) / log (10/0.5). The particle size score is 2 for TCLP, which requires 9.5 mm, and particle size score is 54 for WET, which requires 2 mm. The duration score is calculated as extraction time / 24 h. The duration score is 75 for TCLP, which requires 18 hours, and is 100 for WET, which requires 24 hours. For this example, the total relative sensitivity score for TCLP is 40.1, and for WET is 85.2.

Practicality

Practicality represents the operational feasibility of deploying each method in field or project settings. It is constructed from four components:

1. Hazard / safety (40%) — derived from chemical aggressiveness (e.g., strong acid digestion vs. non-destructive techniques);
2. Time requirement (30%) — shorter analysis time corresponds to higher practicality;
3. Sample preparation burden (15%) — methods requiring extensive grinding or size reduction are less practical;
4. Equipment requirements (15%) — based on expert judgment of field portability and technical complexity.

These factors are combined into a normalized practicality score (0–100), where higher values indicate greater ease of use, safety, and field readiness. The weighting scheme for practicality was intended to reflect the relative importance of operational constraints in real-world deployment contexts. Hazard and safety considerations were assigned the most weight (40%) because methods involving strong acids, high temperatures, or hazardous reagents impose regulatory and personnel constraints that could significantly limit their applicability outside controlled laboratory environments. Time requirement was assigned a 30% weight, reflecting the importance of turnaround time in field decisions, where rapid assessment is often prioritized. Sample preparation and equipment requirements were each assigned lower weights (15%), as their impact on practicality is more context-dependent. While these factors influence ease of deployment, they are often secondary to safety and time constraints and may be mitigated through laboratory infrastructure or standardized preparation procedures.

For example, the Safety score is assigned based on chemical hazard and operational risk, which gives TCLP a score of 60 (mild acetic acid handling) and WET a score of 40 (more acidic conditions, pH ≈ 2.9). The time score is calculated as (1 − extraction time / 24 h) × 100. The time score is 25 for TCLP, which requires 18 hours, and is 0 for WET, which requires 24 hours. The preparation score is assigned based on particle-size reduction requirements, which leads to a score of 60 for TCLP, which requires 9.5 mm, and is 35 for WET, which requires 2 mm. Equipment scores are assigned based on field deployability and laboratory dependence, which gives both TCLP and WET a score of 50, as both require laboratory extraction, agitation systems, and analytical instrumentation. For this example, the total practicality score for TCLP is 51 and for WET is 36.25.

Interpretation and Limitations

The two metrics of relative sensitivity and practicality are not combined into a single composite score. Instead, they are used as independent dimensions to position each method within a two-dimensional analytical space, shown in Figure 6. For each method, the calculated sensitivity score is plotted on the vertical axis, representing analytical aggressiveness, while the practicality score is plotted on the horizontal axis, representing operational feasibility. This approach allows direct visualization of trade-offs between the two metrics without imposing a single aggregated ranking.

Importantly, the framework does not assume direct equivalence between methods with different measurement objectives. Instead, it explicitly incorporates comparability adjustments to reflect the distinction between measuring total composition and simulating environmental release behavior, which is central to hazardous-waste classification decisions.

Scores were assigned using a structured normalization and weighting procedure to ensure reproducibility across methods. For each parameter (e.g., pH, particle size, extraction duration, time requirement), a raw value was first collected from standard protocols or literature sources. These values were then converted into normalized sub-scores on a 0-100 scale, which were combined using predefined weights (as described above) to produce final sensitivity and practicality scores for each method. This process is a semi-quantitative, heuristic tool rather than a fully predictive or empirically calibrated model. The weighting schemes used for both sensitivity and practicality are based on conceptual reasoning and established principles of leaching behavior and field deployment constraints, rather than formal statistical fitting or experimental validation.

Calculation Outcome and conclusion

The distribution of methods in Figure 6 reveals a clear trade-off between analytical sensitivity and operational practicality across PV end-of-life assessment approaches. Leaching-based methods, particularly WET (x = 36, y = 85), occupy the high-sensitivity, low-practicality region, reflecting their strong ability to simulate aggressive leaching conditions at the expense of longer testing times, stricter sample preparation requirements, and increased safety constraints. TCLP (x = 51, y = 40) and JLT-13 (x = 57, y = 36) fall in an intermediate range, indicating moderate sensitivity and practicality, consistent with their role as standardized regulatory methods that balance analytical rigor with operational feasibility. RoHS digestion (x = 44, y = 40) shows a similar sensitivity level to TCLP but with slightly lower practicality, highlighting its analytical strength in total elemental quantification but limited relevance to disposal-specific leaching behavior.

In contrast, screening and field-deployable techniques cluster in the high-practicality, low-sensitivity region. XRF (x = 99, y = 10) and Raman (x = 99, y = 5) represent highly practical, non-destructive methods suitable for rapid field assessment but with limited capability to evaluate leaching-based regulatory risk. These methods enable efficient identification of modules that may contain regulated elements, allowing stakeholders to triage materials without incurring the time and cost associated with laboratory testing. LIBS (x = 89, y = 20) occupies an intermediate position, reflecting its partially destructive nature and enhanced detection capability relative to purely non-destructive techniques. Given their limited ability to simulate leaching behavior, screening results should not be used as a direct proxy for regulatory classification. Instead, samples identified as potentially non-compliant should be subjected to confirmatory leaching tests, such as TCLP (x = 51, y = 40) or WET (x = 36, y = 85), depending on the required level of conservatism.

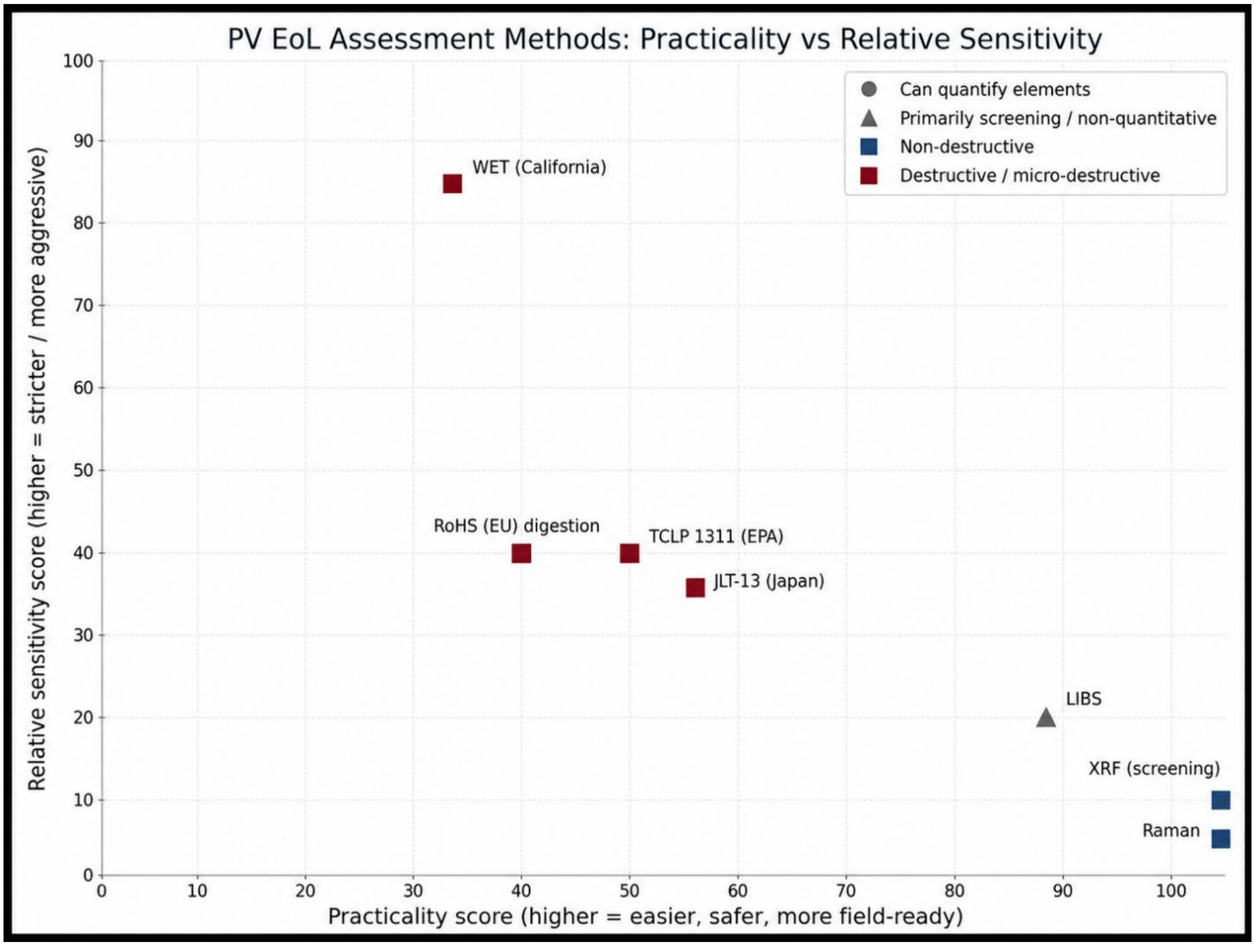


Figure 6. Relative positioning of PV end-of-life assessment methods by practicality and analytical aggressiveness.

Figure 6 highlights a structural mismatch between methods optimized for regulatory classification and those optimized for field deployment. Methods that provide the most conservative assessment of potential leaching risk tend to be the least practical to implement at scale, while methods that are operationally efficient do not directly correspond to regulatory leaching criteria. The results suggest that field-based assessment of PV modules should prioritize high-practicality screening methods for initial evaluation, followed by targeted application of more rigorous analytical tests where necessary. This two-stage approach of screening followed by targeted validation can significantly reduce testing burden while maintaining alignment with regulatory requirements.

Consequences of Mismatch

Method–material mismatch in PV module testing has implications that extend beyond measurement accuracy, influencing regulatory classification, economic outcomes, and circularity pathways. From a regulatory perspective, hazardous waste determination is highly sensitive to the choice of testing methods. In the United States, classification is largely based on TCLP results, meaning that process assumptions—such as particle size reduction and acidic extraction conditions—directly shape whether a module is classified as hazardous waste (Li et al., 2024). Because PV modules are heterogeneous, small variations in sampling or preparation can lead to different classification outcomes for otherwise similar modules. This introduces regulatory uncertainty and challenges the consistency of compliance decisions.

Economically, these classification outcomes have significant downstream consequences. Modules that exceed regulatory thresholds must be managed as hazardous waste, resulting in higher costs for transportation, treatment, and disposal, as well as increased administrative and liability burdens. As a result, method-driven variability can translate directly into project-level financial risk, particularly for large-scale PV assets approaching EoL.

From an environmental and systems perspective, overly aggressive or non-representative testing conditions distort the perceived risk of PV waste. Standard leaching tests have been shown to simulate conditions that are more severe than those experienced by intact or partially damaged modules in real-world environments (First Solar, Inc., 2015). This can lead to conservative over-classification, where modules that pose limited real-world risk are managed under stricter hazardous-waste regimes. Such outcomes may inadvertently hinder the development of circular economy strategies, including reuse and recycling, by increasing regulatory barriers and costs.

Testing methods do not merely measure environmental risk but can actively shape regulatory and economic outcomes. Aligning testing approaches with material structure and real-world exposure conditions is therefore critical to ensuring both environmental protection and the scalability of sustainable PV end-of-life management systems. While PV modules contain trace amounts of regulated substances, their environmental risk must be interpreted in relation to both material design and real-world exposure conditions. Existing evidence suggests that the potential for metal release from intact or partially damaged modules is strongly constrained by encapsulation and limited environmental interaction (Curtin et al., 2020). Such misalignment has important implications for how PV waste is perceived and managed. Overly conservative interpretations may lead to the classification of low-risk modules as hazardous, while also reinforcing regulatory approaches that prioritize worst-case scenarios over representativeness. This highlights the need to distinguish between analytical aggressiveness and environmental relevance when interpreting toxicity testing results.

Synthesis of Regulatory-Technical Alignment

This study demonstrates that the application of conventional toxicity testing methods to PV modules introduces a fundamental method–material mismatch, driven by differences in material structure, sampling requirements, and testing conditions. As a result, testing outcomes are not solely determined by intrinsic material properties but are significantly influenced by methodological assumptions.

More importantly, these findings suggest that toxicity testing in the context of PV EoL management should not be viewed as a purely technical exercise. Instead, it functions as a decision-shaping mechanism, influencing regulatory classification, economic outcomes, and the feasibility of circular pathways. In this sense, testing methods do not simply measure environmental risk—they actively participate in defining it.

Addressing this challenge requires moving beyond direct application of legacy waste-testing protocols toward more context-aware and material-specific approaches. This includes integrating screening and confirmatory methods, improving sampling representativeness, and developing testing frameworks that better align with real-world exposure conditions. Ultimately, aligning testing methods with material realities is essential not only for improving accuracy, but also for enabling consistent regulation, reducing unnecessary costs, and supporting the transition toward more sustainable PV end-of-life management systems.

Industry Landscape

Circularity as a System Design Problem

Transitioning towards a circular economy for solar PV systems in the United States requires a shift from viewing recycling as a downstream technical challenge to understanding it as a system design problem. This section examines how the LAB industry, which is the oldest type of rechargeable battery that is heavily reliant on lead dioxide, metallic lead, and sulfuric acid has achieved near-closed loop material recovery and how those underlying structural conditions can inform the development of circularity in PV systems. The LAB industry is not presented as a direct analog, rather as a mature reference case that reveals the reinforcing economic, logistical, regulatory, and institutional conditions necessary for circular systems to function at scale. This distinction is critical because the value of the comparison is not in the technological similarities but in identifying the systematic drivers that enabled LAB circularity to emerge and persist over time.

By demonstrating that high recycling rates are not an accidental outcome but rather the result of deliberate system design, the LAB industry can be seen as a highly functional circularity model in the United States. Historically, the LAB industry encountered significant environmental and public health challenges due to improper disposal practices, including widespread contamination from lead leakage (CHE, 2017). These earlier failures, coupled with increasing regulatory pressure and material loss, catalyzed a structural transformation in which recycling became embedded as the dominant EoL pathway (Garcia & Sardana, 2024). Regulatory interventions, specifically those associated with hazardous waste classification, fundamentally altered the economic and legal incentives governing disposal and recovery. Disposal became costly, while recycling emerged as the compliant and economically rational option (Franco & Groesser, 2021). Recycling systems operate as a tightly integrated closed loop, in which materials are recovered and reintroduced into production cycles with minimal leakage. Reverse logistics networks connect end users to recyclers, reintegrating recovered materials into manufacturing supply chains and enabling consistent material flows that reduce costs and reinforce the economic viability of closed-loop recycling at scale.

The LAB System as a Functional Circular Model

The relevance of LAB circularity to PV systems is in the suite of mutually reinforcing socio-technical conditions rather than isolated technological solutions. In the LAB ecosystem, circularity is stabilized through a robust interdependency of consistent material demand and recoverability, rather than inherently high material value, coupled with established reverse-logistics infrastructure and strict regulatory frameworks (Rabaia et al., 2024). The PV sector lacks these established feedback loops. The economic viability of PV disassembly is currently constrained by the low specific value of bulk secondary materials (glass and aluminum) relative to high energy requirements and processing costs of recovery. While lead maintains high commodity demand and can be efficiently recovered with minimal material degradation, the recovery of high-value PV constituents like silver and solar-grade silicon is restricted by delamination challenges from the strongly bonded layers (e.g., EVA binding glass to cells), and by thermodynamically intensive processes required to separate and purify materials, increasing both energy input and processing costs (United States, Dept. of Energy, 2022). As a result, recycling remains a cost burden rather than a value-generation activity, reinforcing the commonness of landfilling as a default EoL pathway.

Structural Barriers to PV Circularity

Logistical constraints further exacerbate PV material recovery challenges. PV modules are deployed across highly decentralized environments, including residential rooftops, commercial installations, and utility-scale projects. This creates very few, highly dense collections of PV materials when compared to the LAB industry that has many small aggregation nodes that are for easier, simpler reverse logistics. Spatial dispersion results in low aggregation density at EoL, increasing transportation and handling costs while limiting the feasibility of centralized processing (Curtis et al., 2021). In contrast, the LAB industry benefits from dense routine collection networks embedded within the automotive service infrastructure, enabling efficient aggregation and consistent material flows. The long lifespan of PV modules (20-30 years) delays the emergence of waste streams, generating temporal uncertainty that is based on the different deployment strategies and general use cases of PV farms, repowering aging

PVs to extend the life of the module, and unknown early failures can greatly influence the quality uncertainty recovery yields after decades of field exposure (Rabaia et al., 2024). Additionally, varying environmental conditions and economic decisions rather than just technical degradation influence when PV modules are going to be removed and potentially enter the waste stream. All together, these uncertainties complicate forecasting the amount of PV that needs to be recycled and skew the confidence of investment decisions relating to PV EoL management and recycling infrastructure by hiding both the scale and economic viability of future material recovery. This stands in contrast to the relatively predictable and shorter replacement cycles seen in LAB systems.

PV heterogeneity poses another significant barrier. Variability in PV module design, including differences in cell technologies (e.g., monocrystalline, polycrystalline, thin-film), encapsulant materials (such as ethylene-vinyl acetate versus polyolefin), back sheet composition, frame structure, and junction box configuration, leads to a lack of standardization across the installed base (Gao et al., 2024). This heterogeneity increases the complexity of disassembly and material separation, often requiring specific adaptations that limit throughput and raise operational costs (Gao et al., 2024). As a result, recycling facilities face challenges in achieving economies of scale, particularly since incoming waste streams are inconsistent in composition and condition. The presence of laminated structure and strong adhesive bonds further complicates recovery because they often require energy-intensive thermal or chemical processes to access high-value embedded materials such as silicon, silver, and copper (Gao et al., 2024). These factors collectively reduce recovery efficiency and limit the economic viability of recycling technologies.

Regulatory Fragmentation and Institutional Misalignment

At the same time, the policy landscape that manages PV EoL in the United States remains fragmented and ambiguous, as discussed in the previous section. Currently, there is no comprehensive federal framework governing PV module for take-back, recycling, or disposal. Instead, regulatory treatment varies by state and often depends on how modules are classified under existing waste regulations. In many jurisdictions, PV modules are treated as non-hazardous solid waste unless they fail the TCLP under the Resource Conservation and Recovery Act (RCRA) (RCRA, 1976). As we discuss above, TCLP testing introduces uncertainty, as modules may or may not be classified as hazardous depending on their composition and degradation state. This ambiguity creates risk for asset owners, who may face potential liability if modules are improperly classified or disposed of. In addition, the absence of standardized federal guidance on EoL responsibility results in unclear allocation of obligations among manufacturers, developers, asset owners, and recyclers.

This regulatory uncertainty stands in contrast to the highly structured policy environment that enabled circularity in the LAB industry. Under RCRA, EoL lead-acid batteries are explicitly regulated as universal waste (40 CFR Part 273), which streamlines collection while maintaining environmental protections (RCRA, 1976). The universal waste designation reduces administrative burdens for handlers while ensuring that batteries are managed within a controlled system. RCRA’s cradle-to-grave liability framework imposes strict accountability on generators and handlers of hazardous waste, which means that improper disposal can result in significant legal and financial consequences (RCRA, 1976). This liability structure effectively discourages landfilling and incentivizes participation in established recycling channels.

LAB recycling is supported by well-defined downstream regulatory and market structures. Secondary lead smelters operate under the Clean Air Act regulations, which impose strict environmental standards and monitoring requirements, making sure that recycling processes meet public health and environmental criteria (Li et al., 2024). Industry coordination through organizations such as the Battery Council International has helped standardize practices, facilitate compliance, and promote consistent recovery pathways across the value chain (Li et al., 2024). In addition, initiatives like the Responsible Battery Coalition further reinforce closed-loop systems by aligning stakeholders across the battery lifecycle and advancing policies that support responsible collection, recycling, and material reintegration (RCRA, 1976). Together, these regulatory and institutional mechanisms create a system in which recycling is not only environmentally preferable but also the most legally and economically viable option.

In addition to federal regulation, the LAB system is reinforced by state-level depositfunded programs and mandatory take-back requirements (EPA, 2024). In many states, consumers are required to return a used automotive battery when purchasing a new one or pay a refundable core charge, typically ranging from $5 to $15 (Autozone, 2026). Retailers and distributors are legally obligated to accept used batteries, ensuring the existence of a dense set of accessible collection points. These requirements are created in state statutes and enforced through compliance monitoring and penalties for non-participation. Furthermore, transportation and storage of spent batteries are governed by the U.S. Department of Transportation (DOT) hazardous materials regulations (49 CFR Parts 171-180), which standardize handling procedures and reduce risks during logistics operations (49 C.F.R. §§ 171-180, 2024).

Another barrier to PV circularity is the unfavorable economic balance between recycling costs and recovered material value. Current estimates indicate that recycling costs range from approximately $15-$45 per module; the value of recovered materials often falls below these costs, particularly for crystalline silicon modules (Curtis et al., 2021). This economic gap is driven by high capital and operational expenditures associated with delamination, chemical recovery, and material purification processes, as well as volatility in markets for materials like polysilicon (NREL, 2025). Supply chain disruption, including energy related production curtailments, industrial accidents, and trade restrictions affecting key manufacturing regions, have removed up to 10% of global polysilicon capacity, introducing non-linear price volatility and reinforcing uncertainty in long-term material valuation (International Energy Agency, 2022).

Synthesis of Market and Infrastructure Barriers

The absence of a regulatory and institutional framework in the PV sector that’s comparable to what exists for LABs highlights regulatory clarity as a prerequisite for circularity. Without clearly defined rules governing classifications, responsibilities, and compliance, stakeholders face uncertainty that discourages investment in recycling infrastructure and limits the development of efficient material recovery systems. Comparison with the LAB industry demonstrates that effective circular systems are underpinned by enforceable policies that align economic incentives by making disposal costly, ensuring reliable cost recovery through recycling, and supporting stable secondary markets, while reducing ambiguity for collection, transport, and processing, thereby embedding recovery as the default pathway. For PV systems, achieving similar outcomes will require the deliberate design of regulatory frameworks that provide clear guidance, assign responsibility across the value chain, and create predictable conditions for long-term investment, including stable cost-recovery mechanisms, clearly defined EoL ownership and liability, consistent waste classification standards, and reliable volumes of material supply for infrastructure.

Policy Landscape

Policy as a Driver of Circularity for Photovoltaics

Policy measures can encourage or impede circularity through pathways including economic incentives, regulatory requirements, assigning liability, and establishing market signals (Curtis et al., 2021). Economic incentives encourage circularity by lessening the financial burden of recycling through measures such as tax credits or subsidies, or by discouraging disposal by increasing landfill disposal fees. Requirements, which can be changed through establishing regulations, encourage circularity by mandating that PV modules be decommissioned in specific ways, such as through a takeback requirement or a landfill ban that prevents PV disposal in landfills and thus encourages recycling. Establishing liability defines who is responsible for EoL PV modules. Placing decommissioning requirements on a specific party (such as asset owners or manufacturers) establishes a responsible party who can be held liable for decommissioning. Market signals can be used to encourage circularity by changing procurement standards, increasing ESG (Environment, Social, and Governance) reporting requirements, and pricing carbon. Changing procurement standards can incentivize or require procurement from producers that engage in circularity, such as by mandating that procurement occurs from producers that are using recycled materials. Increasing ESG reporting requirements can encourage public accountability by requiring companies to publicly disclose their ESG data. Pricing carbon encourages circularity by raising the cost of non-recycled material procurement and thereby making recycled materials more cost competitive.

In the United States, there are currently barriers to circularity along all four of these pathways. Recycling is currently more costly than landfill disposal (Libby and Shaw, 2019). Recycling requirements for PV modules are not widely present (Garcia & Sardana, 2024). Liability and PV waste classification are often unclear, and there is little market pull encouraging circularity (Curtis et al., 2021). Additionally, PV recycling in the U.S. faces logistical barriers due to the difficulty of collecting PV modules and transporting them to a recycling facility, as well as the difficulty of selling/redistributing the recycled materials (Curtis et al., 2021). There is also a lack of data about PV module numbers, and modules can be difficult to trace, which can make it difficult to hold entities accountable for PV site cleanup and decommissioning (Curtis et al., 2021). As the volume of modules reaching EoL has increased in recent years, these challenges have become more prevalent, and PV decommissioning has gained political attention (Wade et. al., 2016). Beginning in 2017, statewide PV decommissioning policies have been increasing across the U.S. Figure 7 shows the number of state-level PV circularity policies enacted by year. Understanding the changing PV circularity policy landscape in the United States through aggregating and analyzing circularity policy data will help us to better understand which policy types promote circularity. Circularity-promoting policies can then be advocated for.

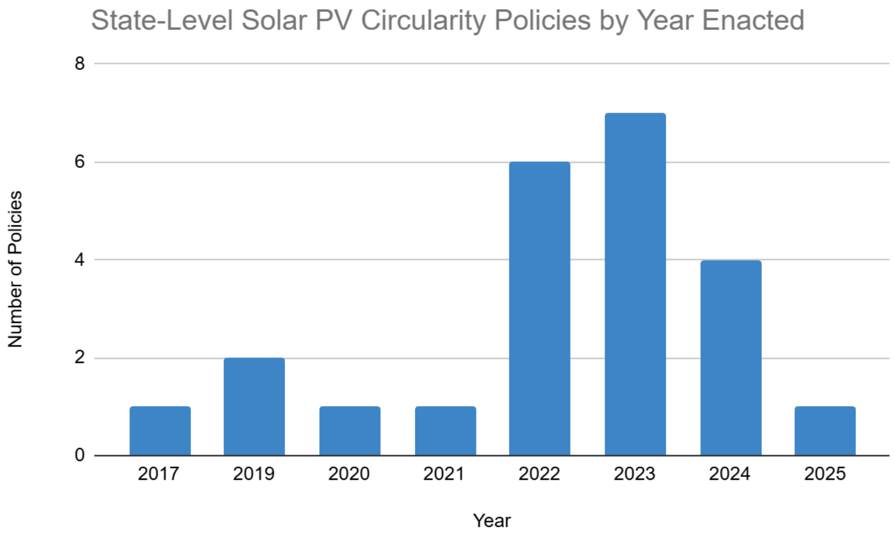


Figure 7. State-level PV circularity policies in the United States, by year enacted

Policy Survey Methods

The policy survey identified all state-level PV decommissioning policies across the U.S., as well as easily identifiable county-level examples. First, a preliminary literature review identified commonly discussed PV circularity policies. Then, keyword searches targeted on each state were used to ensure that as many statewide policies as possible were identified. These keywords were “Solar Panel,” “Photovoltaic,” “Recycling,” “Decommissioning,” and “Universal Waste.” These policies were cataloged and researched further to categorize them by policy mechanism. Policy mechanism categories were developed by identifying policies with similar verbiage, policy structure, and regulated entities. The policy mechanism categories that resulted were: Regulatory Agency Guidance/ Directives/ Planning, Financial Assurance/ Decommissioning Requirement, Alternative Management Standard (Universal Waste Standards), Landfill Ban, and Stewardship/ Extended Producer Responsibility/ Takeback. The policies were also categorized based on the type of legal authority, effect on circularity, and entities that bear the policy burden.

Policy Survey Results

Twenty-three state-level policies have been passed and enacted in 18 states (North Carolina has passed five policies and Texas has passed two) (citations for all policies are in Appendix 1). Appendix 1 lists all enacted statewide PV circularity policies. Eight state-level policies have been proposed and are currently pending legislative action. Twenty state-level policies have been proposed but failed to pass. Additionally, at least three county-level policies have been passed and enacted. The enacted state-level policies fall into several categories, which are described more fully below. Figures 8 and 9 show the enacted statewide policies by policy category and by state.

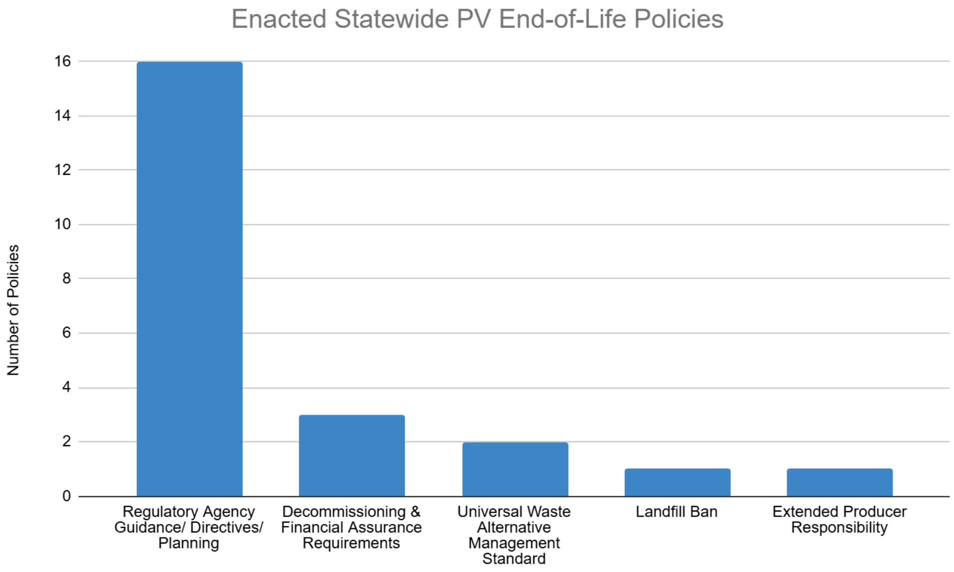


Figure 8. Statewide PV EoL policies that have been enacted in the United States, by policy type

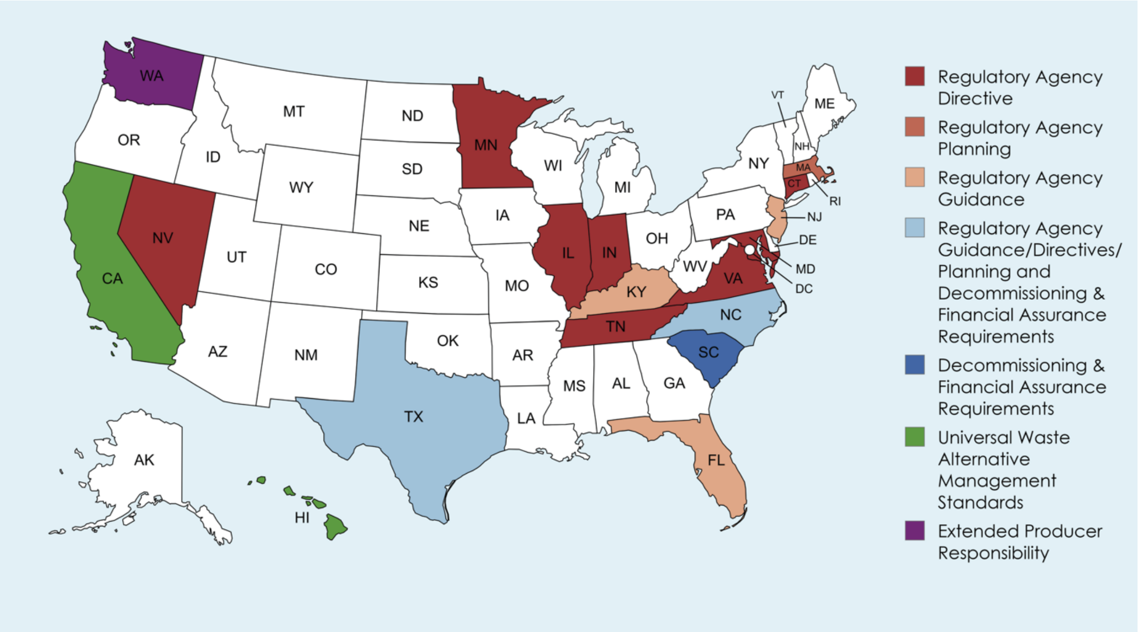


Figure 9. PV EoL Policy Mechanisms in the U.S.

Regulatory Agency Guidance/Directive/Planning

Sixteen policies have been enacted, covering 14 states (North Carolina has enacted three). This type of policy is present in several forms in the U.S., including required studies from state environmental agencies (North Carolina, Tennessee, Connecticut, Indiana, Illinois, Minnesota, Virginia, Maryland, Texas, and New Jersey), a solid waste management plan required from the State Environmental Commission (SEC) in Nevada, the 2030 Solid Waste Master Plan from the Department of Environmental Protection in Massachusetts, and Regulatory Agency Guidance (factsheet) documents from environmental agencies in Kentucky and Florida (Curtis et al., 2021; Nevada Division of Environmental Protection, 2022; MassDEP, 2021; ECAP, 2024; Florida Department of Environmental Protection, 2025). This type of policy is often study-based and is a tool used to gather information, usually by requiring the state environmental agency to compile a document. Regulatory Agencies are required to take action to compile information, but these policies often have little to no effect on the market because market actors are not regulated. However, they are useful for information gathering and issuing recommendations for future action. Table 1 expands on barriers targeted by each policy type, including how the information barrier is targeted by regulatory agency guidance, directives, and planning policies.

Table 1. Barriers to circularity targeted by policy

Policy Type	**Targeted Barriers**
Regulatory Agency Guidance/Directives/ Planning	Information Problems: Establishes working groups and/ or convene stakeholders, compiles data on PV decommissioning volumes and pathways within the state, evaluates policy options, and issues recommendations in the form of a report
Financial Assurance/ Decommissioning Requirements	Liability Certainty: Establishes liability for decommissioning and EOL responsibilities, establishes financial certainty Economic: Often requires financial assurance in some form, establishing the source of decommissioning funding Traceability/ Enforcement: Incentivizes planning for recycling and reuse at project inception, reduces risk of abandoned facilities and unfunded cleanup liabilities
Alternative Management Standard (Universal Waste Standards)	Economic: Reduces decommissioning costs and administrative barriers Logistics/ collection density: Reduces logistical barriers to decommissioning by reducing requirements associated with toxic waste disposal
Landfill Ban	Economic: Incentivizes recycling/ reuse by removing the more economically efficient option of landfill disposal Classification: Clarifies whether disposal at landfills is allowed
Stewardship/Extended Producer Responsibility/ Takeback	Liability Certainty: Establishes liability for decommissioning and EOL responsibilities, establishes financial certainty Economic: Requires financial assurance for decommissioning

Financial Assurance/Decommissioning Requirement

This form of regulation is present in three states (North Carolina, South Carolina, and Texas) and is characterized by a requirement that system owners and operators or PV manufacturers register their plans for decommissioning with the state environmental agency at a project's inception. Plans often include a requirement that the regulated party provide some form of financial assurance for the decommissioning process. This type of policy is useful because it establishes liability for decommissioning and EoL responsibilities, establishes the source of decommissioning funding, and requires planning for recycling and reuse at project inception, reducing the risk of abandoned facilities and unfunded cleanup liabilities. Table 2 provides a comparison of the decommissioning policies in North and South Carolina, illustrating that decommissioning policies may or may not encourage circularity. North Carolina's decommissioning policy, for example, requires recycling when possible, whereas South Carolina's policy does not (North Carolina General Assembly, 2026; SC Department of Environmental Services, 2026).

Table 2. A comparison of decommissioning policies in North and South Carolina.

	North Carolina	**South Carolina**
Removal requirement	√	√
Disposal requirement	√	√
Financial assurance	√	√
Early planning	√	X
Identification of reuse, recycling, and disposal options	√	X
Recycling required when possible	√	X

Alternative Management Standard (Universal Waste Standards)

This form of regulation is present in two states (California and Hawaii) and allows EoL PV modules to be characterized as universal waste, streamlining collection, transport, disposal, and reuse by decreasing the regulatory burden (Department of Toxic Substances Control, 2026; Hawaii Administrative Rules, 2025). The universal waste characterization can be assigned to common forms of hazardous waste that are not considered highly dangerous. Universal waste has less stringent handling, transportation, disposal, and recycling regulations than general hazardous waste. This type of regulation reduces decommissioning costs and administrative barriers and reduces logistical barriers to disposal and recycling. Although this type of policy does not require recycling, it can reduce costs and administrative barriers to recycling. However, it does the same for disposal, and so it does not necessarily promote circularity.

Universal waste policies technically regulate a wide variety of entities (including manufacturers, importers, distributors, installers, system owners and operators, logistic/ transport providers, recyclers, landfill owners and operators, and secondary market refurbishers).

Landfill Ban

This form of regulation is present in North Carolina (NCDEQ, 2026). This legislation prohibits the disposal of PV modules in unlined landfills and requires that non-hazardous, unreusable, and non-recyclable modules be disposed of in industrial or municipal solid waste landfills. North Carolina's policy regulates landfill owners/operators, solid waste facilities, utility-scale solar project owners and operators, and regulators (NCDEQ, 2026). This policy provides clarity about legal disposal options and incentivizes recycling and reuse (increasing circularity) by removing the often less costly option of disposal in an unlined landfill.

Stewardship/Extended Producer Responsibility/Takeback

This form of regulation is present in Washington State. The Photovoltaic Module and Stewardship Program was created by a bill passed in 2017 (the first PV decommissioning legislation passed nationwide) (Department of Ecology, 2026). This legislation requires that manufacturers and importers (the regulated entities) finance and participate in an approved PV module stewardship or takeback program. Unlike decommissioning requirements, this law does not place the decommissioning burden on system owners and operators, but instead on PV manufacturers. This policy establishes liability for decommissioning and EoL responsibilities and establishes financial certainty by requiring financial assurance for decommissioning. The financial assurance requirement provides funding for decommissioning in case the PV system operator goes out of business or is otherwise unavailable to decommission the PVs.

Policy Landscape: Conclusion

So far, most U.S state-level legislation addressing PV decommissioning has been study-based (regulatory agency guidance, directives, and planning) and not included binding market tools (all other policy types discussed in this study). Although these study-based policies are useful for information-gathering purposes and for issuing recommendations, they do not bind market actors via regulation. To promote circularity, policies that regulate market actors are necessary. The most popular approach is currently decommissioning/financial assurance policies. These policies are popular because they mitigate cleanup risk and place the regulatory burden on the asset owner or operator. The EPR/Takeback model is uncommon (only present state-wide in Washington) but is a strong policy option because it effectively requires the development of recycling systems. Although study-based policies are not strong about circularity tools by themselves, they can lead to the implementation of binding approaches, as occurred in Texas and North Carolina. As the PV decommissioning policy landscape continues to develop, promoting understanding of the benefits, drawbacks, and burdens of different policy options will lead to informed decision-making.

Conclusion

This study concludes that the lack of solar PV recycling in the United States is caused by a composition of misaligned economic, regulatory, and social factors. By combining data on costs and policies with insights into community behavior, this research shows that creating a circular economy for solar PV modules is a coordination challenge. It's a system where problems in one area, like confusing and non-standardized regulations, can feed into and often worsen problems in other areas, like the high costs of recycling and community fears.

From a financial perspective, recycling solar modules currently lacks a clear profit motive. With recycling costs estimated between \$15 - \$45 per module, the expense of disassembly, and separating and purifying materials far outweighs the value of the recovered glass, silicon, and silver (Curtis et al., 2021). This disparity in value is worsened by the fact that solar PV modules are deployed in large farms or networks that are spread across the country, but highly concentrated in a few locations. Additionally, these modules last for 20-30 years, making it difficult for recycling companies to predict when or where they will get enough steady business to justify building new facilities because there is significant uncertainty in EoL solar PV volumes. While many states have passed solar PV related laws, most are purely informational and lack the catalyst needed to force a shift away from cheap landfilling towards more sustainable reuse and recycling.

Beyond economics, this study found that how local communities feel about solar projects can be just as influential as laws or money. Even when technical risks are low, if a community views solar modules as toxic, often based on informal stories rather than scientific data, they may pass restrictive local rules or block projects entirely. Current developer outreach often fails because it focuses on simply telling the community what will happen rather than involving them in the process. This creates a cycle of mistrust that can halt the growth of the solar industry regardless of how well the technology works or how low the risks are encapsulated PV modules. Since these tests require crushing the modules in ways that don't happen in the real world, results can vary wildly. This inconsistency creates regulatory risk; recycling and owners are often unsure if a module will be labeled as hazardous waste, leading them to choose the easiest, cheapest option: landfilling.

To understand how to fix this, we investigated LABs, which have a nearly 100% recycling rate in the United States. The LAB industry succeeds because it has four things the solar industry lacks: consistent material value, a dense network for collections and reverse logistics, clear laws that hold owners accountable for the waste, and a steady demand for recycled material back into production. In the solar industry, these links do not exist, and without a similar closed-loop system, recycling remains an expensive option rather than standard practice.

Achieving a circular economy requires more than just better technology and logistics, it requires a coordinated redesign of the entire system. To move forward, the industry needs to apply stewardship funding, standardized collection, modernized testing, and collaborative governance. The stewardship funding will come from policies that build the cost of recycling into the life of the product to ensure recyclers get paid. Standardizing collection will reduce costs and logistical concerns, making recycling more efficient. Updating regulatory frameworks to reflect how PV modules behave in the environment is an important aspect of promoting circularity. Finally, involving local communities during solar project development gives local communities a meaningful seat at the table.

Ultimately, managing the end of a solar module’s life is a design challenge. Sustainability will only occur when economic incentives, laws, and social trust are all pulling in the same direction. Without this alignment, the growth of PV deployment will continue to be hindered by a linear waste problem that undermines green goals and recycling initiatives. By fixing these structural gaps, we can create a scalable system that supports clean energy growth and long-term environmental protection.

Appendix 1

Statewide PV EoL Policies Enacted in the United States

California CA HLTH & S §§ 25100 - 25259 - California Hazardous Waste Control Law, https://leginfo.legislature.ca.gov/faces/codes_displayexpandedbranch.xhtml?tocCode=HSC&division=20.&title=&part=&chapter=6.5.&article=.

Connecticut Conn. Pub. Utils. Reg. Auth., Docket No. 23-08-02, Annual Residential Renewable Energy Solutions Program Review – Year 3, at 51 (Nov. 1, 2023), https://www.dpuc.state.ct.us/dockcurr.nsf/8e6fc37a54110e3e852576190052b64d/6bf949e674ea002d85258a5a00536ec7/$FILE/230802-110123.pdf.

Florida Florida Dep’t of Envtl. Prot., Managing Unwanted or Broken Solar Panels: FAQs (2024), https://floridadep.gov/sites/default/files/Managing_Unwanted_Broken_%20Solar_Panels_FAQs_v4_3.7.24_0.pdf.

Hawaii Haw. Code R. § 11-273.6.2, https://www.law.cornell.edu/regulations/hawaii/Haw-Code-R-SS-11-273-6-2.

Indiana S.B. 33, 123rd Gen. Assemb., Reg. Sess. (Ind. 2023), https://legiscan.com/IN/bill/SB0033/2023.

Illinois S.B. 3790, 102nd Gen. Assemb., Reg. Sess. (Ill. 2022), https://www.ilga.gov/legislation/102/SB/10200SB3790.htm.

Kentucky Kentucky Energy & Env’t Cabinet, Solar Waste Factsheet (2024). https://eec.ky.gov/Environmental-Protection/Compliance -Assistance/DCA%20Resource%20Document%20Library/Solar%20Waste%20Factsheet.pdf.

Maryland Md. Code Ann., Envir. § 2-1303(g) (2022). https://mgaleg.maryland.gov/2022RS/Chapters_noln/CH_38_sb0528e.pdf.

Massachusetts Massachusetts Dep’t of Envtl. Prot., Discussion Draft: Solar Panel Recycling—A Review of Existing Markets & Practices (Aug. 2023), https://www.mass.gov/doc/discussion-draft-solar-panel-recycling-a-review-of-existing-markets -practices-august-2023/download.

Minnesota Environment and Natural Resources Appropriations ,2023, ch. 60, § 36, 93rd Leg., Reg. Sess. (Minn. 2023), https://www.revisor.mn.gov/laws/2023/0/Session+Law/Chapter/60/#laws.3.36.0.

Nevada Nev. Rev. Stat. § 444.570 (2023), https://www.leg.state.nv.us/nrs/nrs-444.html.

New Jersey N.J. Dep't of Envtl. Prot., Solar Panel Recycling Commission Report (2023). https://www.nj.gov/dep/dshw/recycling/Solar%20Panel%20Commission.pdf.

North Carolina Session Law 2019-132, H.B. 329, 2019 Gen. Assemb., Reg. Sess. (N.C. 2019), https://www.ncleg.gov/Sessions/2019/Bills/House/PDF/H329v5.pdf.

North Carolina Session Law 2021-165, H.B. 951, 2021 Gen. Assemb., Reg. Sess. https://www.ncleg.gov/BillLookup/2021/H951.

North Carolina Session Law 2021-165 (H951), Gen. Assemb., Reg. Sess., Plan and Recommendations for Financial Resources for Decommissioning of Utility-Scale Solar Panel Projects, https://www.deq.nc.gov/legislative-reports/plan-and- recommendations-financial-resources-decommissioning-utility-scale-solar-panel-projects/open.

North Carolina N.C. Gen. Stat. § 130A-309.240.Decommissioning and restoration requirements for utility-scale solar projects; recycling of project components required; financial assurance requirements.(2024). https://www.ncleg.gov/Laws/GeneralStatute Sections/Chapter130A.

North Carolina H.B. 600, 2023 Gen. Assemb., Reg. Sess. (N.C. 2023), https://www.ncleg.gov/Sessions/2023/Bills/House/PDF/H600v7.pdf.

South Carolina S.C. Code Ann. § 44-96-40 (2023). https://law.justia.com/codes/south-carolina/title-44/chapter-96/section-44-96-40/.

Tennessee H.B. 2761, 112th Gen. Assemb., Reg. Sess. (Tenn. 2022). https://s3.amazonaws.com/fn-document-service/file-by-sha384/fe803d3c91b5e4870979fbb2ec9ef91eb1c7b906129e3e872ee38e8a7e953ad7c1c8d864c350076df080974a7c51aecf.

Texas Tex. S.B. 1290, 88th Leg., R.S. (2023), https://capitol.texas.gov/BillLookup/History.aspx?LegSess=88R&Bill=SB1290.

Texas Texas H.B. 3228, https://capitol.texas.gov/tlodocs/89R/billtext/html/HB03228E.htm.

Virginia S.B. 499, 2022 Gen. Assemb., Reg. Sess. (Va. 2022). https://legacylis.virginia.gov/cgi-bin/legp604.exe?221+sum+SB499.

Washington Wash. Rev. Code § 70A.510.010. Photovoltaic Module Stewardship and Takeback Program, https://app.leg.wa.gov/RCW/default.aspx?cite=70A.510.

References

Allen, Sylvia. "Supervisors OK Amendments to Ordinance Dealing with Solar Facilities." *Brunswick Times-Gazette. 1*9 February 2025. https://www.brunswicktimes-gazette.com/article_4939bf1a-edf6-11ef-ac02-f79d2ee0bb96.html. Accessed April 25, 2026

AutoZone. 2026. Recycle at AutoZone. https://www.autozone.com/lp/recycle. Accessed March 17, 2026

Breckel, Alex, and Nelson Falkenburg. 2025. "State Policy Approaches to Renewable Energy Siting." Climate Advocacy Lab. https://climateadvocacylab.org/resource/insight-report-state-policy-approaches-renewable-energy-siting. Accessed April 15, 2026

Chemical Safety and Health Unit (CHE). 2017. Recycling used lead-acid batteries: Brief information for the health sector. World Health Organization. https://www.who.int/publications/i/item/WHO-FWC-PHE-EPE-17.02. Accessed April 7, 2026

Curtin, A. M., Vail, C. A., & Buckley, H. L. 2020. CdTe in thin film photovoltaic cells: Interventions to protect drinking water in production and end-of-life. Water-Energy Nexus, 3, 15–28. https://doi.org/10.1016/j.wen.2020.03.007.

Curtis, Taylor L., Garvin Heath, and Parikhit Sinha. 2026. *Knowledge-Based Hazardous Waste Determinations for Solar Photovoltaic Modules*. Golden, CO: National Renewable Energy Laboratory. https://www.nlr.gov/docs/fy26osti/96847.pdf.

Curtis, Taylor L., Heather Buchanan, Ligia Smith, and Garvin Heath. 2021. A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-74550. https://docs.nlr.gov/docs/fy21osti/74550.pdf.

Curtis, Taylor, Ligia Smith, and Rebekah Townsend. 2026. "Knowledge-Based Hazardous Waste Determinations for Solar Photovoltaic (PV) Modules: A Foundational Study." Nrel.gov.

National Laboratory of the Rockies. https://docs.nrel.gov/docs/fy26osti/96847.pdf.

Demessie, E. S. 27 September 2023. Renewable Energy Management - Solar Panel Recycling. EPA. https://www.epa.gov/system/files/documents/2023-10/508-compliant-toolsresource_webinar_solar-panel-recycling_09262023.pdf

Department of Ecology. Solar Panels. State of Washington. Accessed April 19, 2026. https://ecology.wa.gov/waste-toxics/reducing-recycling-waste/our-recycling-programs/solar-panels.

Department of Toxic Substances Control. Photovoltaic Modules (PV modules) – Universal Waste Management Regulations. State of California. Accessed April 19, 2026. https://dtsc.ca.gov/photovoltaic-modules-pv-modules-universal-waste-management-regulations/.

Eisenson, Matthew, Jacob Elkin, Ivonne Norman, Rebecca Coombs, and Chadol Kim. 2025. Review of Opposition to Renewable Energy Facilities in the United States: June 2025 Edition. Columbia Law School: Sabin Center for Climate Change Law. https://scholarship.law.columbia.edu/cgi/viewcontent.cgi?article=1252&context=sabin_climate_change. Accessed April 13, 2026

Environmental Compliance Assistance Program (ECAP). Solar Panel Disposal. January 2024. https://eec.ky.gov/Environmental-Protection/Compliance-Assistance/DCA%20Resource%20Document%20Library/Solar%20W aste%20Factsheet.pdf

Environmental Protection Agency (EPA). 3 January 2024. Battery collection in action case study: Lead-acid battery collection. https://www.epa.gov/electronics-batteries-management/battery-collection-action-case-study-lead-acid-battery-collection. Accessed April 12, 2026.

Faulconer, Justin. 2024. "Virginia Lawmakers Debate Redistricting during the Budget Special Session." NewsAdvance.com. February 22. https://newsadvance.com/news/local/article_e00ca724-d108-11ee-a589-9fc8a808c198.html.

First Solar, Inc. 2015. Assessment of leaching tests for evaluating potential environmental impacts of photovoltaic modules. In Proceedings of the 42nd IEEE Photovoltaic Specialist Conference (PVSC).

Florida Department of Environmental Protection. Managing Unwanted or Broken Solar Panels in Florida. Updated 12 August 2025. https://floridadep.gov/sites/default/files/Managing_Unwanted_Broken_%20Solar_Panels_FAQs_v5_7.8.25.pdf.

Franco, Maria A., and Stefan N. Groesser. 2021. "A Systematic Literature Review of the Solar Photovoltaic Value Chain for a Circular Economy." Sustainability 13 (17): 9615. https://doi.org/10.3390/su13179615.

Gao, S., Chen, X., Qu, J. et al. Recycling of silicon solar panels through a salt-etching approach. Nat Sustain 7, 920–930 (2024). https://doi.org/10.1038/s41893-024-01360-4

Garcia, F., & Sardana, R. November 2024. Solar panel recycling and end-of-life considerations. U.S. International Trade Commission. https://www.usitc.gov/publications/332/executive_briefings/ebot_gracia_sardana_solar_panel_circularity.pdf.

Hawaii Administrative Rules. Hazardous Waste Management: Standards for Universal Waste Management. Updated 7 July 2025. https://health.hawaii.gov/shwb/files/2025/07/11-273.1.pdf.

Hazardous Materials Regulations, 49 C.F.R. §§ 171-180 (2024)

Hunziker, Jacob. 2023. "Withdrawn: Solar Farm Plans in Amherst County Put on Pause by Company, for Now." WSET. May 19. https://wset.com/news/local/withdrawn-solar-farm-plans-amherst-county-put-on-pause-energy-company-energix-shawn-hershberger. Accessed April 13, 2026.

IAP2 International Federation. 2018. "IAP2 Spectrum of Public Participation." https://cdn.ymaws.com/www.iap2.org/resource/resmgr/pillars/spectrum_8.5x11_print.pdf.

International Energy Agency. 2022. "Solar PV Global Supply Chains." IEA. July 2022. https://www.iea.org/reports/solar-pv-global-supply-chains.

Królicka, A., Maj, A., & Łój, G. 2025. Promoting sustainability in the recycling of end-of-life photovoltaic panels and Li-ion batteries through LIBS-assisted waste sorting. Sustainability, 17, 838. https://doi.org/10.3390/su17030838/

Li, F., Shaw, S., Libby, C., Preciado, N., Bicer, B., & Tamizhmani, G. 2024. A review of toxicity assessment procedures of solar photovoltaic modules. Waste Management, 174, 646–665. https://doi.org/10.1016/j.wasman.2023.12.034.

Li, F., Tatapudi, S. R., Shaw, S. L., Libby, C., Bicer, B., & Tamizhmani, G. 2025. Photovoltaic module leach testing: Database development and statistical analysis. Journal of Environmental Management, 377. https://doi.org/10.1016/j.jenvman.2025.124666.

Libby, Cara and Shaw, Stephanie. 2019. Environmental and Economic Considerations for PV Module End-of-Life Management. 2458-2463. https://doi.org/10.1109/PVSC40753.2019.8981209.

Linderman, Justin. 2025. 50 States of Solar Decommissioning. North Carolina Clean Energy Technology Center and DSIRE Insight. https://nccleantech.ncsu.edu/wp-content/uploads/2026/01/50-States-of-Solar-Decommissioning-2025-Snapshot-Final.pdf.

Madison County Planning Commission and Board of Supervisors. 3 December 2025. "Joint Meeting Agenda and Information Packet," Madison County, Virginia. https://www.madisonco.virginia.gov/AgendaCenter/ViewFile/Agenda/_12032025-377. Accessed April 25, 2026.

MassDEP. Massachusetts 2030 Solid Waste Master Plan: Working Together Toward Zero Waste. October 2021. https://www.mass.gov/doc/2030-solid-waste-master-plan-working-together-toward-zero-waste/download. Accessed April 15, 2026.

Masson, G., Jäger-Waldau, A., Kaizuka, I., Lindahl, J., Donoso, J., & de l'Epine, M. 2024. A

Snapshot of the Global PV Market and Industry. https://doi.org/10.1109/PVSC57443.2024.10749131.

Metzner, Mallory. 2023. "Sussex County Council Reviews Proposals for Seven Solar Farms." CoastTV. December 5. https://www.coasttv.com/news/sussex-county-council-reviews-proposals-for-seven-solar-farms/article_341fa6c0-93bc-11ee-9761-9f0b0abc7a7c.html. Accessed April 25, 2026.

Michaud, Gilbert, Marilla Smith, Simeng Hao, Thomas Brelage, Andrew Pellico, Katherine Ambrose, Olivia Rodriguez, and Amelia Bergbower. 2024. Review of Utility-Scale Solar Projects in the Rural Midwest: An Assessment of Knowledge Flows. International Journal of Energy Sector Management, March, 36. https://graham.umich.edu/media/files/Solar-Rural-Midwest-Knowlege-Flows.pdf.

National Renewable Energy Laboratory. "Solar Siting Ordinances." Open Energy Data Initiative. 23 October 2024. https://data.openei.org/submissions/5986. Accessed February 15, 2026.

National Renewable Energy Laboratory. (2025). Spring 2025 solar industry update (Report No. PR-7A40-88936). https://www.nrel.gov/docs/fy25osti/95135.pdf. Accessed April 10, 2026.

Nevada Division of Environmental Protection. Sustainable Materials Management Plan. 2022. https://ndep.nv.gov/land/waste/solid-waste/solid-waste-management-plan. Accessed April 16, 2026 .

Niagara County. 2022. Solar Panel Recycling Law. Niagaracounty.gov. https://www.niagaracounty.gov/government/county_information/niagara_county_solar_panel_recycling_local_law.php. Accessed April 13, 2026.

North Carolina Department of Environmental Quality (NCDEQ). North Carolina Landfill Disposal Bans. https://www.deq.nc.gov/north-carolina-landfill-disposal-bans. Accessed 16 April

2026.

North Carolina General Assembly. https://www.ncleg.gov /Laws/GeneralStatutes. Accessed April 5, 2026.

Ohio General Assembly. *Substitute Senate Bill No. 52*. 134th General Assembly. Signed into law 2021. https://www.legislature.ohio.gov/legislation/134/sb52. Accessed April 25, 2026.

Orleans Hub. "Governor Announces Final State Approval for 125-Megawatt Solar Project in Somerset." 2024. Orleanshub.com. December 24. https://orleanshub.com/governor-announces-final-state-approval-for-125-megawatt-solar-project-in-somerset/. Accessed April 25, 2026.

Pivatto, M., Vidotto, L., Pereira, F. O. R., & Rüther, R. 2025. Circular solar economy: PV modules decision-making framework for reuse. Journal of Cleaner Production, 493. https://www.sciencedirect.com/science/article/abs/pii/S0959652625002914.

Rabaia, Malek Kamal Hussien, Nabila Shehata, Valentina Olabi, Mohammad Ali Abdelkareem, Concetta Semeraro, Kyu-Jung Chae, and Enas Taha Sayed. 2024. "Enabling the Circular Economy of Solar PV through the 10Rs of Sustainability: Critical Review, Conceptualization, Barriers, and Role in Achieving SDGs." Sustainable Horizons 11 (September):100106. https://doi.org/10.1016/j.horiz.2024.100106.

Resource Conservation and Recovery Act (RCRA), 42 U.S.C. § 6901 et seq. (1976)

Rounds, Holly. 2026. Barker/Somerset/Appleton/Hartland NY Community Group. Facebook Groups. March 12. https://www.facebook.com/groups/1435061793970342 /posts/2173837816759399/. Accessed April 13, 2026.

"San Bernardino County Bans Large-Scale Solar, Wind in Some Areas." 2019. PV Magazine USA. March 1. https://pv-magazine-usa.com/2019/03/01/san-bernardino-county-bans-large-scale-solar-wind-in-some-areas/. Accessed April 13, 2026.

Shaw, Stephanie L., Mitchell L. Rencheck, Gabriella A. Siegfried, and Cara Libby. 2024. "A Circular Economy Roadmap for Solar Photovoltaics." Solar Energy 276 (July):112580. https://doi.org/10.1016/j.solener.2024.112580.

"Solar Panel Frequent Questions." 2021. United States Environmental Protection Agency. August 23. https://www.epa.gov/hw/solar-panel-frequent-questions. Accessed April 25, 2026.

South Carolina Department of Environmental Services. https://des.sc.gov/programs/bureau-land-waste-management/solar-panels. Accessed 19 April 2026

Svarc, Jason. “Solar Panel Construction & Components.” Solar Panel Construction (Clean Energy Reviews). https://www.cleanenergyreviews.info/blog/solar-panel-components-construction?utm_source=chatgpt.com Accessed April 5, 2026.

Texas Constitution and Statutes. https://statutes.capitol.texas.gov/?tab=1&code=UT&chapter=UT.302&artSec=. Accessed 19 April 2026.

United States, Department of Energy, Solar Energy Technologies Office. Photovoltaics End-of-Life Action Plan. Mar. 2022. www.energy.gov/sites/default/files/2023-10/SETO-PV-End-of-Life-Action-Plan-1.pdf.

Virginia Coalition for Human Rights (VCHR), 2023a. "Letter to Surrounding Community." 2023. February 24. https://vchr.org/pdf/energix/vchr_material/letter_to_surrounding_community.pdf.

Virginia Coalition for Human Rights (VCHR). 2023b. "VCHR Concerns about Energix in Virginia." https://vchr.org/pdf/energix/vchr_material/piney__river_solar_slide_desk.pdf.

Wade, Andreas, Garvin Heath, Stephanie Weckend, Karsten Wambach, Parikhit Sinha, Zhang Jia, Keiichi Komoto, and Knut Sander. 2016. IRENA and IEA PVPS (2016) - End-of-Life

Management: Solar Photovoltaic Panels. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf.

WGRZ-TV. 2025. "The Fight over Where the Somerset Solar Project Should Go Continues." YouTube. January. https://www.youtube.com/watch?v=8ZqZZi_qBog. Accessed April 13, 2026.

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