Solar Photovoltaic Module Recycling: A Survey of U.S. Policies and Initiatives

Taylor L. Curtis,[1] Heather Buchanan,[1] Garvin Heath,[1] Ligia Smith,[1] and Stephanie Shaw[2]

1 National Renewable Energy Laboratory
2 Electric Power Research Institute

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List of Acronyms

ANSI	American National Standards Institute
BAN	Basel Action Network
CED	covered electronic device
CPUC	California Public Utilities Commission
DEC	Department of Environmental Conservation (New York)
DEQ	Department of Environmental Quality (North Carolina)
DOE	U.S. Department of Energy
DTSC	Department of Toxic Substances Control (California)
EoL	end-of-life
EMS	Environmental Management System
EPA	U.S. Environmental Protection Agency
EPEAT	Electronic Product Environmental Assessment Tool
EPR	extended producer responsibility
GEC	Green Electronics Council
GHG	greenhouse gas
GW	Gigawatt
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
ISRI	Institute of Scrap Recycling Industries
ISTC	Illinois Sustainable Technology Center
LCA	life cycle assessment
LCD	liquid crystal display
MSW	municipal non-hazardous solid waste
MPCA	Minnesota Pollution Control Agency
Mt	metric ton
NREL	National Renewable Energy Laboratory
OH&S	occupational health & safety
O&M	operation and maintenance
OECD	Organization for Economic Cooperation and Development
PV	photovoltaic
RCRA	Resource Conservation and Recovery Act of 1976
REC	Renewable Energy Credit
RIOS	Recycling Industry Operational Standard
SEIA	Solar Energy Industries Association
SERI	Sustainable Electronics Recycling International
SVTC	Silicon Valley Toxics Commission

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Executive Summary

Solar is essential to a zero-carbon energy transition in the United States and around the world. National and international policy focused on reducing carbon emissions and increasing electric grid resiliency continue to drive demand for solar. In the U.S. alone, cumulative solar photovoltaic (PV) operating capacity reached 95 gigawatts $(GW)_{dc}$ at the end of 2020, an annual increase of 19 GW_{dc} from 2019. If current trends persist, U.S. cumulative PV installations could reach 202 GW_{dc} by 2025 (Perea et al. 2021).

The rapid growth and expected continual demand for PV has led to global environmental and supply chain concerns. The United States is reliant on imports of raw materials for solar module manufacturing and imports of PV cells and modules to meet domestic demand (Sun et al. 2020; Mints 2020; Smith Margolis 2019). In 2017, the United States imported 92% of the crystalline silicon (c-Si) modules needed to meet domestic demand, and in 2019 U.S. manufacturers relied entirely on imported wafers to meet manufacturing needs (Smith and Margolis 2019). Moreover, as PV capacity increases in the United States so will the volume of end-of-life (EoL) modules. Estimates based on a 30-year lifetime assumption with early loss scenarios found that cumulative end-of-life (EoL) PV modules could total 1 million metric tons (Mt) in the United States by 2030 and up to 10 million Mt by 2050 (Weckend et al. 2016). Early retirements due to efficiency upgrades and catastrophic events, as well as deployment beyond earlier expectations, will further increase these projections.

Concerns about PV supply chain vulnerabilities and PV module waste have led to government- and industry-led discussions, policies, and initiatives that could have important impacts on recycling-based resource recovery of PV modules in the United States. In this report we identify drivers, barriers, and enablers to PV module recycling and resource recovery in the United States. We also analyze U.S. federal and state policies as well as industry policies that expressly address EoL PV module management and recycling. Some of the findings are listed below.

Drivers for PV Module Recycling

Some drivers identified for domestic PV module recycling include increased supply chain stability, reduced negative environmental impacts, and new and expanded U.S. market opportunities. Domestic PV module recycling can recover high-value materials (e.g., silicon, indium, silver, tellurium, copper) for use in domestic manufacturing or for sale into commodity markets. Domestic recovery of these resources can reduce U.S. dependence on foreign imports and alleviate resource constraints. In addition, the recovery of these materials can reduce waste, and the environmental impacts and total energy needed to mine, transport, and refine virgin materials and to manufacture new PV modules (Curtis et al. 2021b). Domestic resource recovery can lead to new and expanded PV module material and product manufacturing opportunities. Third-party recyclers and lifecycle management companies could expand their services to include PV module handling, transport, and recycling services. New companies may also emerge to provide decommissioning and recycling services (Curtis et al. 2021b; Salim et al. 2019; Xu et al. 2018; Libby and Shaw 2018; Kalmykova et al. 2018; Corcelli et al. 2017; Dominguez and Geyer 2017; Weckend et al. 2016; Ghisellini et al. 2016).

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We also found that cost savings, increased profits, and enhanced competitiveness are drivers for PV module recycling. Manufacturers could lower costs by recycling and reusing recovered materials from PV modules, manufacturing scrap, and warranty returns. Manufacturers, system owners, third-party recyclers and others may also generate revenue by selling recovered materials into commodity markets. Moreover, system owners and manufacturers may also find it advantageous to recycle PV modules to comply with voluntary industry standards to enhance their company's image and their overall competitiveness in the marketplace (Curtis et al. 2021b).

Barriers to PV Module Recycling

Some barriers identified that may impede PV module recycling opportunities in the United States include gaps in data, current recycling technology, services and infrastructure, and regulatory uncertainty. There is a lack of research and publicly available information regarding: the value and markets for recovered PV materials, the volume and composition of near-term EoL PV modules, the development of PV module recycling technology, the assessment of infrastructure needs, and the overall costs associated with PV module recycling (Salim et al. 2019; Choi 2017; D'Adamo 2017; Weckend et al. 2016). Current technology, infrastructure, and processes associated with recycling PV modules are not optimized for cost-effective recovery of high value materials. As a result, the cost of recycling is often outweighed by cheaper more accessible disposal options. In addition, the current regulatory scheme for managing EoL PV modules is complex and varies by jurisdiction, and there is not a clear understanding of the permitting requirements or liabilities associated with handling, transporting, storing, accumulating, treating, or recycling PV modules (Libby and Shaw 2018; NREL 2019; CPUC 2019; DTSC 2019b; Evelyn Butler, Solar Energy Industries Association, telephone conference, February 8, 2019; Matthew Garamone and Parikhit Sinha, First Solar, telephone conference March 4, 2019; Tim Kimmel, Cleanlites Recycling, telephone conference March 5, 2019; Gary Winslow, MiaSolé, email, March 12, 2019; John Martorano, Magnum Computer Recycling, telephone conference July 31, 2019). Moreover, federal and state solid waste laws often regulate PV modules destined for resource recovery in the same manner as those destined for disposal, which does not provide an incentive for recycling, especially when the economics and accessibility of disposal are more favorable. Nor are there many policies in place that require or incentivize PV module recycling and resource recovery in the United States. To date, the most common regulatory mechanisms for EoL product management are extended producer responsibility (EPR) and landfill diversion policies. However, no publicly available study comprehensively analyzes the advantages, challenges, and overall success of these policies or how they compare to other regulatory models, or whether these frameworks make sense for PV modules.

Enablers to PV Module Recycling

Policy can help enable PV module recycling in the United States. Government-funded research and analysis is needed to study and inform: 1) the value of and the markets for recovered materials, 2) the volume and composition of EoL PV modules, 3) module recycling technology and infrastructure needs, 4) permitting requirements and liabilities, and 5) costs associated with PV module recycling (Salim et al. 2019; CPUC 2019; NREL 2019; Libby and Shaw 2018; Tura et al. 2018). Clearly defined regulatory requirements and restrictions can also reduce uncertainty and risk associated with recycling PV modules (NREL 2019; CPUC 2019; Salim et al. 2019). In addition, federal, state, and industry policies can mandate or incentivize resource recovery or

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prohibit disposal which could drive and enable PV module recycling opportunities in the United States (Salim et al. 2019; Tura et al. 2018; Bai et al. 2015; Dong et al. 2016). For example, policies that mandate or incentivize manufacturers to provide PV module labels with concentrations of hazardous material (such as lead) could enable information exchange between stakeholders and eliminate the need for expensive and variable hazardous waste characteristic testing. Moreover, policies that reduce the regulatory burden and legal liability associated with PV modules destined for resource recovery compared to disposal could also incentivize recycling modules making the economics of recycling more competitive with disposal.

PV Module Recycling Policies

We found no federal statutes or regulations that expressly speak to recycling-based recovery of PV modules in the United States, however state- and industry-led policies have started to emerge to address EoL PV module management concerns. We identified four states that have recently enacted laws that address PV module recycling and could impact domestic resource recovery and U.S. recycling. For example, Washington recently implemented a EPR regulation that impacts solar module manufacturers. The regulation will require PV module manufacturers, beginning July 1, 2023, to finance the takeback and reuse or recycling of PV modules sold within or into the state, after July 1, 2017, a no cost to the end user. California also passed a regulation that took effect in January of 2021 that allows for EoL PV modules to be managed as universal hazardous waste. California's universal waste regulation allows for modules being recycled or disposed of to be regulated under less stringent handling, transport, and storage requirements and prohibits the use of heat and chemical treatment and recycling processes. In addition, New Jersey and North Carolina passed legislation in 2019 to study EoL PV module management options to inform future regulation in their respective state.

We also analyzed bills (pending) in the 2020-2021 U.S. state legislatures as well as historic bills proposed that failed in recent years to identify policy trends that impact PV module recycling. We found that California and Hawaii both have proposed (pending) bills that create advisory groups to study and recommend PV module EoL policies in their respective state. Rhode Island has proposed a bill that, if enacted, would create a Photovoltaic Module Stewardship and Takeback Program. In addition, we identified 15 historical state bills that were proposed and failed since 2014 that addressed EoL PV modules.

We also identified recent state-led and industry-led initiatives that focus on EoL management options for PV modules. Working groups in California, Illinois and Minnesota have been formed in the last few years to study PV module recycling and inform future regulation. Moreover, a new industry standard was recently released (NSF 457 Sustainability Leadership for PV Modules and Inverter) which incentivizes PV module recycling. The Solar Energy Industries Association (SEIA) has also developed a national network of recyclers for PV modules.

Methodology

Our results are based on legal- and literature-based research. In addition, our results incorporate feedback and information we received from a series of interviews conducted through teleconference and email exchange with a diverse group of industry experts, including academic and research organizations, industry associations, manufacturers, asset owners, recycling

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companies, consultants, as well as U.S. federal and state regulators and policymakers. The questions used in each interview were tailored to the industry stakeholders' areas of expertise.

This report is intended to inform decisionmakers, including those involved in policy design; it does not endorse any particular policy mechanism over another, nor does it assess all policies or all the impacts that those policies may have on solar markets or related commodity markets.

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1 Introduction

Solar is essential to a zero-carbon energy transition in the United States and around the world. National and international policy focused on reducing carbon emissions and increasing electric grid resiliency continue to drive demand for solar. In the U.S. alone, cumulative solar photovoltaic (PV) operating capacity reached 95 gigawatts $(GW)_{dc}$ at the end of 2020, an annual increase of 19 GW_{dc} from 2019. If current trends persist, U.S. cumulative PV installations could reach 202 GW_{dc} by 2025 (Perea et al. 2021).

The rapid growth and expected continual demand for PV has led to global environmental and supply chain concerns. The United States is reliant on imports of raw materials for solar module manufacturing and imports of PV cells and modules to meet domestic demand (Sun et al. 2020; Mints 2020; Smith Margolis 2019). In 2017, the United States imported 92% of the crystalline silicon (c-Si) modules needed to meet domestic demand, and in 2019 U.S. manufacturers relied entirely on imported wafers to meet manufacturing needs (Smith and Margolis 2019). Moreover, as PV capacity increases in the United States so will the volume of end-of-life (EoL) modules. Estimates based on a 30-year lifetime assumption with early loss scenarios found that cumulative end-of-life (EoL) PV modules could total 1 million metric tons (Mt) in the United States by 2030 and up to 10 million Mt by 2050 (Weckend et al. 2016). Early retirements due to efficiency upgrades and catastrophic events, as well as deployment beyond earlier expectations, will further increase these projections.

The growing amount of decommissioned PV modules in the United States has led to a national discussion on EoL management options and opportunities. EoL management options for PV include reuse, rebuild for reuse,[1] recycling and resource recovery, storage, and disposal. Disposal of PV modules increases the burden on landfill capacity[2] in the United States, while reuse, rebuild for reuse, and recycling options recover valuable materials and provide secondary market opportunities and ancillary benefits (EPA 2019d; SWEEP 2019; Weckend et al. 2016). Domestic resource recovery of PV module material could reduce environmental and supply chain concerns and lead to new and expanded market opportunities, job creation, and economic benefits for PV industry stakeholders in the United States.

But anecdotal evidence suggests that today storage and disposal of PV modules are occurring and that less than 10% are being recycled in the United States (Salim et al. 2019; CPUC 2019; DTSC 2019b; NREL 2019). Industry experts have observed that some PV modules are being disposed of in municipal non-hazardous landfills and federally regulated hazardous treatment, storage, and disposal facilities, while other PV modules are being stored in warehouses until economically viable recycling or other EoL management options become available (Curtis et al. 2021b; ASES 2020; CSSA 2020; CPUC 2019; DTSC 2019b; NREL 2019; Libby and Shaw

[1] This report uses the terms “rebuild” and “rebuilt” to include various degrees of rebuilding, remanufacturing, refurbishing, repairing, or reconditioning PV modules and system components for reuse. This terminology comes from the Underwriters Laboratories Rebuilt Equipment Certification Program (UL 2014).

[2] The U.S. Environmental Protection Agency (EPA) has a database of 2,613 municipal landfills in the U.S. of those landfills the EPA has landfill design capacity data and waste in place data for 1,339 landfills. Of those 1,339 landfills, with capacity data, more than half (763 landfills) have reached 50% or more in capacity, while 204 of those landfills are already at 100% capacity (EPA 2019d). In addition, one projection found that by 2021 only 15 years of landfill capacity in the U.S. will remain (SWEEP 2019).

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2018). As awareness of current practices grows, industry stakeholders, regulators, and policymakers in the United States are starting to study and identify barriers to cost-effective PV module recycling, and to inform policy[3] that aims to drive and enable environmentally sustainable EoL management decisions and increase module recycling.

This report identifies drivers, barriers, and potential enablers to PV module recycling and resource recovery efforts in the United States. In addition to literature-based research, we conducted a number of interviews and interacted with industry stakeholders to identify factors that may drive or act as a barrier to PV module recycling opportunities in the United States. The stakeholder interactions also informed potential solutions to the identified barriers to enable recycling-based recovery of PV module materials in the United States.

Some drivers identified for domestic PV module recycling include increased supply chain stability, reduced negative environmental impacts, and new and expanded U.S. market opportunities. Domestic PV module recycling can recover high-value materials (e.g., silicon, indium, silver, tellurium, copper) for use in domestic manufacturing or for sale into commodity markets. Domestic recovery of these resources can reduce U.S. dependence on foreign imports and alleviate resource constraints. In addition, the recovery of these materials can also reduce waste, and reduce the environmental impacts and total energy needed to mine, transport, and refine virgin materials and to manufacture new PV modules (Curtis et al. 2021b). Domestic resource recovery can lead to new and expanded PV module material and product manufacturing opportunities. Third-party recyclers and lifecycle management companies could expand their services to include PV module handling, transport, and recycling services. New companies may also emerge to provide decommissioning and recycling services (Curtis et al. 2021b; Salim et al. 2019; Xu et al. 2018; Libby and Shaw 2018; Kalmykova et al. 2018; Corcelli et al. 2017; Dominguez and Geyer 2017; Weckend et al. 2016; Ghisellini et al. 2016).

We also found that cost savings, increased profits, and enhanced competitiveness are drivers for PV module recycling. Manufacturers could lower costs by recycling and reusing recovered materials from PV module manufacturing scrap, warranty returns, and other PV modules. Manufacturers, system owners, third-party recyclers and others may also generate revenue by selling recovered materials into commodity markets. Moreover, system owners and manufacturers may also find it advantageous to recycle PV modules to comply with voluntary industry standards to enhance their company's image and advance their overall competitiveness in the marketplace (Curtis et al. 2021b).

Some barriers identified that may impede PV module recycling opportunities in the United States include gaps in data, current recycling technology, services and infrastructure, and regulatory uncertainty. There is a lack of research and publicly available information regarding: the value and markets for recovered PV module materials, the volume and composition of near-term EoL PV modules, the development of PV recycling technology, the assessment of infrastructure needs, and the overall costs associated with PV module recycling (Salim et al. 2019; Choi 2017; D'Adamo 2017; Weckend et al. 2016). Current technology, infrastructure, and processes associated with recycling PV modules are not optimized for cost-effective recovery of high value

[3] "Policy" is used broadly in this report to include not only federal and state statutory and regulatory requirements, but also governmental initiatives and goals, in addition to industry initiatives, standards, and goals.

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materials. As a result, the cost of recycling is often outweighed by cheaper more accessible disposal options. In addition, the current regulatory scheme for managing EoL PV modules is complex and varies by jurisdiction, and there is not a clear understanding of the permitting requirements or liabilities associated with handling, transporting, storing, accumulating, treating, or recycling PV modules (Libby and Shaw 2018; NREL 2019; CPUC 2019; DTSC 2019b; Evelyn Butler, Solar Energy Industries Association, telephone conference, February 8, 2019; Matthew Garamone and Parikhit Sinha, First Solar, telephone conference March 4, 2019; Tim Kimmel, Cleanlites Recycling, telephone conference March 5, 2019; Gary Winslow, MiaSolé, email, March 12, 2019; John Martorano, Magnum Computer Recycling, telephone conference July 31, 2019). Moreover, federal and state solid waste laws often regulate PV modules destined for resource recovery in the same manner as those destined for disposal, which does not provide an incentive for recycling especially when the economics and accessibility of disposal are more favorable. Nor are there many policies in place that require or incentivize PV module recycling and resource recovery in the United States. To date, the most common regulatory mechanisms for EoL product management are extended producer responsibility (EPR) and landfill diversion policies. However, no publicly available study comprehensively analyzes the advantages, challenges, and overall success of these policies or how they compare to other regulatory models, or whether these frameworks make sense for PV modules.

Policy can help enable PV module recycling in the United States. Government-funded research and analysis is needed to study and inform: 1) the value of and the markets for recovered materials, 2) the volume and composition of EoL PV modules, 3) module recycling technology and infrastructure needs, 4) permitting requirements and liabilities, and 5) costs associated with PV module recycling (Salim et al. 2019; CPUC 2019; NREL 2019; Libby and Shaw 2018; Tura et al. 2018). Clearly defined regulatory requirements and restrictions can also reduce uncertainty and risk associated with recycling PV modules (NREL 2019; CPUC 2019; Salim et al. 2019). In addition, federal, state, and industry policies can mandate or incentivize resource recovery or prohibit disposal which could drive and enable PV module recycling opportunities in the United States (Salim et al. 2019; Tura et al. 2018; Bai et al. 2015; Dong et al. 2016). For example, policies that mandate or incentivize manufacturers to provide PV module labels with concentrations of hazardous material (such as lead) could enable information exchange between stakeholders and eliminate the need for expensive and variable hazardous waste characteristic testing. Moreover, policies that reduce the regulatory burden and legal liability associated with PV modules destined for resource recovery compared to disposal could also incentivize recycling modules making the economics of recycling more competitive with disposal.

This report also analyzes federal, state, and industry policies that expressly address PV module recycling opportunities in the United States. Specifically, this report analyzes existing federal and state statutes and regulations, proposed state legislation (i.e., pending), and historic state legislative proposals (i.e., failed, unenacted), as well as state- and industry-led policies and initiatives that explicitly address recycling-based recovery of PV modules in the United States. We conducted legal- and literature-based research and held a number of interviews with industry stakeholders, regulators, and policymakers to identify relevant policies and to help inform the analysis of those identified policies. Literature-based research and industry stakeholder interviews also helped characterize the advantages and challenges associated with the identified policies. Recognizing that federal, state, and industry policies can enable or inhibit PV module recycling opportunities in the United States, this report hopes to inform policy design but does

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not endorse one particular policy mechanism or framework over another. Nor does this report assess any impacts the identified policies may have on the PV market or associated commodity markets in the United States.

We found no federal statutes or regulations that expressly speak to recycling-based recovery of PV modules in the United States; however, state- and industry-led policies have started to emerge to address EoL PV management concerns. The state- and industry-led policies identified have diverse frameworks that cover different EoL management activities and impact different actors in the solar value chain. In 2017, Washington enacted the first law in the United States to require PV manufacturers to take back and reuse or recycle PV EoL modules from end users. Other states, such as New Jersey and North Carolina, passed laws in 2019 to require the study of EoL PV management options, which are designed to develop options for legislative or regulatory consideration and could provide valuable, publicly available information about the costs and liabilities associated with PV module recycling and resource recovery opportunities. California also passed a regulation that took effect in January of 2021 that allows for EoL PV modules to be managed as universal hazardous waste. California's universal waste regulation allows for modules being recycled or disposed of to be regulated under less stringent handling, transport, and storage requirements and prohibits the use of heat and chemical treatment and recycling processes.

We also analyzed bills (pending) in the 2020-2021 U.S. state legislatures as well as historic bills proposed that failed in recent years to identify policy trends that impact PV module recycling. We found that California and Hawaii both have proposed (pending) bills that create advisory groups to study and recommend PV module EoL policies in their respective state. Rhode Island has proposed a bill that, if enacted, would create a Photovoltaic Module Stewardship and Takeback Program. In addition, we identified 15 historical state bills that were proposed and failed since 2014 that addressed EoL PV modules.

We also identified recent state-led and industry-led initiatives that focus on EoL management options for PV modules. Working groups in California, Illinois and Minnesota have been formed in the last few years to study PV module EoL management options and inform future regulation. Moreover, a new industry standard was recently released (NSF 457 Sustainability Leadership for PV Modules and Inverter) which incentivizes PV module recycling. The Solar Energy Industries Association (SEIA) has also developed a national network of recyclers for PV modules.

This report analyzes policies in the United States that may impact EoL PV module recycling and resource recovery.

- Section 2 discusses drivers, barriers, and enablers to PV module recycling and resource recovery in the United States;
- Section 3 discusses current state policies that mandate or encourage PV module recycling;
- Section 4 discusses proposed state legislation that specifically address EoL PV module recycling;
- Section 5 highlights historic legislation that, if enacted as written, would have addressed EoL PV module recycling; and
- Section 6 provides an overview of industry- and state-led initiatives aimed at furthering PV module recycling efforts in the United States.

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2 Drivers, Barriers, and Enablers to PV Module Recycling in the United States

The current solar supply chain in the United States represents a linear economic model. Few PV manufacturers take into consideration design for recyclability and only a few U.S.-based manufacturers have implemented takeback programs to recycle EoL PV modules (NREL 2019; Salim et al. 2019). Moreover, although there is a growing number of third-party companies that accept PV modules, less than 10% of EoL modules are sent to recyclers today (CSSA 2020; ASES 2020). Most asset owners are unsure how to manage EoL PV modules and the cost and accessibility of recycling is often overshadowed by cheaper more accessible disposal options (CPUC 2019; Salim et al 2019; Evelyn Butler, Solar Energy Industries Association, telephone conference, February 8, 2019; SEIA 2019b; Libby and Shaw 2018). Anecdotal evidence suggests that the cost of module recycling in the United States ranges from $15-45 per module, while one study found that disposal tipping fees at non-hazardous landfills ($26/U.S. ton) can cost less than $1 per module and less than $5 per module at hazardous waste landfills ($175/U.S. ton) (Curtis et al. 2021b; ASES 2020; CSSA 2020; Ablison Energy 2020; Evergreen Solar 2020; Intermountain Wind & Solar 2020; CitiGreen, Inc. 2019; Green Coast 2019; Alba Energy 2018; EnergySage 2018; Libby and Shaw 2018).[4] By comparison, in Europe, where countries have nationwide policies that mandate PV module recycling, the cost of recycling is as low as $0.70 per module and recycling rates are as high as 95% (Curtis et al. 2021b; CSSA 2020; ASES 2020).

In this section, we discuss drivers, barriers, and potential enablers to PV module recycling in the United States. In addition to doing literature-based research, we conducted interviews and interacted with solar experts to identify factors that may drive or act as a barrier to PV module recycling in the United States. These stakeholder interactions also informed potential solutions that may enable module recycling.

2.1 Drivers for PV Module Recycling

Drivers are opportunities that motivate actors to adopt a desired behavior and typically benefit specific stakeholders or the public interest. Federal, state, and industry policy can either enable or inhibit a particular opportunity or benefit. In this section we identify some economic and environmental opportunities and benefits of module recycling that may drive actors along the PV value chain to recycle. Table 1 summarizes some of those drivers.

[4] We calculated the per module disposal cost by estimating a typical module weight of 33-50 pounds (Ablison Energy 2020; Evergreen Solar 2020; Intermountain Wind & Solar 2020; CitiGreen, Inc. 2019; Green Coast 2019; Alba Energy 2018; EnergySage 2018; Wholesale Solar 2011) and using the per ton landfill tipping costs of $26/U.S. ton to $89/U.S. ton for nonhazardous Subtitle D landfills and $175/U.S. ton for hazardous Subtitle C landfills provided by (Libby and Shaw 2018).

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Table 1. Drivers for PV Module Recycling

Economic Drivers	Potential Benefits	Actor(s)
Cost savings and increased profits	Recycling and resource recovery can reduce manufacturing costs and create additional revenue streams and tax benefits	Manufacturer, PV Owner, O&M
Enhanced competitiveness	Recycling and resource recovery can increase a business's "green" or "environmentally responsible" image and increase consumer trust	Manufacturer, PV Owner, O&M, Installers, End User
New and expanded market and employment opportunities	Recycling-based resource recovery presents opportunities for new and expanded markets and job creation	Manufacturer, PV Owner, O&M, Installer, Recycler, Government
Environmental Drivers	**Potential Benefits**	**Actor(s)**
Reduced negative environmental impacts	Recycling can reduce waste, greenhouse gases, and other environmental, and the total energy required to mine, transport, refine and manufacture PV modules	Manufacturer, PV Owner, O&M, Installer, Recycler, Government
Reduced resource constraints	Recycling-based resource recovery can conserve high-value materials, prevent resource constraints, reduce raw material import demand, and reduce supply chain concerns	Manufacturer, Government

2.1.1 Economic Drivers

Recycling EoL PV modules can lead to economic benefits for industry stakeholders, new and expanded market opportunities, and job creation in the United States. Recovery of high-value materials (e.g., silicon, indium, silver, tellurium, copper) can be used to manufacture new PV modules, or can be sold into commodity markets (Salim et al. 2019; Xu et al. 2018; Dominguez and Geyer 2017; Weckend et al. 2016). One estimate found that the value of recovered material from EoL PV modules represents a potential $60 million U.S. industry by 2030, and $2 billion by 2050 (Weckend et al. 2016; EPA 2019a).

Reuse of valuable materials recovered from recycled PV modules can provide cost savings to manufacturers and profits for other industry stakeholders (Curtis et al. 2021b; CPSC 2020; Ludt 2019; Salim et al. 2019; Libby and Shaw 2018; Kalmykova et al. 2018; Corcelli et al. 2017; Ghisellini et al. 2016). Manufacturers could lower manufacturing costs by reusing recovered materials from manufacturing scrap, customer returns and other modules. Recycling companies and other industry stakeholders (e.g., reverse logistic companies) can expand their business products and services to include PV module recycling, and they could sell recovered materials on commodity markets. For example, Cleanlites Recycling Inc., and Dynamic LifeCycle Innovations have both expanded their universal and electronic waste management and recycling services to also include PV module collection and recycling (Tim Kimmel, Cleanlites Recycling, teleconference, March 5, 2019; Casey Hines and Amanda Tischer-Buros, LifeCycle Dynamics, teleconference, March 20, 2019). Companies that engage in environmentally sustainable EoL management practices, such as recycling could also enhance their corporate responsibility image and increase consumer trust (Curtis et al. 2021b; Salim et al. 2019; Xu et al. 2018).

Moreover, domestic recovery of PV module material can reduce resource constraints, increase supply chain stability, and lead to new and expanded U.S. market opportunities and job creation.

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Domestic recovery of PV module material could decrease module and module material imports, increase supply stability, and provide an opportunity to expand PV material and module manufacturing in the United States (Curtis et al. 2021b). New companies, such as Solar Sun Recycling are also emerging to offer reverse logistics and recycling services (Curtis et al. 2021b).

2.1.2 Environmental Drivers

Recycling-based resource recovery of PV modules can reduce waste, alleviate constraints on virgin materials, and reduce environmental pollutants associated with production of new PV modules. The reuse of recovered PV module material reduces waste and diverts valuable materials from the landfill. The reuse of these materials also reduces constraints on virgin materials used in PV module manufacturing. Moreover, the reuse of recovered module material reduces lifecycle environmental impacts by reducing the energy output, costs, and environmental pollutants (e.g., greenhouse gas emissions) associated with mining, transporting, and refining virgin materials, and manufacturing and distributing new PV modules (Curtis et al. 2021b; Salim et al. 2019; Celik et al. 2018; Stolz et al. 2018; Dominguez and Geyer 2017).

2.2 Barriers to PV Module Recycling

Barriers are factors that may hinder a desired behavior or outcome. Federal, state, and industry policy can inhibit a particular opportunity, benefit, or desired outcome. Identifying the major barriers associated with PV module recycling may help policymakers formulate policy solutions to overcome future challenges. In this section, we identify technology, process, data, economic and regulatory factors that may inhibit PV module recycling. Table 2 summarizes those barriers.

Table 2. Barriers to PV Module Recycling

Barrier	Description	Actor(s)
Lack of support for research, development, and analysis	Limited policies exist to fund research, development, and analysis for: the valuation of and markets for recovered PV materials, the volume and composition of EoL PV, development of PV module recycling technology and assessment of infrastructure needs, identification and analysis of permitting requirements and liabilities, and the costs associated with PV module recycling	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, Government
Lack of publicly available information and information exchange	Policies do not support information exchange between manufacturers and recyclers or between end users and landfill owners and operators	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Recycler, End User, Landfill Owner/Operator
Lack of economic incentives	Limited economic incentives exist to promote design for recycle or the collection and recycling of EoL PV modules	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Recycler, End User, Landfill Owner/Operator
Complex, varied laws and regulations	The laws and regulations applicable to the EoL management of PV modules are complex, confusing, and vary by jurisdiction	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, End User, Landfill Owner/Operator, Government

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Barrier	Description	Actor(s)
Existing statutory and regulatory schemes do not support recycling and resource recovery	No federal and limited state policies exist to mandate or incentivize PV module recycling; the current statutory and regulatory scheme often mandates compliance with stringent handling, storage, transport, treatment, recycling, and disposal requirements that carry civil and criminal liability for non-compliance	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, End User, Landfill Owner/Operator, Government

2.2.1 Research, Development, and Analysis Barriers

The first group of policy barriers is predominately concerned with the lack of research and publicly available information regarding the incentives, requirements, costs, liabilities, and current market conditions associated with PV module recycling. To date, limited U.S. government funding has been focused on understanding the value of recovered materials from PV modules or the expected volume and composition of EoL PV modules in the United States (Salim et al. 2019; Weckend et al. 2016). The 2016 International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) report is one of the most comprehensive studies conducted, to date, that estimates the expected volume of EoL PV modules, and the value of recovered material. Yet the IEA/IRENA report's estimates are based on raw materials technically recoverable from PV modules, and the findings do not take into consideration the need for material streams of certain purity or loss scenarios associated with modules not collected and recycled (Weckend et al. 2016). The report's EoL PV module projections could also be strengthened by additional assumption factors such as estimates of early retired PV modules due to catastrophic events or decisions to repower PV systems with higher efficiency modules. The IEA/IRENA data could also be updated using current PV installation and projection numbers.

In terms of repowering alone, recent trends suggest that commercial- and utility-scale repowering may become more prevalent in the solar industry, which could increase EoL PV module projections (Balfour 2017; NREL 2019). Similar to technological advances in the electronics industry, PV manufacturers also find ways to improve the efficiency of PV modules over time, which could lead to the early retirement of operational modules (Balfour 2017; EPA 2019a). Industry observations suggest that some commercial- and utility-scale solar project owners and operators may find it advantageous to replace older PV modules with newer, more efficient modules every 10 to 12 years (NREL 2019; CPUC 2019). If commercial- and utility-scale repowering becomes more prevalent this will impact the volume of EoL PV modules in the United States (NREL 2019; CPUC 2019).

Moreover, there is limited publicly available research identifying PV module recycling infrastructure and technology needs in the United States (Salim et al. 2019; Tura et al. 2018). U.S.-based recycling facilities are not designed for PV modules and are not optimized for cost-effective recovery of high-purity materials at high recovery rates (Heath et al. 2020). In fact, we only found two recyclers in the United States that recover high-purity bulk and trace materials from PV modules—We Recycle Solar and First Solar (Curtis et al. 2021b; ASES 2020; Heath et al. 2020). (Curtis et al. 2021b; CSSA 2020; ASES 2020; First Solar 2019; Matthew Garamone and Parikhit Sinha, First Solar, telephone conference, March 4, 2019). Most recyclers are only recovering glass, aluminum frames, and external copper wires from PV modules and are unable

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to recover high value constituents like silver, copper, and high purity silicon (Wambach et al. 2018).

In addition, limited information is available regarding the capital costs associated with establishing collection centers and recycling facilities and purchasing necessary recycling machinery (Curtis et al. 2021b; Choi 2017; D'Adamo 2017). Limited public information is also available regarding projected U.S. locations of near-term EoL PV in relation to recycling and resource recovery operations. Nor is public information available regarding the most cost-effective means to collect, sort, and transport modules between these locations.

No industry or U.S. federal research program exists that comprehensively analyzes the regulatory or economic soft costs associated with recycling EoL PV modules. Information is limited regarding the regulatory and permitting requirements and liabilities associated with PV module recycling and resource recovery operations. Nor is there a clear understanding of what the permitting, siting, and occupational health and safety (OH&S) requirements are for constructing new PV module recycling and resource recovery facilities.

2.2.2 Information Availability and Exchange Barriers

The second group of policy barriers focuses on the lack of information exchange between solar value chain actors (Salim et al. 2019; NREL 2019; Tura et al. 2018; Besiou and Van Wassenhove 2016). For example, no federal, state, or industry policies require or incentivize manufacturers to label PV modules to provide recyclers or landfill operators with the modules' chemical makeup. The lack of transparency between manufacturers and EoL PV module stakeholders compounds highly variable EoL management costs by requiring testing to determine if the module exceeds toxicity thresholds to ensure compliance with EoL management requirements (Libby and Shaw 2018). In addition, costs related to disassembly, collection, sorting, handling, transportation, and operations are often not well documented in analyses to date, which further complicates cost estimate calculations (Salim et al. 2019; Libby and Shaw 2018).

2.2.3 Economic Incentive Barriers

The third group of policy barriers is concerned with the lack of policies to incentivize PV module recycling. The collection, transport, and recycling of PV modules is currently cost prohibitive and more expensive than disposal (Salim et al. 2019; Libby and Shaw 2018; Kadro and Hagfeldt 2017). PV recycling processes are neither automated nor cost-effective, and data on the costs associated with PV module recycling is limited (Heath et al. 2020; Salim et al. 2019; Libby and Shaw 2018). Anecdotal evidence suggests that the cost of module recycling in the United States ranges from $15-45 per module, while one study found that disposal tipping fees at non-hazardous landfills ($26/U.S. ton) can cost less than $1 per module and less than $5 per module at hazardous waste landfills ($175/U.S. ton) (ASES 2020; CSSA 2020; Ablison Energy 2020; Evergreen Solar 2020; Intermountain Wind & Solar 2020; CitiGreen, Inc. 2019; Green Coast 2019; Alba Energy 2018; EnergySage 2018; Libby and Shaw 2018).[5] As a result, anecdotal

[5] We calculated the per module disposal cost by estimating a typical module weight of 33-50 pounds (Ablison Energy 2020; Evergreen Solar 2020; Intermountain Wind & Solar 2020; CitiGreen, Inc. 2019; Green Coast 2019; Alba Energy 2018; EnergySage 2018; Wholesale Solar 2011) and using the per ton landfill tipping costs of $26/

evidence suggest that most early retired and EoL PV modules are landfilled or otherwise disposed of resulting in less than 10% of modules being recycled in the United States (ASES 2020; CSSA 2020; Salim et al. 2019; CPUC 2019b; DTSC 2019b; NREL 2019a). By comparison, in Europe, where countries have nationwide policies that mandate PV module recycling, the cost of recycling is as low as $0.70 per module and recycling rates are as high as 95% (CSSA 2020; ASES 2020). In addition, there are no federal, state, or local incentives to help overcome these costs and enable PV module recycling in the United States (Salim et al. 2019; Libby and Shaw 2018; Kadro and Hagfeldt 2017). Nor are there many federal, state, or private industry funded incentives (i.e., subsidies, grants, awards) to promote U.S. research and development activities for designing easy-to-recycle PV modules (Besiou and Van Wassenhove 2016).

2.2.4 Regulatory Barriers

The last two policy barriers concern the current regulatory scheme for the EoL management and recycling of PV modules. First, few policies in the United States mandate a particular EoL PV management fate or incentivize PV module recycling. No federal or state laws directly ban the disposal of PV modules in landfills, and only one state (Washington state) requires the collection and recycling or reuse of EoL PV modules (NREL 2019; CPUC 2019; Wash. Rev. Code § 70A.510.010 et seq. [2018]).

Second, solid waste permitting requirements in the United States are complex and vary by jurisdiction. In addition, federal, state, and local solid waste laws often regulate PV modules being recycled in the same manner as PV modules being disposed of, which does not provide an incentive to recycle. This is especially true because the economics and accessibility of disposal are more favorable than recycling. Federal, state, and local governments may regulate the handling, transport, storage, accumulation, treatment, and recycling of PV modules as solid waste or hazardous waste pursuant to the Resource Conservation and Recovery Act of 1976 (RCRA) (Curtis et al. 2021b;; NREL 2019; CPUC 2019; DTSC 2019b; Evelyn Butler, Solar Energy Industries Association, telephone conference, February 8, 2019; Matthew Garamone and Parikhit Sinha, First Solar, telephone conference March 4, 2019; Tim Kimmel, Cleanlites Recycling, telephone conference March 5, 2019; Gary Winslow, MiaSolé, email, March 12, 2019; John Martorano, Magnum Computer Recycling, telephone conference July 31, 2019). The complexity of the regulatory scheme and the associated costs and liabilities associated with compliance may create a level of risk that inhibits PV module recycling in the United States (Salim et al., 2019; CPUC 2019; NREL 2019; Libby and Shaw 2018).

Resource Conservation and Recovery Act of 1976

RCRA regulates the management of non-hazardous and hazardous solid waste in the United States (42 U.S.C. §§ 6901-6992k). RCRA is a pollution prevention regulatory scheme that was designed "to promote the protection of health and the environment" and "to conserve valuable material and energy resources" (42 U.S.C. §§ 6901[a]-[d]). Subtitle D of RCRA grants authority to states to regulate non-hazardous waste pursuant to federal guidelines, while Subtitle C of RCRA grants authority to the Environmental Protection Agency (EPA) to regulate hazardous

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U.S. ton to $89/U.S. ton for nonhazardous Subtitle D landfills and $175/U.S. ton for hazardous Subtitle C landfills provided by (Libby and Shaw 2018).

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solid waste. There are two potential barriers associated with RCRA's regulatory scheme that may impede PV module recycling and resource recovery efforts in the United States:

1. EPA's solid waste management plan guidance pursuant to Subtitle D of RCRA has created confusion around the differences between solid waste recovery activities and recycling efforts; and
2. EPA's expanded regulatory definition of solid waste, pursuant to Subtitle C of RCRA, includes recyclable material as "other discarded materials," which may inhibit recycling and resource recovery efforts.

(40 C.F.R. §§ 246.101[v], [w], [x]; 40 C.F.R. § 261.2[a][2][B], [c]; Waterfield 2019; CPUC 2019; NREL 2019; Danielle Waterfield and David Wagger, Institute of Scrap Recycling Industries, Inc., telephone conference, April 25, 2019; Cavender 2015; Gaba 2008; Sweeny 1996; Johnson 1991; Gaba 1989).

These two identified barriers seem to have caused confusion about what constitutes "solid waste" within the context of both the Subtitle D regulation of non-hazardous solid waste and the Subtitle C regulation of hazardous solid waste (Waterfield 2019; NREL 2019; Danielle Waterfield and David Wagger, Institute of Scrap Recycling Industries, Inc., telephone conference, April 25, 2019; Cavender 2015; Gaba 2008; Sweeny 1996; Johnson 1991; Gaba 1989). Although the underlying goals of each subtitle are not generally controversial, the definition as to what constitutes solid waste within the context of each subtitle is the subject of debate and has resulted in regulatory confusion (Waterfield 2019; NREL 2019; Danielle Waterfield and David Wagger, Institute of Scrap Recycling Industries, Inc., telephone conference, April 25, 2019; Cavender 2015; Gaba 2008; Sweeny 1996; Johnson 1991; Gaba 1989). The crux of the issue boils down to the meaning of the phrase "and other discarded materials" in the statutory definition of solid waste (Waterfield 2019; Danielle Waterfield and David Wagger, Institute of Scrap Recycling Industries, Inc., telephone conference, April 25, 2019; Cavender 2015; Sweeny 1996; Johnson 1991; Gaba 1989), which is further explained below.

RCRA defines "solid waste" as

> any garbage, refuse, sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility, **and other discarded material**, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities, but does not include solid or dissolved material in domestic sewage, or solid or dissolved materials in irrigation return flows or industrial discharges which are point sources subject to permits under section 402 of the Federal Water Pollution Control Act, as amended (86 stat. 880), or source, special nuclear, or byproduct material as defined by the Atomic Energy Act of 1954, as amended (68 Stat. 923)(42 U.S.C. § 6903[27] [emphasis added]).

RCRA Subtitle D: State or Regional Solid Waste Plans

Subtitle D of RCRA was designed to:

> assist in developing and encouraging methods for the disposal of solid waste which are environmentally sound, and which maximize the utilization of valuable resources including energy and materials which are recoverable from solid waste and to encourage resource conservation (42 U.S.C § 6941[b]).

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In fact, Subtitle D's congressional findings specifically focus on energy and materials conservation and recovery (42 U.S.C. § 6941a [1]-[6]). It is important to note that in enacting Subtitle D, Congress found that:

- Significant savings could be realized by conserving materials in order to reduce the volume or quantity of material which ultimately becomes waste;
- Solid waste contains valuable energy and material resources which can be recovered and used thereby conserving increasingly scarce and expensive fossil fuels and virgin materials;
- The recovery of energy and materials from municipal waste, and the conservation of energy and materials contributing to such waste streams, can have the effect of reducing the volume of the municipal waste stream and the burden of disposing of increasing volumes of solid waste;
- The technology to conserve resources exists and is commercially feasible to apply; and
- The technology to recover energy and materials from solid waste is of demonstrated commercial feasibility (42 U.S.C. §§ 6941a[1]-[5]).

Congress granted the EPA authority to establish "guidelines for [non-hazardous] solid waste collection, transportation, separation, recovery, and disposal practices and systems" and "cooperative efforts among the [f]ederal, [s]tate, and local governments and private enterprise in order to recover valuable materials and energy from solid waste" (42 U.S.C. §§ 6902[a][8],[11]). Despite the congressional intent of Subtitle D, some argue the EPA's guidelines for state solid waste management plans[6] confuse "recyclable materials" with "solid waste" and "recycling" with "solid waste resource recovery activities" (Waterfield 2019; Danielle Waterfield and David Wagger, Institute of Scrap Recycling Industries, Inc., telephone conference, April 25, 2019; Johnson 1991; Gaba 1989).

Although recyclable materials and recycling are not mentioned in EPA's state solid management guidelines, the guidelines define a solid waste "facility" as "any **resource recovery** system…for the collection, source separation, storage, transportation, transfer, processing, treatment or disposal of **solid waste"** (40 C.F.R. §256.06 [emphasis added]). The EPA's state solid waste management guidelines do not define resource recovery, but the EPA's implementing regulations for Subtitle D define "recovery" to mean "the process of obtaining materials or energy resources from solid waste" (40 C.F.R. § 246.101[v]). In addition, the EPA has defined "recycling" under the implementing regulations to mean "the process by which recovered materials are transformed into new products" (40 C.F.R. § 246.101[x]). Many state and local regulators have interpreted these regulations to mean that "recycling" is a solid waste resource recovery activity, rather than a physical process used to convert material into a valuable product or commodity (Waterfield 2019; Danielle Waterfield and David Wagger, Institute of Scrap Recycling Industries, Inc., telephone conference, April 25, 2019; Johnson 1991). Further complicating the issue is the fact that the EPA's implementing regulations do not define "recyclable material," nor does RCRA provide a statutory definition of "recycling" or "recyclable materials."

[6] These guidelines are outlined in 40 C.F.R. §§ 256.01-256.65.

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As a result, state and local governments often classify and regulate all recycling activities as solid waste activities in the context of a "resource recovery system"[7] which may impede recycling efforts (Waterfield 2019; Danielle Waterfield and David Wagger, Institute of Scrap Recycling Industries, Inc., telephone conference, April 25, 2019; Johnson 1991). For example, if PV modules destined for resource recovery are regulated in the same manner as PV modules being disposed of, then there is no regulatory incentive to recycle because the requirements, costs, and liabilities are the same. This is especially true when the economics and accessibility of disposal are more favorable than recycling, which is the case for PV module recycling and disposal options in the U.S. today. Many state and local governments have understood the EPA's Subtitle D guidelines to mean that recyclable materials (e.g., PV modules) destined for recycling and resource recovery are solid waste and subject to regulation by the state's solid waste management plan (Waterfield 2019; Danielle Waterfield and David Wagger, Institute of Scrap Recycling Industries, Inc., telephone conference, April 25, 2019).

RCRA Subtitle C: National Hazardous Waste Management Program

Subtitle C of RCRA was designed to "protect human health and the environment" from the generation, recycling, transportation, treatment, storage and disposal of hazardous waste[8] (42 U.S.C. §§ 6901[b][2], 6901[b][5], 6901[b][7], 6902[a][4],[b], 6921[a], 6922[a], 6923[a], 6924[a]). Subtitle C of RCRA directs the EPA to "develop and promulgate criteria for identifying the characteristics of hazardous waste" (42 U.S.C. §§ 6901-6939g). In doing so, the EPA expanded the definition of "other discarded materials" to include "any material which is recycled—or accumulated, stored, or treated before recycling…" (40 C.F.R. § 261.2[a][2][B], [c]).[9]

Some argue this expanded definition of "other discarded materials" conflates recycled materials with solid waste and has created a presumption that all materials destined for recycling and resource recovery are solid waste (Waterfield 2019; Danielle Waterfield and David Wagger, Institute of Scrap Recycling Industries, Inc., telephone conference, April 25, 2019; NREL 2019; Cavender 2015; Gaba 2008; Sweeny 1996; Johnson 1991; Gaba 1989). As mentioned above, this issue is further compounded by the fact that RCRA uses the term "recycling" seven times without providing a statutory definition (42 U.S.C. §§ 6901-6992k [1976]; Waterfield 2019). Nor does the statute define "recyclable material" (42 U.S.C. §§ 6901-6992k [1976]). As a result, the conservation and recovery of valuable resources from first life materials, like EoL PV modules, has been hindered by stringent regulatory requirements that regulate the generation, accumulation, collection, transport, storage, and treatment of hazardous solid waste (Waterfield

[7] RCRA defines a "resource recovery system" as "any facility at which solid waste is processed for the purpose of extracting, converting to energy, or otherwise separating and preparing solid waste for reuse" (42 U.S.C. § 6903[24]).

[8] RCRA defines "hazardous waste" as "a solid waste, or combination of solid wastes, which because of its quantity, concentration, or physical, chemical, or infectious characteristics may—cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed" (42 U.S.C. § 6903[5]).

[9] The initial version of the EPA's Subtitle C regulatory definition of "solid waste" was based on a narrow interpretation of "other discarded materials" (45 Fed. Reg. 33091 [May 19, 1980, No. 98]). "Initially there was widespread agreement that the statutory definition of 'solid waste' and 'other discarded materials' encompassed materials which were destined for disposal, rather than recycling" (Waterfield 2019; Danielle Waterfield and David Wagger, Institute of Scrap Recycling Industries, Inc., telephone conference, April 25, 2019).

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2019; Danielle Waterfield and David Wagger, Institute of Scrap Recycling Industries, Inc., telephone conference, April 25, 2019; CPUC 2019; NREL 2019; Evelyn Butler, Solar Energy Industries Association, telephone conference, February 8, 2019; Cavender 2015; Gaba 2008; Sweeny 1996; Johnson 1991; Gaba 1989).

RCRA Implications for PV Recycling and Resource Recovery

Some states are classifying and regulating EoL PV modules destined for recycling and resource recovery as solid waste, which subjects them to the state's solid waste management requirements and potentially to federal and state hazardous waste management requirements (Libby and Shaw 2018; NREL 2019; CPUC 2019; DTSC 2019b; Evelyn Butler, Solar Energy Industries Association, telephone conference, February 8, 2019; Matthew Garamone and Parikhit Sinha, First Solar, telephone conference March 4, 2019; Tim Kimmel, Cleanlites Recycling, telephone conference March 5, 2019; Gary Winslow, MiaSolé, email, March 12, 2019; John Martorano, Magnum Computer Recycling, telephone conference July 31, 2019). The classification of EoL PV modules as solid waste and potentially hazardous waste has led to several barriers to recycling efforts in the United States, including:

- Classification as solid waste triggers several expensive and variable management requirements and restrictions, such as the requirement to determine whether the solid waste is hazardous and must be regulated as hazardous waste. A generator[10] of hazardous waste must accurately determine whether a solid waste is hazardous or not by using their knowledge and/or through the testing of a representative sample by conducting a toxicity characteristic leaching procedure (TCLP) or a state equivalent to determine whether a PV module exhibits hazardous characteristics which are costly and have been found to be highly variable (40 C.F.R. § 261.11). Studies have found that TCLP results for c-Si PV modules vary depend on the sampling location, the sample removal method, the temperature of the glass at the time of sampling, and the test laboratory conducting the TCLP analysis (Curtis et al. 2021b; Libby and Shaw 2018; NREL 2019a).
- If classified as hazardous waste, the generation, transport, storage, accumulation, and treatment of PV modules are subject to strict and costly regulatory requirements and subject the actor (e.g., asset owner) to civil and criminal penalties for noncompliance. These requirements could impact anyone who manages EoL PV modules at any point from module decommissioning to recycling;
- Transporters of PV modules destined for recycling, which are regulated as hazardous waste, may also be subject to specific packaging, documentation, and other transit-related U.S. Department of Transportation (DOT) Hazardous Materials Regulations for highway, rail, air, and vessel transport (Curtis et al. 2021b; 49 U.S.C. §§ 5101-5128; 49 C.F.R. §§ 171-180).

[10] A "generator" is "any person, by site, whose act or process produces hazardous waste…or whose act first causes hazardous waste to become subject to regulation" (40 C.F.R. §260.10).

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- Exporters of PV modules destined for recycling, which are regulated as hazardous waste from the U.S. to other countries may trigger compliance with RCRA and international transboundary requirements, such as the Organization for Economic Cooperation and Development (OECD) Council Decision on the Control of Transboundary Movements of Wastes Destined for Recovery Operations, and the Basel Convention[11] on the Transboundary Movements of Hazardous Wastes and their Disposal (Curtis et al. 2021b; 40 C.F.R. §§ 262.80, 262.81; EPA 2019e; EPA 2019f; Daniel Stoehr, Daniels Training Services, Inc., teleconference, August 30, 2019).
- Certain jurisdictions may presume that EoL PV modules are not only solid waste, but hazardous waste;[12]
- Certain jurisdictions may classify PV system owners and operators of decommissioned PV modules as solid waste generators and possibly hazardous waste generators;
- Certain jurisdictions may classify recycling facilities as solid waste handling facilities, or potentially hazardous waste treatment, storage, and disposal facilities;
- Certain jurisdictions may apply zoning ordinances designed to regulate solid waste management facilities to recycling facilities;
- Certain jurisdictions may apply permitting requirements, designed for solid waste collection vehicles, to collection and transport haulers for materials, such as EoL PV modules (Waterfield 2019; NREL 2019; CPUC 2019; DTSC 2019b; Evelyn Butler, Solar Energy Industries Association, telephone conference, February 8, 2019; John Martorano, Magnum Computer Recycling, telephone conference July 31, 2019; Libby and Shaw 2018; Leslie 2018).

2.3 Enablers to PV Module Recycling

Enablers are solutions or ways to overcome a barrier that inhibits a desired behavior or outcome. Federal, state, and industry policy can enable a desired behavior or outcome. In this section, we outline policy solutions that may enable PV module recycling. Table 3 summarizes those enablers.

[11] The United States is not a party to the Basel Convention; however, the OECD requirements largely reflect the Basel Convention requirements (Jordan Rivera, U.S. Department of Transportation, Headquarters, email, September 30, 2020; Neal Suchak, U.S. Department of Transportation, Headquarters, email, September 30, 2020).

[12] Anecdotal evidence suggests that there is a perception that California, which has more stringent hazardous waste requirements than the federal standard, may presume decommissioned PV modules destined for recycling are non-RCRA, California-only hazardous waste (CPUC 2019; DTSC 2019b; Gary Winslow, MiaSolé, email, March 12, 2019; Eric Stikes and Vince Lucia, Good Sun, teleconference, August 26, 2019). Anecdotal evidence suggests there is a perception that regulators in New Jersey and Arizona may also presume decommissioned PV modules destined for recycling are not only solid waste, but hazardous solid waste (NREL 2019; CPUC 2019; John Martorano, Magnum Computer Recycling, telephone conference July 31, 2019).

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Table 3. Potential Enablers to PV Module Recycling

Enabler	Description	Actor(s)
Increased research and analysis	Policy focus and investment supporting creation of publicly available research and analysis regarding EoL PV module management uncertainties on: • The value of and markets for recovered PV module materials • The volume and composition of EoL PV modules • PV module recycling technology development and infrastructure needs • Permitting requirements and liabilities, and • The costs associated with PV module recycling.	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, End User, Government
Increased and publicly available information and information exchange	Information exchange between manufacturers and recyclers, as well as between end users and landfill owners and operators, can reduce costs, liability uncertainties and increase good faith relationships between solar industry stakeholders	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, End User, Landfill Owner/Operator
Increased economic incentives	Economic incentives given to promote design for recycle and/or collection and recycling can encourage innovation, private industry investment, and make the economics for PV module recycling more desirable	Manufacturers, Owners, Operators, Installers, Logistics Companies, Recyclers, End Users, Landfill Owners/Operators, Government
Industry initiatives, standards, and goals	Global and national voluntary industry initiatives (e.g., SEIA's national PV recycling program), standards (e.g., NSF 457) and goals (e.g., resource recovery) can encourage environmentally sustainable business practices	Manufacturer, PV Owner, O&M, Government
Clearly defined laws and regulations	Clearly defined regulatory requirements and restrictions can reduce uncertainty and risk associated with PV module recycling and resource recovery	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, End user, Government
Statutory and regulatory schemes that support PV module recycling and resource recovery efforts	Federal and state policies can require or incentivize the collection and recycling of PV modules and/or restrict disposal of PV modules	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, End User, Government

2.3.1 Research and Development Enablers

Policy focus and investment in publicly available research and analysis regarding EoL module management uncertainties can enable PV module recycling and resource recovery (Salim et al. 2019; CPUC 2019; NREL 2019; Libby and Shaw 2018; Tura et al. 2018). Understanding the value of and markets for recovered materials and the volume of decommissioned PV modules is important to identify the market value and current demand of recovered materials from EoL PV modules and expected profits and supply (Salim et al. 2019; Weckend et al. 2016). PV module

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recycling infrastructure needs, associated costs, and the most effective recycling technology for recovering high-value materials are important variables, which are necessary to determine in order to encourage investment and reduce economic uncertainty (Curtis et al. 2021b; Salim et al. 2019; Tura et al. 2018). In addition, understanding the capital costs associated with developing collection centers, constructing PV recycling facilities, and purchasing recycling equipment can reduce economic uncertainty and investor risk (Choi 2017; D'Adamo 2017).

Standardized PV module designs that also account for ease of recycling could enable more efficient PV recycling (Heath et al. 2020). A standardized module design could enable faster, easier, and potentially even automated disassembly and recycling (Heath et al. 2020). Better insight and analysis on future PV module designs and chemistries could also inform which technologies may be needed to meet future PV recycling needs (Heath et al. 2020). Similarly, evolving trends in PV module designs and chemistries can impact the supply, demand, and value of certain raw materials for future manufacturing needs as well as life expectancy values (e.g., when and in what volume PV modules will require recycling) (Curtis et al. 2021b; Heath et al. 2020).

Moreover, reverse logistical costs are highly variable, and identifying the location of current recycling infrastructure in relation to near-term EoL PV systems can inform hauling costs as well as guide future infrastructure development (Libby and Shaw 2018). Understanding the regulatory framework associated with recycling EoL PV modules also informs recyclers, haulers, logistics companies, and other EoL management stakeholders about permitting and compliance requirements, costs and liabilities (Curtis et al. 2021b).

2.3.2 Information Exchange Enablers

Reliable information on the makeup and the concentration of materials in a given PV panel model could reduce the costs associated with recycling and resource recovery efforts (Salim et al. 2019; NREL 2019; Tura et al. 2018; Besiou and Van Wassenhove 2016). Labeling requirements could enable information exchange between manufacturers and EoL PV management stakeholders and act as a stop gap measure for those manufacturers that go out of business before the PV module is decommissioned (PSI 2018). This knowledge could eliminate the need to conduct TCLP testing that is required when PV modules are classified as solid waste since generators can use knowledge instead to determine hazardous characteristics (40 CFR § 262.11[d][1]; Libby and Shaw 2018). In addition, transparent information exchange can strengthen relationships between different solar industry stakeholders and help ensure the safe handling and EoL treatment of PV modules.

2.3.3 Economic Incentive Enablers

Economic incentives could help enable PV module recycling and resource recovery efforts in the United States. Government subsidies, grants, and awards can encourage innovation through research and development as well as private industry investment making the economics of recycling more desirable. Similarly, policies that provide a tax credit to incentivize business investment could support the growth of PV recycling or design for recycle, while policies that penalize disposal of PV modules (e.g., surcharge) could indirectly incentivize PV recycling. - Government grants and awards, as well as private investment, can also enable design-for-environment technologies that not only increase the life expectancy of PV modules but are also designed for ease of recycling (Besiou and Van Wassenhove 2016; Salim et al. 2019).

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2.3.4 Industry-Led Enablers

Industry-led initiatives and standards can encourage environmentally sustainable EoL management decisions for PV modules (Tura et al. 2018; Bai et al. 2015; Dong et al. 2016). Solar industry-led initiatives such as the Solar Energy Industries Association's (SEIA) National PV Recycling Program highlights the solar industry's motivation to adopt sustainable EoL management practices despite the absence of favorable policy or economic drivers. Industry-led initiatives like SEIA's PV Recycling Program make it easier for incumbent and new market entrants alike to recycle EoL PV modules, inverters, and other system equipment (SEIA 2019b).

Similarly, global and national voluntary industry standards can encourage environmentally sustainable EoL management decisions for PV (Tura et al. 2018; Bai et al. 2015; Dong et al. 2016). Voluntary industry standards often provide a set of criteria or guidelines for industry to follow to achieve a particular outcome or goal. These standards may include a certification program to reward compliance with a given standard. Certifications are typically awarded after confirmation of compliance by third-party authorities through testing and audits.

There are several PV specific voluntary industry standards that may enable environmentally sustainable EoL management decisions and behaviors and may provide benefits to stakeholder participants. The benefits could include improved performance quality, stakeholder trust, market competitiveness, and/or reduction of liability. For example, the NSF International (NSF) and American National Standards Institute (ANSI) 457 Sustainability Leadership Standard for PV Modules and Inverters provides performance criteria for PV manufacturers to establish environmentally sustainable policies, including responsible EoL management practices and design for recycling (NSF International 2019). Other voluntary industry standards that are not specific to PV may also enable recycling and resource recovery efforts of EoL PV modules in the United States. For example, the International Organization for Standardization (ISO)'s 14001 Environmental Management Systems standard establishes environmental performance requirements that may help a company achieve a specific environmental objective, which could incorporate a particular EoL management fate for PV modules and system components (ISO 2015). Table 4 highlights some of the benefits solar industry stakeholders may gain from complying with voluntary industry standards or engaging in industry-led initiatives like SEIA's National PV Recycling Program.

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Table 4. Benefits of Complying with Industry Standards

Benefit	Description	Actor(s)
Enhance competitiveness	Can give a company a competitive edge over other companies by incorporating business practices that reduce costs and increase consumer trust	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, End user, Government
Increase consumer confidence in environmentally sustainable handling	Can increase a consumer's confidence and trust in the company's business practices	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, End user, Landfill Owner/Operator
Demonstrate commitment to quality and/or improvement	Can demonstrate the company's commitment to quality and/or improvement, and in turn increase consumer confidence and a company's competitiveness	Manufacturer, Owner, Operator, Installer, Logistics Company, Recycler, End User, Landfill Owners/Operators,
Provide clear quality benchmarks for employees	Can provide clear quality benchmarks to ensure consistency and high-quality products	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, End User, Government
Support due diligence for corporate social responsibility	Can support due diligence and increase product quality and the company's social responsibility image	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler
Reduce legal concern related to hazardous waste management	Can reduce the liability associated with hazardous products	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, End User
Reduce environmental and human health impacts	Can require the reduction of product and business practice impacts on the environment and human health	Manufacturer, PV Owner, O&M, Installer, Logistics Company, Hauler, Recycler, End User, Government

2.3.5 Statutory and Regulatory Enablers

Clearly defined regulatory requirements can reduce uncertainty and risk associated with recycling PV modules (NREL 2019; CPUC 2019; Salim et al. 2019). Regulation can also mandate or incentivize environmentally sustainable EoL PV module management decisions or prohibit a particular behavior (Salim et al. 2019; CPUC 2019; Salim et al. 2019; Weckend et al. 2016). A multi-faceted regulatory approach placing management and financial responsibility on multiple PV supply chain actors may enable an EoL PV management strategy for the solar industry without overburdening one actor.

The statutory and regulatory framework could also take into consideration current law and, where possible, act in concert with existing policy. For instances, policies that reduce the regulatory burden of recycling PV modules compared to disposal can complement renewable portfolio standards and environmental policies by ensuring increased deployment is met with enhanced resource recovery. End-of-life PV module management policies could also leverage existing laws. For example, states could utilize existing EoL product policies that prohibit disposal (e.g., refrigerators, HVAC [heating, ventilation, and air conditioning] systems, electronics) and add an additional category to include PV modules.

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To date, the two most common regulatory mechanisms used to encourage recycling and resource recovery of other consumer product materials are: (1) extended producer responsibility policies (EPR); and (2) landfill diversion policies. These policy mechanisms have largely been applied to the U.S. electronics industry, but no publicly available study comprehensively analyzes the advantages, challenges, and overall success of these policies or how they compare to other regulatory models (e.g., point-of-sale fee model).[13] More importantly, there is no publicly available analysis regarding whether EPR and landfill diversion policies, especially those designed for EoL electronic products, are well suited for EoL PV modules. Although certain electronics, like liquid crystal display (LCD) panels and monitors, have similarities to PV modules based on their sandwich-like structure, high glass content, and the difficulty of recovering valuable materials during the recycling process, they have a substantially shorter life expectancy than PV modules, among other differing characteristics.

A review of EPR, landfill diversion, and other regulatory EoL product management policies for other industries, such as those in place for electronics, could provide valuable insight for solar industry stakeholders, regulators and policymakers as they start to identify regulatory barriers and policy solutions to encourage environmentally sustainable EoL PV management decisions and behaviors. This report does not endorse one particular policy mechanism or framework over another. This report provides a survey of electronic EoL policies in the United States because EPR and landfill diversion policies, applied to the U.S. electronics industry, are two common regulatory mechanisms used to encourage product resource recovery. This report focuses specifically on electronic EoL management policies that include or could include LCD panels and monitors based on their similarities to PV modules as explained above. See Table C-1 for more information on U.S. electronic EoL policies.

Extended Producer Responsibility Policies

Extended producer responsibility (EPR) is a type of product stewardship policy that requires manufacturers of a product, such as electronics or PV modules, to physically and/or financially provide for the collection and recovery of those EoL products (Atasu and Subramanian 2012; Salim et al. 2019). The goal of EPR is to create environmentally sustainable business practices and products (e.g., design for recycle) (ERI 2016). EPR can include a variety of requirements:

- A registration requirement for manufacturers who sell a regulated product in the regulating state
- A requirement for the manufacturer to label the regulated product it sells in the state
- A requirement for product manufacturers to take back some portion of the regulated products they sell in the state and reuse or recycle the product
- A requirement for either the state regulatory agency and/or manufacturers to educate the public on product recycling and other related topics.

As of 2019, no federal electronic device EoL management requirements exist, but 21 states and the District of Columbia have EPR programs in place that mandate electronic manufacturers to take back covered electronic devices (CEDs) sold to customers and to reuse or recycle those

[13] A point-of-sale fee model is a regulatory scheme where the purchaser pays an upfront fee at the point of purchase and that fee goes towards the EoL management of that product. California utilizes this model for certain EoL electronic products (Cal. Public Resources Code §§ 42460-486 [2003]).

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CEDs sold.[14] These policies explicitly include or could include LCDs. All 22 jurisdictions with some type of EPR program in place require that the manufacturer who sells a regulated CED to register that product in that jurisdiction.[15] Three of those states have mandates for either the state regulatory agency and/or the manufacturers to educate the public about product recycling and other related topics.[16] Figure 1 illustrates the number of jurisdictions with some type of EPR program in place and the breakdown of different types of EPR requirements.

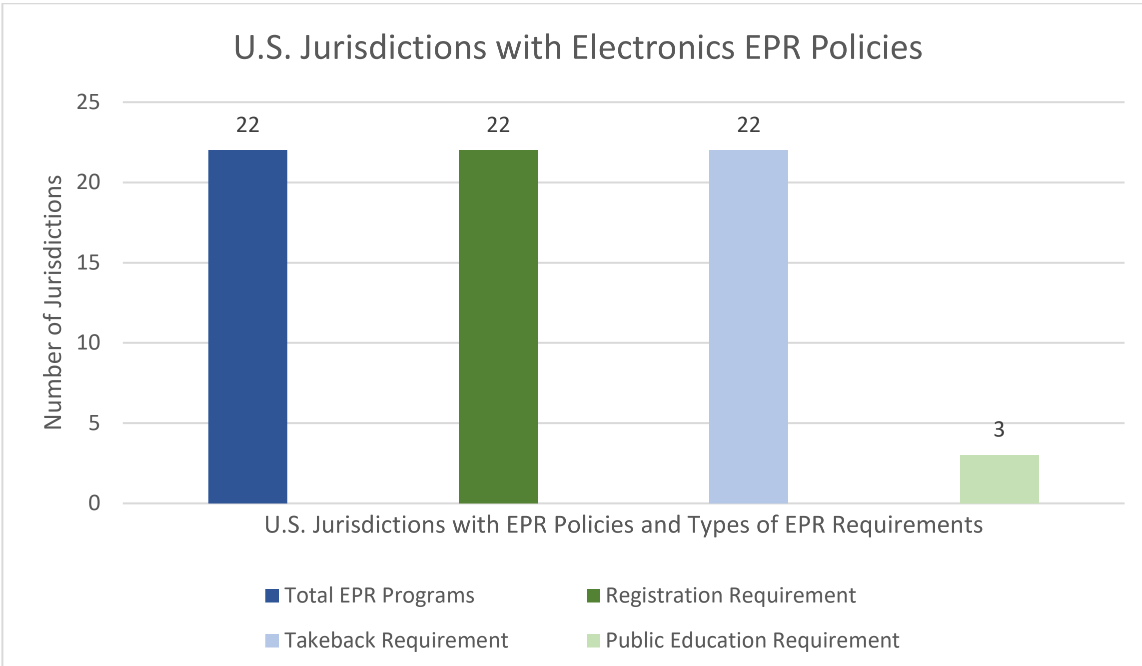

Figure 1. EPR policies and breakdown by requirement type

Landfill Bans

Landfill bans typically prohibit anyone from "knowingly" disposing of a regulated product in a municipal non-hazardous solid waste (MSW) landfill; however, some policies do not require that a person have knowledge of disposal to incur liability. As such, an MSW landfill owner who unknowingly disposes of a regulated product could be subject to civil or administrative fines or penalties, or criminal violations, depending on the policy. As of 2019, no federal policies ban the disposal of electronic devices, but 17 states and the District of Columbia have enacted some type of landfill ban for CEDs that explicitly include, or are broad enough that they could include,

[14] There are several different electronic EPR programs in the United States that have varying registration and labeling requirements, funding structures, takeback requirements, and public education requirements. As of 2019, Maryland does not have an EPR program in place but does have a voluntary manufacturer takeback policy for CEDs. Maryland is not represented in Figure 1.

[15] As of 2019, California, Maryland, and Utah also have a registration requirement for electronic manufacturers but do not utilize an EPR policy model (mandatory manufacturer takeback requirement) and are not represented in Figure 1.

[16] As of 2019, Colorado, Maryland, and Utah (voluntary) also have public education policies in place but do not utilize an EPR policy model (mandatory manufacturer takeback requirement) and are not represented in Figure 1.

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LCDs.[17] Of those 18 jurisdictions, 15 also require at least some elements of an EPR program (e.g., registration, take back, or public education). Figure 2 illustrates the total number of states with a CED landfill diversion policy and of those total number of states with a CED landfill diversion policy, those that also have some type of EPR program, in addition to a landfill ban.

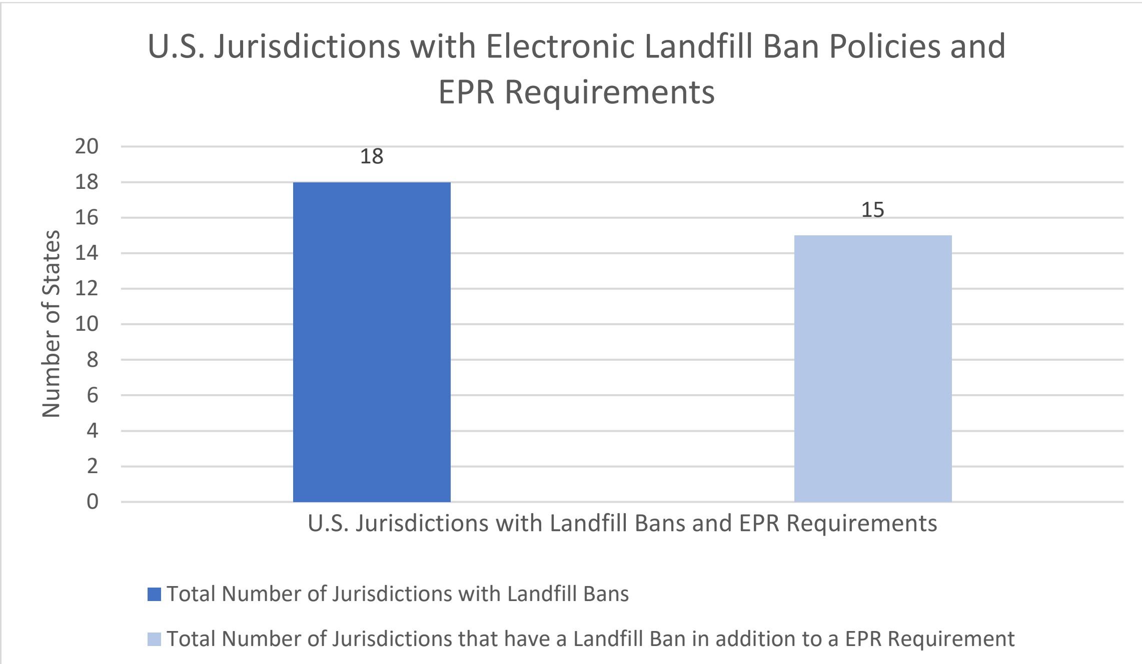

Figure 2. U.S. jurisdictions with electronic landfill ban policies and EPR requirements

3 Enacted PV Module Recycling Policies in the United States

This section analyzes state policies[18] that explicitly address PV module recycling. Washington, New Jersey, North Carolina, and California are the only U.S. states with laws or regulations that directly address PV module recycling. However, California, Hawaii, and Rhode Island have proposed bills, that, if enacted, would directly address PV modules recycling. There are also state-led working groups in California, Illinois, and Minnesota to study EoL management options, which include recycling PV modules. Figure 3 maps state policies in the United States that address PV module recycling. This report section summarizes these policies and identifies several associated potential advantages and challenges of each policy. We characterize "advantages" as potential factors that enable PV module recycling in the United States and contribute to the overall success of the policy's intended purpose. By contrast, we characterize

[17] As of 2019, one state (West Virginia) recently changed its landfill ban to a conditional landfill ban. CEDs are banned from solid waste landfills in West Virginia only if a county or regional solid waste authority determines that there is a cost-effective recycling alternative for handling CEDs (WVDEP 2016). West Virginia's conditional landfill ban is represented in Figure 2. As of July 2019, Berkeley County is the only county in the state that is enforcing the ban (Nicole Hunter, West Virginia Solid Waste Management Board, email, July 3, 2019).
[18] We use "policy" in this report broadly to include not only state statutory and regulatory requirements but also government initiatives and goals and independently formed working groups.

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“challenges” as potential factors that may impede PV module recycling in the United States and the overall success of the policy’s intended purpose.

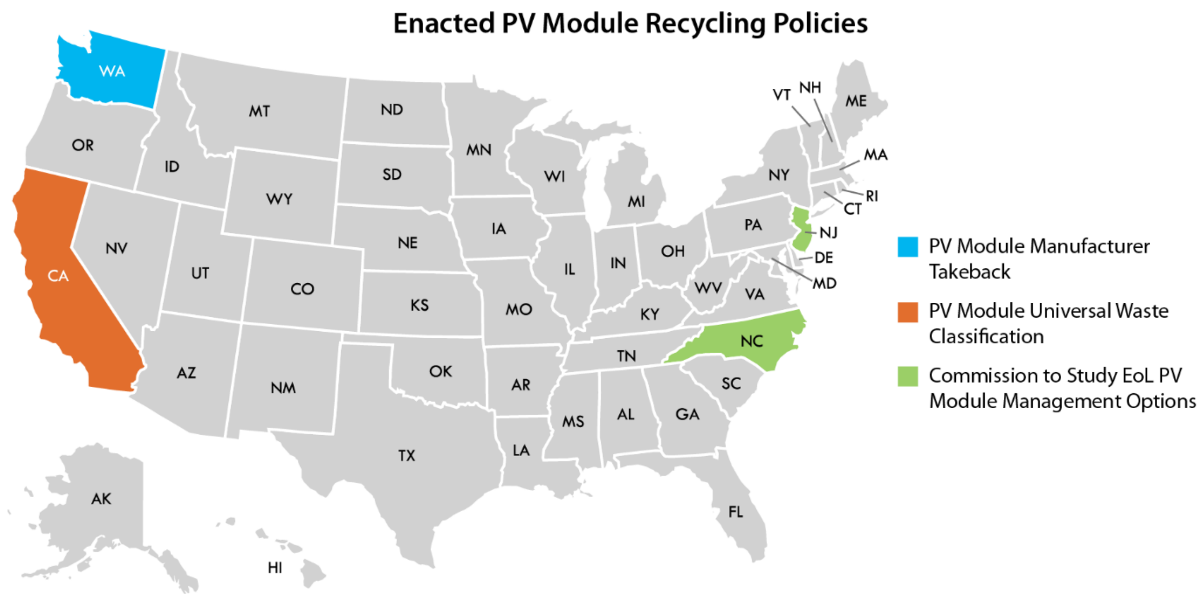

Figure 3. Enacted PV module recycling policies

3.1 Washington State’s PV Module Stewardship and Takeback Program

In 2017, the Washington State Legislature passed Senate Bill 5939 to promote a sustainable local renewable energy industry through modifying tax incentives (S.B. 5939, 65th Leg., 3rd Spec. Sess. (Wa) [2018]).[19] A portion of the bill created the Photovoltaic Module Stewardship and Takeback Program which requires PV module manufacturers[20] to finance and implement a takeback and recycling or reuse stewardship plan for PV modules sold after July 1, 2022, at no cost to the owner (Wash. Rev. Code § 70A.510.010[5]). Beginning July 1, 2023, no manufacturer, distributor, retailer, or installer may sell or offer to sell PV modules within or into

[19] This law was amended in 2020 by Section 1 of House Bill 2645 ((H.B. 2645, 2019-2020 Leg., Reg. Sess. [Wash. 2020]). Section 2 of House Bill 2645 was vetoed by the Governor and is discussed briefly in Section 5 of this report.
[20] “Manufacturer” means “any person in business or no longer in business but having a successor in interest who, irrespective of the selling technique used, including by means of distance or remote sale: (i) Manufactures or has manufactured a photovoltaic module under its own brand names for use or sale in or into this state; (ii) Assembles or has assembled a photovoltaic module that uses parts manufactured by others for use or sale in or into this state under the assembler's brand names; (iii) Resells or has resold in or into this state under its own brand names a photovoltaic module produced by other suppliers, including retail establishments that sell photovoltaic modules under their own brand names; (iv) Manufactures or has manufactured a cobranded photovoltaic module product for use or sale in or into this state that carries the name of both the manufacturer and a retailer; (v) Imports or has imported a photovoltaic module into the United States that is used or sold in or into this state. However, if the imported photovoltaic module is manufactured by any person with a presence in the United States meeting the criteria of manufacturer under (i) through (vi) of this subsection, that person is the manufacturer
(vi) Sells at retail a photovoltaic module acquired from an importer that is the manufacturer and elects to register as the manufacturer for those products; or (vii) Elects to assume the responsibility and register in lieu of a manufacturer” (Wash. Rev. Code § 70A.510.010[2][c]; WSDE 2019a; WSDE 2019b).

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Washington unless the manufacturer has submitted and obtained approval for a stewardship plan from the Washington Department of Ecology (Department) (Wash. Rev. Code § 70A.510.010[8]). PV modules covered by the state's Module Stewardship and Takeback Program include:

- PV modules used for residential, commercial, or agricultural purposes that are installed on, connected to, or integral with buildings
- Freestanding off-grid power generation systems such as water pumping stations, electric vehicle charging stations, solar fencing, solar-powered signs, and solar-powered streetlights21
- PV modules that are part of a system connected to the grid or utility service (Wash. Rev. Code § 70A.510.010[2][e]; WSDE 2019b).

Manufacturer Requirements

Manufacturers must complete and submit a stewardship plan to the Department, then implement the plan by July 1, 2022. Manufacturers can create and implement stewardship plans individually or join a registered stewardship organization and allow that organization to create and implement the plan on the manufacturer's behalf (Wash. Rev. Code § 70A.510.010[2][g], [4], [5]). The stewardship plan must outline how the manufacturer will:

- Finance the takeback program
- Accept all PV modules they have sold within or into the state after July 1, 2017
- Minimize the release of hazardous substances and maximize the recovery of other components
- Provide convenient take back opportunities in regions of Washington where its modules are used
- Disseminate applicable information about its program to relevant stakeholders
- Implement performance goals to reuse and/or recycle at least 85% of the PV modules the manufacturer collects (Wash. Rev. Code § 70A.510.010[5]).

After initial approval of the stewardship plans, the manufacturer must submit and publicly publish annual reports about the previous year's implementation of the manufacturer's plan, including achievement assessments of the plan's performance goals and recommendations to the Department of Ecology or the Washington State Legislature on potential modifications to improve the effectiveness of the takeback program. (Wash. Rev. Code § 70A.510.010[6], [7]).

Department of Ecology Regulatory Authority and Program Financing

The Department of Ecology approves each manufacturer's plan and reviews subsequent annual reports. In addition, the Department of Ecology may collect a flat fee from every participating manufacturer to cover the costs of administering the program and an annual fee from each manufacturer based on the manufacturer's pro rata share of the preceding year's PV module sales in Washington state (Wash. Rev. Code § 70A.510.010[9]). The Department of Ecology may, after warning noncompliant manufacturers of their need to comply, impose a penalty of up to

[21] Washington State's Module Stewardship and Takeback Program does not cover consumer electronic devices that contain electronic circuit boards intended for everyday use by individuals, such as watches or calculators, or products used in yard applications, such as walkway lighting (WSDE 2019b).

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$10,000 per sale of a PV module in Washington state (Wash. Rev. Code § 70A.510.010[8]). The Department of Ecology must deposit all fees and penalties into a PV module recycling account, which can only be used for funding the program's administration costs (Wash. Rev. Code § 70A.510.010[10]).

In July 2019, the Department of Ecology released guidance for manufacturers explaining the manufacturers' responsibilities and requirements under the program and how the Department of Ecology will review and approve stewardship plans (WSDE 2019b). The guidance also states that stewardship plans must follow the Department of Ecology's Interim Enforcement Policy for Conditional Exclusion for Electronic Wastes. The Department of Ecology's Interim Enforcement Policy, which is intended to encourage recycling of electronic waste, states that covered electronic wastes "generated, transported, collected, accumulated and recycled do not have to be counted as dangerous waste (i.e., hazardous waste) or manifested when transported off-site" (WSDE 2007). See Table A-1 for more information on Washington's Photovoltaic Module Stewardship and Takeback Program.

Advantages

Potential advantages associated with Washington's Stewardship and Takeback Program:

- Requires environmentally sustainable EoL PV module management, which complements Washington's goal of reaching 100% GHG-free electricity by 2045
- Incentivizes recycling over disposal by clarifying that PV modules destined for recycling, which follow the Department's Interim Enforcement Policy, are not subject to stringent dangerous waste requirements, which still apply to PV modules destined for disposal
- Reduces the cost and uncertainty regarding permitting and liability associated with classifying PV modules as dangerous waste (i.e., hazardous waste)
- Requires recycling PV modules, which could lead to job creation and new and expanded market opportunities
- Provides a reuse option for compliance, which could lead to job creation and encourage secondary solar market opportunities
- Creates a revenue stream to fund the Department's program costs
- Creates a free, accessible Takeback Program for consumers and requires dissemination of information and education about the takeback program (Christine Haun, Washington Department of Ecology, telephone conference, May 10, 2019; PSI 2018; 2019 Wash. Sess. Laws 1608; Governor Jay Inslee 2019).

Challenges

Potential challenges associated with Washington's Stewardship and Takeback Program:

- May disproportionately impact manufacturers, distributors, retailers, or installers, which could ultimately discourage the sale of PV modules in Washington because no other U.S. jurisdiction has a similar requirement
- Does not apply to PV modules sold in the state prior to 2017 or account for orphaned PV modules that were manufactured by companies no longer in business, which will exempt many EoL PV modules from the recycling requirements

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- Access to recycling programs may not be practical for smaller PV modules (e.g., solar walkway lighting) (EPA 2019a; PSI 2018).

3.2 North Carolina's Commission to Study and Adopt Regulations to Govern the Management of PV Modules

On July 19, 2019, the North Carolina General Assembly passed House Bill 329 to study and consider the adoption of regulations to govern the management of EoL PV modules used in utility-scale projects (2019 N.C. Sess. Law 2019-132).[22] The law tasked the Department of Environmental Quality, which includes the Environmental Management Commission with considering:

- Whether PV modules are properly characterized as solid waste under state and federal law
- Whether PV modules exhibit characteristics of hazardous solid waste
- Preferred EoL PV module and associated equipment management methods and economic and environmental costs and benefits associated with each method
- The expected economically productive life cycle of different types of PV modules
- The volume of PV modules deployed in the state and the projected deployment in the future and the impact that volume would have on state landfills if landfill disposal were permitted
- A survey of federal, state, and international regulatory requirements related to EoL PV module and associated equipment management, decommissioning, and financial assurances
- The necessity of financial assurance requirements for PV system decommissioning
- Necessary infrastructure to collect and transport EoL PV modules for reuse, refurbishment, recycling or disposal
- Whether stewardship programs for recycling EoL PV modules should be established for applications other than utility-scale solar project installations, and if so, fees that should be established for manufacturers to sell PV modules into the state. (2019 N.C. Sess. Law 2019-132).

The Department of Environmental Quality established a stakeholder working group and submitted quarterly joint interim reports on their activities and progress to the General Assembly beginning December 2019 and submitted a final report January 1, 2021. (2019 N.C. Sess. Law 2019-132). The final report included the Department of Environmental Quality's findings and recommendations, as well as a detailed summary of the research and data to support the findings (NCDEQ 2021). In the final report, the Environmental Management Commission:

- Estimated that North Carolina has more than 4,000 MW of installed solar capacity and that figure is expected to double in the next five years
- Estimated that 8.5 million PV modules will be decommissioned between 2036 and 2040

[22] "Utility-scale solar project" means a ground-mounted PV, concentrating PV, or concentrating solar power project directly connected to the electrical grid that generates electricity for sale. The term includes the solar arrays, accessory buildings, transmission facilities, and any other infrastructure necessary for the operation of the project. The term does not include renewable energy facilities owned or leased by a retail electric customer intended primarily for the customer's own use to offset the customer's own retail electricity consumption at the premises" (2019 N.C. Sess. Law 2019-132).

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- Found that the recycling capacity for solar PV modules is still in development and noted that in the future, sufficient infrastructure to support transportation and recycling of EoL PV modules will need to be developed
- Established the following order of preference for management of retired and EoL PV modules: 1) direct reuse, 2) refurbishment/repair for reuse, 3) recycling if reuse and repair for reuse are not feasible, and 4) disposal
- Determined that EoL PV modules that no longer serve the purpose for which they are intended are solid waste
- Determined that PV modules that exhibit hazardous characteristics under the TCLP test must be managed as hazardous waste, but nonhazardous PV modules may be managed as solid waste
- Requested the development of a sample preparation procedure for TCLP testing of PV modules for representative and accurate waste characterization due to inconsistency and variability concerns associated with TCLP testing results
- Stated that the Department of Environmental Quality, in consultation with the EPA, anticipates a future rulemaking proceeding to define EoL PV modules as universal waste in 2021. The Commission noted that the purpose of PV universal waste regulations is to facilitate recycling, provide regulatory clarify, and eliminate the need to conduct TCLP testing on EoL PV modules
- Found that the establishment of a fee system paid for by manufacturers to support a stewardship program may create a disincentive for recycling, especially given the lack of accessible recycling facilities
- A network of collection and consolidation points for EoL utility-scale PV modules would not be needed; instead, utility-scale PV system owners are advised to anticipate and evaluate collection and transportation costs during the facility's decommissioning planning (NCDEQ 2021).

Advantages

Potential advantages associated with North Carolina's Commission Study:

- Studied EoL PV management options, such as recycling, as well as associated barriers, to inform the development of new regulations
- Established an order of preference for the management of EoL PV modules, which emphasizes the benefits of recycling
- Estimated the volume of future deployment of PV modules and associated decommissioning levels to inform market conditions, private and public investment decision, and infrastructure needs necessary to support recycling
- Emphasized the need for future investment in infrastructure to support recycling of EoL PV modules
- Determined when decommissioned EoL PV modules constitute solid or hazardous waste, which may reduce regulatory uncertainty as well as liability concerns associated with management
- Development of a TCLP sampling procedure may create standardized results, which may increase the validity of test results

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- Development of PV universal waste regulations may reduce some of the costs and liabilities associated with collecting, storing, and transporting decommissioned hazardous PV modules (as compared to fully-regulated hazardous waste) and may deter the abandonment of PV modules (Way 2019; NCDEQ 2021).

Challenges

Potential challenges associated with North Carolina's Commission Study:

- Does not mandate the adoption of rules and regulations, which makes it unclear whether the Commission's final report will have any bearing on the development of EoL PV management options
- Does not recommend immediate investment in infrastructure to support cost effective and efficient recycling options for EoL PV modules
- Does not address modules from rooftop or residential PV systems
- Anticipates the development of universal waste regulations, which often treat recycling and disposal in the same manner and therefore may not provide an incentive for recycling EoL PV modules under current market conditions (Way 2019; NCDEQ 2021).

3.3 New Jersey's Commission to Investigate Options for EoL PV Recycling

On August 9, 2019, the New Jersey state legislature passed Senate Bill 601, which created the New Jersey Solar Panel Recycling Commission (2019 N.J. Sess. Law Serv. Ch. 215 [West]; Governor Phil Murphy 2019). The Commission is tasked with investigating options for recycling and other EoL management methods for PV and other solar energy generation structures. The Commission is also tasked with developing recommendations for legislative, administrative, or private sector action (2019 N.J. Sess. Law Serv. Ch. 215 [West]). The Commission consists of nine voting members:

- The Commissioner of Environmental Protection (or their designee)
- The Commissioner of Community Affairs (or their designee)
- Two Governor-appointed members of New Jersey's business community with experience or expertise in Class D recycling[23] and the disposal of consumer electronics
- One Governor-appointed representative of a non-profit organization that promotes recycling in New Jersey
- Two Governor-appointed members who work in the solar power industry
- Two Governor-appointed academic community members with expertise in recycling (2019 N.J. Sess. Law Serv. Ch. 215 [West]).

[23] Class D recyclables include used oil, batteries, thermostats, lamps, oil-based finishes, mercury-containing devices, consumer electronics, latex paints, and antifreeze (N.J. Admin. Code § 7:26A-1.3 [2017]).

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The Commission can use the services of any state, county, or municipal employee to investigate options for EoL PV recycling and management (2019 N.J. Sess. Law Serv. Ch. 215 [West]). The Commission must submit findings of its investigation and recommendations as a final report to the Governor and post it on the Department of Environmental Protection's website no later than August 2021 (2019 N.J. Sess. Law Serv. Ch. 215 [West]). The bill also authorizes the Department of Environmental Protection to adopt rules and regulations regarding EoL PV module recycling or management options based on the Commission's final report (2019 N.J. Sess. Law Serv. Ch. 215 [West]).

Advantages

Potential advantages associated with New Jersey's Commission to investigate options for PV module recycling:

- Requires analysis of EoL PV module management options, such as recycling, as well as associated barriers, which may inform the development of new regulations
- May engender the development of infrastructure necessary to support recycling, leading to secondary market opportunities and job creation
- Addresses barriers to PV recycling, which reflect information gathered through coordination with a diverse group of stakeholders including state and local entities
- Grants authority to the Department of Environmental Protection to adopt rules and regulations based on the Commission's findings (2019 N.J. Sess. Law Serv. Ch. 215 [West]; Salim et al. 2019; Tura et al. 2018; InsiderNJ 2019).

Challenges

Potential challenges associated with New Jersey's Commission to investigate options for PV module recycling:

- Does not mandate that the Department of Environmental Protection adopt rules and regulations concerning recycling or other EoL PV module management options, which makes it unclear whether the Commission's final report will have any bearing on the development of EoL PV management options
- Does not identify a funding source to satisfy the Act's requirements
- Does not explicitly address whether EoL PV modules destined for recycling and resource recovery will be classified and regulated as solid waste, which may lead to uncertainty regarding the applicability of regulations as well as associated costs and potential liabilities
- No public information can be found on the study's results or progress (2019 N.J. Sess. Law Serv. Ch. 215 [West]).

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3.4 California's Universal Waste Regulations

In September 2020, the DTSC enacted regulation R-2017-04, which allows for discarded PV modules[24] that exhibit toxicity characteristic of hazardous waste to be managed as universal waste in California (Cal. Code Regs. tit. 22 § 66273.7.1). California's universal waste regulations include notification, reporting, transportation, storage, and handling requirements that are less stringent than California's hazardous waste regulations (Cal. Code Regs. tit. 22 §§ 66273.1-66273.84). Specifically, DTSC regulations:

- Clarify that PV modules that are refurbished or reused are not waste and not subject to the universal waste regulations;
- State that a party who is subject to an enforcement action who claims that a PV module is not waste bears the burden of demonstrating that there is a known market or disposition for its use as a PV module;
- Clarify that a PV module becomes "waste" on the date it is discarded (PV modules that are abandoned, relinquished, or recycling are considered waste when they are disconnected or remove from service (DTSC n.d.);
- Establish universal waste requirements for universal waste handlers[25] (e.g., asset owners, installers, manufacturers, distributors/warehouses, storage facilities, recyclers, treatment facilities) and universal transporters[26] that generate, accumulate, treat, transport or dispose of PV modules that exhibit toxicity characteristics of hazardous waste; and
- Specify the management standards for different levels of treatment to ensure treatment is performed safely by universal waste handlers that do not have a hazardous waste facility permit that they would otherwise be required to obtain (Cal. Code Regs. § 66273.75).

The DTSC universal waste regulations authorize and require universal waste handlers[25] to:

- Comply with notification, annual reporting, and recordkeeping requirements (e.g., one-time notification to the DTSC that includes information regarding types of modules collected, the source of modules, and indication as to whether the handler plans on collecting more than 5,000 kg – approximately 11,023 pounds – or more of PV modules at one time) (Cal. Code Regs. tit. 22 § 66273.32);
- Collect, store, and accumulate PV modules for up to one year before they must be taken to a destination facility for disposal (Cal. Code Regs. tit. 22 § 66273.35);
- Dismantle separate components from the PV module (e.g., metal frames) without breaking PV module glass (Cal. Code Regs. tit. 22 § 66273.72);

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[24] The term "PV modules" "includes integrated components that cannot be separated without breaking the module glass," which can include "the protective glass, conductive metal contact, metal framing the PV cells,…and the top and back layer (Cal. Code Regs. tit. 22 § 66260.10). A PV module is "discarded" or considered waste when it is abandoned, relinquished, or becomes a recyclable material (Cal. Code Regs. tit. 22 § 66273.7.1).

[25] Under California law, a universal waste handler is defined as (1) "any person, by site, whose act or process produces [universal waste] or whose act first cases a [universal waste] to become subject to regulation," (2) "the owner or operator of a facility, including all contiguous property, that receives universal waste from other universal waste handlers, accumulates universal waste, and sends universal waste to another universal waste handler, to a destination facility, or to a foreign destination; or (3) the owner or operator of a facility who is authorized to treat universal waste" (Cal. Code Regs. tit. 22 §§ 66273.9).

[26] Under California law, a universal waste transporter is defined as "a person engaged in the offsite transportation of universal waste by air, rail, highway, or water (Cal. Code Regs. tit. 22 §§ 66273.9).

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- Allow universal waste handlers, with separate prior authorization from DTSC, to intentionally break the PV module's glass in order to process the module (Cal. Code Regs. tit. 22 § 66273.32)27;
- Prohibit from disposing of PV modules except for disposal at a universal waste destination facility,
- Prohibit dilution or treating universal waste except for responding to releases or by following the requirements in the universal waste regulations (Cal. Code Regs. tit. 22 §§ 66260.9-.10, 66273.35, 66273.71-.73); and
- Comply with specified labelling requirements (Cal. Code Regs. tit. 22 §§ 66260.9-.10, 66273.35, 66273.71-.73).

The DTSC universal waste regulations for PV modules also:

- Restrict universal waste transporters[28] from transporting more than 220 pounds of PV modules (i.e., approximately 5 PV modules) at once unless the modules' packaging conforms to the regulatory requirements to prevent leakage, breakage, or release of any PV module or its constituent parts (Cal. Code Regs. tit. 22 §§ 66273.33.6, 66273.51);
- Prohibits universal waste transporters from storing universal waste PV modules at a transfer facility for longer than 10 days in industrial zoned areas and for more than 6 days in other zoned areas (Cal. Code Regs. § 66273.53);
- Prohibits universal waste transporters from transporting universal waste PV modules to a place other than a universal waste handler, a universal waste destination facility, or a foreign destination (Cal. Code Regs. § 66273.55); and
  Restrict universal waste handlers and universal waste destination facilities who treat universal waste PV from using chemicals or heat to process PV modules without a hazardous waste facility permit (restricts to physical/mechanical technologies) (Cal. Code Regs. § 66273.73; CSSA 2020, presentation by Chosu Khin, DTSC).

Economic Impact Analysis

DTSC's economic impact statement found that this regulation will affect approximately 3,000 businesses statewide with a fiscal impact of $10–$25 million (DTSC 2019a). State businesses and individuals are expected to save more than $11 million overall with the regulation (DTSC 2019b). Most of the cost savings come from the reduced fixed annual costs for generators who no longer have to manage and ship PV modules as hazardous waste (DTSC 2019b). DTSC also noted that, when electronic waste was added to California's universal waste program, the creation of approximately 25 electronic waste treatment facilities followed, and, although DTSC cannot predict the number of businesses established as a result of this regulation, it found that stakeholders are interested in expanding their businesses to handle PV modules should they be classified as universal waste (DTSC 2019b; DTSC 2019c).

[27] Universal waste handlers who intentionally break PV modules require authorization from the DTSC (Cal. Code Regs. tit. 22 § 66273.73 [2020]). However, universal waste handlers who remove replaceable components or dismantle PV module components without breaking the module do not require authorization from the DTSC to conduct those activities (Cal. Code Regs. tit. 22 §§ 66273.71, 66273.72 [2020]).
[28] "Universal waste transporter" means a person engaged in the offsite transportation of universal waste by air, rail, highway, or water (Cal. Code Regs. § 66273.9).

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Advantages

Potential advantages associated with California's regulations to include PV modules as a universal waste category:

- May reduce some of the costs and liabilities associated with collecting, storing, and transporting discarded hazardous PV modules (as compared to fully-regulated hazardous waste)
- May deter the abandonment of PV modules, which are categorized as hazardous waste under California law and redirect them to other EoL management options, such as recycling
- Clarifies regulatory standard for EoL PV modules destined for recycling-based resource recovery
- Complements the state's recently enacted goal of 100% clean energy by 2045
- Specifies management standards to safely handle and treat PV modules (CPUC 2019, DTSC 2019a, Cal. Code Regs. tit. 22 §§ 66273.1-66273.84)

Challenges

Potential challenges associated with California's regulations to include PV modules as a universal waste category:

- Does not allow for processing PV modules by heat or chemicals in California, which are processes commonly used for PV module recycling
- Does not necessarily eliminate the requirement to determine whether the PV module exhibits toxicity characteristics either by previous knowledge or by California's toxicity testing protocol – the Waste Extraction Test (WET)[29]
- May create a presumption that all decommissioned PV modules destined for recycling and resource recovery are not only solid waste, but hazardous waste
- Restricts transport unless transported to another universal handler, an authorized waste destination facility, or a foreign destination
- May create a presumption that PV facility owners and operators are generators of solid waste and potentially hazardous waste
- May create a presumption that PV facilities have the potential to be considered a hazardous waste facility
- Regulates PV modules destined for recycling in the same manner as those being disposed of
- May result in more disposal of PV modules until the accessibility and economics of recycling are more favorable (Cal. Code Regs. tit. 22 §§ 66273.1-66273.84; NIST 2021; Finney et al. 2019; NREL 2019, CPUC 2019, DTSC 2019).

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[29] In some instances, PV modules may pass the EPA toxicity characteristic leaching procedure (TCLP) to determine whether a PV module exhibits hazardous characteristics but fail California's WET procedure designating the PV module California-only hazardous. Anecdotal evidence suggests that modules that could be regulated as solid waste – those that do not fail the TCLP but fail California's WET procedure adds substantial costs and liabilities to handle, accumulate, store, transport, and treat PV modules in the state of California (NREL 2019, CPUC 2019, DTSC 2019b).

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4 Proposed Legislation (Pending)

This section summarizes proposed, but not yet-enacted U.S. legislation that addresses PV module recycling. As of February 2021, no proposed federal legislation existed that expressly speaks to recycling-based recovery of PV modules in the United States, however state policies have stated to emerge to address EoL PV management concerns. Bills in the legislatures of California, Hawaii, and Rhode Island address PV module recycling. These proposals are diverse regulatory frameworks that cover different life cycle activities and actors in the PV value chain.

Figure 4 below identifies proposed legislation and regulation in the United States that address EoL management options for PV.

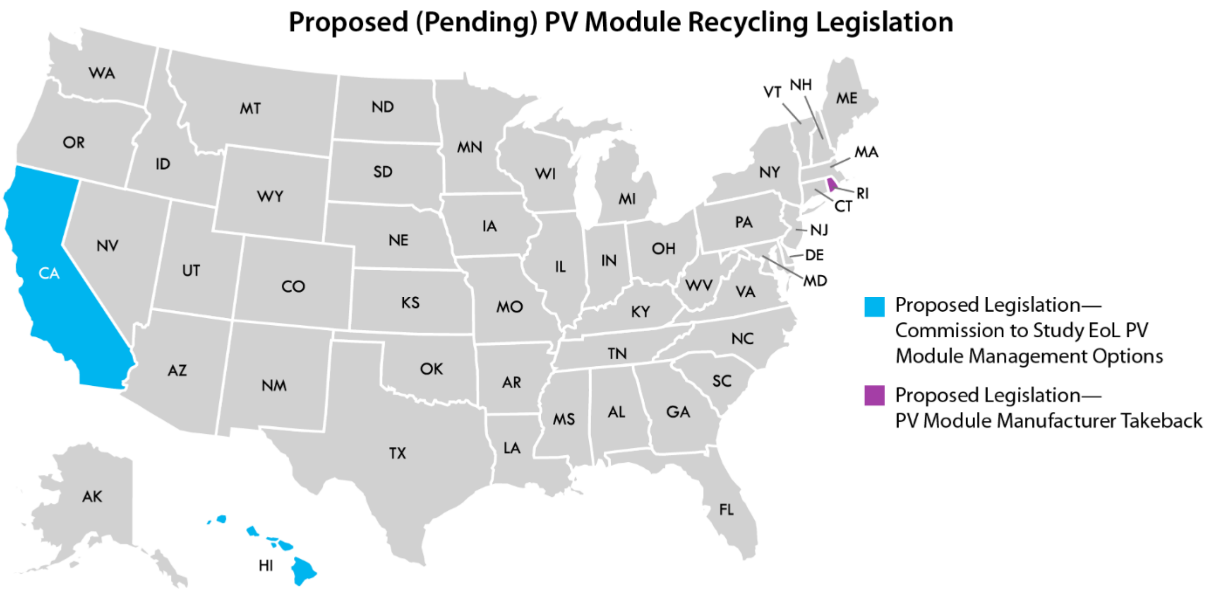

Figure 4. Proposed (pending) PV module recycling legislation

4.1 California Senate Bill 207 (introduced January 11, 2021)

California's Senate Bill 207, if enacted, would require the Secretary for Environmental Protection to convene the Photovoltaic Recycling Advisory Group to study and recommend policies to the legislature that will ensure as close as possible to 100% of all PV panels in California are reused or recycled at end of life safely and cost-effectively (S.B. 207, 2021-2022 Leg., Reg. Sess. [Cal. 2021]). The Secretary for Environmental Protection must appoint the following members to the group:

- The Director of Resources Recycling and Recovery or their designee
- The Director of Toxic Substance Control or their designee
- A photovoltaic panel or solar energy system manufacturer
- An organization that represents one or more photovoltaic panel manufacturers.
- An electronic waste recycler or an organization that represents one or more electronic waste recyclers

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- A photovoltaic panel or solar energy system repair dealer or an organization that represents one or more photovoltaic panel or solar energy system repair dealers
- An environmental organization that specializes in waste reduction and recycling
- A representative of the solar industry
- A standards organization that has a focus on photovoltaic or electrical engineering (S.B. 207, 2021-2022 Leg., Reg. Sess. [Cal. 2021]).

The group must meet for the first time on or before April 1, 2022 (S.B. 207, 2021-2022 Leg., Reg. Sess. [Cal. 2021]). The group must develop and submit its policy recommendations on or before April 1, 2025 (S.B. 207, 2021-2022 Leg., Reg. Sess. [Cal. 2021]). The group must consult with any relevant entities to inform its recommendations (S.B. 207, 2021-2022 Leg., Reg. Sess. [Cal. 2021]).

4.2 Hawaii's House Bill 1333 (introduced January 27, 2021)

Hawaii's House Bill 1333, if enacted, would require the Hawaii State Energy Office to work with the Department of Health on a comprehensive study to determine best practices for disposing of and recycling discarded clean energy products, with an emphasis on solar panels and cells (H.B. 1333, 31st Leg., Reg. Sess. [Haw. 2021]). The comprehensive study would have to address:

- "The amount of aging photovoltaic and solar water heater panels in the State that will need to be disposed or recycled;
- Other types of clean energy materials expected to be discarded in Hawaii in significant quantities, including glass, frames, wiring, inverters, and batteries;
- The type and chemical composition of those clean energy materials;
- Best practices for collection, disposal, and recycling of those clean energy materials;
- Whether a fee should be charged for disposal or recycling of those clean energy materials; and
- Any other issues that the Hawaii state energy office and the department of health consider appropriate for management, recycling, and disposal of those clean energy materials" (H.B. 1333, 31st Leg., Reg. Sess. [Haw. 2021]).

The Hawaii State Energy Office would be required to submit an interim report on the study's progress to the legislature at least 20 days before the legislature convenes the regular session of 2022 (H.B. 1333, 31st Leg., Reg. Sess. [Haw. 2021]). The Hawaii State Energy Office would also be required to submit a final report to the legislature at least 20 days before the legislature convenes the regular session of 2023 (H.B. 1333, 31st Leg., Reg. Sess. [Haw. 2021]). The final report must include findings, recommendations, and any proposed legislation resulting from the study (H.B. 1333, 31st Leg., Reg. Sess. [Haw. 2021]). The bill currently has a subsection that would appropriate money from the general state revenues to support the purposes of the bill, but the exact amount is yet to be determined (H.B. 1333, 31st Leg., Reg. Sess. [Haw. 2021]). The bill, if enacted, would go into effect on July 1, 2021 (H.B. 1333, 31st Leg., Reg. Sess. [Haw. 2021]).

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4.3 Rhode Island House Bill 5525 (introduced February 12, 2021)

Rhode Island's House Bill 5525, if enacted, would create a Photovoltaic Module Stewardship and Takeback Program requiring PV module manufacturers[30] to finance and implement a takeback and recycling or reuse stewardship plan for PV modules sold in or into Rhode Island after July 1, 2021, at no cost to owners (H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)). The bill specifies that the Department of Environmental Management must develop and implement guidance to aid manufacturers in preparing and implementing self-directed stewardship plans by July 1, 2022 (H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)). Beginning July 1, 2023, no manufacturer, distributor, retailer, or installer would be able to sell or offer PV modules for sale within or into Rhode Island unless the manufacturer of the PV module had submitted a stewardship plan to the Department of Environmental Management and obtained approval H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)). PV modules covered by the program would include PV modules that are:

- "Are installed on, connected to, or integral with buildings;
- Are used as components of freestanding, off-grid, power generation systems, such as for powering water pumping stations, electric vehicle charging stations, fencing, street and signage lights, and other commercial or agricultural purposes; or
- Are part of a system connected to the grid or utility service" (H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)).

Manufacturers would have to submit a stewardship plan to the Department of Environmental Management and implement the plan by July 1, 2022 (H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)). In lieu of developing a plan individually, manufacturers would also have the option to join a registered stewardship organization and allow that organization to create and implement the plan on the manufacturer's behalf (H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)).
The stewardship plan must outline how the manufacturer will:

- Finance the takeback program
- Accept all their PV modules sold within or into the state after July 1, 2021
- Minimize the release of hazardous substances and maximize the recovery of other components
- Provide convenient takeback opportunities in each county of Rhode Island where its modules are used
- Disseminate applicable information about its program to relevant stakeholders
- Implement performance goals to reuse and/or recycle at least 85% of the PV modules the manufacturer collects (H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)).

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[30] "'Manufacturer' means any person in business or no longer in business but having a successor in interest who, irrespective of the selling technique used, including by means of distance or remote sale: (i) manufactures or has manufactured a PV module under its own brand names for sale in or into this state; (ii) assembles or has assembled a PV module that uses parts manufactured by others for sale in or into this state under the assembler's brand names; (iii) resells or has resold in or into this state under its own brand names a PV module produced by other suppliers, including retail establishments that sell PV modules under their own brand names; (iv) manufactures or has manufactured a cobranded PV module product for sale in or into this state that carries the name of both the manufacturer and a retailer; (v) imports or has imported a PV module in the U.S. that is sold in or into the state; (vi) sells at retail a PV module acquired from an importer that is the manufacturer; or (vii) elects to assume the responsibility and register in lieu of a manufacturer" (H.B. 5525, 2021 Leg., Reg. Sess. [R.I. 2021]).

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After initial approval of the stewardship plans, the manufacturer would have to submit and publish annual reports about the previous year's implementation of the manufacturer's plan, starting in 2024 (H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)). The annual reports would have to include achievement assessments of the plan's performance goals and could include recommendations to the Department of Environmental Management or the Rhode Island Legislature on potential modifications to improve the effectiveness of the takeback program (H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)).

The Department of Environmental Management could collect a flat fee from every participating manufacturer to cover the costs of administering the program and an annual fee from each manufacturer based on the manufacturer's pro rata share of the preceding year's PV module sales in Rhode Island (H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)). The Department of Ecology could, after issuing a warning of non-compliance, impose a penalty of up to $10,000 per sale of a PV module in Rhode Island (H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)). The Department of Ecology would have to deposit all fees and penalties into a PV module recycling account that could only be used to fund the program's administration costs (H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)).

The Department of Environmental Management would also have to develop guidance for manufacturers that explains how to prepare and implement a stewardship plan.[31] The Department of Environmental Management would have to establish a process to develop the guidance by January 1, 2022 and complete the guidance by July 1, 2022.[32]

5 Historic Legislative Proposals (Unenacted)

Since 2012, seven states have proposed historic legislation (i.e., failed and was not enacted) aimed at addressing EoL management options for decommissioned PV modules. These historic bills would have enacted a range of policies regulating different life cycle activities and actors in the PV value chain. These historic bills although not enacted provide examples of diverse policy frameworks that could be used to manage EoL PV modules. Table 5 below provides a summary of historic EoL PV management legislation since 2012.

Table 5. Summary of Historic (Unenacted) Legislation that Addressed PV Module Recycling

State	Description
Arizona	***Senate Bill 1309***, introduced in 2017, would have established a renewable energy technology environmental impact study committee to: • Collect information on the environmental impacts of production, recycling and disposal of solar energy panels and electronic waste • Study the lifespan of solar energy panels and electronic equipment • Review opportunities to expand solar panel and electronic waste recycling or reuse in the state • Collect additional information and make recommendations related to the environmental impact of the disposal of solar panels and electronic waste and potential strategies to address the environmental impact of the disposal of solar panels and electronic waste (S.B. 1309, 53rd Leg., 1st Reg. Sess. [Ariz. 2017]).

[31] H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)
[32] H.B. 5525, 2021 Leg., Reg. Sess. (R.I. 2021)

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State	Description
	House Bill 2828, introduced in 2020, would have placed EoL management requirements on any person who sells, leases, or manufacturers PV panels for residential, commercial, and industrial use (specialty environmental components) and would prohibit anyone from disposing of PV panels in solid waste landfills in Arizona (H.B. 2828, 54th Leg., 2d Reg. Sess. [Ariz. 2020]). The bill would require any person who sells or leases PV panels in Arizona to pay a fee of $5 per panel sold for residential, commercial, or industrial use to the Department of Revenue to be deposited into an established Specialty Environmental Component Fund (Fund) (H.B. 2828, 54th Leg., 2d Reg. Sess. [Ariz. 2020]). The Fund would be used to pay for recycling orphaned waste and to reimburse approved recycling facilities that receive specialty environmental components for disposal (H.B. 2828, 54th Leg., 2d Reg. Sess. [Ariz. 2020]).
Hawaii	***Senate Bill 2279**,* introduced in 2014, would have established a task force in the Department of Health to study the feasibility of a PV waste recycling program in the state and to make recommendations on how to address the expected increase in PV waste in upcoming years (S.B. 2279, 27th Leg., Reg. Sess. [Haw. 2014]). ***House Bill 2413***, introduced in 2020, would have required the Hawaii State Energy Office to work with the Department of Health on a comprehensive study to determine best practices for disposing of and recycling discarded clean energy products, with an emphasis on solar panels and cells (H.B. 2413, H.D. 1, 30th Leg., Reg. Sess. [Haw. 2020]).
Maryland	***House Bill 1242**,* introduced in 2018, would have established a solar PV recycling fee of 10% of the cost of installation collected by the Department of the Environment. Installers who filed the recycling fee within a certain number of days after the solar facility was installed would have received a credit of 0.6 percent of the total solar PV recycling fee paid. The recycling fees would have been exempt from taxation (H.B. 1242, 2017-2018 Leg., Reg. Sess. [Md. 2018]). ***House Bill 125**,* introduced in 2019, would have established a solar PV recycling fee of 10% of the cost of installation collected by the Department of the Environment. The bill would have also established a 20% charge on the first sale price of each renewable energy credit (REC). The recycling fees would have been exempt from taxation (H.B. 125, 2019 Leg., 439th Sess. [Md. 2019]). ***House Bill 165***, introduced in 2020, would have combined the key features of House Bill 1242 and House Bill 125 (H.B. 165, 2020 Leg., 441st Sess. [Md. 2020]). ***Senate Bill 891***, introduced in 2020, would have required the Department of the Environment to establish and adopt guidelines to help solar panel manufacturers prepare and implement self-directed solar panel stewardship programs to ensure the safe, convenient, and environmentally sound takeback and recycling of decommissioned solar panels. The bill also would have required manufacturers to adopt a Department-approved solar panel stewardship plan to sell solar panels in Maryland after January 1, 2022. The individual stewardship plans would have had to, among other things: • Minimize the release of hazardous substances and maximize recovery of other valuable materials • Apply to all solar panels sold in Maryland on or after July 1, 2020 • Establish performance goals for the combined reuse and recycling of collected out-of-service solar panels (S.B. 891, 2020 Leg., 441st Sess. [Md. 2020]).
Minnesota	***House Bill 2909*** and ***Senate Bill 2698**,* introduced in 2014, would have established a solar PV module stewardship plan. The companion bills would have required producers of solar PV modules sold in the state to implement and finance a

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State	Description
	statewide product stewardship program that manages the solar PV modules by reducing their waste generation, promoting their recycling and providing for negotiation and execution of agreements to collect, transport and process the solar PV modules for EoL recycling. On or after a certain date, no producer, wholesaler or retailer would have been permitted to sell solar PV modules in the state without participating in an approved stewardship program. Solar panel producers would have been required to submit a stewardship plan to the Pollution Control Agency and receive approval of the plan or submit documentation that demonstrates the producer has entered into an agreement with a stewardship plan. The bills included details on the information that a stewardship plan would have been required to include. The bills would have prohibited the disposal of solar PV modules in mixed municipal solid waste (H.B. 2909, 88th Leg., Reg. Sess. [Minn. 2014]/S.B. 2698, 88th Leg., Reg. Sess. [Minn. 2014]). ***House Bill 3333,*** introduced in 2018, was identical to House Bill 2909 and Senate Bill 2698 (H.B. 3333, 90th Leg. Sess., Reg. Sess. [Minn. 2018]).
New York	***Senate Bill 7789*** and ***Assembly Bill 10209,*** introduced in 2016, would have required PV panel manufacturers to, individually or collectively with other manufacturers, establish and maintain a program for the collection, transportation, recycling, disposal and proper management of out-of-service solar panels. The manufactures would have been prohibited from issuing fees or other charges to consumers or persons participating in the program. Manufacturers would have been required to conduct education and outreach efforts, including creating and maintaining a web-based program that allows contractors and consumers to identify collection sites for decommissioned solar panels. Manufacturers would have been required to submit an annual report on their collection program (S.B. 7789, 2015-2016 Senate, Reg., Sess. [N.Y. 2016]/ A.B. 10209, 2015-2016 Stat Assemb., Reg. Sess. [N.Y. 2016]). ***Assembly Bill 7757*** and ***Senate Bill 2837,*** introduced in 2017, were similar to Assembly Bill 10209/Senate Bill 7789 (A.B. 7757, 2017-2018 State Assemb., Reg. Sess. [N.Y. 2017]/ S.B. 2837, 2017-2018 Senate, Reg. Sess. [N.Y. 2017]). ***Senate Bill 942***, introduced in 2019, was similar to Assembly Bill 10209/Senate Bill 7789 and Assembly Bill 7757/Senate Bill 2837 (S.B. 942, 2019-2020 State Assemb., Reg. Sess. [N.Y. 2019]).
North Carolina	***Senate Bill 568***, introduced in 2019, would have placed EoL management requirements on utility-scale owners and operators and PV module manufacturers and would prohibit anyone from disposing of PV modules (or energy storage system batteries) in landfills. The bill would place decommissioning requirements on the owner or operator of a utility-scale solar project to restore the land and to either reuse or recycle a PV module (or an energy system battery) at the EoL. The bill would also require solar panel manufacturers who sell PV modules in North Carolina starting January 1, 2021, to implement a stewardship plan to take back, collect, and recycle or reuse all the PV modules it sells in the state (S.B. 568, 2019-2020 Gen. Assemb., Reg. Sess. [N.C. 2019]).
Washington	***House Bill 2645***, introduced in 2020, would have required the convening of a PV module recovery, reuse, and recycling working group to review and recommend potential methodologies for EoL PV module management. The working group, which would have been made up of representatives from various parts of the PV value chain, would have been required to submit a report to the legislature and the

State	Description
	governor that summarized the group's recommendations (H.B. 2645, 2019-2020 Leg., Reg. Sess. [Wash. 2020]).[33]

6 Industry- and State-Led Initiatives

Industry- and state-led initiatives are also starting to emerge in the United States to address EoL management options for PV systems. Industry stakeholders have made strides to encourage environmentally sustainable EoL PV module management practices. California, Illinois, and Minnesota have also formed working groups to research and analyze EoL PV management options and opportunities in their respective states to inform policy solutions that may drive and enable environmentally sustainable EoL management decisions and behaviors.

6.1 Industry-Led Initiatives

There are global and national voluntary industry standards that may encourage environmentally sustainable EoL management decisions for PV, including design for recycle as well as recycling and resource recovery of EoL PV modules (Tura et al. 2018; Bai et al. 2015; Dong et al. 2016). SEIA has also developed a national program to encourage PV recycling among its membership in the United States.

6.1.1 SEIA National PV Recycling Program

In 2016, SEIA launched a member-based National PV Recycling Program (PV Recycling Program) that aggregates the services offered by recycling vendors and PV manufacturers. The PV Recycling Program establishes a network of cost-effective recyclers that can responsibly manage EoL PV modules and system components (SEIA 2019a; SEIA 2019b; CPUC 2019). SEIA's PV Recycling Working Group identifies preferred recycling partners through an evaluation process that may include a site visit to ensure practices meet SEIA's standards (SEIA 2019b). Preferred partners must process EoL PV modules and system components in the United States (CPUC 2019; Evelyn Butler, Solar Energy Industries Association, telephone conference, February 8, 2019). The PV Recycling Program lists U.S. firms capable of recycling PV modules, inverters, and other related equipment (SEIA 2019b).[34] The PV Recycling Program is only available to members and includes:

- Access to SEIA vetted recycling vendors and service providers
- Single point of contact for recycling vendors
- Exclusive pricing regardless of size and volume for members
- Minimum quantities normally aggregated at the waste generator level are aggregated at a total member-level for program recycling vendors
- Engagement in recycling process improvement as EoL PV system volume increases and as recycling vendor network grows
- Access to data on industry-level recycling (SEIA 2019b).

[33] Only Section 2 of this bill, which was the section that would have created the working group, was vetoed by the Governor (Governor Jay Inslee 2020).
[34] SEIA's National PV Recycling Program partners include: Cascade Eco Minerals, Echo Environmental, First Solar, and Green Century Recycling.

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While the above benefits are available only to members, the services of SEIA's recycling partners are available to anyone (Evelyn Butler, Solar Energy Industries Association, email, September 4, 2019).

6.1.2 Selected Voluntary Industry Standards

The absence of federal and state regulations mandating PV recycling, landfill diversion, or best management practices has resulted in the development of global and national voluntary industry standards that may enable environmentally sustainable EoL PV management decisions and behaviors. These standards provide guidelines for solar industry stakeholders to follow that promote PV recycling in the United States. In addition, other industry standards that are not specific to PV that may also enable recycling and resource recovery efforts of EoL PV modules. These industry standards are often designed through a consensus-based multi-stakeholder process and focus on environmentally sustainable business practices. Table 6 below provides a summary comparison of the selected industry standards discussed in this section.

Table 6. Comparison of Selected Voluntary Industry Standards

Name	Primary User	Information Source(s)	Take Back Required?	Minimum Mass Recovery Rate (%)	Disclosure of Disposal & Recycling Volumes or Material?
Silicon Valley Toxics Coalition (SVTC) Solar Scorecard	Manufacturer, Purchaser, Owner	Self-Reported	Yes	No	Yes
ANSI/NSF 457 Sustainability Leadership Standard for PV Modules	Manufacturer, Purchaser, Owner	Self-Reported & Audited	Yes	No	Yes
ISO 14001 Environmental Management Systems Standard	Manufacturer, Owner, Recycler,	Audited	N/A	N/A	N/A
SERI Responsible Recycling (R2) Standard	Owner, Recycler	Audited	No	No	Yes
Recycling Industry Operating Standard (RIOS)	Owner, Recycler	Audited	No	No	Yes
R2/RIOS	Owner, Recycler	Audited	No	No	Yes
Ethical Reuse, Recycling and Disposition of Electronic Equipment and Information Technology (e-Stewards)	Owner, Recycler	Audited	No	Yes, for mercury recovery by end processors	Yes

PV-Specific Voluntary Industry Standards

This section provides an overview of selected existing international and national voluntary standards that are directly applicable to the solar industry. These programs were chosen to reflect a range of styles and requirements for voluntary industry standards, and do not encompass all existing programs or those in development.

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Silicon Valley Toxics Coalition Solar Scorecard

In 2010, the Silicon Valley Toxics Coalition (SVTC) developed the Solar Scorecard (SVTC 2021a). The purpose of the Solar Scorecard is to promote transparent environmental and social justice practices in the solar industry. The Solar Scorecard is based on a set of survey questions provided to PV manufacturers who may voluntarily provide information about their business practices to SVTC for inclusion in the annually published Solar Scorecard. Twenty-nine PV manufacturing companies have voluntarily provided information to SVTC at least once in the last 6 years for inclusion in the Solar Scorecard (SVTC 2021b). The categories, metrics and scoring criteria have evolved over time to become more detailed and rigorous as new scientific and engineering advances have been made (Wade et al. 2018). Thus, it is not possible to directly compare responses over time. Several categories of the Solar Scorecard address EoL PV management practices, including:

- EPR requirements to take back and ensure EoL PV modules are recycled
- Green design and use of recycled materials in PV module manufacturing
- Compliance with ISO 14001 Environmental Management Systems Standard
- Report requirements regarding associated landfill waste
- Analysis of EoL disposal and recycling processes (SVTC 2021b).

Residential or institutional purchasers, investors, installers, and other entities may use the Solar Scorecard to identify PV manufacturers that follow environmental and social responsibility practices.

NSF/ANSI 457 Sustainability Leadership Standard for PV Modules and Inverters

In 2017, the Green Electronics Council (GEC) and NSF International facilitated the development of the NSF/ANSI 457 Sustainability Leadership Standard for PV Modules and Inverters (NSF International 2019). The purpose of the standard is to establish sustainable performance criteria and corporate performance metrics that exemplify sustainable leadership in the solar market. The standard provides a framework and a set of performance objectives for PV manufacturers for the design and manufacturing of PV modules and inverters . PV manufacturers may obtain an NSF/ANSI 457 certification through an audit process to demonstrate compliance with both product sustainability and corporate performance criteria (ANSI 2020). Table 7 identifies the seven performance categories for NSF/ANSI 457 certification through which ratings of gold, silver, and bronze may be achieved.

In 2019, the NSF/ANSI 457 standard was listed on the Electronic Product Environmental Assessment Tool (EPEAT) registry. EPEAT is an online eco-label tool created by GEC with a grant funded by the EPA (EPA 2019b). It is intended to help purchasers evaluate, compare and select electronic products based on their environmental attributes (e.g., toxicity of materials, recyclability) (EPA 2019b). Federal U.S. regulations mandate federal agencies' use of EPEAT by requiring them to "ensure at least 80 percent of their personnel's electronic devices are EPEAT registered" (Exec. Order No. 13834, 83 Fed. Reg. 23771 [2018], Efficient Federal Operations; 48 C.F.R. §§ 23.700-.705 [2001]). In addition, a number of corporations have also made EPEAT procurement commitments. Listing PV modules in the EPEAT registry could facilitate the inclusion of environmental performance criteria in future PV module purchase

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orders, streamline the implementation of standardized sustainability criteria, and serve as a template for a national eco-label for PV modules (Wade 2018).

Table 7. NSF/ANSI 457 Sustainability Leadership Standard Requirements

Performance Category	Description
Management of substances	Listing of declarable substances; Avoidance or reduction of high global warming potential emissions; Reduction of substances of concern
Preferable materials use	Recycled content declaration
Life cycle assessment (LCA)	Conduct PV module life cycle assessment
Energy efficiency & water use	Efficiency and tare loss reporting; Water inventory
EoL management & design for recycling	Product take back and processing
Product packaging	Eliminate substances of concern; Recyclability of packaging
Corporate responsibility	Environmental management systems; Conformance to occupational health and safety performance; Corporate reporting and commitment to performance; Conflict mineral disclosure

Source: NSF International 2019

Other Voluntary Industry Standards

This section provides an overview of selected existing international and national voluntary industry standards that could apply to the solar industry.

ISO 14001 Environmental Management Systems Standard

In 2015, the ISO revised the ISO 14001 Environmental Management Systems (EMS) Standard to include sustainable resource use, climate mitigation, and lifecycle EoL considerations (ISO 2015). The purpose of the international standard is to enhance an organization's environmental performance by establishing a systematic framework for the organization to achieve environmentally sustainable objectives and to demonstrate compliance with environmental, health, and safety (EH&S) regulatory requirements (ISO 2015). The standard provides a strategic set of criteria for an organization to develop an effective EMS to identify, manage, monitor and control environmental concerns related to their organization (ISO 2015).

Organizations (e.g., PV module manufacturers, installers, and O&M entities) may obtain an ISO 14001 certification from a third-party certifier that audits the organization's business practices against the requirements of the standard (ISO 2015). The requirements are categorized into a set of clauses that provide guidance for organizations to achieve an effective EMS (ISO 2015). Table 8 below identifies ISO 14001's substantive clauses.

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Table 8. ISO 14001 Standard Requirements

Clause	Description
Context of the organization	Provides general requirements and guidance on developing the scope of an EMS including the importance of understanding an organization's needs and expectations of interested parties
Leadership	Provides requirements focused on establishing environmental policies and guidance on how an organization can demonstrate leadership and commitment to the established policies
Planning	Provides guidance on how to identify and address risks and opportunities and how to plan actions to achieve environmental objectives
Support	Provides a set of requirements to ensure an organization has support systems (e.g., effective means of communication) in place to ensure the success of the EMS
Operation	Provides operational planning requirements and guidance on how to prepare and respond to environmental emergences
Performance Evaluation	Provides requirements and guidance on how to monitor, measure, analyze, and evaluate the EMS
Improvement	Provides requirements and guidance on how to address an organization's practices that do not comply with the EMS and how to implement corrective actions to ensure future compliance

Source: ISO 2015

SERI Responsible Recycling (R2) Standard

In 2020, Sustainable Electronics Recycling International (SERI) revised the Responsible Recycling (R2) Electronics Recycling Standard to include additional best practices for the EoL management of electronics. The purpose of the international standard is to encourage environmentally sustainable electronics recycling practices. SERI is an ANSI-accredited standards development organization dedicated to aiding the implementation of transparent, environmentally, and socially responsible business practices (SERI 2020).

Electronics processors and recyclers, some of which have started to accept EoL PV modules, may obtain an R2 Standard certification through an audit process to demonstrate that the recycler's business practices conform to the requirements of the standard (SERI 2020). Table 9 below highlights selected R2 Standard requirements that may be applicable to enabling environmentally sustainable EoL PV management practices in the United States.

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Table 9. SERI R2 Standard Requirements

Requirement	Description
Hierarchy of responsible management strategies	Requires electronic recyclers to develop and adhere to a policy for managing used and EoL electronic equipment based on a reuse and recycling and recovery hierarchy
Environmental, health, and safety management system	Requires electronic recyclers to plan and monitor its environmental, health, and safety practices
Legal requirements	Requires electronic recyclers to comply with all applicable environmental, health and safety, data security, and transport/export requirements
Sorting, Categorization and Processing	Requires electronic recyclers to categorize materials into controlled or uncontrolled streams; identify devices and components that can be reused; test repair and refurbish, and adequately package equipment and components going to reuse, or transfer to qualified downstream vendor
Tracking throughput	Requires electronic recyclers to maintain business records sufficient to document the flow of equipment, components, and materials
Focus Materials	Manage, both on-site in through selection of downstream vendors, focus materials (materials or components specified in the standard as requiring greater care) in a manner protective of worker, public and environmental health and safety

Source: SERI 2020

However, note that the R2 Standard does not specifically apply at this time to recycling PV modules. SERI has created a PV Panel Recycling Working Group comprised of experts from the reuse and recycling vendor, manufacturer, customer, scientific expert and public interest representative communities that has been meeting since fall of 2020. The group is tasked with reviewing the current R2v3 requirements and recommending to the R2 Consensus Body if PV modules would appropriately fit under the existing metrics and framework as designed for traditional electronics, or if their inclusion would require new PV-specific metrics to be reasonably applicable. This recommendation will occur in spring of 2021.

Subsequently, the Consensus Body, the entity which develops revisions through an ANSI approved process and recommends R2 Standard changes to the SERI Board, will decide whether to recommend changing the R2 Standard to include PV panels. If revisions are determined to be appropriate, a Technical Advisory Committee (TAC), with additional PV industry representatives added, will assist the Consensus Body in drafting proposed language revisions to the R2 Standard. Through an ANSI-approved process, the proposed revisions will be released for public comment, responded to by the TAC, and considered a final time by the Consensus Body who will vote on sending the revision to the SERI board for a vote.

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Recycling Industry Operating Standards (RIOS)

In 2002, the Institute of Scrap Recycling Industries (ISRI) facilitated the development of the global Recycling Industry Operating Standard, which was most recently updated in 2016 (RIOS 2021a). The purpose of the standard is to provide a systematic framework for recyclers to achieve measurable environmentally sustainable performance objectives and to demonstrate compliance with EH&S requirements. RIOS is accredited by ANSI and integrates ISO 90001 (quality), ISO 14001 (environment), and OHSAS 18001 (health and safety) standard requirements into a single streamlined management system to foster healthy, safe, and sustainable recycling practices (RIOS 2021b).

R2/RIOS

In 2009, ISRI and SERI collaborated to release a combined R2/RIOS Standard for electronic recyclers (ISRI 2011; RIOS 2021a) to simplify the process for those companies desiring both certifications. The R2/RIOS Standard combines key provisions of the R2 Standard with the framework of the RIOS Standard to ensure electronic recycling facilities adhere to safe and sustainable recycling practices. Electronic recyclers, some of which have started to accept EoL PV modules, may obtain an R2/RIOS Standard certification, and are designated a Certified Electronics Recycler, through an audit process to demonstrate that their business practices conform to the requirements of the standard (RIOS 2021a).

e-Stewards Standard for Ethical Reuse, Recycling and Disposition of Electronic Equipment and Information Technology(e-Stewards)

In 2009, the Basel Action Network (BAN) developed the first version of what was updated in 2020 and now called the e-Stewards Standard for Ethical Reuse, Recycling and Disposition of Electronic Equipment and Information Technology Standard v4, or e-Stewards (e-Stewards 2021a). The purpose of the international standard is to encourage environmentally responsible electronics recycling and reuse practices. The standard incorporates the ISO 14001 Standard requirements and tailors those requirements for electronics recycling and resource recovery entities (e-Stewards 2021a).

Electronic recyclers, electronic refurbishing organizations, asset managers, and material recovery operations may obtain an e-Stewards certification through an audit process to demonstrate that the organization's business practices conform to the requirements of the standard (e-Stewards 2021a). In addition to annual audits, participants are subject to the Performance Verification Program, which includes additional requirements such as unannounced site inspections and GPS tracking of e-waste to verify downstream commitments are upheld (e-Stewards 2021b). The requirements of the standard focus on compliance with international waste trade requirements, such as the Basel Convention[35] and Organization for Economic Cooperation and Development (OECD) treaties, EH&S management system norms, and OH&S best practices (e-Stewards 2021).

[35] The Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal was adopted in 1989 by the Conference of Plenipotentiaries in Basel, Switzerland (Basel Convention 2019). The Basel Convention establishes standards and restrictions on the transboundary movement of hazardous waste and solid waste (EPA 2019c). Although the United States is not a party to the Basel Convention, U.S. importers and exporters must comply with the convention's requirements to trade covered waste with party countries (EPA 2019c; Lia Yohannes and Kathy Lett, U.S. Environmental Protection Agency, teleconference, April 10, 2019).

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In addition, e-Stewards provides the opportunity for companies, governments and institutions to become Enterprise members. This membership states the participant commits to make best "commercially reasonable" efforts to use e-Stewards certified recyclers to recycle their information technology assets and to provide a short annual report on related progress.

6.2 State-Led Initiatives

State-led initiatives have also developed in California, Illinois, and Minnesota to address EoL PV management concerns.

California

In 2018, California Public Utilities Commission (CPUC) and CalRecycle signed a memorandum of understanding to cooperate on the development of consistent regulation of EoL PV modules, electric vehicle batteries, and energy storage batteries in response to state policy changes (CPUC and CalRecycle 2019). California lawmakers passed Senate Bill 100 in 2018, establishing a target for 100% zero-carbon electricity by 2045 (S.B. 100, 2017-2018 Senate, Reg. Sess. (Cal. 2018)).[36] In addition, California amended the state's building energy code to require PV on all new single-family homes and multi-family buildings that are no more than three stories tall beginning in 2020 (CPUC 2019). As a result of policy changes, in 2019, CPUC, CalRecycle, California Energy Commission, and the California Air Resources Board formed a working group to develop approaches to address EoL management of PV equipment and electric vehicle batteries in the state. As of January 2021, the California Energy Commission and the California Air Resources Board were also planning to sign onto the 2018 CPUC and CalRecycle memorandum (Paulina Kolic, CalRecycle, email, September 6, 2019; Teresa Bui, CalRecycle, email, January 8, 2021).

Illinois

The Illinois Sustainable Technology Center (ISTC), at the University of Illinois, launched a Solar Panel Recycling Initiative in 2017 in response to the Illinois Future Jobs Act of 2016 and the growing projections of decommissioned PV in the state. The Illinois Future Jobs Act requires the state to increase installed PV capacity to approximately 2,700 MW by 2030—up from 87 MW in 2018 (Holm and Martin 2018). As part of the Solar Panel Recycling Initiative, ISTC in conjunction with the Illinois Environmental Protection Agency, formed a PV EoL management stakeholder working group. The working group includes a diverse set of stakeholders that hopes to identify barriers to PV module recycling and to develop policy, technical, and economic solutions that may enable environmentally sustainable EoL PV management decisions and the recovery of valuable resources in Illinois (ISTC 2019).

Minnesota

The Minnesota Pollution Control Agency (MPCA), Minnesota Department of Commerce, and Minnesota Solar Energy Industries Association also formed a solar panel strategy working

[36] The law also requires the California Air Resources Board, charged with regulating emissions standards from vehicles, to plan for 100% of total retail sales of electricity in California to come from renewable energy resources and zero-carbon resources by 2045 (CPUC 2019).

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group[37] in the summer of 2019.[38] The working group was formed in response to the steady growth of installed PV capacity in Minnesota, in addition to projections of near-term EoL PV (Minnesota Department of Commerce 2019; Minnesota Solar Panel Recycling Strategy Working Group 2019). One projection found that cumulative EoL PV modules could total 6-8.5 million in Minnesota by 2050 (MPCA Forthcoming). As a result, the working group hopes to assist in development of environmentally sustainable policy, financial, and technical EoL management options for PV equipment in Minnesota.

7 Conclusion

The projected volume of decommissioned PV modules in the United States presents not only EoL management concerns, but also material recovery and secondary market opportunities. PV recycling and resource recovery efforts can reduce negative environmental impacts associated with the life cycle of a PV module, reduce resource constraints, and present opportunities for new and expanded markets and job creation in the United States. Policy measures and industry standards can enable actors along the PV value chain to take proactive and collaborative action to implement environmentally sustainable EoL PV management decisions.

Publicly available research and analysis regarding the value and volume of recovered materials from EoL PV modules as well as PV recycling infrastructure and technology needs could help inform policy to drive environmentally sustainable EoL management decisions and behaviors. Understanding the costs, liabilities, and current market conditions associated with PV recycling and resource recovery can also reduce investor risk and uncertainty directly, which may help to enable secondary solar markets in the United States. A multi-faceted regulatory approach that places the management and financial responsibility on multiple value chain actors may also help enable an EoL PV management strategy that does not overburden one actor. A regulatory framework that is complemented by industry standards, takes into consideration current law and, where possible, acts in concert with existing policy could also help enable an EoL PV management strategy and guide secondary solar market opportunities in the United States. Publicly available analyses of the advantages and challenges of early-stage policies, once they are implemented, can inform subsequent policy development. Clearly defined federal and state regulation can mandate and/or incentivize PV recycling and resource recovery, while changes to the current regulatory scheme for the management of solid waste could also reduce the barriers associated with the handling, transport, accumulation, storage, and treatment of PV modules destined for recycling and resource recovery.

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[37] The working group includes state agencies, manufacturers, recyclers, and national and state trade associations, among others (Minnesota Solar Panel Recycling Strategy Working Group 2019).

[38] In 2017, the MPCA Commissioner's Office initially gave the MPCA permission to work with the Minnesota Public Utilities Commission and the Minnesota Department of Commerce to research and present policy options to handle the incoming stream of PV waste, which eventually led to the current working group (MPCA 2018; Amanda Cotton, MPCA, email, August 15, 2019).

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Appendix A. Breakdown of Selected Enacted Policy: Requirements

Table A- 1. Washington: Enacted Regulatory Requirements (Wash. Rev. Code § 70A.510.010)

Regulated Entity—Threshold	Regulatory Requirement
A manufacturer that sells or offers for sale a PV module in or into the state or a stewardship organization designated to act as an agent on behalf of a manufacturer or manufacturers (Wash. Rev. Code § 70A.510.010[8]).	Must prepare and submit to the Washington Department of Ecology (Department) stewardship plan and receive approval by January 1, 2020 or within 30 days of its first sale of a PV module in the state and implement the approved stewardship plan (Wash. Rev. Code § 70A.510.010[5]). Stewardship plans must follow the requirements of Wash. Rev. Code § 70A.510.010[5][a] and the Department's Stewardship Plan Guidance.
A stewardship organization designated to act as an agent on behalf of a manufacturer or manufacturers in operating and implementing the stewardship program (Wash. Rev. Code § 70A.510.010[4]).	Must provide to the Department a list of the manufacturers and brand names that the stewardship organization represents within 60 days of its designation by a manufacturer as its agent (Wash. Rev. Code § 70A.510.010[4]).
A manufacturer or its designated stewardship organization (Wash. Rev. Code § 70A.510.010[7]).	Must provide to the Department a report for the previous calendar year that documents implementation of the plan and assesses achievement of the performance goals beginning April 1, 2022 (Wash. Rev. Code § 70A.510.010[7]).

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Table A- 2. California: Enacted Universal Waste Regulations (Cal. Code Regs. tit. 22 §§ 66273.1-66273.84)

Regulated Entity—Threshold	Regulatory Requirement

Universal Waste Handler	• Must comply with the applicable universal waste regulations found at Cal. Code Regs. tit. 22, §§ 66273.30–.32 and 66273.34–.39
	• Must not accumulate waste PV modules for more than one year, and accumulation times must be documented by including accumulation start dates on labels and maintaining an inventory system
	• Must ensure PV module management prevents releases of any constituent of a module to the environment, including preventing breakage that would cause a release, under reasonably foreseeable conditions
	• Must immediately clean up and contain any broken modules and any module constituents using a container that will prevent a release of module constituents to the environment
	• Must label or mark waste modules themselves or the containers holding modules as "Universal Waste-PV module(s)"
	• Must keep detailed records of all shipments of universal waste coming and going from the handler's facility
	• Must be authorized by DTSC under Cal. Code Regs. tit. 22, §66273.70 if they treat universal wastes
	• May send PV modules to an authorized universal waste destination facility for disposal
	• Must obtain an EPA identification number before accumulating waste in quantities of 5,000 kilograms (11,000 pounds) or more
	• Must not dispose of, dilute, or treat universal waste unless the prohibited activity is in response to a release
	• Must submit a closure plan, including a cost estimate, to the DTSC and provide notice before closure
	• Must follow all notification, annual reporting, and record-keeping requirements listed in Cal. Code Reg. tit. 22, § 66273.74, including, but not limited to:
	  ○ Written notice to DTSC no later than 30 days before accepting waste PV modules accumulated from an off-site source
	  ○ Annual reporting for accepting more than 100 kilograms (220 pounds of waste from off-site sources within a year
	  ○ Shipment records maintained for at least three years (e.g., bills of lading, invoices, logs, manifests) for waste PV modules sent off-site and waste PV modules accepted from other handlers.

Universal Waste Transporter	• Must not transport waste PV modules unless they are transported to another universal handler, an authorized waste destination facility, or a foreign destination • Must not transport more than 100 kilograms (220 pounds) of PV modules unless the modules are contained as described in Cal. Code Regs. tit. 22, § 66273.33.6(a)(2).

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Appendix B. Breakdown of Selected Recent Historic Policy (Unenacted)

Table B- 1. New York: Historic Legislation (S.B. 942, 2019-2020 State Assemb., Reg. Sess. [N.Y. 2019])

Regulated Entity—Threshold	Regulatory Requirement
Any solar panel manufacturer that wants to sell, offer to sell, distribute, or offer to distribute solar panels in New York	• Would have had to establish and maintain a program for collection, transportation and recycling of out-of-service solar panels, either individually or collectively with other solar panel manufacturers, free of charge to consumers or program participants. The collection program must: ○ Compile a list of solar panel wholesalers in New York by July 1, 2021 ○ Establish a system to collect, transport, and recycle out-of-service solar panels from all collection sites ○ Not include any fees or other charges to consumers ○ Conduct educational and outreach efforts as prescribed by the Act by July 1, 2021; ○ Develop and update, as prescribed by the Act, educational and other outreach materials for distribution to qualified contractors, contractor associations, and consumers by July 1, 2021 ○ Provide an opportunity for the Department of Environmental Conservation (DEC) to review and offer feedback and suggestions on the collection program. • Would have had to individually or collectively with other solar panel manufacturers submit an annual report, as prescribed by the Act, on its collection program to the DEC by April 1, 2022 • Would have had to handle and manage any out-of-service panels that cannot be recycled and have been determined to be or contain hazardous waste, as defined by regulations by the DEC, consistent with the requirements for the management and disposal of hazardous waste.
Any solar panel wholesaler or retailer that wants to sell, offer to sell, distribute, or offer to distribute solar panels for final sale in New York	Would have had to ensure that the solar manufacturer of the solar panel they sell, offer to sell, distribute, or offer to distribute for final sale in New York has established a program for collection, transportation, and recycling of out-of-service solar panels in accordance with the Act and the DEC's regulations.
Any transporter	• Would have been prohibited from knowingly commingling solar panels with solid waste or recyclable materials • Would have been prohibited from knowingly delivering solar panels or knowingly causing such materials to be delivered to an incinerator, a landfill, a transfer station, or a facility in the state, who the transporter knows or should know will either commingle such materials with other solid waste or deliver such materials to an incinerator or a landfill for disposal
Any operator of an incinerator, landfill, or a transfer station	• Would have been prohibited from knowingly accepting solar panels for disposal or knowingly commingling solar panels with other solid waste or cause such materials to be transferred to an incinerator or landfill for disposal • Would have been required to post, in a conspicuous location at the facility, a sign stating that solar panels are not accepted at the facility

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Any consumer or qualified contractor who replaces a solar panel from a building	Would have been required to deliver the solar panel to an appropriate collection site
Any person or contractor who demolishes a building	Would have been required to ensure all solar panels are removed from the building prior to demolition and must deliver the solar panels to a collection site
Any department, authority, instrumentality, or municipal corporation of the state administering a program that involves the removal or replacement of a solar panels as a result of any statutory requirement	Would have been required to inform contractors of their statutory obligations to deliver the solar panels to a collection site and prohibit the disposal of the solar panel in a solid-waste facility
Any contractor, organization, or subcontractor of such organization who contracts with or receives funding or financing provided in whole, in part by, or through any department, agency, instrumentality, or political subdivision of the state for the sale, distribution, service, removal, collection, and recycling of solar panels	Would have been required to ensure the collection, transportation, and proper management of out-of-service solar panels in accordance with the provisions of title 31 of article 27 of the environmental conservation law

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Table B- 2. Arizona Historic Legislation (H.B. 2828, 54th Leg., 2d Reg. Sess. [Ariz. 2020]))

Regulated Entity - Threshold	Regulatory Requirement
Any person who leases, sells solar panels	Would have been required to either: • Pay a fee of $5 per panel sold or leased for any residential, commercial, or industrial use to the Department of Revenue; or • Ensure the manufacturer of the solar panels being sold or leased has an established recycling program reported to the Department of Environmental Quality annually
Anyone using solar panels for residential, commercial, or industrial use	Would have been prohibited from disposing of solar panels in solid waste landfills
Solar panel manufacturers	• Would have been required to establish a recycling program for the solar panels it makes that are sold or leased in Arizona • Would have been required to submit annual reports on the details and progress of the program, including a description of the program and the number and types of panels recycled • Would have been required to pay the fee of $5 per panel if the manufacturer does not have a recycling program or if they fail to submit annual reports about the program to the Department of Environmental Quality

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Appendix C. Electronic Device EoL Policies

Table C- 1. Summary of Electronic Waste EPR Requirements and Landfill Disposal Policies (as of 2019)

Jurisdiction	Statute Citation	Type	State Program Website
Arkansas	Ark. Code § 25-34-111 (2010).	Grant of authority to enact landfill ban[39]	Electronics Reuse and Recycling
California	Cal. Public Resources Code §§ 42460 to 42486 (2003).	EPR (registration-hybrid), landfill ban	Electronic Waste Recycling Act of 2003
Colorado	Colo. Rev. Stat. §§ 25-17-301 to 25-17-308 (2012).	Landfill ban, public education program	Electronics and Computer Waste
Connecticut	Conn. Gen. Stat. §§ 22a-629 to 22a-640 (2007).	EPR (registration and take back), landfill ban	Connecticut's Electronics Recycling Law
District of Columbia	D.C. Code §§ 8-1041.01 to 8-1041.12 (2014).	EPR (registration and take back), landfill ban	D.C. Electronics Recycling
Hawaii	Haw. Rev. Stat. §§ 339d-1 to 339d-27 (2008).	EPR (registration and take back)	Electronic Device and Television Recycling Law
Illinois	Ill. Comp. Stat. ch. 415, §§ 150/1 to 150/999 (2008).	EPR (registration and take back), landfill ban	Electronic Waste Recycling
Indiana	Ind. Code §§ 13-20.5-1-1 to 13-20.5-10-2 (2009).	EPR (registration and take back), landfill ban	Electronic Waste
Maine	Me. Rev. Stat. Ann. tit. 38, §§ 1610, 1661, 1663 (2004).	EPR (registration and take back), landfill ban	Electronics Recycling
Maryland	Md. Environment Code Ann. §§ 9-1727 to 9-1730 (2005).	EPR (registration, optional take back and public education program)	e-Cycling in MD

[39] The Arkansas legislature passed a statute in 2010 that gave the Pollution Control and Ecology Commission the authority to pass regulations banning electronics from state landfills, but the agency has yet to pass such regulations.

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Jurisdiction	Statute Citation	Type	State Program Website
Michigan	Mich. Comp. Laws §§ 324.17301 to 324.17333 (2008).	EPR (registration and take back)	Electronic Waste TakeBack Program
Minnesota	Minn. Stat. §§ 115a.1310 to 115a.1330 (2007).	EPR (registration and take back)	Minnesota's Electronic Recycling Act
Missouri	Mo. Rev. Stat. §§ 260.1050 to 260.1101 (2008).	EPR (registration and take back)	Electronic Waste
New Hampshire	N.H. Rev. Stat. Ann. §§ 149-M:27 (2007).	Landfill ban	Managing Waste Electronics
New Jersey	N.J. Rev. Stat. §§ 13:1E-99.94 to 13:1E-99.114 (2008).	EPR (registration and take back), landfill ban	E-Cycle New Jersey
New York	N.Y. Environmental Conservation Law §§ 27-2601 to 27-2621 (2010).	EPR (registration, take back, and public education program), landfill ban	E-Waste Recycling
North Carolina	N.C. Gen. Stat. §§ 130A-309.130 to 130A-309.1421, 130A-309.10(f) (201507).	EPR (registration and take back), landfill ban	North Carolina Electronics Management Program
Oklahoma	Okla. Stat. tit. 27A, §§ 2-11-601 to 2-11-611 (2008); Okla. Admin. Code § 252:515-39-4 (2010).	EPR (registration and take back)	E-Waste Information
Oregon	Or. Rev. Stat. §§ 459.247, 459Aa.300 to 459Aa.365 (2007).	EPR (registration and take back), landfill ban	Electronics Waste
Pennsylvania	Pa. Cons. Stat. tit. 35, §§ 6031.101 to 6031.702 (2010).	EPR (registration and take back), landfill ban	Electronic Recycling Management Program
Rhode Island	R.I. Gen. Laws §§ 23-24.10-1 to 23-24.10-17 (2008).	EPR (registration and take back), landfill ban	Electronic Waste
South Carolina	S.C. Code §§ 48-60-05 to 48-60-170 (2010).	EPR (registration and take back), landfill ban	South Carolina's Electronics Recycling Legislation

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Jurisdiction	Statute Citation	Type	State Program Website
Utah	Utah Code Ann. §§ 19-6-1201 to 19-6-1205 (2011).	EPR (registration-hybrid)	Recycle Utah
Vermont	Vt. Stat. Ann. tit. 10, §§ 6621a, 7551 to 7564 (2010).	EPR (registration and take back), landfill ban	Vermont e-Cycles
Virginia	Va. Code §§ 10.1-1425.27 to 10.1-1425.38 (2008).	EPR (registration, take back, and public education program)	Virginia's Computer Recovery and Recycling Act
Washington	Wash. Rev. Code Ann. §§ 70.95N.010 to 70.95N.902 (2006); Wash. Admin. Code § 173-900-010 to 173-900-997 (2016).	EPR (registration and take back)	E-Cycle Washington
West Virginia	W. Va. Code §§ 22-15A-22 to 22-15A-28 (2008).	EPR (registration and take back), conditional landfill ban	E-Waste West Virginia
Wisconsin	Wis. Stat. §§ 287.07, 287.17 (2009).	EPR (registration and take back), landfill ban	E-Cycle Wisconsin

Sources: NCSL 2018; ERCC 2019a; ERCC 2019b

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