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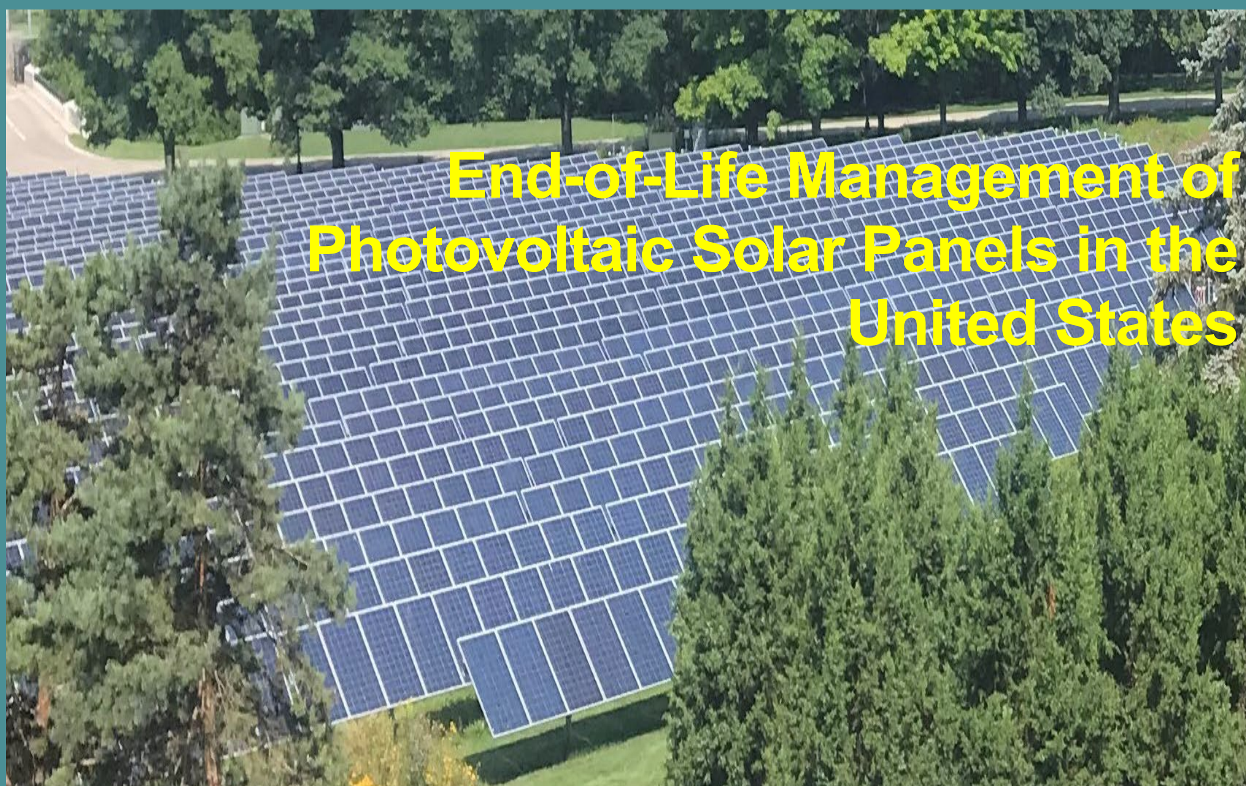

End-of-Life Management of Photovoltaic Solar Panels in the United States

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Land Remediation and Technology Division,
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NOTICE/DISCLAIMER

The U.S. Environmental Protection Agency, through its Office of Research and Development, funded the research described herein under an approved Quality Assurance Project Plan (Quality Assurance Identification Number K-LRTD-0032822-QP-1-1 Impact of Materials Management Application. It has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA external document.

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Foreword

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Gregory Sayles, Director

Center for Environmental Solutions and Emergency Response

Abstract

Solar energy is regarded as clean technology, but what happens to solar panels once they reach the end of their lifetime is vital for sustainability and achieving a circular economy. Current solar panels have an average lifespan of about 25 years. Millions of solar panels installed from the early 2000s are approaching the anticipated end-of-life. Growing solar panel waste presents a new environmental challenge and unprecedented opportunities to create value and pursue new economic avenues. Increasing interest in panel recycling reflects the relative importance of recovered materials, primarily silicon, silver, and lead. However, only about 10% of panels are recycled today.

Currently recycling costs exceed recovery economics, and in the absence of a federal and state mandates to recycle, a large volume of materials could be headed to a landfill. When released into the environment, hazardous materials present in end-of-life solar panels can be sources of significant pollution and health issues. Concern for the heavy metals present is essential to demand the proper management designed to avoid poor management practices that could contribute to another recycling crisis. The solar panel industry should develop technology to enable safe disposal and recycling of end-of-life or reuse and repurposing that could reduce the amount of waste and virgin materials extraction. Clear criteria and analytical methods should be developed to evaluate the obsolescence of solar panels to ensure proper management decisions. Considerations of a landfill option should be replaced with well-managed recycling to avoid environmental pollution from hazardous materials with PV panels, aid the recovery of valuable materials present in the panels.

This report supports EPA/ORD effort aimed at understanding the flow of used PV panels by reviewing the end-of-life of solar PV panels flow projections in the United States at national, regional, and state levels, and the assumptions and limitations built into the projections. This report documents a preliminary assessment of available data and development of the model that can be used as a starting point to track domestic flows of used electronics from generation to collection and reuse to final disposition.

Acknowledgement

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1. Introduction and Background

1.1 Report Objectives, Scope, and Organization

The main objectives of this report are to 1) project the mass of end-of-life (EoL) photovoltaic (PV) panels out to 2050 by state; and 2) evaluate the current solar PV panel recycling market in the United States (U.S.). Generating predictable waste volumes may help federal, state, and local governments; recyclers; manufacturers; landfill owners and operators; consumers; and other stakeholders address key challenges related to sustainable EoL management of solar PV panels. Sustainable EoL management in this context specifically means the repair, reuse, and recycling of solar PV panels. The scope of the analyses in this report includes the 50 contiguous states and PV panels that comprise most of the current market (i.e., crystalline silicon [c-Si] and thin-film cadmium Telluride [CdTe] panels).

The EPA, its regional offices, and the waste and recycling sector in the U.S. need to begin planning to lay the groundwork for managing the amount of EoL PV panels sustainably, build the recycling market, and capitalize on beneficial reuse opportunities. This report seeks to help EPA (including the regional offices) understand the EoL management practices and projected estimates of PV panels and assess whether existing recycling technologies and reuse pathways are sufficient to meet the projected PV EoL volume in the next 20 to 30 years. To that end, this report presents the following information by section:

- Section 2 – Overview of PV Panel Systems
- Section 3 – Projected Quantities of EoL PV Panels by Region and State
- Section 4 – EoL PV Panel Management Practices
- Section 5 – State Legislation and Working Groups Leading on Sustainable EoL PV Panel Management
- Section 6 – Assessment of the Current U.S. Recycling Market
- Section 7 – Conclusions and Future Research Recommendations.

1.2 National Solar Trends and Projections

Solar power is the fastest growing energy source in the United States. In 2020, 40 percent of new U.S. electric generation capacity came from solar, compared to 4 percent in 2010, a 36-fold increase (Feldman & Margolis, 2021). Strong growth is occurring primarily at the utility-scale, where since 2015, new solar PV installations have more than doubled (see **Figure 1**). Market growth is being driven by strong federal and state policies, state renewable portfolio standards (RPS), and increasing demand for clean energy in public and private consumers. Additionally, module prices are continuing to trend downward, driven by stronger than expected global demand despite supply disruptions and other challenges caused by the COVID-19 pandemic and U.S.-imposed tariffs on Chinese products (Feldman & Margolis, 2021). Strong growth is expected to continue in the near-term resulting from the Biden Administration's clean energy initiatives (SEIA/Wood Mackenzie, 2021).

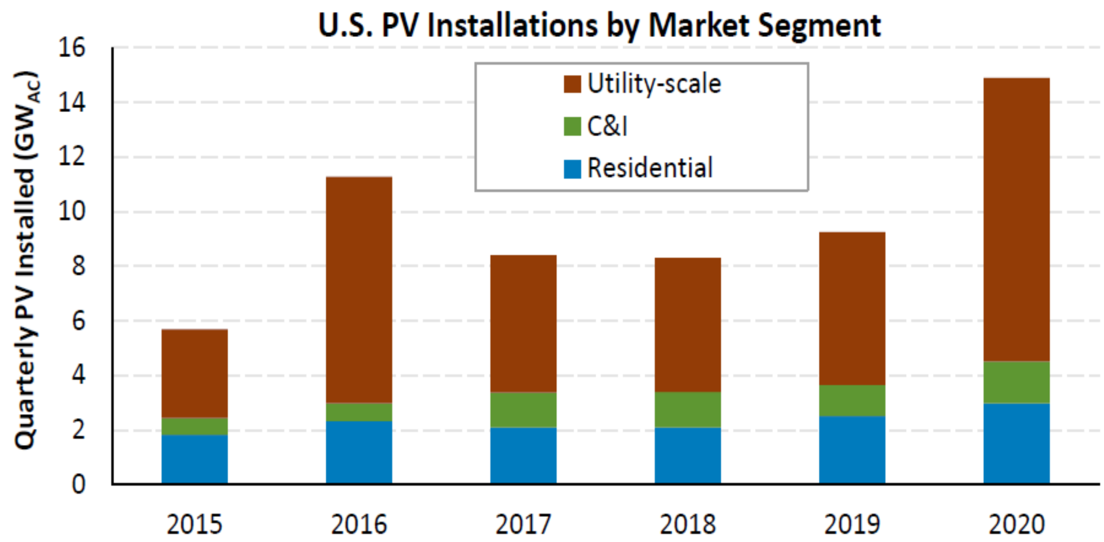


Figure 1. U.S. PV Installations by Market Segment, 2015-2020 (GW alternating current; EIA, 2021)

The top 10 solar generating states generated more than 5 percent of their electricity from solar in 2020, with California continuing to serve as the national leader with approximately 22 percent of its total electricity generation from solar (SEIA/Wood Mackenzie, 2021; Feldman & Margolis, 2021). At the end of 2020, cumulative solar power was reported to range from 73.8 GW of alternating current (GW_{AC}, EIA 2021b, see **Figure 2**) to 95.5 GW direct current (GW_{DC}, SEIA/Wood Mackenzie, 2021) of solar PV systems installed in the U.S., of which the largest share are utility-scale, followed by residential, then commercial and industrial (C&I).

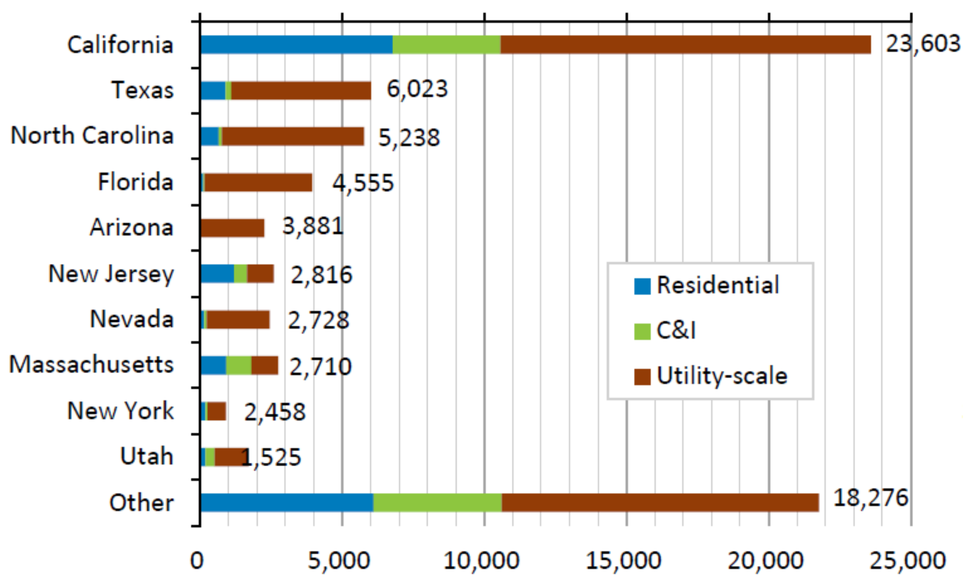


Figure 2. Cumulative Installed PV Capacity, as of December 2020 (MW alternating current, EIA 2021b)

The EIA estimates record solar installations in 2021 and 2022: 21 GW_{AC} in 2021 and 19 GW_{AC} in 2022, respectively, compared to 15 GW_{AC} in 2020. Projections of electricity generation from solar out to 2050 vary by source and modeled scenario (see **Figure 3**). The NREL's 2020 Standard Scenarios mid-case version projects the greatest amount of electricity generation from solar. EIA's AEO2021 reference-case projects 13 percent more electricity generation compared to their AEO2020 version, and the BloombergNEF's New Energy Outlook 2020 scenario is on par with the EIA AEO2020. While the projections vary, solar will continue to expand as states continue to increase their RPS.

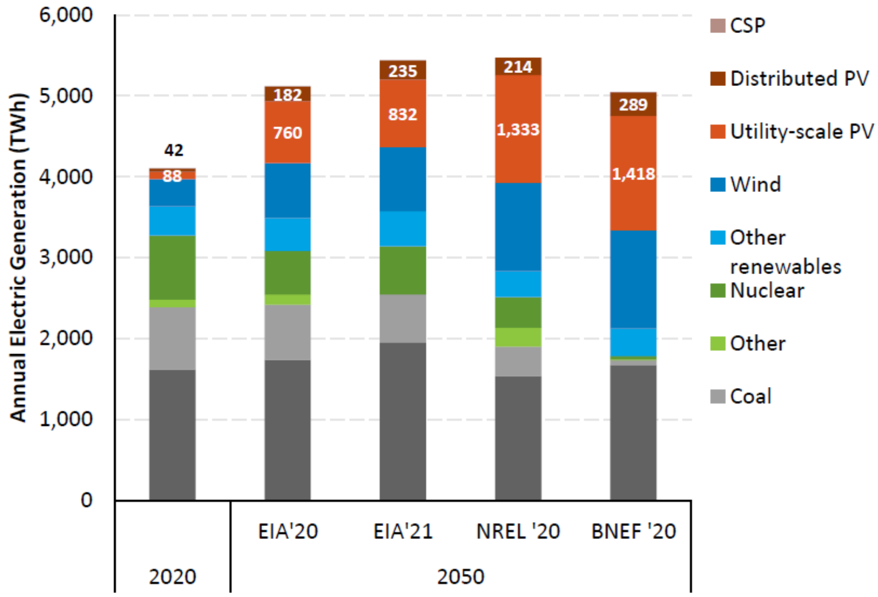


Figure 3. 2050 Projections of Electricity Generation from Solar from Various Sources (Feldman & Margolis, 2021)

Figure note: Data sources include BloombergNEF 2020 (BNEF '20) New Energy Outlook 2020; EIA 2021 (EIA '21) Annual Energy Outlook, reference case; EIA, 2020 (EIA '20) Annual Energy Outlook; NREL, 2020 (NREL '20) Standard Scenarios, mid case.

As the solar panel market continues to grow, so will the quantity of decommissioned panels. Some of the first installed panels are reaching the end of their lifetimes, which is generally estimated at 25 to 30 years. End of life, in many cases, typically means a PV panel still functions but not as efficiently. Most operational panels may still achieve 70-80 percent efficiency at 25-30 years (Curtis et al., 2021); however, they tend to be replaced by more efficient panels. A portion of installed panels may not last to their expected lifetimes due to low quality, improper citing and installation, and damage from hurricanes, fires, and other disasters.

The most widely cited estimate of EoL PV panels, the IRENA and IEA-PVPS 2016 report, estimates nearly 60 million to 78 million metric tons of EoL PV panels globally by 2050. The U.S. is projected to make up the second-largest global share of this estimate, ranging between 7.5 million and 10 million metric tons of PV panels as shown in **Figure 4** (IRENA-IEA PVPS, 2016). There is anecdotal evidence that the current PV panel waste is much more than the data presented in Figure 4.

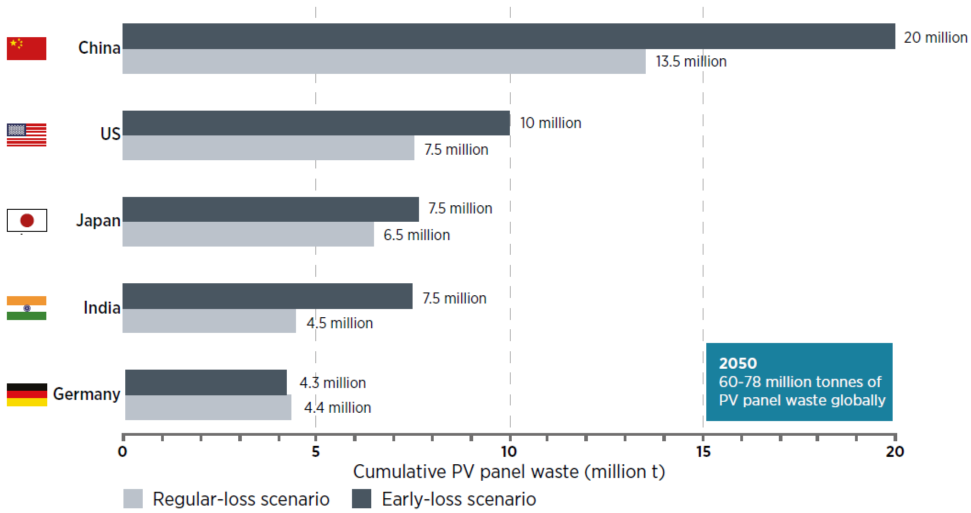


Figure 4. IRENA and IEA-PVP 2016 PV EoL Estimates by 2050, Regular-loss and Early-loss Scenarios (IRENA and IEA-PVP, 2016).

2. Overview of PV Panel Systems

PV systems are comprised of PV cells and other components, which convert sunlight directly into electricity. While hundreds of brands and models of PV cells and modules exist, this section describes a general solar PV module, the major components of widely available PV systems, and a brief discussion on next generation solar cells.

2.1 Solar PV Integration Models

One of three typical models are referred to when talking about solar PV installations – grid-tied, off-grid, and hybrid – as illustrated in **Figure 5**. The main differences include the need for a charge controller and energy storage solution (i.e. a battery) for electricity generation that is not tied to the grid. All three models are considered because the focus of this report is on solar panel EoL management.

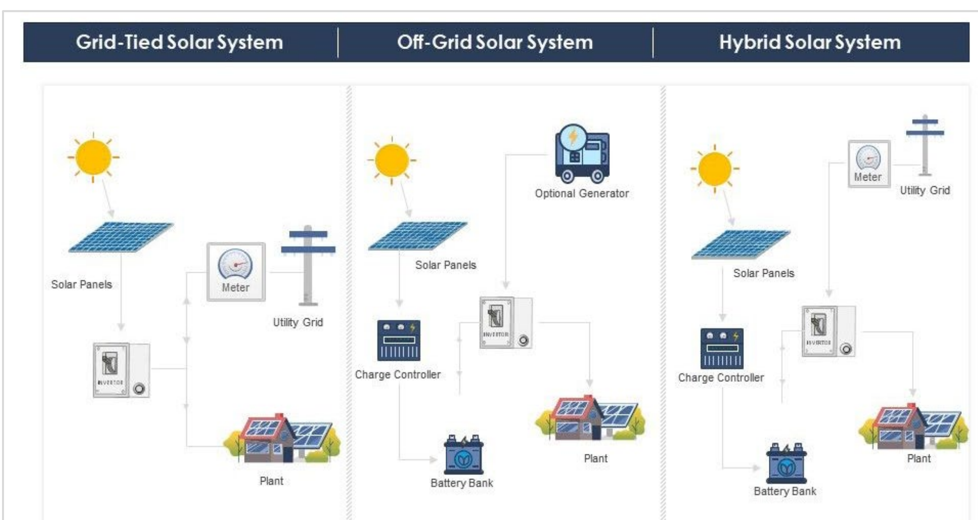


Figure 5. Three Typical Solar PV Integration Models.

2.2 Main Components of PV Panels

The main components of a solar panel or module include the following, in general order of manufacturing and assembly:

- Solar PV cells
- Ethylene vinyl acetate (EVA) film (for encapsulation)
- Tempered glass (3 to 5 mm thick)
- Fluoropolymer as commonly used rear backsheet
- Extruded aluminum frame, and the
- Junction box (diodes and connectors).

Figure 6 visualizes a cell, module, and array. This report uses the terminology of PV module or panel when discussing one panel. An installation of panels is an array. **Figure 7** presents the individual components of a typical C-Si PV panel, and **Figure 8** presents a schematic of two types of thin-film panels, CdTe and CIGS for perspective on how construction differs by panel type.

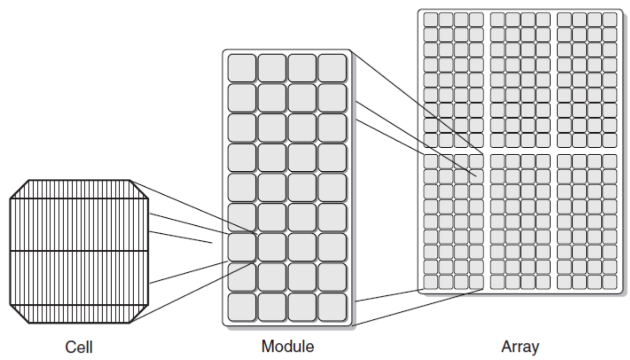


Figure 6. Schematic of a PV Cell, Module, and Array (Infinite Power, n.d.)

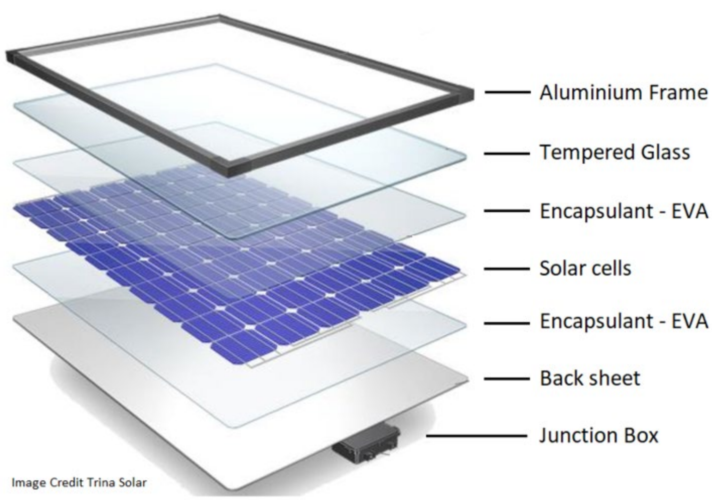


Figure 7. Main Components of a typical c-SI PV Panel (Source Clean Energy Reviews, Trina Solar)

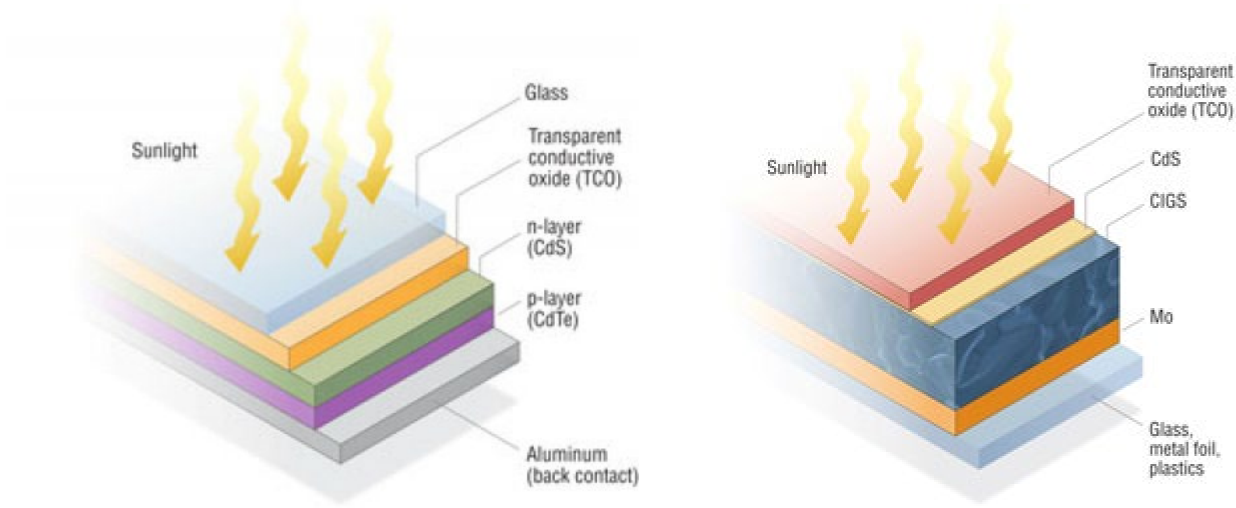


Figure 8. Schematic of CdTe and CIGS thin-film PV panels (U.S. DOE SETO, n.d.) Left: Thin Film-CdTe, Right: Thin-film CIGS.

PV cells are manufactured with at least two layers of semiconductor material, one with a positive charge and the other negative. When light enters the cell, some of the photons from the sunlight are absorbed by the semiconductor atoms, freeing electrons from the cell's negative layer to flow through an external circuit and back into the positive layer. This flow of electrons is what produces an electric current. The PV panel produces DC and an inverter is used to convert them to AC. DC energy always flows in the same direction, while AC changes direction frequently. AC is the standard because it can easily be converted to higher or lower voltages and be transmitted over long distances. However, household items may use either type of current. For example, plug-in appliances such as refrigerators, electric ovens, and microwaves run on AC, while most batteries and, in turn, most electronic devices run on DC. Traditional solar panels produce DC. The junction box contains connectors, cables, and a bypass diode. Inverters are used to convert DC energy into AC energy to enable the electricity generated to be used in the home or sent back to the electric grid. Power adapters for electronic devices act as power converter that converts DC-AC, AC-DC, and DC-DC. They convert the AC grid supply back to the device's DC power. AC solar panels are a different design where microinverters are integrated into the PV cells, so a separate inverter does not need to be attached to the panel. Panels produce only DC. An inverter is needed to obtain AC. The remainder of this section describes the major components of a generic, commercially available PV module.

Solar PV Cells

The most commercially available PV cells technology includes monocrystalline, polycrystalline, and thin-film (see **Table 1**). Concentrating PV and building-integrated PV (BIPV) are commercially available but make up a very small share of the market and are therefore included as next generation solar cells in this report (see **Section 2.3**).

Both monocrystalline and polycrystalline are c-Si technology and are the most common on the market. Both types require large amount of Si to manufacture, yet polycrystalline panels less efficient than monocrystalline panels. Most residential panels contain 60 mono or polycrystalline cells linked together to generate 30-40 volts, depending on the type of cell used (Svarc, 2020). Commercial and utility-scale systems may contain 72 or more cells and operate at a higher voltage. An average home needs approximately 28 to 34 panels to meet its energy needs (SHDEC, 2020). Thin-film PVs are fast-growing, are generally less efficient than c-Si, and tend to be cheaper. Some of this growth is due to the increased demand for clean energy, but growth in their market share is slower.

Table 1. Major Types of Commercially-Available PV Cell Technology

PV Cell Technology	**Relative Efficiency and Cost[1]**	**Presence on the Market**	**Brief Description**	**Typical Cost ($ per watt)**
Monocrystalline	Highest efficiency (rating of 20%-25%), highest cost	Widely; 1st generation panels	Manufactured from single Si crystal; requires large amount of Si; requires least area for a given power; performance degrades in low sunlight conditions	1.59
Polycrystalline	High efficiency (rating of 15-20%) although slightly less than mono, lower cost	Widely; 1st generation panels	Manufactured by fusing different crystals of Si; performs best at high temperatures due to low thermal coefficient; performance degrades in low sunlight conditions	1.42
Thin-film: ▪ Cadmium telluride (CdTe) ▪ Copper indium gallium selenide (CIS/CIGS) ▪ Amorphous silicon (A-Si)	Lower efficiency (max rating of 12-20%), lowest cost	▪ Limited; most firms are start-ups developing experimental technologies ▪ Newest addition to the market: CIS/CIGS	Manufactured by depositing 1 or more layers of PV material on substrate; performs best at high temperatures; performance less affected by low sunlight conditions; use less Si than mono and polycrystalline	0.67

[1] Adapted from Svarc, 2020 and SEIA, n.d.

The efficiency of a PV cell is the amount of electrical power coming out of the cell compared to the energy from the light shining on it, which indicates how effective the cell is at converting energy from one form to the other (U.S. DOE SETO, n.d.). The PV cell is composed of semiconductor material, of which the most used include the following:

- Silicon – the most used semiconductor material used in solar cells, representing approximately 95% of the modules sold today (U.S. DOE SETO, n.d.).

- Thin-film CdTe – the second most common PV material after silicon, but not as efficient.
- Thin-film copper indium gallium diselenide (CIGS) – these materials have optimal properties, but combining the four elements is complex, making it challenging to transition from lab to market.

By weight, typical c-Si PV panels today contain about:

- 76% glass (panel surface)
- 10% polymer (encapsulant and backsheet foil)
- 8% aluminum (mostly the frame)
- 5% silicon (solar cells)
- 1% copper (interconnectors) and
- less than 0.1% silver (contact lines) and other metals (mostly tin and lead). (IRENA and IEA-PVPS, 2016; Sander et al., 2007 and Wambach and Schlenker, 2006).

By weight, CIGS panels today are composed of:

- 89% of glass
- 7% aluminum
- 4% polymers
- Small percentages of semiconductors and other metals including copper, indium, gallium and selenium (IRENA and IEA-PVPS, 2016; Sander et al., 2007 and Wambach and Schlenker, 2006).

Similarly, CdTe thin-film panels consist of:

- 97% of glass
- 3% polymers
- Small percentages of semiconductors and other metals including nickel, zinc, tin, and cadmium telluride (IRENA and IEA-PVPS, 2016).

Table 2. Mass Composition of 1,000 kg of C-Si PV Panel Waste as an Input to the Recycling Process

Material	Quantity (kg)	% Weight of Module (wt/wt)
Glass, containing antimony (0.01-1%/kg of glass)	700	70%
Aluminum frame	180	18%
Copper connector	10	1%
Polymer-based adhesive (EVA) encapsulation layer	51	5.1%
Back-sheet layer (based on polyvinyl fluoride)	15	1.5%
Silicon metal solar cell	36.5	3.56%
Silver	0.53	0.053%
Aluminum, internal conductor	5.3	0.53%
Copper, internal conductor	1.14	0.114%
Various metals (tin, lead)	0.53	0.053%
Total	1,000	100%

Source: Latunussa et al., 2016

Note: Assuming that 1000 kg of PV waste corresponds to approximately 73 square meters of panels, assuming panels with a mass of 22 kg and a surface area of 1.6 square meters.

Table 3. First Solar Series 6 PV Module Composition (typical weight)

Material	Quantity (kg)	% Weight of Module (wt/wt)
Glass, front (substrate) and back (cover) glass	0.043	84.5%
Frame and bars, aluminum	0.717	12.5%
Laminate material, polyolefin	0.009	2.02%
Frame adhesive, silicon-based adhesive	30.00	0.83%
Junction box and cable assembly, polyphenylene housing and halogen-free electrical cables	0.20	0.56%
Semiconductor material, thin-film CdTe	4.44	0.12%
Bussing material	0.29	0.025%
Total	35.502	100%

Source: Miller, Peters, and Zhavari, 2020

EVA Film

EVA is a polymer layer used to encapsulate the cells and hold them in place during manufacturing. The EVA film must be durable and tolerant of extreme temperature and humidity because it is a key factor in preventing moisture and dirt egress into the PV cells, which in turn will decrease long-term performance of the module. The PV cells are first encapsulated with the EVA before being assembled within the glass and backsheet.

Glass

The front glass sheet protects the PV cells from the weather (e.g., consistent high or low temperatures, extreme temperature change) and impact from debris (e.g., airborne debris, hail, branches) depending on impact speed and density. The glass is high-strength, tempered glass typically 3.0 to 4.0 mm thick (Svarc, 2020). The glass used tends to be high transmissive, which has a very low iron content. An anti-reflective coating on the rear side helps to reduce losses and improve light transmission. (Svarc, 2020).

Backsheet

The backsheet is the bottom layer of most solar panels and acts as a moisture barrier and final external skin to provide both mechanical protection and electrical insulation (Svarc, 2020). The most common backsheet is a fluoropolymer (e.g. Dupont's Tedlar) which presents a challenge for EoL management The backsheet can be made of different polymers, each offering different levels of protection, thermal stability, and long-term UV resistance. Some panels may use glass as the rear backsheet instead of a polymer backsheet because glass is more durable and longer lasting; this translates to a higher cost product.

Aluminum Frame

The aluminum frame protects the edge of the laminate section housing the PV cells and provides a solid structure to mount the panel. Frames are typically aluminium and designed to be lightweight, stiff, and able to withstand extreme stress and loading from high winds (Svarc, 2020).

Junction Box

The junction box is a small, weatherproof enclosure on the panel's rear side. Its main purpose is to securely attach the cables required to interconnect the panels for an installation. The junction box also houses the bypass diodes and solar MC4 connectors. Diodes only allow current to flow in one direction, preventing back current that happens when cells are shaded or dirty. Depending on panel manufacture, the bypass diodes may not last as the PV cells. In most cases, the panels are replaced. Some panels are manufactured with non-serviceable junction boxes, however. Solar MC4 connectors are weather-resistant plugs and sockets that allow panels to be connected

Figure 9. Example of a Solar Module Junction Box (Svarc, 2021).

2.3 Next Generation Solar Cells

Researchers are pursuing new PV technologies with the aim of creating a high-efficiency, longer-performing, and lower-cost system. Indirect benefits may also include easier manufacturing and/or disassembly, depending on individual R&D goals. Next generation solar cells are not discussed in detail in this report, but include the following:

- Perovskites – made from hybrid organic-inorganic materials
- Organic PV (OPV) – made from organic materials
- Quantum dots
- Concentrating PV - Use lenses and mirrors to reflect concentrated solar energy onto high-efficiency cells; require direct sunlight and tracking systems to be most effective; primarily located in the desert Southwest U.S.

- Building-integrated PV (BIPV) – Serve as both the outer layer of a structure and generate electricity for on-site use or export to the grid. Provide savings in materials and electricity costs, reduce pollution, and add to architectural appeal of a building.

3. Projected Quantities of EoL Solar PV Panels by Region and State

This section presents the methodology used to project EoL solar PV panels (**Section 3.1 and Appendix A**), the projections nationally, regionally, and by state (**Section 3.2 and Appendix B**), and the assumptions and limitations built into the projections (**Section 3.3**).

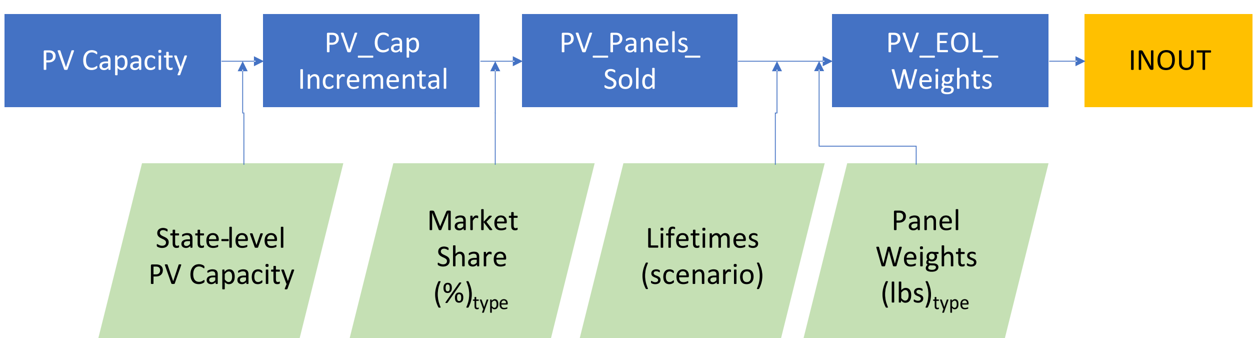
3.1 Methodology

Several data sources were used in the projections that built on each other. First, installed solar capacity data were collected, the market share between residential and commercial was calculated, and panel lifetimes, typical panel generation capacity, and weight were defined. A Weibull function and parameters similar to those used by IRENA and IEA-PVPS (2016) were used. All data and calculations are presented in the Excel workbook PV_EoL_Model. Additional documentation about the worksheets used in the calculation of PV panel entering EoL management each year between 2010 and 2085 within the model is provided in **Appendix A**.

PV EOL Model

An Excl model was developed. Appendix A presents a description of each of the worksheets in the model. Process flow mapping is captured in **Figure 10**. The INOUT worksheet is the main user interface and presents the results nationally and for any specified state or region. The calculations used to estimate the volume of PV EoL panels generated starts on the PV_Capacity worksheet and concludes on the PV_EOL_Weight worksheet. Supporting datasets are used to further refine the data at each step in the model's calculations. Panel weights index by consumer type (residential/commercial) and market share and lifetimes are indexed by consumer segment.

Figure 10. PV EoL Projections Model Process Flow Map



Installed Solar PV Capacity (MW)

Solar Energy Industries Association (SEIA) provides data on solar energy installed by state and economic quarters. Data used in the model has been updated as of Q4 2020. SEIA contains data by U.S. state on PV MW installed, number of PV installations, national ranking, solar companies, growth projection, and growth projection rank. SEIA data was used to predict future growth projections of PV by state between 2021 through 2024.

The EIA's 2020 Annual Energy Outlook (AEO) projections of solar PV capacity growth for the years between 2025 and 2050 were used to supplement the SEIA state capacity data. A national average annual growth rate of 6.8 percent is applied to extend the projected growth in PV capacity out to mid-century.

Market Share

Market shares are the percentage of total installed solar PV capacity in 2019 for two customer segments (residential versus commercial). This calculation relies on three datasets from EIA:

- EIA-861, Non-Net Metering Distributed Capacity (MW), and Net Metering Capacity (MW).
- EIA-860, Existing nameplate Capacity Energy Source, Producer Type and State.

To calculate the market share, the residential capacity from the two EIA-861 datasets were summed. For simplicity we assumed that the commercial segment includes all non-residential installed PV capacity (commercial, industrial, and electric utilities). After combining these three datasets, the percentage of total installed solar PV capacity by state was calculated.

Lifetimes

An assumption of 30-year average panel lifetime was used1. Both early-loss and regular-loss scenarios were modelled using the Weibull function based on the following formula:

$$F(t) = 1 - e^{-(\frac{t}{T})^{\alpha}}$$

Where t is time in years, T is average lifetime, and α is the shape factor which controls the typical S shape of the cumulative Weibull curve.

The same parameters used in IRENA-IEA PVPS, 2016 were used, including alpha shape factors of 2.4928 (Frischknecht, et al., 2016) and 5.3759 (Kuitsche, 2010; Zimmerman, 2013), to model early-loss and regular-loss scenarios, respectively. The regular loss assumes a 30-year lifetime. The early loss scenario accounts for infant, mid-life, and wear-out failures before 30 years. The early-loss scenario represents failures requiring panel replacement such as broken glass, broken cells, ribbons and cracked backsheet with isolation defects; however, only panels with serious functional or safety defects requiring full replacement are included in the alpha factor (Frischknecht, et al., 2016). Early loss may be caused by factors such as damage during transit or installation, or exposure to harsh weather conditions. The early-loss shelf life of solar modules is estimated to contribute more than 80 percent to the solar module recycling market in 2017 (Holm and Martin, 2019). As noted in IRENA-IEA PVPS (2016):

- 0.05% of installed modules fail annually
- 0.05% of modules fail before leaving manufacturer per year, and

- 2% of modules are broken in production per year.

The model provides a third scenario (mid loss) that represents a middle of the road scenario with an alpha factor of 3.6.

Table 4 presents the parameters used by loss scenario. The larger the alpha used in the Weibull function, the steeper the curve and a higher probability of loss from 30 years on which is represented in the regular-loss scenario. The early-loss scenario uses a smaller alpha resulting in a flatter curve and more loss earlier in the life-span of the panel.

Table 4. Weibull Parameters by Loss Scenario

Scenarios	α (shape)	t (scale)
Regular Loss	5.3759	30
Early Loss	2.4928	30
Mid Loss	3.6	30

Panel Generation Capacity and Weight

Solar panel size and weight were collected from Intermountain Wind & Solar. Commercial and residential panels vary in size and weight based on the number of cells.

The capacity per panel is used to convert annual incremental installments of PV capacity (MW) to the number of PV solar panels installed each year. The panel weight is multiplied by the number of new panels installed each year to estimate the total installed weight.

For the purposes of this model, the difference in panel weight across the two customer segments (residential and commercial) are captured. There are different panel arrangements although the types of panels for residential and commercial are similar. Residential PV panels are, on average, 65 inches by 39 inches and 33 pounds (lbs) to 50 lbs. Commercial PV panels are, on average, 78 inches by 39 inches and 50 lbs or more. PV panels range from 60 to 72 cells for residential and commercial, respectively.

The midpoints of the weight ranges found in the literature are used in the model. **Table 5** presents the assumed capacity per panel and panel weight for the residential and commercial customer segments.

Table 5. Assumptions of Power and Weight by PV Panel Type

Panel Type	Capacity (watts/panel)	Average Panel Weight (lbs)
Residential	350	40
Commercial	400	50

3.2 EoL PV Panel Projections

By 2050, there may be 7.9 million to 9.1 million metric tons of EoL PV panels nationally between the regular loss and early loss scenarios, as presented in **Table 6**. These estimates align relatively well with the IRENA and IEA-PVPS (2016) estimates for the U.S. of 7.5 million to 10 million metric tons of panel waste by 2050. The projections do not match exactly due to different data sources (i.e., the IRENA authors had additional information from industry and a bigger data set to work with).

Appendix B presents incremental totals for all three scenarios by state. The estimates only present the total mass of panels that may reach EOL status; no estimates in terms of the management pathways for the EoL PV panels. Additionally, no estimates of PV EoL panels from installations in Puerto Rico and the U.S. territories are included.

Table 6. National Incremental PV Panel EoL Projections for the Regular Loss, Mid Loss, and Early Loss Scenarios (metric tons)

Year	Regular Loss (metric tons)	Mid Loss (metric tons)	Early Loss (metric tons)
2015	16	611	6,834
2020	2,153	25,985	131,051
2025	36,357	184,222	506,311
2030	236,255	657,479	1,281,707
2035	925,865	1,676,217	2,544,631
2040	2,531,027	3,358,850	4,212,169
2045	5,059,933	5,606,635	6,302,028
2050	7,883,322	8,267,484	9,087,051

Figure 11 presents a graph of the PV panel EoL projections by Region, followed by a map of the EPA regions (**Figure 12**) for reference**. Table 7** presents the numerical PV panel EoL projections by region. The graph shows, for all regions, that PV panel waste begins to increase rapidly beginning in 2035 with Regions 9, 4, and 6 potentially generating the greatest mass of PV panel waste by 2050.

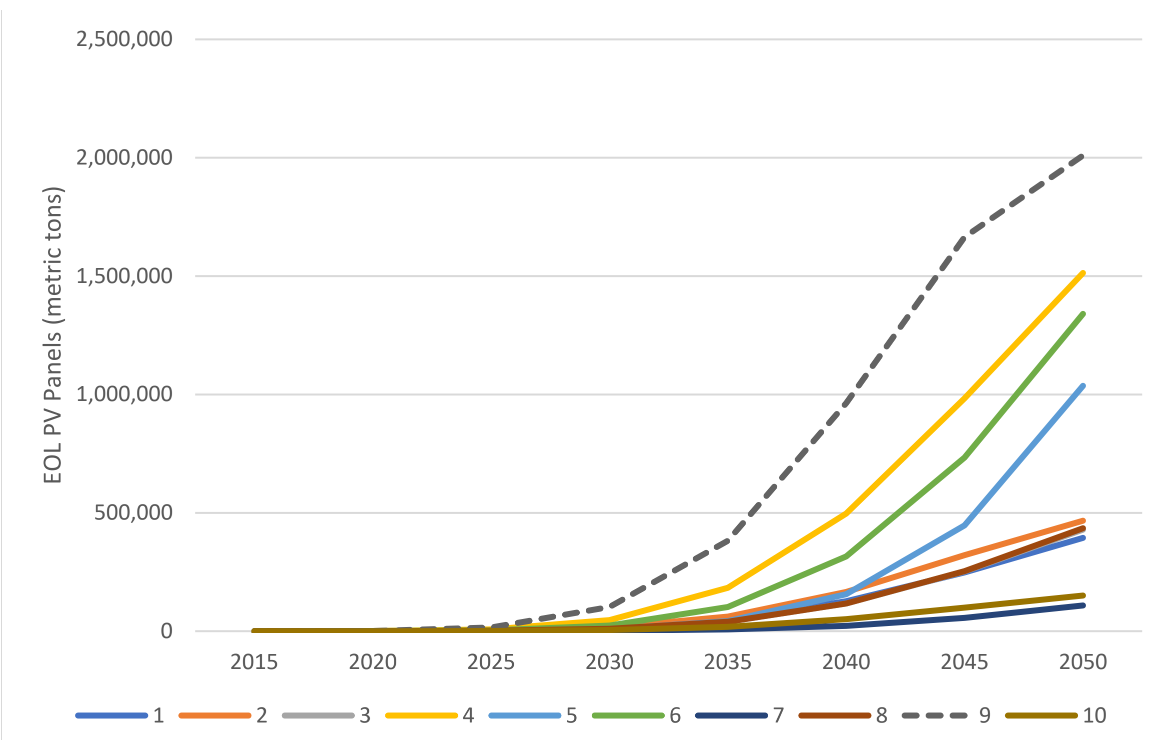


Figure 11. PV EoL Projections by Region, 2015 to 2050 (metric tons)

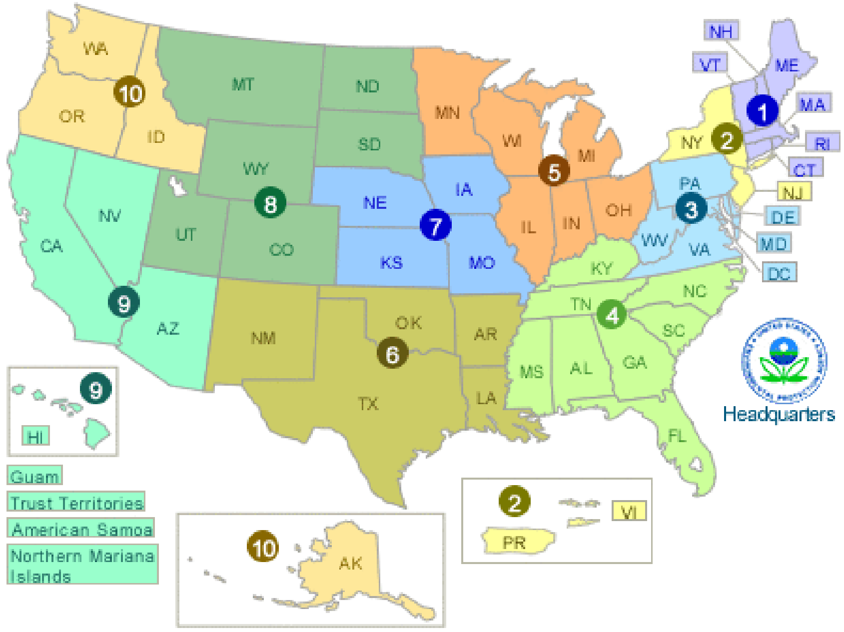


Figure 12. Map of the 10 EPA Regions

Table 7. EoL Mass of Solar PV Projections, 5-year increments, 2015 to 2050 (metric tons) for the Early Loss, Mid Loss, and Regular Loss (RL) Scenarios by Region

Region by Scenario	2015	2020	2025	2030	2035	2040	2045	2050
EL	6,834	131,051	506,311	1,281,707	2,544,631	4,212,169	6,302,028	9,087,051
1	360	6,899	26,096	62,783	123,527	212,948	352,066	600,297
2	460	8,812	34,000	84,385	160,476	250,499	344,464	438,588
3	275	5,269	21,240	60,097	129,169	223,730	342,368	495,361
4	1,361	26,094	100,465	251,222	493,287	810,935	1,210,180	1,750,635
5	244	4,683	20,403	79,828	237,605	532,609	1,035,519	1,891,342
6	661	12,671	52,846	164,594	380,671	690,970	1,089,181	1,590,940
7	44	847	3,614	12,072	29,528	55,726	90,635	135,820
8	281	5,379	21,449	60,207	130,150	227,649	352,042	512,173
9	3,017	57,843	216,216	480,891	810,065	1,127,067	1,373,321	1,526,152
10	133	2,555	9,982	25,629	50,152	80,037	112,252	145,745
ML	**611**	**25,985**	**184,222**	**657,479**	**1,676,217**	**3,358,850**	**5,606,635**	**8,267,484**
1	32	1,368	9,641	33,377	82,711	164,960	285,070	464,260
2	41	1,747	12,385	43,906	109,577	211,659	333,634	449,047
3	25	1,045	7,495	28,538	78,694	168,663	296,850	452,942
4	122	5,174	36,647	129,986	328,375	652,104	1,080,263	1,586,307
5	22	929	6,797	30,687	110,883	310,002	703,319	1,385,807

Region by Scenario	2015	2020	2025	2030	2035	2040	2045	2050
6	59	2,512	18,195	73,285	216,790	493,759	913,455	1,445,866
7	4	168	1,224	5,135	16,012	38,186	73,512	120,555
8	25	1,067	7,627	28,757	79,089	170,115	301,728	465,042
9	270	11,469	80,608	270,788	620,784	1,083,482	1,512,320	1,750,719
10	12	507	3,603	13,019	33,302	65,920	106,485	146,939
RL	**16**	**2,153**	**36,357**	**236,255**	**925,865**	**2,531,027**	**5,059,933**	**7,883,322**
1	1	113	1,912	12,300	47,210	126,117	247,928	394,102
2	1	145	2,445	15,867	61,773	166,131	320,965	466,591
3	1	87	1,464	9,722	39,947	116,447	252,467	428,950
4	3	429	7,238	46,949	183,129	497,018	983,457	1,513,232
5	1	77	1,304	9,097	43,140	156,468	446,277	1,036,442
6	2	208	3,525	23,845	102,241	315,662	733,533	1,340,360
7	0	14	236	1,616	7,155	23,063	56,370	108,638
8	1	88	1,494	9,874	40,338	117,183	254,131	434,925
9	7	950	16,029	102,354	382,649	962,778	1,665,095	2,009,551
10	0	42	709	4,631	18,282	50,162	99,709	150,530

The top 10 states projected to generate the largest amount of EoL solar PV panels under the Regular Loss scenario by 2050 are California, Texas, Florida, New York, Nevada, North Carolina, Indiana, Colorado, Arizona, and Virginia as presented in **Figure 13**. These states somewhat align with the states that currently have the largest installed solar electricity generating capacity in 2021. The exceptions are New Jersey, Massachusetts, and Georgia, which are currently in the top 10 generating capacity in 2021; these states "replace" Indiana, Colorado, and Virginia (see the PV_Capacity tab in the PV_Waste_Model workbook).

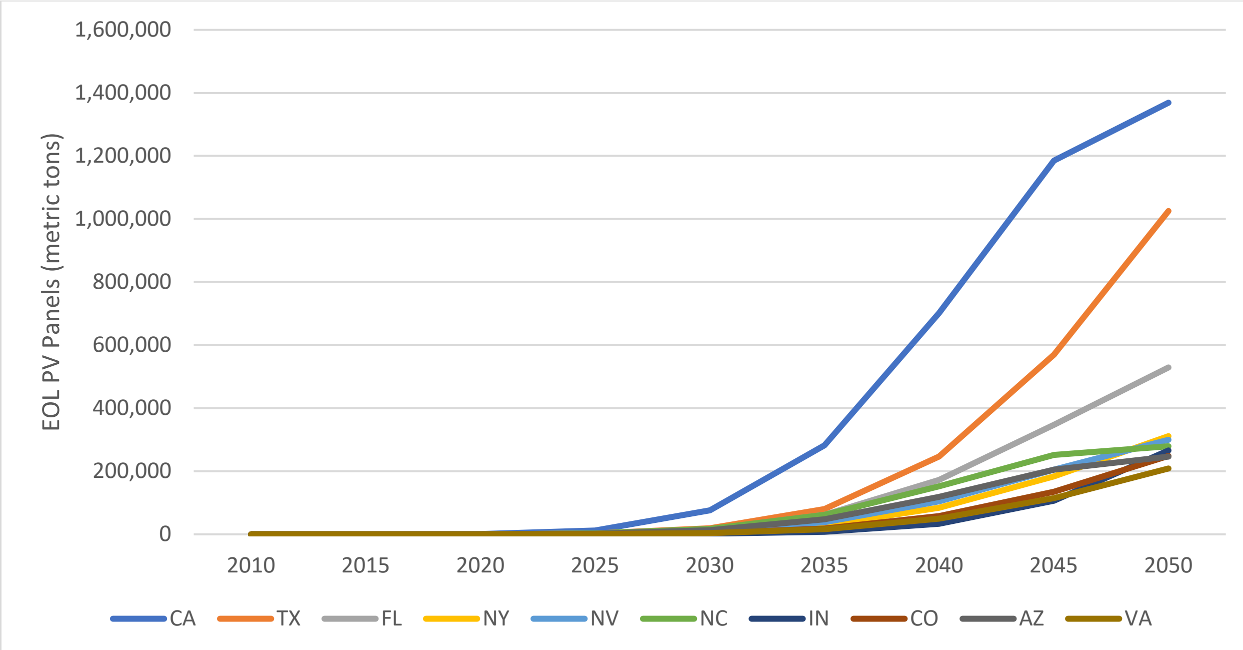


Figure 13. The Top 10 States Projected to Generate the Most EoL PV Panel Waste in 2050 (metric tons)

3.3 Assumptions

Several assumptions were made to develop the EoL PV panel estimates as summarized below.

- Disaggregating the national IRENA estimates to state data without all of the IRENA inputs is not straightforward. The method used to project EoL PV panels includes publicly available data plus the IRENA (2016) methodology assumptions.
- The EoL weight projections assume a standard weight for residential versus commercial panels.
- Curtis et al. (2021a) notes that the IRENA 2016 report estimates may be underestimated, but no analysis identifying where or how the IRENA estimates may be underestimated are included in the report or presented elsewhere. Areas of underestimation likely include the mid loss scenarios where panels are removed due to a change in homeowner or upgrade to newer, or more efficient technology.
- EoL PV projections by state are based on the state's actual and projected electricity generation capacity. Transboundary or international exports of EoL PV panels are not incorporated.
- State projections, in general, do not specifically factor in any new state legislation (i.e., after the IRENA estimates were published, 2016 and later). States such as Washington that will require manufacturer takeback programs will impact estimates of PV EoL projections.
- The designation of solar PV panels as universal waste in California may impact the EoL projections if more panels are repaired or refurbished for the secondary market.
- The quantity of panels circulating in the secondary market in the U.S. and those exported from the U.S. is not considered and data have not been found to date.

- The EoL projections do not include any data for U.S. Territories and the Commonwealth of Puerto Rico.
- The EoL projections do not include off-grid equipment, which may be larger for residential versus commercial situations.

4. EoL PV Panel Management Practices

EoL may occur in any of the following situations:

- The end of the period or performance for a solar project (decommissioning)
- Early failure including damages during shipping and installation
- Mid-life failure
- Identified safety issues
- Economic viability
- End of expected life failure (the general rule of thumb is 25 to 30 years)
- Damage from weather (e.g., hail, extreme winds) and natural disasters (e.g., hurricanes, flooding, fires)
- Homeowners who choose to un-install an existing solar installation
- Waste generated from solar panel manufacturing
- A generator who decides to discard unused solar panels
- Panels that were found (illegally dumped or abandoned), and
- Replaced parts (e.g., inverters) from panel refurbishment.

Decommissioning of a solar project may include any of the following (Enbar, 2016):

- Equipment removal, disposal, and recycling
    - Inverters and other electronic components
    - Module mounting structures
    - Concrete
    - Electrical equipment
    - Wiring
- Equipment abandoned in place
    - Underground conduit
    - Certain structures that pose no environmental harm

- Equipment reuse
  - Infrastructure improvements (roads, fences)
  - Substations, communication towers
  - Maintenance building.

Sustainable EoL management practices – renewal, reuse, recycling – are generally desired more than disposal or abandoning in place by the solar industry and PV panel owners and operators when panels reach their EoL. EoL does not always mean a PV panel, or its components are no longer operational, but in today's thinking, PV supply chains in the U.S. tend to be characterized as linear instead of circular. Few PV manufacturers design for extended product durability, reuse, or recycling (specifically in terms of ease of disassembly and extraction of valuable materials for recovery). Limited PV panel take-back programs exist in the U.S.; the classification certain types and brands of PV panels as hazardous and state policy and regulations are perceived as barriers to reuse and recycling; and the secondary market in the U.S. is growing, but still has low consumer confidence and may remain low due to performance uncertainty of the reused panels. (Curtis et al., 2021).

This section provides a summary of solar panel waste classification (as it relates to material storage, handling, and disposal in **Section 4.1**), followed by a summary of EoL management practices of storage (**Section 4.2**); transportation (**Section 4.3**); secondary markets, repair and reuse (**Section 4.4**); recycling (**Section 4.5**); and disposal (**Section 4.6**).

4.1 Waste Classification

Because solar panels may consist of components that are themselves, at certain levels, considered hazardous (e.g., silver, copper, lead, arsenic, cadmium, and selenium), someone must first determine they are indeed a 'waste' or 'discarded material' and then confirm whether that waste is hazardous. When PV panels are improperly handled and/or disposed, the potential risk of hazardous materials leaching into the environment and spontaneous fire increases.

EoL solar equipment, when considered a waste, is regulated under RCRA as a non-hazardous, hazardous, or universal waste. Subtitle D of RCRA grants authority to states to regulate non-hazardous solid waste at an equal or less stringency than the federal regulations. States may also delegate regulatory authority to local governments, which may result in different regulations across jurisdictions, adding to the complexity of EoL management.

Residential PV system equipment that is considered solid waste may be excluded from the definition of hazardous solid waste and RCRA hazardous waste regulations in some U.S. jurisdictions (40 CFR Section 261.4(b)) because EPA considers it household hazardous waste (HHW). HHW must meet two requirements:

- The waste must be generated by individuals on the premise of a temporary or permanent residence, and
- The waste stream must be composed primarily of materials found in wastes generated by consumers in their homes.

NREL (2021) notes that these criteria are unclear for residential PV systems. Some may not believe residential PV systems meet the two criteria defined above, and it is unclear whether a residential PV system still retains its HHW designation after it is decommissioned and passed to a third-party for handling, transport, storage, and EoL management.

For non-residential sources of solar panel waste, the person that determines whether solar equipment is a solid waste is responsible for proper management. As noted in NREL (2021), anecdotal evidence suggests there is confusion about when PV equipment becomes a solid waste and is subject to RCRA regulation. California is working clarify when PV modules are considered solid waste through guidance that states PV modules are considered solid waste when they are disconnected or removed from service, which may prompt a reuse determination on-site.

Under RCRA, the person or entity that determines the solar equipment is a solid waste is referred to as a generator. Generators may be subject to RCRA regulations unless an exclusion applies, including designation as a household hazardous waste, universal waste, or in some circumstances, if the discarded PV equipment is destined for recycling. If an exclusion does not apply, the generator needs to make a hazardous waste determination using acceptable knowledge. Acceptable knowledge may include processing and manufacturing inputs, products, by-products, and intermediaries; chemical or physical characterization of the waste, information on the chemical and physical properties of the chemicals used or produced by the process or otherwise contained in the waste; analytical testing confirming the waste properties, or other reliable information. If acceptable knowledge is not available, sampling and analyses must be performed using an approved method such as the Toxicity Characteristic Leaching Procedure (TCLP) to confirm whether the solar equipment contains hazardous waste. PV modules that fail the TCLP must follow applicable hazardous waste regulations, while those that pass must follow applicable non-hazardous solid waste regulations. Standard TCLP may underestimate the hazard, as the hazardous materials are sealed under the encapsulant. If the encapsulant is intact, it is difficult to see the true level of hazard. Additionally, states may require additional and different testing to the TCLP test, which may subject the waste to state-specific hazardous waste regulations.

Solar panels that do or may contain hazardous material include the following:

- CdTe panels due to cadmium
- Gallium arsenide (GaAs) panels due to arsenic
- Some older Si solar panels due to hexavalent chromium coatings and lead solder, while all silicon panels produced today still use lead solder containing ~10 g of lead and
- Newer, thin-film CIS/CIGS panels due to copper and/or selenium
- Panels with electronic components (e.g., drivers, inverters, circuit boards) because they typically contain hazardous constituents such as lead, arsenic, cadmium, selenium, and chromium.

Studies presenting TCLP results for PV modules are highly variable and may produce different results depending on the sample location on the module, the method of sample removal, the test laboratory's protocols when conducting the TCLP analysis, and other factors such as the condition of encapsulant (Curtis et al., 2021a).

Certain PV equipment may be excluded from the definition of hazardous waste, when the following applies; however, state programs may or may not adopt all the federal exclusions listed below:

- Metal frames from PV system modules – included under RCRA as scrap metal, including processed scrap metal, unprocessed home scrap metal, and unprocessed "prompt" scrap metal that is intended for recycling (40 CFR part 273.9).

- Hazardous secondary material that includes the following when certain regulatory conditions are met:
    - Generated and legitimately reclaimed within the U.S. or its territories that is under control of the generator (40 CFR part 261.4(a)(23)).
    - Generated and then transferred (40 CFR part 261.4(a)(24).
    - Exported from the U.S. and reclaimed at a reclamation facility in another country (40 CFR part 261.4(a)(25)).

The solar panel manufacturer may be best suited to determine if the panel should be handled as a hazardous or non-hazardous waste. Panel owners should have the documentation regarding what technology and brand was installed, which can help with the determination. A waste generator may forego sampling and analytical testing, though documentation supporting the determination must be maintained and made available for review by the designated regulatory authority. There is one exception if the solar panel equipment is considered a hazardous waste that allows for the generator to less follow less stringent regulations. An approved subset of hazardous wastes may be classified as universal wastes under RCRA. EPA's universal waste regulations streamline the hazardous waste management standards for certain categories of hazardous waste to promote the collection and recycling of universal waste, ease the regulatory burden on retail stores and other generators that wish to collect and transport these wastes, and to encourage the development of municipal and commercial programs to reduce the quantity of these wastes going to MSW landfills or combustors. The federal universal waste regulations are found in 40 CFR Part 273 and apply to five types of universal waste:

- Batteries
- Pesticides
- Mercury-coating equipment
- Lamps, and
- Aerosols.

As of mid-2021, solar panels have not been nationally designated as electronic waste or as universal waste at the federal level. However, individual states may petition EPA to classify solar panels as electronic or universal waste. To do so, the relevant state agency must apply to EPA for review and approval. To date, only California has petitioned to add solar panels to their universal waste program. The change was approved by EPA in 2020, which is expected to promote solar panel recycling and reuse over landfilling. Prior to this change (as of January 1, 2021), solar panels were subject to California's hazardous waste regulations. All other states require a hazardous waste determination.

4.2 Storage

While not a permanent solution, solar panels may be stored for later EoL management, or for later repair if applicable. Long-term storage of large quantities of solar panels is largely applicable to manufacturers, waste haulers, utilities, and select commercial and industrial installations where the commercial or industrial company owns and operates the panels. Long-term storage is applicable to residential homeowners.

Until a determination confirms a panel is not hazardous, storage and handling of the panels must follow RCRA or state hazardous waste regulations. Solar panels cannot be accumulated and consolidated with universal waste electronic devices if the solar panels are determined to be hazardous. This applies to broken panels as well. Broken pieces must be cleaned up and properly packaged/containerized as to minimize the potential release, with structurally sound containers to prevent releases such as leaks (NCDEQ, 2019).

Solar panels are typically placed in storage containers or warehouses where they are protected from the weather. Long-term storage is common practice, and even recommended by EPRI until the recycling market becomes widely available and more cost-effective (Enbar, 2016). As noted above, solar panel waste may need to be stored according to hazardous waste regulations if applicable and separate from other universal wastes unless the waste is being stored in a state where solar panel waste is classified as a universal waste (i.e., California).

Under CA's universal waste requirements, handlers may accumulate PV solar panels for up to one year, while the general hazardous waste requirements only allow for accumulation for 90 days (for large quantity generators). The longer accumulation period allows handlers to transport the panels to destination facilities in bulk and theoretically on a less frequent basis, which may lower transportation costs. Universal waste requirements also require fewer labeling and recordkeeping requirements compared to general hazardous waste.

4.3 Transportation

PV equipment regulated as hazardous waste may be subject to additional transportation requirements including specific packaging, documentation, and other transit-related requirements for highway, rail, air, or water transport. The Department of Transportation (DOT) Hazardous Materials Regulations should be consulted for specific requirements. RCRA hazardous waste and universal waste requirements may apply for international transboundary export (40 CFR parts 260.10, 273.9).

4.4 Secondary Markets, Repair, and Reuse

Secondary or after markets bring together buyers and sellers to trade commodities that have previously been introduced to a primary market. A secondary market supplies spare parts, accessories, second-hand equipment, and other goods and services used in repair and maintenance. In the U.S., solar manufacturing capacity is around 6 GW, which amounts to less than half of the estimated demand forecasted by SEIA/Wood Mackenzie (2021). Demand is being driven by consumer perception of grid reliability and the desire to be self-sufficient; uncertainties surrounding natural disasters and the desire to be off-grid; consumers looking for affordable alternative energy systems; more efficient technology available, inverter and other equipment replacement in conjunction with the need to comply with more stringent fire, building, and electrical standards and codes; early retirements of equipment; and tax incentives (SEIA/Wood Mackenzie, 2021; Curtis et al., 2021a). The secondary market can serve several duties at once by filling critical supply chain gaps, reducing environmental and social impacts from mining raw materials, conserving resources, creating new jobs, and keeping solar panel waste out of the landfill.

Secondary markets exist in the U.S., Latin America and the Caribbean, Middle East, Africa, and Asia. Afghanistan, Pakistan, Djibouti, Somalia, and Ethiopia have the strongest secondary markets, largely off-grid, and have plenty of sun radiation to justify energy production from used (versus new) solar panels. However, these reuse panels have shorter lifetime and many of the developing countries lack the capability to recycle solar panels. Used solar panels in working order, or with high potential for repair and refurbishment are commonly sold for off-grid applications for residential energy, cold storage, solar well pumps, Wi-Fi, solar irrigation, battery charging, and other uses (World Bank, 2020). Second-hand solar panels are also commonly purchased for replacement parts (as part of repowering a solar panel system) and price-conscious consumers. Industry experts note that any panel less than 10 years old and ranges from 100 W to 350+W has resale value, with the average price approximately 50-75 percent less than new modules and starting at $0.10/W (Schmid, 2021). Wood Mackenzie (2021) estimates the repowering of existing solar equipment to replace inverters that have reached their 10-year lifespan to reach 800 GW_{DC} between 2021 and 2025.

A comprehensive list of solar businesses involved in the secondary market does not exist and there are limited companies exclusively dedicated to solar panel repair and reuse. One challenging aspect is the number of different module designs and composition, which makes it harder to automate disassembly for repair and reuse. Standards for PV module and equipment repair are not publicly available, which requires additional effort on the service providers to learn the ins and outs of various brands and models. Several other barriers to the secondary market are synthesized in **Section 6.3** (Drivers, Barriers and Enablers to a Circular Economy).

EnergyBin (www.energybin.com), a members-only business-to-business (B2B) online exchange network, appears to be the leader in this space with more than 1,000 solar companies as members, including solar panel manufacturers and makers of solar equipment, distributors and suppliers, developers, EPCs, installers and O&M companies. Members list or seek solar components for sale or resale. Solar installers may also be entering the secondary market. B2B Solar (www.b2bsolarenergy.com) is one example of a solar installer that recently tapped into the secondary market to find consumers for the overproduction of solar equipment. B2B Solar is based in Texas and appears to focus on that region, whereas EnergyBin has national reach.

Missionary or donation-based work is another avenue for the reuse of solar panels and equipment. For example, Working for the Son Solar (WFTSS) is a 501c3 charity providing donated and repurposed PV components to families in Mexico. They have also worked with California State University – Fresno researchers to repair panels, including those with cracked glass, for reuse. Another example, Good Sun, works with members of local schools and government agencies in Nevada County. Good Sun conceptualized a repowering program in Nevada (Re-Power) after winning a DOE grant in 2017 which leverages used solar equipment to install solar PV at local schools, municipal buildings, and low-to-middle income homes. Good Sun also delivers educational and vocational trainings, and seeks to support community connectedness and cultural preservation.

Manufacturer Take-Back Programs

Very little information is available on manufacturer take-back programs through internet searches on 'manufacturer take-back program' or 'OEM take-back'. First Solar is the most well-known solar company with a take-back program. This is likely because there is little incentive for industry to invest in PV recycling, repair, or reuse due to current market conditions and regulatory barriers. This may change in the short-term as a direct result from the recently enacted legislation in Washington state requiring PV module manufacturers to finance and implement the takeback and reuse or recycling of PV modules at no cost to owners.

Additional Standards and Regulatory Considerations for Panel Reuse and Repair

Local regulations should be reviewed when planning to reuse PV panels and equipment during any of the following phases: project design reviews, construction permits, permits to operate, land-use permits, and community planning and zoning. Specifically, reusing PV panels and system components may be limited in jurisdictions that have incorporated any of the following codes and standards:

- The Institute of Electrical and Electronic Engineers (IEEE) 1547 equipment standard
- The UL 1741 testing standard
- Section 1509.7.2 of the International Code Council's (ICC) International Building Code, and
- The National Fire Protection Association's National Electric Code Section 690.12.

California, New England, and Hawaii have incorporated the IEEE 1547 equipment standard and the UL 1741 testing standard into their interconnection regulations, which may prohibit the reuse of older PV modules for grid-tied rooftop and ground-mounted applications if the projects do not use smart inverters with the reused panels, or if the design is otherwise out of compliance (Curtis et al., 2021b; IEEE, 20218). Jurisdictions that have adopted Section 1509.7.2 of the ICC's International Building Code as a fire and building regulation can prohibit the reuse of older PV modules that is not equivalent to already approved roof coverings in fire rating classification (Curtis et al., 2021b). State and local electrical regulations may also prohibit the reuse of PV systems and equipment such as inverters in rooftop and building-mounted, grid-tied and off-grid applications.

4.5 Recycling

Most PV panels on the global market (i.e., c-Si, CIGS, and CdTe PV panels) are composed of similar materials such as glass, aluminum, and semiconductors; however, recycling solar modules is complex due to the different brands and model designs of PV panels, which may require different methods of disassembly and processing. Glass and aluminum comprise approximately 80-90% by weight of most PV panels as shown in **Figure 14**. Each PV panel component needs to be dissembled and separated to be recycled properly. Additionally, because the modules were designed for durability versus disassembly, they are not easy to take apart and the potential to damage the solar cells which contain the most valuable materials is high; only the undamaged solar cells can be recovered and reused in new products.

Although a recycling solution is technically feasible, incentives for consumers, peer influence, and attitudes towards recycling reflect the real-world situation and help develop practical strategies toward a circular economy (Deng et al., 2021; Walzberg, 2021)

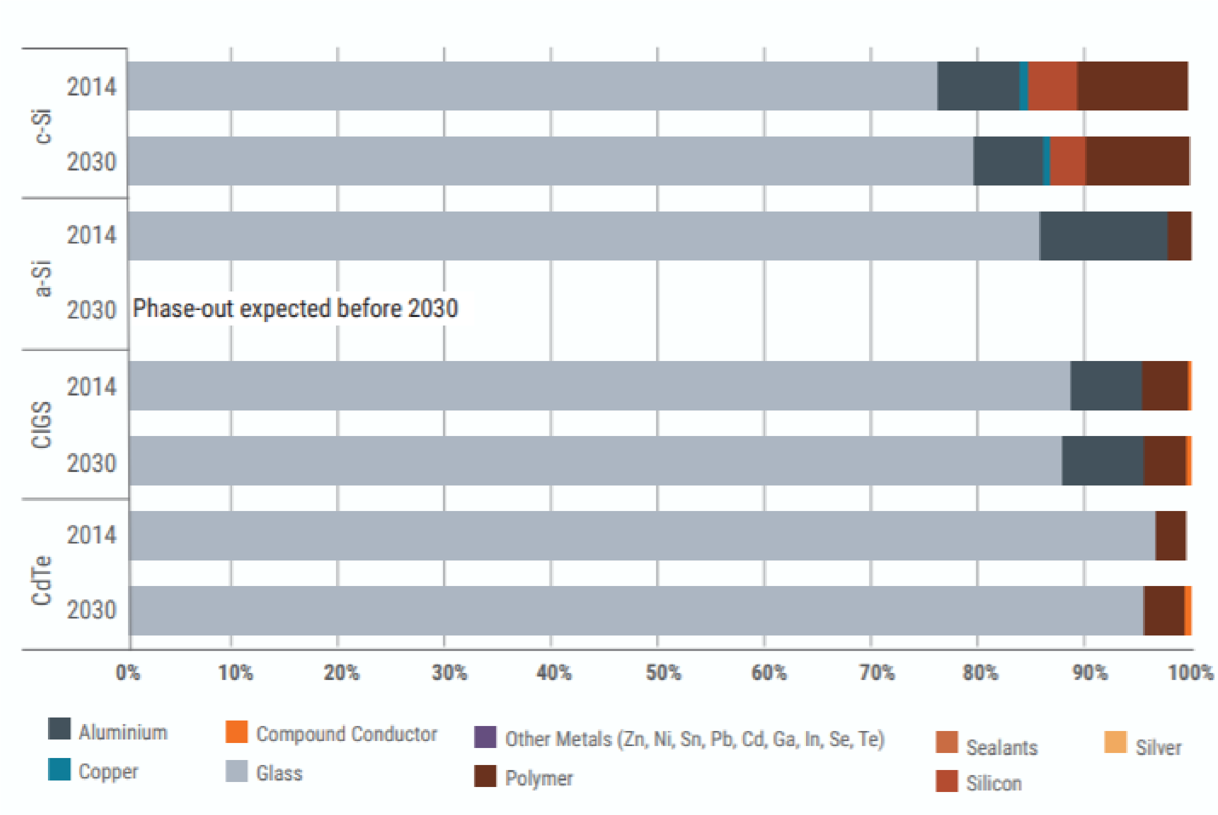


Figure 14. Typical Composition of Different Solar PV Panel Categories (SEIA, 2020)

Overview of the PV Panel Recycling Process

The general process for recycling is presented in **Figure 15**. First, the frame is disassembled from the module, followed by the wires and junction box. The modules may undergo coarse crushing to make this process easier. The sandwiched panel is delaminated to recover the glass, silicon, EVA, and other metals, which can be sold for repurposing. Anything that cannot be repurposed will be contained as HazMat for proper disposal or sent to, most likely, an industrial versus municipal waste landfill. Wide-scale commercial application of this process is still in development.

Figure 16 and Table 8 and Table 9 summarize the recycling processes for c-Si panels and thin film panels, respectively.

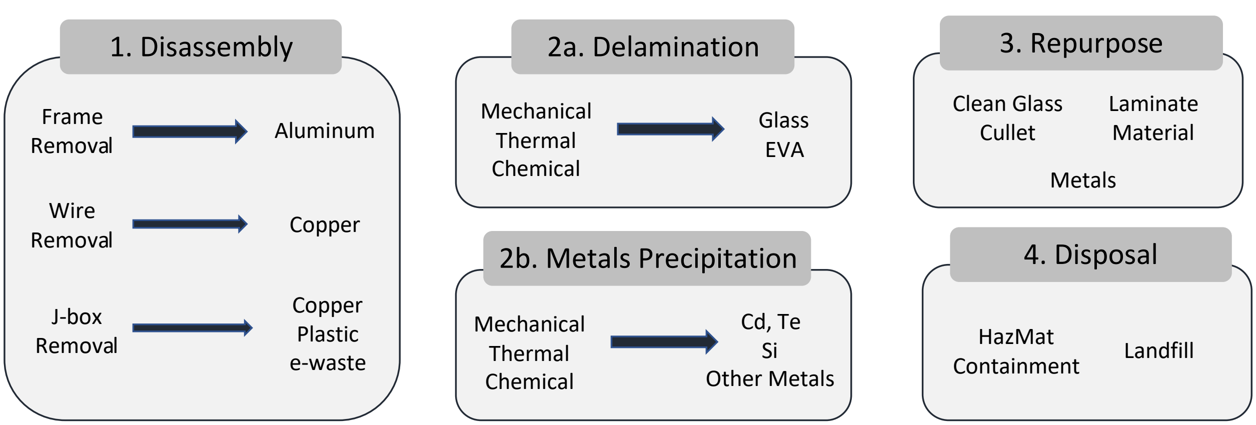
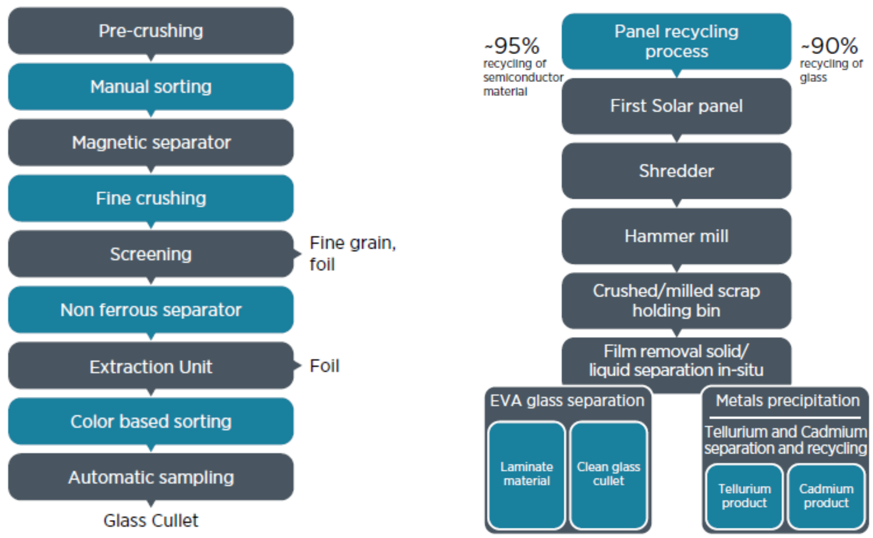


Figure 15. General Process for Recycling Solar Modules (adapted from EPRI, 2018)

Figure 16. First Solar Recycling Processes for Laminated Glass and Thin-Film PV Panel Recycling. Left: Process for Laminated Glass, Right: Process for Thin-Film Panel Recycling.



Source: Weckend, Wade, & Heath, 2016.

Table 8. Typical Recycling Process for c-Si Solar PV Modules

Tech.	Process	Advantages	Disadvantages
Delamination	Physical disintegration	Efficient waste handling	Other materials mix with EVA
			Damage to solar cells
			Apparatus decomposition
	Thinner dissolution	Organic layer removal from glass	Time necessary for delamination depends on area
		Waste chemical reuse	Expensive equipment
		Simple removal of EVA	Hazardous for human health
	Nitric acid dissolution	Complete removal of EVA and metal layer from the wafer	Dangerous emissions
		Possible recovery of the whole cell*	Cell defects due to inorganic acid
	Thermal treatment	EVA fully eliminated.	Involves high energy consumption.
		By reusing wafers, possible to regain whole cell	Dangerous emissions
		Used as a supplementary process to accelerate dissolution process	Very costly process

Tech.	Process	Advantages	Disadvantages
	Ultrasonic irradiation	Simplified removal of EVA.	Waste solution treatment.
Material Separation	Dry and wet mechanical process	Non-chemical process.	No removal of dissolved solids
		Simple process.	
		Requires low energy.	
		Equipment available.	
	Etching	Simple and effective process.	High energy demand for some processes because of high temperatures.
		Recovery of high purity materials	Use of chemical.

Adapted from Chowdhury et al., 2020.

*Current silicon wafers are so thin that cell or wafer recovery may be economical.

Table 9. Typical Recycling Process for Thin Film Solar Modules

Technology	Process	Advantages	Disadvantages
Delamination	Physical disintegration	Feasible to obtain various wastes by treatment (split modules, submodules and laminated modules)	Mixing of the various material fractions
			Loss from each material fraction
			Glass still partly combined with the EVA
			Breakage of solar cells
	Thinner dissolution	Organic layer removed from glass	Time necessary for delamination depends on area
		Reprocessing solutions	Cannot be dissolved fully and EVA still adheres to glass surface
		Simple removal of EVA	
	Thermal treatment	Complete elimination of EVA	High energy consumption
		Possible to recover whole cell by reusing wafers	Hazardous emissions
	Radiotherapy	Easy to eliminate EVA	Slow procedure
			Very expensive process
Material Separation	Erosion	No chemicals required	Additional treatment of pre-purification is necessary
		Glass can be recovered	
	Vacuum blasting	Removal of semiconductor layer without chemical dissolution	Emission of metallic fractions
		Glass can be recovered	Relatively long processing time
		Non-chemical process	

Technology	Process	Advantages	Disadvantages
	Dry and wet mechanical process.	Simple procedure	No removal of dissolved solids
		Needs low energy	
		Apparatus usually available	
	Tenside chemistry	Tensides are reusable	Emulsions must be adapted to different cell technologies
		Metals fully removed from glass	Delamination time depends on the area
	Leaching	Complete elimination of metal from glass	Very high use of chemicals
		Further extraction of metal solutions possible	Complicated control of the chemical reactions
	Flotation	Comparatively easy method	Material separated at various stages of flotation
		Limited use of chemicals	Inadequate purity of materials
	Etching	Recovery of high purity materials	High energy demand because of high temperatures
		Low cost and effective process	Chemical usage
Material purification	Hydrometallurgical	Commercially applicable	Many separation and absorption steps
		Low and controllable emissions	Chemical process steps must be adapted to respective technology
		Easy water management	
	Pyrometallurgical	Established industrial process	High throughput necessary
		Feedstock can contain different materials	Some materials are lost in slag
			Heavy metals or unwanted materials

Adapted from Chowdhury et al., 2020.

Waste By-Products from the Recycling Process

A brief literature review of life cycle assessments (LCA) focusing on EoL panel recycling was conducted. A handful of LCA studies were identified and reviewed with the objective of identifying the type of waste by-products generated from the recycling process, their amounts, and how these by-products were managed.

Regarding the outputs of the recycling processes for c-Si and CdTe PV panels, yield for glass and nonferrous metal for c-Si PV is 59-75% and 13.5-21.8%, respectively, and yield for glass, semiconductor, and copper in CdTe PV recycling is over 90% (Frischknecht et al., 2020).

Latunussa et al. (2016) was the only study identified that specifically quantified the waste by-products generated and their ultimate disposition. **Figure 17** presents the study's LCA boundary for c-Si PV recycling and **Table 10** presents the inputs and outputs in tabular format for the c-Si PV panel. Waste sent to a landfill includes 14 kg of contaminated glass, 2 kg of fly ash (hazardous), 306 kg of liquid waste, 50 kg of sludge (hazardous). The fly ash and sludge were the only waste by-products requiring special (hazardous) waste disposal.

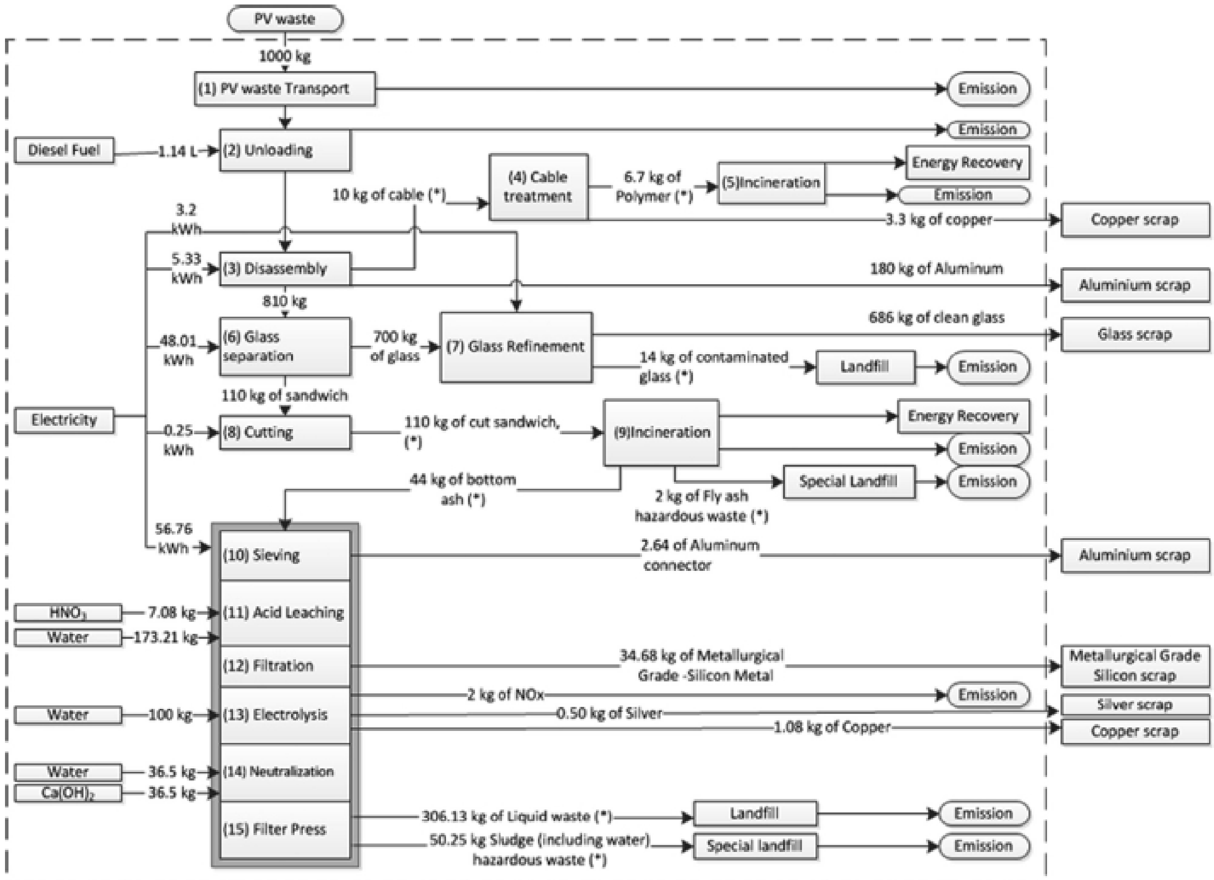


Figure 17. LCA Schematic of a c-Si PV Waste Recycling Process

Note: the asterisks represent transport between processes. Source: Latunussa et al. (2016).

Table 10. Summary of Inputs and Outputs of the LCA FRELP Process for Recycling 1,000 kg of c-Si PV Waste Panels (Latunussa et al., 2016)

Category	Output	Quantity	Units	Notes
Recovered Materials	Aluminum scrap	182.65	kg	None
Recovered Materials	Glass scrap	686	kg	None
Recovered Materials	Copper scrap	4.38	kg	None
Recovered Materials	Silicon metal	34.68	kg	Metallurgical grade
Recovered Materials	Silver	0.5	kg	None
Waste to Landfill	Contaminated glass	14	-	Disposal in landfill

Category	Output	Quantity	Units	Notes
Waste to Landfill	Fly ash	2	-	Hazardous, disposal in hazardous waste landfill
Waste to Landfill	Liquid waste	306.13	-	Disposal in landfill
Waste to Landfill	Sludge	50.25	-	Hazardous, contains metallic residue, disposal in hazardous waste landfill

4.6 Disposal

Anecdotally, many sources report that broken or damaged panels are being landfilled rather than recycled because of challenges faced by the recycling sector (e.g., high transportation and dismantling costs); however, no estimates are available on the amount of solar PV panels currently being disposed in municipal waste, industrial waste, or hazardous waste landfills. Refer to Section 4.1 Waste Classification for more information on how a PV panel is classified as hazardous waste if applicable. For any material classified as a hazardous waste and destined for landfill disposal must be disposed in a hazardous waste landfill.

5. State Legislation and Working Groups Leading on Sustainable EoL Management

State legislation, policies, and programs may act as drivers or barriers to sustainable EoL management. Policy is critical to a circular economy, especially for PV equipment, to ensure its safe handling, storage, transport, reuse, recycling, and disposal. As discussed in Section 4.1 (Waste Classification), federal and state solid waste regulations exist that need to be navigated. This is also the case for PV repair and reuse. Interconnection fire, building, and electric regulations in the U.S. may also vary by jurisdiction and may prohibit the reuse of PV modules in certain secondary grid-tied and off-grid applications (NREL, 2021). Variable regulations also exist for recycling and materials recovery of PV system materials in terms of storage, transport, and handling.

As of June 2021, four states have enacted legislation to address PV system decommissioning, PV equipment reuse, and/or EoL management for PV system equipment – California, New Jersey, North Carolina, and Washington. California, Hawaii, and Rhode Island also proposed bills in the past year that would directly address repair, reuse, and recycling of PV equipment. **Figure 17** presents states with enacted and currently proposed legislation. Several other states proposed bills that were not enacted in past years – Maryland, New Jersey, and New York. In addition to the state legislation, state-led working groups in California, Illinois, and Minnesota are researching solar equipment reuse and EoL options.

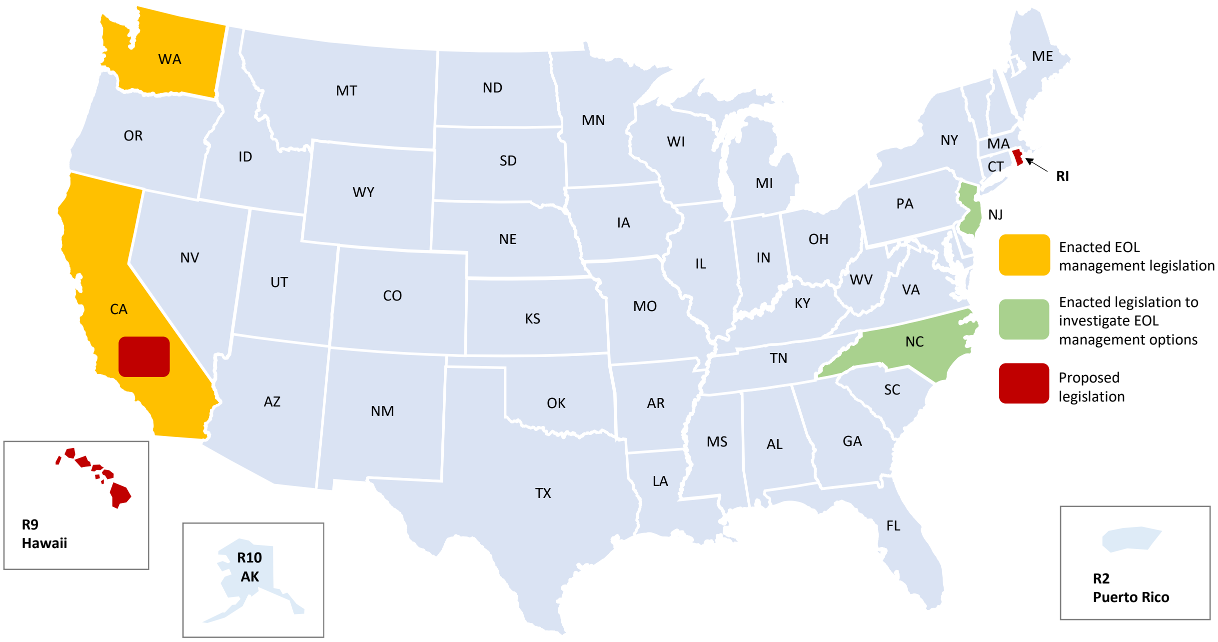


Figure 18. Location of States with Enacted and Proposed Legislation Focusing on Solar PV Panel EoL Management

Note: California has both enacted and proposed legislation (as of June 2021).

5.1 State Legislation

Enacted Legislation

California

In September 2020, the Department of Toxic Substances of California (DTSC) enacted regulation R-2017-04 to add EoL PV modules to the State Universal Waste regulations with the intent of encouraging proper waste disposal, a reduction in waste abandonment, and cost savings for PV module waste generators. These panels would then be subject to less stringent hazardous waste regulations. Specifically, the DSTC regulations:

- Clarify that a PV module becomes waste on the date it is discarded, and that PV modules abandoned, relinquished, or recycled become waste when they are disconnected or removed from service.
- Clarify PV modules that are refurbished or reused are not waste and are not subject to universal waste regulations.
- Require a party who claims 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.
- Establish universal waste requirements for universal waste handlers and universal waste transporters of PV modules that exhibit toxicity characteristics of hazardous waste.
- Specify the management standards for different levels of treatment to ensure treatment is performed safely.

Additional requirements not noted in this report are included in the regulation for universal waste handlers and transporters.

New Jersey

In August 2019, Senate Bill 601 was passed, creating the New Jersey Solar Panel Recycling Commission. The Commission is tasked with investigating EoL management options for solar energy generation systems and developing recommendations for legislative, administrative, and private-sector action. A final report will be submitted to the Governor for consideration by August 2021. The Bill also authorizes the New Jersey Department of Environmental Protection to adopt rules and regulations regarding EoL PV recycling or management options based on the Commission's final report.

North Carolina

House Bill 329 was passed in the 2019 General Session, requiring the North Carolina Environmental Management Commission (EMC) of the North Carolina Department of Environmental Quality (NCDEQ) to establish a regulatory program to "require the environmental management commission to adopt rules to establish a regulatory program to govern the management of end-of-life photovoltaic modules and energy storage system batteries, and decommissioning of utility-scale solar projects and wind energy facilities, and require the Department of Environmental Quality to establish a stakeholder process to support development of the rules."

Under the bill, the NC EMC must develop the program by January 1, 2022, including regulations and a system of implementation and enforcement. The NCDEQ must consider explicit issues stated in the bill:

- Whether PV modules are properly characterized as solid waste under state and federal law
- Whether PV modules exhibit hazardous waste characteristics or contain any constituent of hazardous waste
- The preferred methods of end-of-life management (i.e., reuse, recycled, refurbish, or disposal)
- The economic and environmental cost and benefits
- An evidence-based economically productive life cycle
- The volume of PV panels and batteries deployed in the state, projected PV deployment, and the impact that volume would have on state landfills if landfill disposal were permitted
- Other federal, state, and international regulatory requirements related to EoL PV modules and solar equipment management, decommissioning, reuse, refurbishment, recycling and disposal
- Whether financial assurance requirements are necessary
- The infrastructure necessary to collect and transport EoL PV panels and other solar equipment for EoL management, and
- Whether to construct a stewardship program for recycling EoL panels other than utility-scale solar projects, and if so, what fees should be established for manufacturers to sell PV modules in the state.

On January 1, 2021, the NCDEQ issued a final report on the Commission's findings, which may be used in the development of future regulations.

Washington

The Washington State Senate passed Bill 5939 on July 7, 2017, with the intent of stimulating and investing in distributed renewable energy generation (i.e., wind, solar, microgrid) to reduce the state's reliance on fossil fuel energy. Bill 5939 has no recycling or disposal requirements but is a companion bill to HB 2645 (passed March 2020) concerning the Photovoltaic Module Stewardship and Takeback Program, which requires PV module manufacturers to finance and implement a takeback and recycling or reuse stewardship plan for PV modules sold after July 1, 2017 at no cost to owners. Tax credits and incentives are also provided. The overall goal of this legislation is to establish an environmentally sound system for recycling PV modules, minimizing hazardous waste and recovering valuable materials during this process.

Beginning July 1, 2023, no manufacturer, distributor, retailer, or installer may sell or offer for sale PV modules within or into Washington unless the manufacturer of the PV module has submitted a stewardship plan to the Department of Ecology (by July 2022) and obtained approval. The intent of the stewardship plan is to develop a framework for how manufacturers will fund the manufacturer takeback program, collection, management, and recycling of the PV modules. The PV modules under the program include the following:

- PV modules used for residential, commercial, agricultural, or utility purposes that are installed on, connected to, or integral with buildings, or are a part of a system connected to the grid or utility service; and
- Freestanding, off-grid power generation systems.

The responsibility for the PV waste management would be on the manufacturer, giving the customer a viable way to return and recycle spent or damaged PV modules. The plan would also provide the manufacturer or installer a viable path to sell their systems and/or services, thereby introducing financial stability. The Washington state program will also require the minimization of the release of hazardous substances and the recovery of rare earth metals similar to California Senate Bill 489.

As part of the takeback program, the Department of Ecology may collect a flat fee from every participating manufacturer to cover the administration costs 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. Non-compliance fees up to $10,000 per sale of a PV module are also included in the legislation and will be used for administration costs.

Proposed Legislation

California

Senate Bill 207, introduced January 1, 2021, would require the state's Secretary for Environmental Protection to convene a Photovoltaic Recycling Advisory Group to study and recommend potential policies to the state legislature to ensure safe and cost-effective reuse or recycling of PV modules in California. The Group's recommendations are to be submitted to the legislature no later than April 1, 2025.

Hawaii

House Bill 1333 was introduced January 27, 2021, and would require the Hawaii State Energy Office to work with the Hawaii State Department of Health on a comprehensive study to determine best practices for disposing of and recycling discarded clean energy products such as PV modules and equipment, and batteries. The study is investigating similar topics to the NC law related to projected EoL solar waste

Hawaii may need to manage, the type and chemical composition of clean energy equipment, best practices for EoL management, and whether a fee structure should be developed for disposal or recycling of clean energy materials. An interim report is to be submitted in 2022 followed by a final report in 2023.

Rhode Island

House Bill 5525, introduced February 12, 2021, would create a Photovoltaic Module Stewardship and Takeback Program requiring PV module manufacturers to finance and implement a takeback and recycling or reuse plan for PV modules sold in or into Rhode Island after July 1, 2021, at no cost to owners. 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. No manufacturer, distributor, retailer, or installer would be able to sell of offer PV modules for sale within or into Rhode Island beginning July 1, 2023, unless the manufacturer or the PV module had submitted a stewardship plan to the Rhode Island Department of Environmental Management and obtained approval. The potential requirements of the Bill are similar to Washington's legislation.

5.2 State Working Groups

Working groups in California, Illinois, and Minnesota are working on various initiatives to build initiative and collaboration around sustainable EoL management for PV modules.

In California, the California Public Utilities Commission (CPUC); the California Department of Resources Recycling and Recovery (CalRecycle); the California Air Resources Board (CARB), and the California Energy Commission (CEC) are collaborating to develop consistent approaches to the collection and recycling of solar PV panels, electric vehicle batteries, energy storage batteries, and related equipment.

The Illinois Sustainable Technology Center (ISTC) at the University of Illinois created the Solar Panel Recycling Initiative in 2019 in response to the Illinois Future Jobs Act of 2016. ISTC is working with the Illinois Environmental Protection Agency to facilitate the PV EOL management stakeholder working group to identify and evaluate barriers to integrating PV into the circular economy and develop solutions to promote sustainable management options.

In Minnesota, the Minnesota Pollution Control Agency (MPCA) started a stakeholder working group along with the Minnesota Department of Commerce and Minnesota SEIA. The intent of the group is to develop and implement PV panel EoL policy and programs that conserve resources, protect health, promote renewable energy, and support PV panel recycling infrastructure and technology.

6. Current U.S. Recycling Market

This section compiles current data on recycling facilities that process solar PV panels and equipment in the U.S. (**Section 6.1**) and internationally (**Section 6.2**). **Section 6.3** synthesizes findings on drivers, barriers, and enabling factors to a circular economy with specific focus on the recycling and reuse (secondary market) components of the value chain.

6.1 PV Panel Recycling Facilities in the U.S.

More than 20 facilities recycling solar PV panels and/or equipment, or just components of solar panels (e.g., glass, aluminum frames) have been identified in the U.S. as presented in **Figure 18** and **Table 10**.

The identified recycling facilities were primarily sourced from two leading databases – the SEIA's PV Recycling Partner Network (available for members only) and the ENF Solar Recycling Database. Table 10 specifically does not include scrap metal processing facilities that presumably would accept aluminum frames from EoL solar PV panels because these facilities tend not to advertise the types of products (e.g. solar panels) that scrap metal comes from on their websites.

The top 10 solar electricity generating states in 2021 are California, Texas, North Carolina, Florida, Arizona, Nevada, New Jersey, New York, Nevada, North Carolina, Massachusetts, New York, and Georgia (SEIA 2021; AEO 2020 Projected Growth). Nearly all of these states except New Jersey, New York, North Carolina, and Massachusetts have at least one solar panel recycling facilities located there. Surprisingly, no dedicated solar panel recycling facilities were identified through internet searches in some states that have enacted or recently proposed solar panel EOL-related legislation (i.e., Washington, Hawaii, Rhode Island, and North Carolina). EoL PV panels generated in these states would presumably be transported to another state for processing.

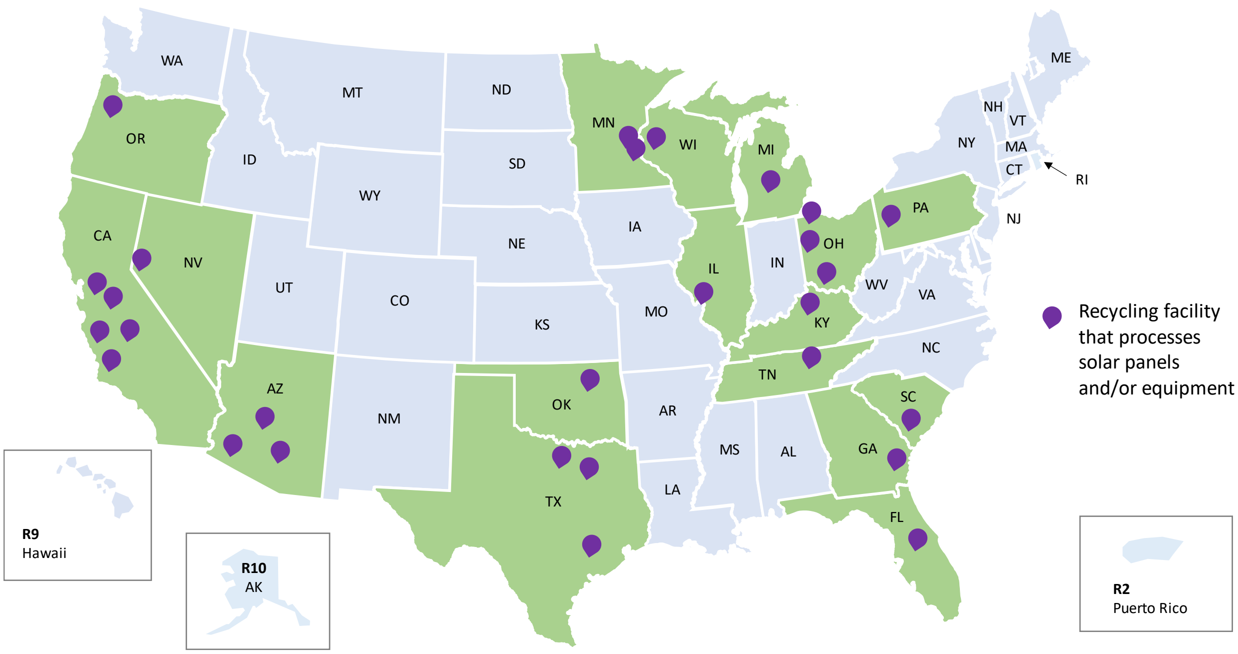


Figure 19. Locations of Known Solar Panel Recycling Facilities in the U.S.

Note: Recycling facilities included in this map are listed in Table 10, which may not include all facilities in the U.S. that recycling solar PV panels.

C-Si PV modules are mainly treated in recycling facilities designed for the treatment of laminated glass, metals, or other electronic waste, and only the bulk materials (glass, aluminum, and copper) are recovered. In contrast, the cells and other materials such as plastics are incinerated (Frischknecht et al., 2020). Only two companies identified were found to recover the high-purity bulk and trace materials from PV modules – We Recycle Solar and First Solar.

We Recycle Solar based in Phoenix, Arizona, has a provisional patent technology that can process up to 100,000 pounds of solar equipment per day of c-Si and CdTe modules in each of their 10 facilities across the U.S., Japan, South Korea, and Belgium. The company's current focus is on large-scale recycling best suited for sourcing from manufacturers, utilities, or installers, rather than individual customers. We

Recycle Solar recycles all related equipment, including batteries, which streamlines the disposal process and helps companies meet any end-of-life requirements from local or state authorities. Although larger volume materials, such as Al, and Cu are commonly recovered, the information on the recovery of trace materials is lacking.

First Solar has a unique value proposition, which combines manufacturing, sales, and recycling. The First Solar recycling process can recover approximately 90 percent of panel glass and semiconductor materials (only from CdTe panels) for reuse. The company also implemented an EoL fee. This fee was originally included in the upfront cost for their PV panels but was to a pay at decommissioning model in 2013. There is potential for other solar panel manufacturers to enter into the recycling space in the near-term, particularly if states in addition to Washington implement manufacturer take-back programs.

Table 11. Solar Equipment Recycling Facilities in the U.S.

Company Name	Location	Solar Recycling Services	Type of Solar Products Recycled[1]
CEM	▪ Okmolgee, OK ▪ Waxahachie, TX ▪ Lawrenceburg, KY ▪ Upper Sandusky, OH ▪ Yuma, AZ ▪ Natrona Heights, PA ▪ Hardeeville, SC ▪ Portland, OR (coming soon, glass processing only)	▪ Drop-off ▪ Transfer station ▪ Drop-off ▪ Processing ▪ Drop-off ▪ Drop-off ▪ Drop-off ▪ Processing	Solar Panels, Glass
Cleanlites Recycling	▪ Cincinnati, OH ▪ Spartanburg, SC ▪ Mason, MI ▪ Minneapolis, MN	▪ Recycling and Drop-off	Solar Panels
Dynamic Lifecycle Innovations	▪ Minneapolis, MN ▪ Onalaska, WI ▪ Nashville, TN	▪ Recycling	Solar Panels, Cable, Junction Box, Frame
Echo Environmental	▪ Carrollton, TX	▪ Recycling	Solar Panels
FabTech	▪ Gilbert, AZ ▪ Savannah, GA	▪ Recycling	Solar Panels
First Solar	▪ Tempe, AZ (headquarters)	▪ Recycling	Solar Panels

Company Name	Location	Solar Recycling Services	Type of Solar Products Recycled[1]
Green Lights Recycling	▪ Blaine, MN	▪ Recycling	Solar Panels
Interco -- A Metaltronics Recycler	▪ Madison, IL	▪ Recycling	Solar Panels
Metal & Catalyst Resources	▪ Houston, TX	▪ Recycling	Chemical Elements
Mitsubishi Electric	▪ Cypress, CA	▪ Recycling	Solar Panels
Recycle PV Solar	▪ South Lake Tahoe, NV	▪ Recycling	Solar Panels
Recycle1234	▪ Union City, CA	▪ Recycling ▪ Drop-off ▪ Reuse	Solar Panels
Solar Silicon	▪ Ventura, CA	▪ Recycling	Wafer
Silrec	▪ Lexington, KY	▪ Recycling	Ingot, Wafer
Solar Recycling Experts	▪ Tehachapi, CA	▪ Recycling	Solar Panels
Solar Sun's Recycling	▪ Orlando, FL	▪ Recycling	Cell, Solar Panels
Surplus Service	▪ Fremont, CA	▪ Recycling	Solar Panels
TT&E Iron & Metal Inc. [2]	▪ Raleigh, NC	▪ Drop-off ▪ Recycling	Aluminum frames
We Recycle Solar	▪ Phoenix, AZ	▪ Recycling	Cell, Solar Panels, Chemical Elements, All Related Equipment

Source: ENF Solar, n.d.
[1] Companies included in this table may recycle other products and materials that are not solar equipment.

[2] This is a scrap metal processing facility. A dedicated search for scrap metal processing facilities that accept solar panels was not undertaken. Most company websites do not specifically mention solar waste processing as a service, but they would likely accept the aluminum frames.

6.2 International PV Recycling Facilities

For general information, a list of recycling facilities in select international countries are presented in **Table 11**. These companies could open a location in the U.S. in the future, or panels from the U.S. could be exported to one of these international locations for recycling. China would likely a potential destination for U.S. EoL PV panels if they are not already being exported for processing and recovery.

Table 12. Solar Recycling Companies in Select International Locations

Country	Company Name
Australia	Cyber Computer Recycling & Disposal E3Sixty Solar Infoactiv Ojas Infrastructure PV Industries Reclaim PV Recycling
Germany	Aurubis Envaris Reiling Glas Recycling Rieger & Kraft Solar SiC Processing (Deutschland)
United Kingdom	H&H Pro ILM Highland Recycle Solar Technologies Solar2Recycle
Japan	Eiki Shoji NPC Inc. Okaishi Construction Trinity
China	Bocai E-energy Chaoqiang Silicon Material FH Solar Jiangsu Juxin Energy Silicon Technology Kunshan Suda Jingwei Electronic Technology Suzhou Hedeying Metal Suzhou Huizhijie PV Technology Suzhou Minlai Photovoltaic New Energy Suzhou Shunhui New Energy Technology Yezon-PV
India	Jumbo Solar Poseidon Solar Services

Source: ENFSolar, n.d.

6.3 Drivers, Barriers, and Enablers to a Circular Economy

Several drivers, barriers, and enablers related to sustainable PV panel EoL management exist at the national level.

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. Economic and environmental drivers are presented in **Table 12**.

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. A variety of barriers are presented in **Table 13**.

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. The main enablers are presented in **Table 14**.

The main stakeholders who may be impacted are identified for each driver, barrier, and enabler. The stakeholder groups include manufacturers, installers, PV owners, operation and maintenance (O&M) service providers, companies managing solar logistics and EoL PV panel waste haulers, recycling companies, the government (local, state, federal), end users of recycled materials, and landfill owners and operators.

In summary, the barriers currently outweigh the drivers and enablers at the national level and most likely at every state level too, although a deep dive into each state's market was not performed. The cost to recycle EoL solar panels tends to be cost-prohibitive largely because there is not enough volume to achieve economies of scale currently. This will likely change in the next 10 to 20 years given EoL PV panel projection estimates. Most recycling companies currently focus on recovery of the aluminum frames and panel glass; only two companies – We Recycle Solar and First Solar – are recovering the other valuable materials that make up less than 10 percent total of a PV panel. One potential uncertainty in the future recycling market is changing technology and panel materials. Silver is the most valuable material per unit mass in the c-Si module followed by aluminum (Holm & Martin, 2020); however, if less silver is used in future module design to reduce manufacturing costs, that will decrease the value of the modules for recycling. Another question still to be answered is who will pay for EoL management, specifically recycling, of PV panels. Manufacturer take-back programs are scarce, but this may change if recently enacted legislation in Washington is successful. Based on an NREL analysis (Curtis et al., 2021a), a multifaceted regulatory approach that places responsibility across the value chain is recommended. Consistent, clearly defined federal, state, and local regulations could mandate and incentivize recycling and secondary markets. These laws could prohibit disposing PV modules, provide an exemption from stringent regulation, or require reuse.

Table 13. Drivers to a Circular Economy for PV System Materials and Stakeholders Who May Be Impacted

Driver	Description	Manufacturer	Installer	PV Owner	O&M Provider	Logistics, Hauler	Recycler	Government	End User	Landfill Operator
Cost savings and increased profits	May reduce manufacturing costs and achieve additional revenue streams; may decrease project costs.	x	-	x	x	-	-	-	x	-
Enhanced competitiveness	May increase a business's green or environmentally responsible image and increase consumer trust.	x	x	x	x	-	-	-	x	-
New and expanded market and employment opportunities	Provide opportunities for new and expanded markets and job creation.	x	x	x	x	-	x	x	-	-
Reduced negative environmental impacts	Reduces waste, the generation of greenhouse gases and other air pollutants, and electricity consumption during manufacturing and additional resource use and environmental impacts from mining raw materials, transport, refining, and manufacturing of products .	x	x	x	x	-	x	x	-	-
Reduced resource constraints	Conserve high-value materials, prevent resource constraints, and reduce import demand for raw materials.	x	-	-	-	-	-	x	-	-

Note: Adapted from Curtis et al., 2021

Table 14. Barriers to a Circular Economy for PV System Materials and Stakeholders Who May Be Impacted

Barrier	Description	Manufacturer	Installer	PV Owner	O&M Provider	Logistics, Hauler	Recycler	Government	End User	Landfill Operator
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; ▪ volume and composition of EoL PV systems; ▪ development of PV module recycling technology and assessment of infrastructure needs; ▪ identification and analysis of permitting requirements and liabilities; and ▪ costs associated with PV module recycling.	x	x	x	x	x	x	x	-	-
Lack of publicly available information and exchange between solar value chain actors	Company policies do not support information exchange between manufacturers and recyclers or between end users and landfill owners and operators.	x	x	x	x	x	x	-	x	X
Lack of economic incentives	Limited economic incentives exist to promote design for recycling or reuse, or for the collection, transport and repair/reuse/recycling of EoL PV modules.	x	x	x	x	x	x	-	x	x
Current technology, infrastructure, and processes	Current technology, infrastructure, and processes are not optimized for efficient, cost-effective repair, reuse, or recycling of PV system equipment.	-	x	x	x	-	x	-	-	-
Lack of critical information and data	Research and data play an important role in investment decisions during early stages in new and expanded market opportunities. Limited information and data are available regarding the: ▪ value of and markets for reused PV equipment and recovered PV materials; ▪ volume and composition of retired PV equipment; ▪ condition and characteristics of used PV equipment; ▪ quality, reliability, safety, and technical viability of repaired and reused PV equipment; ▪ repair and recycling technologies, processes, and services; and ▪ costs for repair and refurbishment; and infrastructure needs.	-	x	x	x	x	x	x	x	-

Barrier	Description	Manufacturer	Installer	PV Owner	O&M Provider	Logistics, Hauler	Recycler	Government	End User	Landfill Operator
Unclear, complex, and varied laws and regulations at state and local level	Laws and regulations applicable to reuse and recycling of PV equipment may be unclear, complex, varied by jurisdiction, and often require compliance with stringent handling, storage, transport, treatment, recycling and disposal requirements that are subject to civil and criminal liability for non-compliance.	x	x	x	x	x	x	x	x	X
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.	x	x	x	x	x	x	x	x	x
Low market confidence in reused and repaired PV equipment	Inadequate consumer confidence in reused and repaired PV system equipment to support reuse and repair for reuse secondary markets.	x	x	x	x	-	-	-	-	-

Note: Adapted from Curtis et al., 2021a

Table 15. Enablers to a Circular Economy for PV System Materials and Stakeholders Who May Be Impacted

Enabler	Description	Manufacturer	Installer	PV Owner	O&M Provider	Logistics, Hauler	Recycler	Government	End User	Landfill Operator
Increasing investment in research and development, and analysis	Several factors could reduce market uncertainty and investment risk, and increase consumer confidence towards reused and repaired PV panels, including for the: ▪ value of and markets for recovered PV module materials; ▪ volume and composition of EoL PV modules; ▪ PV module recycling technology development and infrastructure needs; ▪ permitting requirements and liabilities; and ▪ costs associated with PV module recycling.	x	x	x	x	x	x	x	x	-
Increased and publicly available information and information exchange	Information exchange between manufacturers and recyclers, and between end users and landfill owners and operators, can reduce costs, liability uncertainties and increase good faith relationships between solar industry stakeholders.	x	x	x	x	x	x	x	x	x
Increased economic incentives	Economic incentives may be provided to promote design for recycling and/or collection + recycling can encourage innovation, private industry investment, and make the economics for PV module recycling more desirable.	x	x	x	x	x	x	x	x	x

Enabler	Description	Manufacturer	Installer	PV Owner	O&M Provider	Logistics, Hauler	Recycler	Government	End User	Landfill Operator
Collaboratively developed 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. When collaboratively developed, there may be more buy-in across stakeholders and a broader push to increase recycling and reuse.	x	-	x	x	-	-	x	-	-
Clearly defined laws and regulations	Clearly defined regulatory requirements and restrictions can reduce uncertainty and risk associated with PV module recycling and resource recovery.	x	x	x	x	x	x	x	x	-
Statutory and regulatory schemes that support PV module recycling and resource recovery efforts	Federal and state policies can require or incentivize the collection, repair, reuse, and/or recycling of PV modules and/or restrict disposal of PV modules.	x	x	x	x	x	x	x	x	-

Note: Adapted from Curtis et al., 2021a and 2021b

7. Future Research Recommendations

By 2050, there may be 7.9 million (early loss scenario) to 9.1 million metric tons (regular loss scenario) of EoL PV panels entering the waste stream nationally based on the methodology and assumptions discussed in Section 3. While state-specific estimates vary based on current and projected installed PV capacity, it is clear that some states will be more burdened than others. Despite the number of barriers presented in Section 6, the status of the solar recycling and reuse market in the U.S. remains promising. Grandview Research's 2020 summary report[2], for example, estimates a market size value of $160.8 million in 2020, a revenue forecast of $338.8 million in 2027, and a growth rate of 12.8 percent from 2020 to 2027 (Grandview Research, 2020). Recently enacted state legislation, specifically in Region 9 and 10, and the federal government's push to increase solar electricity generating capacity are also promising drivers to move towards a more circular economy.

Potential future research activities to refine the PV panel EoL projection estimates, and advance sustainable EoL management options are summarized below.

- Targeted research and data collection on:
  - The secondary market and best practices for collection and repair
  - A proper protocol for recertification of reuse panels
  - The off-grid market and small-scale solar (e.g., landscape lighting, solar-powered cooking stoves, etc.)
  - Best practices for solar takeback programs
  - Develop a solar panel specific TCLP procedure with defined encapsulant conditions
- Comprehensive review and policy assessment specific to the solar secondary market by state to further understand which states may be prohibitive to panel reuse
- Compile case studies on panel reuse in U.S. territories, indigenous lands, and in low-income households
- EoL model refinements:
  - Improve on static assumptions used in the calculations for market share over time
  - Consider alternative Loss scenarios that modulate the t value (average life expectancy) and alpha parameter
  - Investigate solar installation in Puerto Rico and U.S. territories and estimate potential EoL panel material
  - User improvements, such as automating the regional selection when selecting a state in the INOUT worksheet, adding a filterable results tab with sort by state.
- Regulatory guidelines and enforcement are needed to prevent lead from getting into the environment from the material recovery and end-of-life management practices

2 Only the free summary version of Grandview Research (2020) was reviewed for this report.

8. Conclusion

Growing PV panel waste presents a new environmental challenge and unprecedented opportunities to create value and pursue new economic avenues. Untill recenlty, more than 80% of PV panels installed across the world were crystalline-Si panels. Typically, more than 90% of their mass is composed of glass, polymer and aluminum, which can be classified as nonhazardous waste. However, smaller constituents of c-Si panels can present recycling difficulties since they contain silicon, silver, and traces of elements such as tin and lead (together accounting for around 4% of the mass). Thinfilm panels (9% of global annual production) consist of more than 98% glass, polymer and aluminium (nonhazardous waste) but also modest amounts of copper and zinc (together around 2% of the mass), which is potentially environmentally hazardous waste. They also contain semiconductor or hazardous materials such as indium, gallium, selenium, cadmium tellurium and lead. Hazardous materials need particular treatment and may fall under a specific waste classification depending on the jurisdiction. Since end-of-life PV panels are not listed as hazardous waste, they should be evaluated using the characteristic hazardous waste method (US Environmental Protection Agency Method 1311 Toxicity Characteristic Leaching Procedure). No federal regulations currently exist in the US for collecting and recycling end-of-life PV panels, and therefore the country's general waste regulations apply. California is developing a regulation for the management of end-of-life PV panels within its borders, though several steps remain before this regulation is implemented.

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Appendix A – EoL Projections Model Documentation

Table A-1. PV EoL Model Worksheets and Description

Type	Sheet Name	Description	Data Sources
Results	INOUT	Provides an interface for Users. Users select the region or state of interest using a drop down box. Model results, tables, and figures are presented at right.	Summarized view of data in other worksheets.
Results	Pivot_State	Pivot table summarizing the PV EoL data by state and scenario in million pounds and metric tons.	RTI calculated using data from the PV_EOL_Weight worksheet.
Results	Pivot_Region	Pivot table summarizing the PV EoL data by state and scenario in million pounds and metric tons.	RTI calculated using data from the PV_EOL_Weight worksheet.
Intermediate Worksheets	PV_EOL_Weight	This sheet multiplies the unit sales by the average product weight listed on the INOUT sheet. Provides results (national, state, regional) by scenario of the weight of PV panels in million pounds by consumer segment, year.	RTI calculated using data from the PV_Panels_Sold worksheet, Lifetimes worksheet, and the weights presented on the INOUT worksheet.
Intermediate Worksheets	PV_Panels_Sold	This sheet converts the incremental installed capacity to the equivalent number of PV panels by state and panel type. It pulls information from Market Share and PV_CapIncremental sheets. Data table breaks out regional sales to one of the four consumer segments: residential, commercial, institutional, and education.	RTI calculated using data from other worksheets.
Intermediate Worksheets	PV_CapIncremental	Data table incremental installed PV capacity by state by year (2010 to 2050). This sheet decomposes the total installed capacity from PV_Capacity sheet for years 2010 through 2050. For years 2010 to 2020, we use the national incremental capacity percentages to back cast the time-series of incremental capacity additions from the SEIA data for total installed capacity in 2020.	RTI calculated.

Type	Sheet Name	Description	Data Sources
Intermediate Worksheets	PV_Capacity	Data table of installed solar PV capacity by state between 2020 and 2050. Total Capacity expressed in megawatts (MW).	2020 as of Q4 – Solar Energy Industries Association (SEIA), Capacity by U.S. State 2020 Annual Energy Outlook (AEO) – Annual grow rate in installed solar PV capacity 6.8% for years 2025-2050.
Input Data	MarketShare	Data table provides state market share allocation by consumer segment and product type.	2019 - EIA-861, Net Metering 2019 - EIA-861, Non-Net Metering Distributed 2019 – EIA-860 Existing Capacity by State
Input Data	Lifetimes	Calculates the percentage of installed capacity that is retired to End of Life Management (ELM) for recycling and/or disposal.	Weibull parameters for early loss and regular loss from IRENA, 2016.
Input Data	LookUps	Provides lists of state names and state region assignments.	Not applicable.

Appendix B – EoL Projections by State

Tables B-1, B-2, and B-3 present EoL projection data (metric tons) by state in 5-year increments from 2015 to 2050 for the early loss, mid loss, and regular loss scenarios, respectively. Data are presented alphabetically by state.

Table B-1. EoL Mass of Solar PV Estimates and Projections, 5-year increments, 2015 to 2050 (metric tons) for the Early Loss (EL) Scenario by State

State	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
National	EL	6,834	131,051	506,311	1,281,707	2,544,631	4,212,169	6,302,028	9,087,051
AK	EL	1	14	58	179	409	731	1,129	1,602
AL	EL	22	419	2,060	10,486	35,275	83,323	166,351	307,340
AR	EL	29	557	2,393	8,103	19,976	37,835	61,610	92,241
AZ	EL	372	7,135	26,683	59,324	99,708	138,248	167,603	184,857
CA	EL	2,255	43,245	160,506	348,930	573,213	778,080	922,936	993,828
CO	EL	119	2,274	9,549	30,230	70,443	127,921	200,451	288,576
CT	EL	63	1,209	4,621	10,954	19,623	28,811	36,984	43,369
DC	EL	8	154	628	1,816	3,914	6,694	9,928	13,514
DE	EL	11	217	919	2,987	7,114	13,133	20,892	30,543
FL	EL	444	8,509	33,644	88,496	175,012	279,413	388,674	495,493
GA	EL	206	3,949	14,821	33,299	56,563	79,191	96,956	108,089
HI	EL	108	2,070	7,940	19,037	34,483	51,120	66,243	78,456
IA	EL	11	220	920	2,878	6,636	11,956	18,600	26,581
ID	EL	44	837	3,134	6,981	11,755	16,328	19,831	21,916
IL	EL	29	554	2,641	12,268	38,629	87,144	166,654	294,414
IN	EL	37	703	3,443	17,324	57,798	135,742	269,546	495,204
KS	EL	6	118	482	1,420	3,107	5,378	8,064	11,101
KY	EL	4	84	472	3,524	15,395	43,558	103,410	229,211
LA	EL	15	281	1,241	4,599	12,197	24,364	41,652	65,541
MA	EL	225	4,308	15,911	34,100	55,205	73,908	86,415	91,573
MD	EL	100	1,915	7,359	17,744	32,317	48,137	62,666	74,581
ME	EL	7	144	813	6,130	26,951	76,593	182,628	406,660
MI	EL	16	308	1,610	9,738	36,950	94,849	204,911	411,207
MN	EL	116	2,232	8,397	19,004	32,516	45,828	56,486	63,430
MO	EL	22	417	1,796	6,158	15,338	29,268	47,988	72,353
MS	EL	25	471	2,025	6,894	17,070	32,433	52,967	79,536
MT	EL	5	102	504	2,604	8,850	21,056	42,323	78,748
NC	EL	501	9,601	35,378	75,303	121,048	160,965	186,870	196,444
ND	EL	0	1	7	144	605	1,516	3,090	5,755
NE	EL	5	93	416	1,617	4,448	9,124	15,983	25,786
NH	EL	10	183	782	2,610	6,359	11,937	19,281	28,629

State	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
NJ	EL	268	5,138	18,995	40,815	66,251	88,919	104,239	110,785
NM	EL	91	1,739	7,014	19,596	40,946	68,339	99,088	131,802
NV	EL	281	5,393	21,087	53,599	102,662	159,619	216,540	269,010
NY	EL	192	3,674	15,005	43,571	94,225	161,581	240,225	327,802
OH	EL	28	534	2,520	11,359	34,983	77,709	146,488	254,954
OK	EL	5	101	528	3,231	12,355	31,889	69,252	139,736
OR	EL	71	1,355	5,304	13,529	26,000	40,539	55,143	68,695
PA	EL	51	983	3,943	10,832	22,290	36,752	52,687	69,273
RI	EL	27	520	1,960	4,466	7,695	10,913	13,535	15,302
SC	EL	133	2,542	9,604	22,013	38,144	54,377	67,794	77,071
SD	EL	0	3	40	1,104	4,758	11,986	24,493	45,641
TN	EL	27	520	2,461	11,206	34,780	77,674	147,157	257,450
TX	EL	521	9,993	41,671	129,065	295,196	528,543	817,578	1,161,619
UT	EL	146	2,796	10,549	24,085	41,574	59,061	73,381	83,113
VA	EL	103	1,984	8,298	25,923	59,728	107,542	167,205	238,808
VT	EL	28	535	2,010	4,523	7,694	10,786	13,224	14,764
WA	EL	18	348	1,487	4,940	11,987	22,438	36,148	53,532
WI	EL	18	351	1,792	10,136	36,730	91,337	191,434	372,134
WV	EL	1	16	93	795	3,806	11,472	28,989	68,641
WY	EL	11	205	800	2,041	3,919	6,108	8,304	10,339

Table B-2. EoL Mass of Solar PV Estimates and Projections, 5-year increments, 2015 to 2050 (metric tons) for the Mid Loss (ML) Scenario by State

State	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
National	ML	611	25,985	184,222	657,479	1,676,217	3,358,850	5,606,635	8,267,484
AK	ML	0	3	20	80	235	530	966	1,497
AL	ML	2	83	630	3,461	14,870	45,808	109,786	223,046
AR	ML	3	110	807	3,416	10,753	25,812	49,893	81,976
AZ	ML	33	1,415	9,944	33,414	76,548	133,369	185,561	213,575
CA	ML	202	8,575	60,150	199,804	450,251	769,485	1,045,771	1,168,375
CO	ML	11	451	3,271	13,317	39,810	91,218	168,974	266,116
CT	ML	6	240	1,696	5,889	14,147	26,011	38,529	47,816
DC	ML	1	31	220	850	2,371	5,092	8,868	13,122
DE	ML	1	43	313	1,293	3,944	9,203	17,336	27,763
FL	ML	40	1,687	12,042	44,198	114,774	229,350	371,663	509,841
GA	ML	18	783	5,509	18,612	42,969	75,537	106,226	123,894
HI	ML	10	410	2,905	10,151	24,593	45,641	68,318	85,819
IA	ML	1	44	316	1,278	3,785	8,597	15,798	24,681
ID	ML	4	166	1,167	3,926	9,007	15,719	21,914	25,284
IL	ML	3	110	826	4,265	17,095	49,992	114,686	223,088
IN	ML	3	139	1,056	5,755	24,510	75,018	178,818	361,333
KS	ML	1	23	168	656	1,856	4,037	7,120	10,669
KY	ML	0	17	131	952	5,448	20,500	58,138	140,176
LA	ML	1	56	410	1,831	6,177	15,739	32,079	55,541
MA	ML	20	854	5,984	19,733	44,007	74,285	99,422	108,885
MD	ML	9	380	2,689	9,424	22,926	42,745	64,312	81,264
ME	ML	1	28	225	1,649	9,500	35,918	102,280	247,656
MI	ML	1	61	472	2,927	14,322	48,430	125,501	275,826
MN	ML	10	443	3,116	10,565	24,523	43,377	61,447	72,311
MO	ML	2	83	604	2,576	8,185	19,812	38,586	63,874
MS	ML	2	93	682	2,897	9,156	22,054	42,765	70,487
MT	ML	0	20	154	852	3,703	11,500	27,750	56,764
NC	ML	45	1,904	13,327	43,799	97,189	163,078	216,621	234,891
ND	ML	0	0	1	29	213	775	1,990	4,164
NE	ML	0	18	136	625	2,186	5,739	12,008	21,332
NH	ML	1	36	265	1,111	3,458	8,219	15,746	25,643
NJ	ML	24	1,019	7,139	23,574	52,671	89,110	119,595	131,458
NM	ML	8	345	2,475	9,388	25,516	53,393	90,662	130,663
NV	ML	25	1,069	7,609	27,420	69,392	134,987	212,669	282,951
NY	ML	17	729	5,246	20,332	56,907	122,549	214,039	317,589
OH	ML	2	106	794	4,019	15,742	45,236	102,247	195,996
OK	ML	0	20	154	965	4,764	16,206	42,210	93,248

State	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
OR	ML	6	269	1,912	6,904	17,518	34,174	54,003	72,087
PA	ML	5	195	1,397	5,250	14,087	29,104	48,791	69,385
RI	ML	2	103	726	2,471	5,764	10,255	14,626	17,356
SC	ML	12	504	3,553	12,126	28,411	50,792	72,856	87,046
SD	ML	0	1	6	211	1,639	6,081	15,728	33,008
TN	ML	2	103	773	3,941	15,560	44,986	102,209	196,925
TX	ML	47	1,981	14,350	57,685	169,580	382,609	698,611	1,084,438
UT	ML	13	554	3,906	13,305	31,083	55,389	79,150	94,136
VA	ML	9	393	2,852	11,520	34,090	77,385	142,109	221,862
VT	ML	2	106	747	2,525	5,836	10,272	14,467	16,904
WA	ML	2	69	504	2,109	6,541	15,497	29,602	48,071
WI	ML	2	70	534	3,157	14,690	47,949	120,619	257,253
WV	ML	0	3	25	201	1,275	5,134	15,434	39,546
WY	ML	1	41	289	1,042	2,642	5,152	8,137	10,855

Table B-3. EoL Mass of Solar PV Estimates and Projections, 5-year increments, 2015 to 2050 (metric tons) for the Regular Loss (RL) Scenario by State

State	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
National	RL	16	2,153	36,357	236,255	925,865	2,531,027	5,059,933	7,883,322
AK	RL	0	0	4	26	112	343	788	1,417
AL	RL	0	7	117	880	4,852	20,404	65,253	163,316
AR	RL	0	9	155	1,067	4,757	15,457	38,077	73,849
AZ	RL	1	117	1,977	12,628	47,210	118,733	205,056	246,455
CA	RL	5	711	11,981	76,237	282,676	701,747	1,185,472	1,368,987
CO	RL	0	37	633	4,296	18,563	57,815	135,448	248,633
CT	RL	0	20	335	2,165	8,292	21,652	39,752	52,911
DC	RL	0	3	43	286	1,187	3,495	7,629	12,891
DE	RL	0	4	60	412	1,802	5,705	13,631	25,574
FL	RL	1	140	2,363	15,520	61,937	172,120	346,931	529,254
GA	RL	0	65	1,094	7,002	26,280	66,500	116,027	141,966
HI	RL	0	34	574	3,713	14,285	37,553	69,676	94,282
IA	RL	0	4	61	415	1,782	5,507	12,781	23,215
ID	RL	0	14	232	1,483	5,547	13,966	24,164	29,139
IL	RL	0	9	155	1,138	5,959	23,649	71,717	170,898
IN	RL	0	12	197	1,472	8,064	33,664	106,956	266,080
KS	RL	0	2	33	219	916	2,728	6,039	10,378
KY	RL	0	1	24	196	1,373	7,320	28,517	85,304
LA	RL	0	5	78	548	2,549	8,768	23,020	47,710
MA	RL	1	71	1,193	7,575	27,942	68,800	114,587	128,845
MD	RL	0	31	531	3,439	13,257	34,968	65,219	88,961
ME	RL	0	2	40	337	2,379	12,761	49,941	150,012
MI	RL	0	5	86	678	4,144	19,418	68,177	185,702
MN	RL	0	37	619	3,962	14,913	37,895	66,584	82,460
MO	RL	0	7	116	800	3,586	11,744	29,191	57,162
MS	RL	0	8	131	903	4,034	13,150	32,517	63,322
MT	RL	0	2	29	215	1,196	5,075	16,365	41,267
NC	RL	1	158	2,659	16,863	62,046	152,171	251,702	279,290
ND	RL	0	0	0	3	42	273	1,082	3,010
NE	RL	0	2	26	183	870	3,084	8,359	17,884
NH	RL	0	3	51	349	1,547	4,981	12,142	23,281
NJ	RL	1	84	1,423	9,040	33,375	82,299	137,423	155,278
NM	RL	0	29	483	3,208	13,127	37,844	80,278	130,936
NV	RL	1	89	1,497	9,776	38,479	104,745	204,890	299,827
NY	RL	0	60	1,021	6,827	28,398	83,832	183,542	311,313
OH	RL	0	9	149	1,089	5,610	21,842	65,051	152,410
OK	RL	0	2	28	222	1,368	6,454	22,797	62,431

State	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
OR	RL	0	22	376	2,457	9,687	26,425	51,853	76,221
PA	RL	0	16	273	1,808	7,345	20,957	43,833	70,215
RI	RL	0	9	144	924	3,486	8,894	15,731	19,702
SC	RL	0	42	705	4,523	17,104	43,786	77,873	98,441
SD	RL	0	0	1	18	306	2,092	8,467	23,806
TN	RL	0	9	145	1,062	5,503	21,567	64,637	152,338
TX	RL	1	164	2,780	18,800	80,440	247,139	569,361	1,025,434
UT	RL	0	46	775	4,971	18,770	47,943	84,952	106,728
VA	RL	0	33	552	3,739	16,062	49,613	115,059	208,799
VT	RL	0	9	148	949	3,565	9,029	15,776	19,351
WA	RL	0	6	97	665	2,937	9,428	22,902	43,752
WI	RL	0	6	98	758	4,450	20,000	67,794	178,892
WV	RL	0	0	4	38	294	1,708	7,097	22,511
WY	RL	0	3	57	371	1,462	3,986	7,817	11,482

10. PEER REVIEWERS

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