Solar Energy’s Secret – Hazardous Waste:

The Case for a National Recycling Framework
Preface

About the WISE Program

The Washington Internships for Students of Engineering (WISE) program was founded in 1980 to engage engineering and computer science students in the legislative process. Participating professional engineering societies provide the opportunity for competitive students in the United States to spend nine weeks in Washington D.C. to independently research, write, and present a topical engineering-related public policy paper. Throughout the summer, the students have the opportunity to interact with elected officials, federal agencies, and nongovernmental organizations to observe the intersection between science, technology, and public policy. By the end of the summer, the students acquire a greater understanding of how engineers can contribute to regulatory public policy decision-making. For more information regarding the WISE program, visit www.wise-intern.org.

About the Author

Colby Buehler is a recent graduate from the University of Connecticut. After receiving his degree in Chemical Engineering, he will be attending Yale University as a Ph.D. student in Environmental Engineering in the fall. Eager to engage with any aspect related to the environment on UConn’s campus, Colby conducted research on herbicide drift and air quality, completed a minor in environmental engineering, and participated in green student groups such as EcoHusky. This interest culminated in attending the United Nations Framework Convention on Climate Change in Bonn, Germany as a member of UConn@COP. Deeply invested in environmental scholarship, he was awarded a National Science Foundation Graduate Research Fellowship to study environmental engineering. On UConn’s campus Colby was also an active member of the Trombone Choir, and served as president of Tau Beta Pi’s Connecticut Beta chapter and the Honors Council.

Acknowledgments

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All US maps were created using https://mapchart.net/.
# List of Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
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<tr>
<td>BNL</td>
<td>Brookhaven National Laboratory</td>
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<td>BOS</td>
<td>Balance of System</td>
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<tr>
<td>C2C</td>
<td>Cradle-to-Cradle</td>
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<tr>
<td>C2G</td>
<td>Cradle-to-Grave</td>
</tr>
<tr>
<td>CdTe</td>
<td>Cadmium Tellurium</td>
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<tr>
<td>CIGS</td>
<td>Copper Indium Gallium Selenide</td>
</tr>
<tr>
<td>c-Si</td>
<td>Crystalline Silicon</td>
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<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>DTSC</td>
<td>Department of Toxic Substances Control</td>
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<tr>
<td>EH&amp;S</td>
<td>Environmental Health and Safety</td>
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<tr>
<td>EOL</td>
<td>End-of-life</td>
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<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
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<td>EPR</td>
<td>Extended Producer Responsibility</td>
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<tr>
<td>EVA</td>
<td>Ethylene Vinyl Acetate</td>
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<td>e-waste</td>
<td>Electronic Waste</td>
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<td>GW</td>
<td>Gigawatt</td>
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<tr>
<td>IEA-PVPS</td>
<td>International Energy Agency Photovoltaic Power Systems Programme</td>
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<tr>
<td>IEE</td>
<td>Institute for Electrical Engineering of the National Academy of Sciences</td>
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<tr>
<td>kWh</td>
<td>kilo-Watt hour</td>
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<td>kWp</td>
<td>kilo-Watt peak</td>
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<tr>
<td>LCA</td>
<td>Life Cycle Analysis</td>
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<tr>
<td>METI</td>
<td>Ministry of Economy, Trading and Industry</td>
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<tr>
<td>MOE</td>
<td>Ministry of Environment</td>
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<tr>
<td>MW</td>
<td>Megawatt</td>
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<tr>
<td>NEDO</td>
<td>New Energy and Industrial Technology Development Organization</td>
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<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
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<td>PAYG</td>
<td>Pay As You Go</td>
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<tr>
<td>PAYP</td>
<td>Pay As You Put</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
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<tr>
<td>RCRA</td>
<td>Resource Conservation and Recovery Act</td>
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<tr>
<td>SB</td>
<td>Senate Bill</td>
</tr>
<tr>
<td>SEERA</td>
<td>Secure E-waste Export and Recycling Act</td>
</tr>
<tr>
<td>SEIA</td>
<td>Solar Energy Industries Association</td>
</tr>
<tr>
<td>SETO</td>
<td>Solar Energy Technologies Office</td>
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<tr>
<td>SVTC</td>
<td>Silicon Valley Toxics Coalition</td>
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<tr>
<td>t</td>
<td>tons</td>
</tr>
<tr>
<td>TCLP</td>
<td>Toxicity Characteristic Leaching Procedure</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>WEEE</td>
<td>Waste Electrical and Electronic Equipment</td>
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Executive Summary

Solar is a growing green energy source in the United States. After being decommissioned, panels can either be re-used, disposed of into a landfill, or recycled. While current waste levels are low, only between 6,500-24,000 tons in 2016, waste will rapidly grow to 170,000-1,000,000 tons by 2030 and 7,500,000-10,000,000 tons by 2050. Currently the majority of panels are disposed of at landfills where their precious metals and other valuable materials cannot be recovered. The solar industry has only just started looking into recycling methods with companies such as First Solar leading the way in the US.

Photovoltaic (PV) solar panels come in two main forms: crystalline silicon (c-Si) and thin film. Both contain hazardous materials, precious metals, and energy intensive compounds. c-Si panels rely on extremely high purity silicon cells and silver to produce electricity. The two main thin film technologies, Cadmium Tellurium (CdTe) and Copper Indium Gallium Selenide (CIGS) contain toxic heavy metals that can be reclaimed for a high value.

The process of dealing with EOL panels involves a complex logistics chain of organizing the decommissioning, transport, recycling, and disposal of non-recyclable parts in a landfill. Most recycling currently consists of glass and metal smelters taking the majority of the waste. While large scale PV specific recycling centers are not common in the US, recycling rates of 90% or higher for most panel components have been demonstrated.

PV recycling offers numerous benefits. Recycling lessens impact on landfills and reclams hazardous waste that can be reused in future panels. Thin film panels in particular contain precious metals such as indium, gallium, copper, and silver that may be of limited supply to the PV industry in the future. As a green energy source, recycling can move the industry towards a more sustainable closed-loop production cycle. Manufacturers might also face repercussions if they do not address the waste of an industry that is supposed to be environmentally friendly.
No PV specific federal legislation exists surrounding recycling. Panels are subject to the Resource Conservation and Recovery Act (RCRA) for disposal which tests them according to the Toxicity Characteristic Leaching Procedures (TCLP) standards for toxicity. Some federal R&D initiatives on PV recycling processes and economics have come out of the National Renewable Energy Laboratory (NREL) and the Brookhaven National Laboratory (BNL). Washington became the first state to implement a mandatory recycling program and other states such as New York are working on the issue. California is in the process of classifying PV waste as universal waste under certain conditions.

Abroad, the European Union (EU), through the Waste Electrical and Electronic Equipment (WEEE) Directive, has led the PV waste issue. They implemented a mandatory recycling program for all EU members with a public-private non-profit PV Cycle leading the compliance efforts. Japan and China have invested significantly into R&D but have not made any legislative action.

The PV waste issue has many similarities to the electronic waste (e-waste) issue but in this case the US can be proactive rather reactionary. States should adopt a mandatory, extended producer responsibility (EPR) recycling program. If it is not politically viable or waste volumes are too small to warrant a mandatory program voluntary approaches should be incentivized. PV waste should be classified as universal waste to aid transport and collection. The EPA can act as the central authority and bring together relevant stakeholders to grow the US PV recycling infrastructure. R&D efforts should be focused on redesigning of panels as well as scale up of economically feasible recycling processes.

Proactive PV recycling policy measures can ensure that valuable materials are recovered, waste is diverted from landfills, solar moves towards a sustainable closed loop production standard, and manufacturers keep their green branding. While the US has some time before large quantities of waste are generated, now is the time to implement and iterate on solutions.
Defining the Issue
Solar as a Green Energy Source in the US

Solar power is widely thought of as a zero emission, green energy production solution to the world's growing energy needs. Along with other renewables, solar appears to be here to stay in the United States (US) as the national capacity has grown from a mere 218 megawatts (MW) in 2005 to over 51,000 MW in 2017 [1]. As seen in Figure 1, California has been a clear leader in development with nearly 40% of the entire US solar capacity. Other markets such as North Carolina, Arizona, Nevada, and New Jersey are quickly growing their solar energy sectors as prices continue to fall.

![Solar capacity map](image)

**Figure 1.** Solar capacity for each state through the first quarter of 2018 [2].

Solar offers a promising way to reduce US reliance on fossil fuels which operate at a high environmental cost [3]. For each gigawatt (GW) of power produced by solar rather than coal, 1000 tons of CO$_2$, 10 tons of sulfur dioxide, 4 tons of nitrogen dioxide, and 0.7 tons of particulates are prevented from entering the atmosphere [3]. While solar does not produce any emissions during its operational lifetime, there are associated environmental costs with the production and disposal
of panels. After being decommissioned, panels can either be re-used, disposed of into a landfill, or recycled. Recycling has been receiving increasing attention recently as the preferred method for disposal as it reclaims precious metals and helps promote a closed-loop production cycle.

The rapid expansion of solar, or photovoltaic (PV), technology in the US will eventually lead to a waste problem when the panels reach their end-of-life (EOL) stage. Proper EOL management will be necessary to ensure that solar is a sustainable energy generator, maintains its clean energy branding, and that there will be enough resources available to continue using solar as a viable energy source.

**Scope**

Solar panels exist in many forms and in numerous devices from calculators to PV solar farms. For the purposes of this paper, only residential and utility solar PV panels will be considered. These panels represent the majority of the volume of waste that will be produced in the coming years as outlined in the next section.

**End-of-Life Waste Issue**

There are two ways of looking at the expected PV panel waste accumulation for the future: regular and early loss scenarios. The regular loss scenario assumes the panels operate for their manufacturer guaranteed lifespan, roughly 30 years, with no premature retirement or failures [4]. Early loss includes all likely “infant”, “mid-life”, and “wear-out” failure possibilities before the
panel’s 30 year lifetime is up [4]. These causes are explained in Table 1. Overall the vast majority of panels end up making it to their EOL and early loss is only a minor contributor to waste. The two scenarios represent the extremes of the actual amount of waste that will be generated.

Table 1. Explanation of early loss causes [4].

<table>
<thead>
<tr>
<th>Failure Type</th>
<th>Early Loss Percentage</th>
<th>Typical Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infant (0-5 years)</td>
<td>1%</td>
<td>Light-induced degradation, bad installation, poor planning, electrical system failures</td>
</tr>
<tr>
<td>Midlife (5-11 years)</td>
<td>2%</td>
<td>Degradation of anti-reflective coating on glass, discoloration of ethylene vinyl acetate binder, delamination and cracked cell isolation</td>
</tr>
<tr>
<td>Wear-out (12+ years)</td>
<td>97%</td>
<td>Increased likelihood of midlife failure causes, long-term exposure to temperature changes, repeated snow and wind loads</td>
</tr>
</tbody>
</table>

Figure 2 shows the solar waste profiles under regular and early loss alongside the cumulative PV capacity for the US. While current waste levels are low, only between 6,500-24,000 tons in 2016, waste will rapidly grow to 170,000-1,000,000 tons by 2030 and 7,500,000-10,000,000 tons by 2050. This waste projection does not include scrap produced during production of panels. Scrap is a constant source of material that manufacturers can accurately predict and recycle internally [5].

Figure 2. Solar panel waste and capacity from 2016 to 2050 in the US [4].

This level of waste production presents environmental, economic, and social consequences. PV panels contain various levels of hazardous materials which can cause concern
for local municipalities with large levels of waste. While the panels themselves do not represent a cause of concern for groundwater contamination, certain panel types contain rare and precious metals which provide an economic incentive for recovery and reuse rather than disposing of them into a landfill. By not recycling, the total cost of solar panel decommissioning includes disposal and all revenue that could have resulted from reintroducing precious metals back into the market.

In the coming years, landfill capacity is expected to drop across many regions in the US [6]. By growing the US PV recycling infrastructure, solar can help alleviate stress on landfills and move towards being a sustainable industry. Additionally, if panels end up in these already crowded landfills solar manufacturers might be scrutinized by the public for a lack of environmental stewardship in a supposedly green energy field. While the waste volumes are low it is important to bring awareness to the issue and determine the best course of action.

Advocates

Several groups within the US have brought up the issue of solar waste and recycling. Environmental groups inside and outside of the US have raised concerns over the toxicity of PV panel components and the amount of projected waste. Industry leaders have advanced their green image by organizing working groups and developing recycling programs for their environmentally minded customers. The work of the following groups has resulted in the discussion of solar recycling on numerous environmentally focused websites but has promoted some discussion on larger platforms as well.

Silicon Valley Toxics Coalition

One of the first groups to bring the issue of solar waste to the attention of the public was the Silicon Valley Toxics Coalition (SVTC). In 2009 they released the white paper Toward a Just and Sustainable Solar Energy Industry which stressed that there is only a limited amount of time to ensure that the solar industry operates in a green, sustainable manner. Their recommendations
included reducing the amount of toxic materials in the panels, mandate Extended Producer Responsibility (EPR), increase recycling programs, and manufacture panels in a recycling friendly manner [7]. In 2010, the SVTC introduced the Solar Scorecard which ranks solar manufacturers according to the recommendations provided in their initial white paper. They continue to be active in their support of PV recycling programs and legislation that provide positive environmental change for the industry.

Solar Energy Industries Association

Another group bringing attention to the issue is the Solar Energy Industries Association (SEIA). SEIA, the largest non-profit solar advocacy group, has made it a priority to look into the waste issue. The Corporate Social Responsibility Committee of the SEIA brings together numerous leading manufactures in the US. They monitor legislation proposals for the US as well work the development of a national PV recycling program through their PV Recycling Working Group. This working group meets weekly and includes many of the top PV recyclers worldwide. Evelyn Butler, who heads the PV Recycling Working Group, said that the manufacturers want to develop a sustainable industry and are concerned that if they do not develop a robust recycling program they might be viewed poorly by the public. Manufacturers hope that their efforts on developing recycling infrastructure will allow for a voluntary collection program to be economically advantageous and that people will choose recycling over landfills in the future.

IEA-PVPS Task 12 and IRENA

The International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) is a subgroup of the IEA focused on PV research. There are 32 member countries to the IEA-PVPS, of which the US is one of [8]. The IEA-PVPS focuses on 16 tasks related to the solar industry in general. Task 12, PV Sustainability, involves the investigation of the recycling of modules, conducting life-cycle assessments, and identifying Environmental Health and Safety (EH&S) issues within the industry [8].
The International Renewable Energy Agency (IRENA) was founded in 2009 to promote the adoption of sustainable and renewable energy across the world [4]. In 2016, the IRENA coauthored a report with the IEA-PVPS entitled *End-Of-Life Management: Solar Photovoltaic Panels*. The report profiled PV waste in the US as well as other leading solar countries. It was the first prediction of solar waste volumes to 2050 and estimated that the future global recycling market could put 78 million tons of materials worth over $15 billion back into the market [4]. It also strongly advocated for an EPR approach which it defines as “an environmental policy approach in which a producer’s responsibility for a product is extended to the post-consumer stage of a product’s life cycle” [4].

**First Solar**

One of the first major solar recycling success stories in the US has come from the company First Solar. They manufacture Cadmium Tellurium (CdTe) panels which contain relatively large amounts of precious metals when compared with traditional silicon, making recycling economically viable. First Solar developed their recycling program in 2005 [9]. For each panel they sell, they set aside enough money to recycle it in the future based on estimated costs. First Solar registers each panel they sell, collects panels when designated for decommissioning, and ultimately recycles them [9]. They have proven that recycling is financially viable and continue to bring awareness to the waste issue.

**Background**

**Solar Panel Basics**

**How They Work**

Solar panels convert sunlight into electricity through the photovoltaic effect. Solar panels are collections of several smaller cells which are made by placing two thin semi-conductor sheets of slightly different chemical composition close to each other [7]. When sunlight hits one of the
semi-conductor sheets, electrons can escape to the other sheet leaving a hole behind. This creates an electrical field which can be used as an energy source.

**Solar Panel Market**

The PV market is well characterized. PV technology has undergone numerous developments during the past few decades but the crystalline silicon (c-Si) panel still holds the majority of the market share by far. c-Si panels, which were the first to be produced, are considered first generation technology and account for 91% of current capacity globally [10]. In the coming years other PV technologies are expected to increase their market share dramatically. Second generation thin film technologies, which include Copper Indium Gallium Selenide (CIGS), CdTe, and a few other niche designs, currently only hold 9% of the global market share. By 2030 the share of c-Si panels is expected to decrease to 45% while thin film technologies will increase to 11%. Third generation technologies, such as advanced c-Si, organic, and CIGS heavy metal alternatives are expected to fill the remaining 44%. In this report the focus will be only on c-Si and CIGS/CdTe panels as they will play the largest role in the coming years.

The prediction of the PV panel market will be important for estimating future waste streams as each design presents unique EOL management problems due to its composition. Figure 3 shows how the composition of the most common panel designs will change between 2014 and 2030. The general trend for all panel types is that they will be smaller and lighter [11]. For c-Si panels the focus is on minimizing the amount of silicon required to be used. For thin film panels alternative heavy metals are being considered to replace the hazardous and expensive materials used today.
How They Are Made

Panels, by mass, primarily consist of glass. The glass helps protect the underlying components from harsh weather. A transparent polymer, known as an encapsulant, helps bind the glass to the underlying solar cell. A weather proof composite, or substrate, serves as the back laminate. Solar cells go in between the substrate and the cover glass and use semiconductors to conduct electricity. Solar cells are soldered in a series to create a panel. After assembly, the panel is then mounted onto an aluminum frame. Cables run from the cells inside of the module into an inverter which converts the energy from direct current (DC) to alternating current (AC). Methods specific for c-Si and thin film are given below.

To produce a c-Si panel there are three main steps [12]. First, silicon ingots are cut into wafers to form the c-Si cell, producing some amount of scrap material. This scrap could amount to as much as 50% of high purity, energy intensive, silicon [7]. The cells are then doped with small impurities to facilitate electron transfer between the two semi-conductor layers (e.g. phosphorus on one and boron on the other) [7]. Modules are created by attaching glass and a conductor (silver...
in most cases) to the wafers using an encapsulant [12]. The most common encapsulant used is ethylene vinyl acetate (EVA). The cells are also laminated with a polymer to ensure protection from the environment [7]. Finally the balance of system (BOS) is added. The BOS consists of an aluminum frame and copper wires to transfer the electricity. Figure 4 shows the common structure for c-Si panels and compares it to the thin film design.

![Diagram of solar panel structures](image)

**Figure 4.** Common structure for (a) c-Si and (b) thin film PV modules [13].

Most of the same principles can be applied to thin film panels. Like their name implies, thin film panels are significantly thinner than c-Si panels because they use narrow layers of metal instead of silicon cells to generate electricity.

**Solar Recycling Basics**

PV recycling occurs in a three-stage process. First a logistics management network needs to coordinate the removal and transportation of the panels. Next the panels enter a recycling center to be processed. Finally, any leftover waste or materials that could not be recycled need to be disposed of.

**Logistics**

Once cited for decommission the panels need to be picked up and transported to the recycling facility. This process is easier for utility scale solar rather than residential. For utility scale solar, all of the panels are generally of the same type and from the same manufacturer making it easy to identify who to contact about disposal options. In general utility scale solar is ground mounted providing easy access to the panels. For residential solar, this process is more
labor intensive. Residential solar is generally mounted on rooftops requiring extra caution in decommissioning. Panels are dismounted and are then loaded onto a truck. Either they go to a central collection point to wait for additional panels if the initial pickup did not have many panels or they are brought directly to the treatment or recycling facility.

Recycling

Recycling Centers

Several methods exist for recycling PV waste. Each follows a similar pattern of pre-disassembly, which involves the removal of metal frames, elimination of the encapsulant and delamination, and the recovery of metals and substrate [14]. Currently most panels end up going to a general waste recycling facility. Glass recycling plants take in the majority of panels as glass comprises the bulk of panel mass. The electronic equipment is disassembled and is taken to another facility for processing or be disposed of according to electronic waste regulations.

PV specific recycling centers typically specialize in one type of panel, either c-Si or thin film, due to the compositional differences between the two. For both types of centers, the first step is disassembly. The electronic equipment, cables, and aluminum frame are taken off to be recycled directly. In general the delamination process falls under three broad categories: mechanical, thermal, or chemical [14]. Mechanical processes shred and crush the panel into pieces in order to extract the solar cell piece by piece. In thermal processes, the encapsulant, most commonly EVA, is burned off through and the resulting gas is passed through a scrubber [15]. Chemical processes involve using various chemical to remove the encapsulant, producing waste as a result.

Figure 5 shows a simplified flow diagram for a typical c-Si recycling process. c-Si panels are shredded to make them easier to process. Valuable materials are extracted through a thermal or chemical process, and etching recovers the silicon. For thin film panels, the focus is on the
recovery of the precious metals and glass. Ultimately not all of the panel can be recycled and some goes to the landfill as waste.

![Figure 5. Simplified recycling and disposal paths for c-Si solar waste [16].](image)

**Recycling Rates**

**Table 2.** Recycling rates and panel composition for c-Si, CIGS, and CdTe technologies [28].

<table>
<thead>
<tr>
<th>Component</th>
<th>c-Si Weight %</th>
<th>CIGS Weight %</th>
<th>CdTe Weight %</th>
<th>Recovery %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>71</td>
<td>88</td>
<td>96</td>
<td>90</td>
</tr>
<tr>
<td>Silica</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>90</td>
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<td>Aluminum</td>
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<td>90</td>
</tr>
<tr>
<td>EVA</td>
<td>9</td>
<td>4</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Copper</td>
<td>0.1</td>
<td>0.1</td>
<td>0.02</td>
<td>95</td>
</tr>
<tr>
<td>Silver</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
<td>95</td>
</tr>
<tr>
<td>Indium</td>
<td>0</td>
<td>0.28</td>
<td>0</td>
<td>85</td>
</tr>
<tr>
<td>Gallium</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
<td>85</td>
</tr>
<tr>
<td>Selenium</td>
<td>0</td>
<td>0.52</td>
<td>0</td>
<td>85</td>
</tr>
<tr>
<td>Nickel</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>85</td>
</tr>
<tr>
<td>Zinc</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>85</td>
</tr>
<tr>
<td>Tin</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>85</td>
</tr>
<tr>
<td>CdTe</td>
<td>0</td>
<td>0</td>
<td>0.12</td>
<td>80</td>
</tr>
</tbody>
</table>

Recycling technology has advanced to the point that high percentages of most components can be handled and recovered. Table 2 shows the effectiveness of recycling for each
dominant panel type in the market today. While there are some concerns about the purity of certain components such as glass and silicon, most are able to be reintroduced into the material stream for future panel manufacturing. Glass and silicon which do not meet the high standards of the PV industry can still be used for other purposes. The one component which cannot be recycled currently is EVA, the encapsulant hydrocarbon. The chemical or thermal methods result in EVA being dissolved into a waste solution or evaporated and released as an emission. Research is currently looking into how to recover EVA.

Hazardous Waste Basics

As seen in Table 2, panels contain numerous heavy metals. Under the Resource Conservation and Recovery Act (RCRA) many of these metals are considered to be hazardous. Panels are tested for hazardous compounds under the US Environmental Protection Agency's (EPA) Method 1311 Toxicity Characteristic Leaching Procedures (TCLP) standards. The limits on these metals can be seen in Table 3.

For c-Si panels silver and lead are the main concern. Silver is the most commonly used conductor in c-Si panels and lead is found in the solder used to connect solar cells together. Thin film technologies utilize many of these regulated heavy metals in their design. CdTe and CIGS panels rely heavily on cadmium and selenium respectively. Alternative designs are being developed that utilize other metals such as tin and zinc instead of indium and gallium for CIGS panels but they are far from being market ready [4]. In addition the electronic components such as the inverter and circuit boards contain hazardous metals such as lead, arsenic, cadmium, selenium, and chromium [17].

<table>
<thead>
<tr>
<th>Heavy Metal</th>
<th>Hazardous Waste Code</th>
<th>EPA Allowable Limits (mg/L or ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>D004</td>
<td>5.0</td>
</tr>
<tr>
<td>Barium</td>
<td>D005</td>
<td>100.0</td>
</tr>
<tr>
<td>Cadmium</td>
<td>D006</td>
<td>1.0</td>
</tr>
<tr>
<td>Element</td>
<td>Code</td>
<td>Limit</td>
</tr>
<tr>
<td>-------------</td>
<td>------</td>
<td>-------</td>
</tr>
<tr>
<td>Chromium</td>
<td>D007</td>
<td>5.0</td>
</tr>
<tr>
<td>Lead</td>
<td>D008</td>
<td>5.0</td>
</tr>
<tr>
<td>Mercury</td>
<td>D009</td>
<td>0.2</td>
</tr>
<tr>
<td>Selenium</td>
<td>D010</td>
<td>1.0</td>
</tr>
<tr>
<td>Silver</td>
<td>D011</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Panels that exceed the TCLP limits are classified as hazardous waste, requiring additional disposal requirements and administrative overhead [19]. Hazardous waste is disposed of at RCRA hazardous waste certified landfills. These landfills contain numerous precautions to ensure no hazardous waste enters the environment such as having a double liner, double leachate collection system, and leak detection system [20]. The effectiveness of these facilities comes at a heavy financial cost.

Universal waste is a subcategory of hazardous waste that exists to streamline hazardous waste standards for “certain categories of hazardous waste that are commonly generated by a wide variety of establishments” [21]. The EPA aims to increase collection and recycling, minimize the regulatory burden involved in transporting hazardous waste, and minimize the amount of universal waste entering landfills [21]. This unique universal waste designation is applied to certain batteries, pesticides, mercury-containing equipment, and lamps under 40 CFR 273 [21]. States have the option to create their own universal waste designations which several states have done for items such as electronics, cathode ray tubes, antifreeze, and more.

**Cradle-to-Grave and Cradle-to-Cradle Life Cycle Analysis**

Life cycle analysis (LCA) determines the environmental impact of a product from the extraction of the raw materials required to produce it to its disposal and every process in-between [15]. LCA is a useful tool to understand the environmental impact of PV panels and the associated benefits and costs of recycling. PV panels require considerable quantities of energy from non-renewable sources in order to be produced which come with a high environmental impact [22]. While PV power constitutes a much greener energy source than others, the solar industry’s
reliance on non-renewable resources such as the mining of precious metals and the use of fossil fuels to implement thermal recycling must be acknowledged. Recycling can help alleviate reliance on non-renewable resources. Cradle-to-grave (C2G) and cradle-to-cradle (C2C) approaches to manufacturing explain the benefit of recycling PV panels.

PV power’s reliance on non-renewable resources is explained through a Cradle-to-Grave (C2G) LCA approach. In a C2G approach a panel’s environmental impact starts with the extraction of raw materials and ends at disposal. Manufacturers that operate with a C2G approach do not place high value on making their products easily recyclable or reusable as they intend for them to end up in landfills. There is also little reason to reduce the amount of energy required in production or material used in the product unless there is a significant economic incentive.

The Cradle-to-Cradle (C2C) approach reverses the priorities of manufacturing as seen in Figure 6. In a C2C approach manufacturers try to instill economic growth while returning materials back to their source [23]. For PV manufacturers that means more than recycling. Reducing the amount of materials required for PV modules and replacing hazardous or high environmental impact materials should be the first step. This could manifest in c-Si panel production through reducing the amount or the required purity of silicon and use of copper instead of silver for a conductor. For thin film panel production utilizing alternative metals such as tin and zinc could help reduce environmental burden. Both panel types would benefit from replacing EVA with a recyclable material. Upcycling is the process of using waste products or undesirable materials to reduce environmental impact. Recycling of scrap from production and restoration of panels for reuse serve as options for upcycling. Where redesign and upcycling fail, the standard environmental practices of reduce, reuse, and recycle come into play.
Recycling is thus only one method in the C2C approach to lessen environmental impact. Manufacturers that have a sense of responsibility for their products already employ C2C approaches (see the Solar Scorecard put out by the SVTC for relevant companies) through EPR take back and recycling programs. EPR approaches encourage testing for alternative materials, expanding recycling technologies, and designing easily recycled panels [10]. While most of this report focuses on the benefits from recycling, the ultimate goal should be to move towards a C2C manufacturing approach.

**The Case for Recycling**

When a PV panel cannot be reused or restored, recycling is the next best option. Numerous studies and reports have documented the environmental and socio-economic benefits from recycling PV panels. Recycling offers a better hazardous material management strategy, the ability to reclaim valuable materials, moves the industry to a more sustainable production cycle, and promotes corporate responsibility.
Hazardous Waste Management

The main environmental concern surrounding the PV EOL issue is the leaching of hazardous materials. Cadmium, lead, nickel, and chromium are all toxic elements that have been shown to mobilize through the soil under [24]. Under a worst-case scenario experiment, meaning the panels were shredded and crushed, these metals exceeded EU restrictions on soil and water concentrations [24]. Despite consisting of a relatively small percentage of a panel’s total weight these toxic materials could have negative environmental impacts if left to decay without proper treatment. For panels that fail to classify as hazardous waste, minor amounts of hazardous waste could leach into soil and groundwater when panels are left in a municipal landfill. Panels which are classified as hazardous and get disposed of at RCRA hazardous waste landfills have little to no concern of entering the local environment. In areas with landfill restrictions, incineration of the panels can lead to the release of toxic materials into the air [7]. Recycling can recover large amounts of toxic materials, serving as an alternative treatment method to letting solar panels sit in expensive hazardous waste landfills.

Reclamation of Valuable Materials and Sustainable Practices

Recycling can reclaim precious and rare metals in order to produce additional panels and bring the industry closer to a closed loop production model. It is estimated that by 2030, for every 100 c-Si panels entering their EOL stage, another 42 panels could be made from reusing the materials collected during recycling [10]. Many metals utilized in PV technology, thin film in particular, come as “byproducts” of refining other metals [25]. Indium, gallium, selenium, tellurium, and cadmium are such “byproduct” metals which rely on the demand for their “host” metals in order to have a steady supply. Studies have suggested that for a rapid expansion of solar these materials will be constrained [25], [26]. Recycling of EOL panels will likely not help the rapid expansion of solar as there will not be enough waste within the next 20 years to fuel current capacity increase projections [26]. Growth in the production of “byproduct” metals will be crucial.
However, by 2050 EOL recycling will be crucial for continuing to use solar as a major energy source by reintroducing large quantities of crucial metals to the market [26]. In order for solar to play a role in the future of the US energy portfolio, a concerted effort moving towards a closed loop production cycle including recycling needs to be made.

Recycling aluminum and silicon in particular can have a large positive environmental impact. Aluminum comes from large surface bauxite ore mines [27]. These mines are highly destructive to the surrounding environment and are largely located around the equator which directly impacts rainforests [27]. Along with reducing the amount of metals required for panels recycling is an easy way to help preserve the environment from the damages of additional raw material mining. The silicon used for c-Si panels needs to be of extremely high purity, 99.99% or higher, which causes the production to be extremely energy intensive [7], [13], [26], [28]. Reusing silicon from panels requires 30-90% less energy than using raw materials [7]. Recycling aluminum and silicon results in large reductions in carbon dioxide emissions when compared to using only primary materials [15].

**Corporate Responsibility and Public Accountability**

Recently, corporations around the country have voluntarily committed to developing more sustainable practices [29]. The reasons for the self-adoption of these practices include avoiding unwanted future regulation, minimizing costly hazardous waste production, and protecting the environment from pollution [29]. Investors in solar manufacturers are likely to have one, if not all, of these desires as well. Thus solar manufacturers, as well as many other industries, have a fiduciary responsibility to support sustainable practices [29]. As the founder of Recycle PV put it, “[s]olar is supposed to be renewable and clean energy, but there is this dirty side to it” [30]. If solar ignores the problem or does not address it fully their image and the future of solar being seen as a green energy source will be jeopardized.
In summary, recycling has a positive environmental benefit, promotes more sustainable designs, and offers an opportunity to grow a robust industry of logistics providers, recycling centers, and more. Low waste volumes have slowed activity in the US but more PV panels enter into their EOL stage each and every year. While recycling alone cannot solve the waste issue, it will need to play a major role in transitioning to a closed-loop production system.

Policy Efforts

In the US, states have led the solar waste policy effort. No attention has been paid to the issue by the federal government in terms of direct legislation and there has only been a token level of support of research and development (R&D) initiatives. Washington and California have championed the issue thus far but their solutions leave much to be desired. Outside of the US, other countries with strong PV markets have looked into the issue. The EU serves as the world leader for PV recycling and both Japan and China have invested more resources than the US into the solar waste issue.

Federal

No federal legislation directly addresses the solar waste issue. Solar panels, like other types of solid waste, fall under the RCRA of 1976 for guidelines on disposal. Nearly all solar panels end up in landfills as there is no federal EOL decommissioning policy. There is one, minor exception. The Bureau of Land Management (BLM) requires that all utility-scale solar farms on its land post a bond that covers the decommissioning, disposal, and restoration of the land [31]. This does not require the solar panels to be recycled, merely disposed of properly. Due to the lack of federal guidance, several states have started to look at the issue.

Policy efforts can also be reflected in R&D priorities and funding opportunities. Two national laboratories have contributed to the area of solar panel recycling and life cycle analysis. The National Renewable Energy Laboratory (NREL) has led significant research efforts on PV
technology in general. Between 1994 and 2009 the NREL helped companies develop thin film PV technologies, get them on the market, and establish recycling programs for these panels [32]. First Solar is one of the companies that greatly benefitted from NREL R&D. More recently the NREL has contributed to life-cycle analysis research on solar panels and their disposal. In addition, Dr. Garvin Heath, a senior scientist for the NREL, is the leader of IEA-PVPS’s Task 12 program where he has authored numerous reports on PV recycling R&D.

The Brookhaven National Laboratory (BNL) has put together numerous life cycle and economic reports on PV recycling. Dr. Vasilis Fthenakis and Dr. Jun-Ki Choi led research those aspects of PV recycling between 2000 and 2015. In 2009 the BNL organized the Photovoltaics Recycling Scoping Workshop which brought together industry leaders in manufacturing and PV material supplying as well as two representatives from PV Cycle to discuss the future of US PV recycling [33]. In recent years the BNL has not kept up the same productivity in PV recycling research.

State

Currently there are nine states with an EOL solar disposal policy and three additional states which offer guidance to local governments. They can be broken up into four main categories: statewide recycling policy, statewide decommissioning policy, decommissioning policy under certain circumstances, and decommissioning guidance. See Table 4 and Figure 7 for detailed information on the policy types. States with a recycling or decommissioning plan require an adequate amount of money be set aside to ensure for proper EOL decommissioning, although they vary how they go about financing the policies.
Washington

In 2017 Washington became the first state to require that solar panels be recycled at EOL. With the adoption of Senate Bill (SB) 5939, solar panel manufacturers that sell new panels in the state must provide a stewardship plan to the Department of Ecology outlining how they will finance the takeback and recycling at EOL, minimize environmental impact, educate the customer on their takeback plan, and more. This implements the EPR model of financing EOL management. Manufacturers are also allowed to join into a national recycling program (e.g. SEIA) if it meets all of the requirements laid out. All types of solar energy are subject to this law.

California

California is the only state that classifies solar panel waste as universal, rather than hazardous waste. The state passed SB No. 489 in 2015 which allowed for the Department of Toxic Substances Control (DTSC) to designate EOL modules as universal waste, removing a great deal of administrative burden for disposal. So far, however, no action has been taken by the department. California hopes to foster a reuse and recycling program in the state and reduce disposal into landfills. In addition, Cal Gov Code § 51191.3 specifies that local governments can require decommissioning funds to be set in place for solar EOL through the use of an administrative fee, differing from the EPR approach used in Washington.
Table 4. Federal and state policies on EOL solar waste management and their sources [31].

<table>
<thead>
<tr>
<th>State</th>
<th>Applicability</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLM</td>
<td>BLM-managed lands</td>
<td>43 U.S.C. 1764(i); 43 CFR 2805.12(g)</td>
</tr>
<tr>
<td>Washington</td>
<td>Statewide</td>
<td>WAC 463- 72,</td>
</tr>
<tr>
<td>California</td>
<td>Statewide</td>
<td>Cal Health &amp; Saf Code § 25259, Cal Gov Code § 51191.3</td>
</tr>
<tr>
<td>Hawaii</td>
<td>Class A, B, and C Agricultural Land</td>
<td>HRS § 205-4.5</td>
</tr>
<tr>
<td>New Jersey</td>
<td>Commercial Farm Lands, Pinelands Management Area</td>
<td>N.J.A.C. § 2:76-2A.12, N.J.A.C. § 7:50-5.36</td>
</tr>
<tr>
<td>Vermont</td>
<td>Statewide (over 1MW)</td>
<td>CVR 30-000-056</td>
</tr>
<tr>
<td>New Hampshire</td>
<td>Statewide (over 30MW)</td>
<td>RSA 162-H</td>
</tr>
<tr>
<td>Nebraska</td>
<td>Statewide for solar easements</td>
<td>R.R.S. Neb. § 66- 911.01</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>Statewide for solar easements</td>
<td>60 Okl. St. § 820.1</td>
</tr>
<tr>
<td>Louisiana</td>
<td>State-owned lands</td>
<td>LAC 43:V.921</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>Guidance provided to local governments</td>
<td>N/A</td>
</tr>
<tr>
<td>North Carolina</td>
<td>Guidance provided to local governments</td>
<td>N/A</td>
</tr>
<tr>
<td>New York</td>
<td>Guidance provided to local governments</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Other

Seven states require a decommissioning plan under certain circumstances, none of which require recycling. In the case of Vermont and New Hampshire, only solar farms operating over 1 MW and 30 MW, respectively, need to provide a decommissioning plan. For Hawaii and New Jersey, only certain land types require a plan. Hawaii requires that Class A, B, and C agricultural land have decommissioning plans as well as financial security for the decommissioning similar to that of the BLM. New Jersey commercial farm lands and areas under the protection of the Pinelands Commission require a decommissioning plan for solar farms. Louisiana requires plans for all solar farms put on State land but does not require any plan for private land. In Nebraska and Oklahoma solar easements, which allow system owners to secure rights to continued sunlight access from neighboring property, require a decommissioning plan. Overall these plans only affect a small number of installations and they do not help support the buildup of solar recycling infrastructure.

Three states only offer guidance to local governments on how to deal with solar panel decommissioning and recycling. Massachusetts, North Carolina, and New York offer materials
such as estimations of decommissioning costs and ways to finance their policies. New York is considering moving towards a statewide recycling program financed through EPR, similar to Washington. S2837B, which passed the senate on June 13th 2018, would make it illegal to dispose of solar panels in landfills. Virginia has a requirement that local governments with ordinances on solar facility siting add a decommissioning plan but does not technically have a statewide decommissioning policy.

**International**

Few countries have acted on the solar waste issue. The European Union (EU) is the only entity to directly adopt PV specific waste regulations. Japan has invested into R&D initiatives for quite some time but has taken no legislative action. China has developed a model for their solar waste profile and invested heavily into c-Si recycling R&D through their National High-tech R&D Programme PV Recycling and Safety Disposal Research although no policy measures for EOL treatment are in place yet.

**The European Union: WEEE Directive**

Historically, the EU has been the leader in terms of PV deployment. This led to manufacturers selling in the EU market to begin developing EOL strategies. Due to the desire to create a sustainable and green solar market, solar manufacturers created PV Cycle in 2007 [4]. PV Cycle is a pan-European non-profit organization which offers recycling and collection services. Currently PV Cycle has over 250 members which account for 90% of the EU market [22]. As the international PV market grew the EU imported panels at a high rate. Panel manufacturers in China and other countries did not have the same sustainable mindset as the EU companies which formed PV Cycle. Advocates for PV recycling argued that regulation was needed to ensure that manufacturers promoting responsible EOL management were not put at an economic
disadvantage for their stewardship [4]. In 2012, the EU became the first to regulate PV EOL with a revision of the Waste Electrical and Electronic Equipment (WEEE) Directive [4].

The WEEE Directive originally came into effect in 2003 but proved to be too weak to cause meaningful impact on the e-waste issue [4]. The updated directive called for each of the 28-member states to develop their own PV collection and treatment regime but they must approach the issue from an EPR framework. Thus, those who sell PV panels on the EU market, regardless of where they are located, are liable for the collection, treatment, and disposal management.

Manufacturers must meet certain financial, reporting, and information responsibilities under the WEEE Directive [4]. Producers must cover the collection, which includes transportation and dismantling, and recycling costs associated with their panels. They must also help pay for public collection points and initial treatment facilities which separate the panels into their various components. Manufacturers have the choice of either joining a compliance scheme, such as joining PV Cycle, or develop their own. They must make monthly or annual reports on the number of panels sold, taken back, and brought to EOL treatment. Finally, manufactures have a responsibility to educate those who purchase from them on the EOL procedures and make it clear that panels need to be recycled.

All of these responsibilities add costs to the manufacturer which the WEEE Directive approaches in two ways. The first financing approach is through individual pre-funded or collective joint-and-several liability schemes while the second is through contractual arrangements between producers and customers. The EU implemented these financing methods after finding that the prefunding mechanism (having customers pay a fee at the time of purchase) was only useful for very low quantities of waste during the original WEEE Directive.

To help ease into the requirements, moving targets for collection and recycling were set. Between 2012 and today the EU has moved from a flat collection target of 4 kg per inhabitant to 85% of the total waste generated, as seen in Table 5 [4]. Due to the long lifespan of PV panels, the collection target will likely always be based upon the amount of waste generated during the
particular year rather than the amount of equipment put on the market. The recycling and recovery targets help promote high value recycling. High value recycling includes recovering a large mass percentage of each panel as well as recognizing that smaller components that are toxic, rare, or contain a high embedded energy are valuable to recycle as well [4].

Table 5. Annual collection and recovery targets (by mass percentage) under the WEEE Directive [4].

<table>
<thead>
<tr>
<th>WEEE Directive Version</th>
<th>Effective Years</th>
<th>Annual collection targets</th>
<th>Annual recycling/Recovery Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>2003-2012</td>
<td>4 kg/inhabitant</td>
<td>75% recovery, 65% recycling</td>
</tr>
<tr>
<td>Revised</td>
<td>2012-2016</td>
<td>4 kg/inhabitant</td>
<td>Start with 75% recovery, 65% recycling, 5% increase after 3 years</td>
</tr>
<tr>
<td>Revised</td>
<td>2016-2018</td>
<td>45% of all equipment put on the market</td>
<td>80% recovered and 70% prepared for reuse and recycled</td>
</tr>
<tr>
<td>Revised</td>
<td>2018+</td>
<td>65% of all equipment put on the market or 85% of waste generated</td>
<td>85% recovered and 80% prepared for reuse and recycled</td>
</tr>
</tbody>
</table>

While the WEEE Directive was a step in the right direction it is not perfect. Each member country has implemented EPR in a slightly different manner, making it hard for manufacturers to keep track of all of their legal requirements for EOL management. Overall, however, the US can look to the WEEE Directive as a success on the solar waste issue and use it to help guide policy discussion moving forward.

Japan

Japan is classified as an advanced market without PV specific waste legislation, similar to the US. Panels are currently handled by the Waste Management and Public Cleansing Act which serves as a general waste framework [4]. Japan, however, has been actively working on the issue. In April 2016 the Ministry of Environment (MOE) and Ministry of Economy, Trading and Industry (METI) released a report entitled Guidelines on Management of End-of-Life PV Panels which includes government projections for waste volumes in the coming years [4]. Their estimations
differ greatly from those presented in the IRENA and IEA-PVPS report mentioned earlier which indicates models for waste generation have some disagreement currently. The MOE and METI have presented roadmaps on how to promote proper EOL treatment using recycling which could lead to additional policy initiatives in the future.

Industry in Japan has been actively engaging in R&D in the solar waste area. Companies have collaborated with European countries and one company has developed a feasible recycling method [34]. See Figure S-4 for the New Energy and Industrial Technology Development Organization’s (NEDO) recycling method. While there is no law requiring them to, the MOE has encouraged manufacturers to be involved in the recycling of solar panel waste [34].

China

China, the current leader in solar panel capacity, has no legislative framework to address the issue. Like Japan, however, they are looking into the issue. The Chinese operated Institute for Electrical Engineering of the National Academy of Sciences (IEE) has developed its own panel waste projections [4]. Between 2012 and 2015 China’s National High-tech R&D Programme PV Recycling and Safety Disposal Research worked on thermal and physical R&D initiatives for c-Si recycling [4]. While solar waste is not an issue due to low volumes, China has made steps towards developing the technology it will need in the future.

Implementation of Solar Recycling Programs

Below the case for a national recycling program will be made along with various methods for implementation. When possible, comparisons will be drawn to the e-waste issue. First the various enforcement methods will be examined. Next, funding mechanisms and their success in other markets will be discussed. Following that, the universal waste classification and its role in transportation, handling, and cost savings. To ensure all states have access to the recycling resources they need, the placement of recycling facilities will be discussed along with the need
for a central authority on the issue. The section will conclude with a summary of where the infrastructure in the US stands as of today.

**Voluntary versus Mandatory**

Recycling programs in the US are largely a voluntary endeavor. Panels will only make it to a proper treatment facility if the owner is environmentally minded. Certain exceptions apply, as is the case in Washington, but they are not the rule. Voluntary recycling programs come in one of two general forms, direct and indirect. In a direct voluntary program the manufacturer operates its own recycling and logistics infrastructure, thus controlling the entire EOL management process [4]. An example of a direct voluntary program is First Solar’s CdTe takeback and recycling initiative. Indirect voluntary collection schemes have manufacturers contract service providers to collect and treat their panels [4]. The members of SEIA’s recycling working group that do not themselves operate recycling centers are indirect voluntary recyclers. Voluntary initiatives come about either due to environmental stewardship on the part of the manufacturer or an economic incentive to create a program.

Voluntary programs, while well-intentioned, have not been shown to produce desirable results on their own. During the 2000’s, the mature PV market of Germany had a voluntary collection scheme. It was found that consumers, especially residential households, were unlikely to engage with the process [4]. Voluntary programs also can put certain manufacturers at an economic disadvantage. If one company develops an environmentally sustainable PV design and a recycling mechanism for their panels it will likely cost more to install than another company that only produces the cheapest possible design with a much greater amount of hazardous or precious materials. This would result in more hazardous waste as toxic panels without a recycling mechanism would be landfilled [9].

In the EU, a mandatory program is in place through the revised WEEE Directive. The EU sets target goals for recovery that companies must comply with but they do not specify how the
company needs to comply with them. It also allows each member country to specify its own enforcement and implementation of the directive. This EPR legislative approach ensures manufacturers operate on a level playing field and there are no free riders. The most common method for compliance is through PV Cycle, which is explained below. Mandatory approaches can also come in a top down approach. In this situation the government would be responsible for either contracting out the collection, transport, and treatment of panels or it would need to build, operate, and maintain its own infrastructure. Mandatory methods ensure the proper disposal of hazardous materials and recovery of valuable resources and can help spark innovation by encouraging environmentally focused designs. The EPA would likely be the regulatory body ensuring compliance with a mandatory recycling program.

A public-private approach can bridge the gap between a voluntary and mandatory system. Public-private programs can operate in voluntary or mandatory environments as they help enforce compliance with relevant legislation and serve the interests of manufacturers. The best example of a public-private approach is PV Cycle. In response to the WEEE Directive PV Cycle was formed by industry leaders to help companies with compliance and facilitate takeback and recycling programs across the EU [34]. After the WEEE Directive was revised to specifically target PV panels PV Cycle switched from operating under a voluntary scheme to a mandatory one. Paid for by the companies that join its program, it offers over 300 collection locations as well as its own receptacles, collection, transport, recycling and reporting of panels [4]. PV Cycle demonstrates how a public-private method can work well under an already established PV recycling legislative framework. It is possible that the SEIA recycling program could serve a similar function as PV Cycle in the US.

While a mandatory recycling program would ultimately result in a greater recycling rate of panels it is unlikely that it would be implemented. Solar waste can be compared to the e-waste issue. The volume of e-waste is much larger than solar panels and no federal mandate for recycling exists. The US operates in a different political manner than the EU and trying to adopt
a similar program would be extremely difficult. Instead, like in the e-waste issue, the most productive policy efforts will come down to the states.

Many states have implemented e-waste laws relating to landfill bans or recycling programs as seen in Figure 8. While certain states include more types of e-waste in their legislation than others, it is clear that many states are concerned about the issue. Twenty five states have implemented an e-waste recycling program [35]. Of these twenty-five, twenty-four use an EPR model. California uses an advanced recycling fee (ARF) model instead, which is paid for by the consumer.

![Map of the United States showing states with e-waste landfill bans, recycling programs, or both.](image)

**Figure 8.** States with some form of e-waste landfill ban (blue), e-waste recycling program (yellow), or both (green) [35]–[37].

States with existing e-waste landfill bans or e-waste recycling programs might be more receptive to PV recycling. If enough states pass PV recycling legislation then a federal mandate might be plausible. Until then efforts should be made at the state level to pass similar landfill bans and recycling programs to encourage growth of the PV recycling industry.

**Funding Mechanisms and Costs**

The implementation of solar recycling programs come with costs but several financing options exist. The costs associated with the program can be broken up into three systems: the
physical, the financial processing, and the management and financing. The physical system includes the collection, storage, treatment, recovery, recycling, and disposal of the panels [4]. The financial processing system determines the amount of recovered material from the recycling process and the cost of operating the system. The management and financing system determine the administrative costs for the system. These costs do not need to be paid for by the same entity necessarily. Ideally the revenue from collection, recycling, and treatment fees will fully fund the implementation of the system.

The legislative trend for recent PV specific legislation inside and outside of the US is to utilize an EPR approach for recycling. This mandates that the “producer”, meaning the manufacturer or the entity selling the panel to the “consumer”, is responsible for organizing the decommissioning, recycling, and disposal process. This legislative approach can be seen in Washington’s SB 5939, New York’s S2837B, and the WEEE Directive. Many states use EPR financing approaches for the e-waste issue as well. To the knowledge of the author, no regulatory PV specific recycling program has been enacted without an EPR framework. For that reason, only EPR methods for funding the system will be discussed below.

EPR approaches have the option to either have the producer or consumer pay for the recycling. The most popular methods include producer-financed compliance, consumer-financed upfront recycling fee, and consumer-financed EOL [4]. These methods can either be in the form of a Pay As You Go (PAYG) or Pay As You Put (PAYP) approach. In PAYG, the collection and recycling of EOL panels is paid for by the market participants. PAYP instead is financed through an upfront fee predicting the costs for recycling in the future. PAYG involves shared, real time costs while PAYP involves individualized, estimated costs.

A producer-financed compliance funding mechanism requires manufacturers to either join a compliance scheme to share the costs of recycling with other members, such as with PV Cycle, or handle all costs individually. Due to economies of scale, joining a compliance scheme costs less than running internal programs. One study found that joining a compliance scheme reduced
the total cost of recycling c-Si panels by 55.28% and CdTe by 2.28% [12]. The difference for c-Si is more pronounced due to the high cost of processing which will be explored later. Due to shared costs and infrastructure, costs for recycling can change frequently to reflect the flow of waste to the facilities and revenue from selling recovered materials [4]. The fees associated with this form come in various forms. For example, utility solar farms could charge a small fee for each kWh of power produced to cover costs.

Consumer-financed upfront recycling fees are an example of PAYP in action. In this method the manufacturer predicts how much it will cost to recycle the panels in the future and charges the customer that value upfront. This form of funding is generally associated with internal recycling programs rather than a compliance scheme. For example, First Solar operates on a consumer-financed upfront recycling fee. Consumer-financed EOL funding mechanisms differ by deferring the cost of recycling until the panels are decommissioned. This does not help industry build up the infrastructure they need and can cause consumers to try to avoid recycling in order to save money.

Consumer-financed methods could be problematic for implementation in the future as it will be difficult to predict the costs associated with the large influx of waste during the next few decades. PAYG methods are preferred to PAYP as they are more flexible and help share the financial burden with other market players. A proportional PAYG producer-financed funding mechanism has proven to be effective in the EU and serves as the best approach for the US. Each state, however, should determine which method would work best for them.

**Classification as Universal Waste**

Designating PV panels as universal waste can facilitate the transport of EOL panels as well as reduce the amount of administrative burden for manufacturers, logistics providers, and other entities working to responsibly recycle the panels. PV panels contain numerous hazardous materials and the classification of PV waste as universal waste would help streamline hazardous
waste requirements while still ensuring proper disposal. This effort could come at either the state or federal level.

Federal standards for universal waste management are found in 40 CFR part 273. It describes the applicability of the standards to batteries, pesticides, mercury containing compounds, and lamps. Transportation of these materials is not subject to hazardous waste manifests which track the hazardous waste from the time when it leaves the generator site to when it reaches the management site [38]. This reduces the amount of paperwork required to pick up and transport the waste. Additionally, universal waste transporters are able to be stored at transfer facilities for up to 10 days without being designated as universal waste handlers, giving them greater ability to bulk items for transport and decide optimal shipping times [38]. If the waste is being exported for disposal in other countries it is subject to the hazardous waste standards set forth in 40 CFR part 272, subpart H. The PV recycling industry would benefit greatly from these requirements rather than stricter hazardous waste requirements.

PV recycling requires large amounts of panels to make the process financially viable (which will be discussed in detail later). Certain recycling centers currently only operate a few days a week as running the process every day on a few panels is expensive. Having the ability to bulk together shipments of PV waste for transport to recycling centers would help recycling centers make more money and could help encourage additional investment into the industry.

Classification of PV panels as universal waste is not unprecedented. California passed SB No. 489 designating PV panels as universal waste although it has not implemented it yet. The legislature intended for SB 489 to “[f]oster a comprehensive and innovative system for the reuse, recycling, and proper and legal disposal of end-of-life photovoltaic modules” [39]. Draft text was released on August 21st, 2017 by California’s DTSC. In the draft it specifies that PV waste can only be considered universal waste if it meets the hazardous waste requirements under RCRA’s TCLP and is not damaged to the point that it is no longer recognizable as a PV module [40]. The draft also allows for less restrictive transportation and temporary storage of PV modules.
The SVTC has been critical of the way California plans to treat PV waste as universal waste. If PV waste is handled similar to e-waste, they argue, then PV waste will have the same problem of being shipped off to foreign countries for disposal or recycling [41]. A federal bill, HR 5579, known as the Secure E-waste Export and Recycling Act (SEERA), would have limited the ability for waste to be shipped to other countries and promoted responsible recycling practices in the US. The bill was introduced in the House and subsequently referred to the House Committee on Foreign Affairs but has not come out of committee review. The PV industry has the chance to do what the electronics industry did not: offer responsible take-back and recycling programs. Classification of PV waste as universal waste can help but it needs to be done in an environmentally friendly manner.

Placement of Facilities

The placement of treatment and storage facilities will contribute substantially to the economic and environmental success of the recycling program. The transportation and processing of panels at their EOL requires a certain amount of energy. Thermal and chemical processes require energy intensive procedures that can partially counteract the energy saved from using solar panels over fossil fuels, known as the avoided burden [42]. Additionally, if panels need to be transported far distances in order to make it to recycling centers the burden of recycling could outweigh the benefit from an energy perspective [43]. A breakdown on the avoided and recycling related burdens is shown in Figure 9.
The desire to minimize the environmental burden creates the need for a central planning authority to coordinate the location of recycling centers throughout the US. This further supports the need for a national compliance scheme similar to that of PV Cycle. Optimal placement of recycling locations should apply to both manufacturing scrap and EOL modules as some smaller manufacturers might be unable to build an internal process to handle their own scrap [45]. The position of the central authority in relation to the rest of the PV market can be seen in Figure 10. The central authority needs enough of an outside presence from the industry to be able to independently determine the optimal location of facilities and help contract out the work necessary to maintain the system.

**Figure 9.** Relative contributions of recovered materials to the potential benefits (left) and relative contributions of the recycling processes to the environmental burdens (right) of first generation (a) c-Si and (b) CdTe recycling processes [44].
Figure 10. The role of a central planning authority in relation to the PV market (encompassed by the dashed line) [45].

Governments or industry partnerships can serve as a central authority. PV Cycle serves as the central authority for the EU, contracting out work and planning the opening of PV specific facilities. The environmental and economic benefits of utilizing a central planning authority outweigh its absence regardless which type of central authority is chosen. It is possible that the US EPA could serve as the central authority and bring various cohorts such as the SEIA recycling program and Recycle PV together to help organize facility placement.

The placement of facilities has been a topic of research among academics recently. Recent studies looked into the optimal placement of facilities in Germany [43], [45] and in New York [42]. While their methods will not be discussed here their results can be seen in Figure S-1 and Figure S-2 of the supplementary information. The Germany study was carried out by members of the BNL who could help determine optimal locations within the US. While more research will need to be done the methods from these studies and others can help expedite the planning for a national program with many complex variables.
Current US Infrastructure

PV recycling in the US is a growing industry with many actors but few plants are capable of handling large quantities of panels. The primary actors in the recycling industry are general waste electronic companies rather than solar manufacturers. Figure 11 shows the location of recycling centers throughout the US and what type of panel they process. Note that this may not include all centers but these represent the major recyclers. One recycler, Cleanlites, did not respond with their locations that handle PV waste although they do accept panels. See Table S-1 for links to the companies’ webpages and exact locations.

<table>
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<td>Green Century Recycling</td>
<td>8</td>
</tr>
<tr>
<td>SolarSilicon Recycling Services</td>
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**Processing Type**
- All panels
- c-Si only
- CdTe
- Silicon recycling

**Figure 11.** Current PV recycling location and companies in the US.

Two prominent groups have formed to facilitate the buildup of US PV recycling infrastructure. The first, SEIA, has already been mentioned. The SEIA National PV Recycling Program brings companies together in order to meet recycling needs. Once a manufacturer joins onto their program they gain access to partnered recycling facilities at a discounted rate along with other benefits such as market research, single point contact with recyclers, and minimum waste volume aggregation with other companies [46]. SEIA has partnered with four companies to
provide recycling services to their members. Green Century Recycling, First Solar, and Cleanlites are all current partners while their relationship with ECS Refining is in question as the company went out of business on June 29th of 2018 [46], [47]. SEIA has proven to be a successful organizing group for the voluntary recycling of solar panels across the country and will continue to improve US infrastructure in the future.

The second much smaller and more recent group is Recycle PV. Recycle PV is a collaboration of Solar CowboyZ, a renewable energy consultant firm, Rinovasol, a restoration and recycling firm primarily located in Germany and China with plans to expand further in the US, and PV Cycle, the non-profit recycling company for the EU [48]. Like SEIA’s program, Recycle PV aims to include “solar panel manufacturers, installers, distributors, utilities, solar system owners, developers and solar finance companies” [49]. While they do not have the same US based industry presence as SEIA they have a key partnership with PV Cycle which brings invaluable insight to the world of PV recycling. In August PV Cycle plans to open a dedicated c-Si recycling plant in Arizona that can handle up to 10,000 pounds per day and following a successful pilot run expand to two other locations to provide coverage for the northeast and southeast [50]. This plant will accept panels from across the country and could serve as one of the most successful c-Si recycling initiatives.

Other companies and recycling firms operate outside of these two groups. Solar manufacturers are not required to join into these groups and some operate small internal scrap recycling programs. Silicon recycling firms, metal refining companies, general waste recyclers, e-waste recyclers, and more all play a role in preventing PV waste from reaching landfills. They will continue to be the primary recyclers of panels in the short term until robust PV specific infrastructure can be assembled.

Overall while the PV recycling infrastructure in the US is continuing to mature, it is not prepared to deal with the massive quantities of waste that will be generated in the future. Careful
planning and coordination between all stakeholders will be necessary in order to ensure that panels do not end up in landfills and that recycling makes environmental and economic sense.

**Issues Regarding Implementation of Recycling Programs**

The main barrier to building recycling infrastructure in the US is the economic viability of the process. Even with funding mechanisms in place, companies will need to develop more cost-efficient methods and practices for recycling. R&D initiatives can aid the growing industry but a focus on scalability and partnerships with national laboratories will be most beneficial with limited resources. Additionally, historical waste poses the issue of who is responsible for its remediation and what happens in mandatory recycling programs when a company closes down.

**Economics**

With the EOL management policies in place, the recycling industry could thrive and create numerous jobs, but currently there is no strong economic incentive to recycle. The reclamation of valuable metals such as copper, aluminum, silver, and nickel, rare metals such as gallium, indium, and germanium, and other components such as silicon and glass could generate $450 million worth of raw material by 2030 and up to $15 billion globally by 2050 [4]. A large recycling industry could help support the growth of a repair and reuse service industry, waste collectors, pre-treatment companies, general waste utilities and regulators, as well as producers and contractors [4]. Currently low waste volumes prevent recycling from being economically viable [51].

Some panel types are more viable to recycle than others. c-Si panels, which contain relatively low amount of valuable metals (silver being the only major valuable component), have been shown to give a much lower return than thin film technologies [52]. Only four large scale recycling processes have been developed by companies. The first one, for c-Si panels, was developed by Deutsche Solar in 2003, the second, for CdTe panels, by First Solar in 2005, the
third, for c-Si, by Veolia in partnership with PV Cycle in 2017, and the fourth, for c-Si, by Recycle PV [12], [50], [53].

Deutsche Solar decided to shut down its recycling operation due its poor economic viability while First Solar has added an internal recycling center to each of its production facilities to handle manufacturing scraps and panel take backs [12]. Veolia opened the first dedicated PV recycling center in France to handle all of the countries c-Si recycling mandated by the WEEE Directive. The plant aims to handle 4,000 tons by 2022 but it is too early to tell how successful their process is. Recycle PV has not yet opened their facility and not much is currently known about their process. Traditionally, landfilling has always been a cheaper option than recycling for c-Si panels [52]. The Veolia and Recycle PV plants for c-Si specific recycling will gather better economic data on the long-term economic viability of the process in the modern day. A European study of c-Si recycling found that on average a recycling plant would lose roughly $1 per kilogram of PV waste [52]. The case for recycling will be hard to make without dramatic reductions in cost or increases in recovery of valuable materials.

There have been numerous suggestions on how to make the process economically viable. D’Adamo et al suggests several options for increasing the viability of c-Si recycling including developing methods to easily recycle thin film alongside c-Si, utilizing economies of scale, and increasing the purity from recycled silicon. Dustin Mulvaney, who helped create the SVTC report, states that recycling will not be viable without a carbon tax [54]. He points out that recycling is inefficient economically currently because it is cheaper to use raw materials even though they are more energy intensive [54]. If the energy cost, and thus the amount of carbon required, is factored into the cost through a carbon tax recycling would likely be the cheaper and preferred method for panel production. The IEA-PVPS Task 12 report on trends in PV recycling notes that a large, centralized facility rather than small, internal recycling processes would make the process more viable [14]. One study found that once a plant can operate at a rate of 20,000 tons of PV waste per year the process of recycling c-Si panels can become profitable [52]. Due to large logistical
costs per panel associated with returning small residential solar systems, some have suggested that initial efforts be focused on the recycling of utility scale installations [55]. Goe et al suggest that a recycling mandate, in order to produce an economy of scale, with collection rate targets, increased gate fees (the amount of money required to dispose of waste at a landfill), and subsidies for recycling technology could make widespread collection of PV waste economically viable. The recycling of scrap alongside EOL panels can also help increase the financial stability of a plant [12]. Much more will need to be done in order to make recycling an economically viable EOL management option.

In addition to the economic viability of the process itself, competition between recyclers can both increase and decrease the profitability of a recycling center. Recycling centers need large quantities of waste in order for their processes to make financial sense. If too many recycling centers open in one area each will split the available waste and profitability will decrease. Competition also incentivizes recyclers to improve upon their process and logistics chain in order to gain an advantage over nearby plants. Reaching a balance between a healthy amount of competition, adequate coverage for areas with high levels of waste, and processing for each type of solar panel will be key to the success of the industry’s economic viability. This again supports the argument for a central authority to help plan the country’s recycling infrastructure.

The cost of developing a recycling center, however, should be compared to the cost of landfilling. In addition to the loss in revenue from not recovering precious metals if panels end up in a landfill, they are expensive to build and maintain. Landfills cost millions of dollars to construct and maintain which can be a hefty determent for areas even with plenty of land available. Recycling centers take up less physical space than a landfill, reclaim metals, and cost less to build and maintain.
Research and Development of Recycling Technology

Numerous R&D projects are going on in relation to PV recycling but the US is falling behind. The IEA-PVPS did a survey of the international community and found 178 relevant patents [14]. One hundred and twenty eight were for c-Si recycling methods while only 44 were related to thin film technologies and the remaining six being related to other PV types. See Figure 12 for the breakdown on each country. They also found that the majority of these patents were coming from the Asian market with China, Japan, and Korea having over 75%. The US in total only had 5 patents for c-Si and 12 for thin film. The larger number of thin film patents are at least in part due to the success of First Solar. While patents do not tell the whole story about PV recycling development (e.g. a company is working on cutting edge technology and does not want to file yet), it is clear that the US is not leading, especially for c-Si.

![Figure 12: Number of effective PV module recycling patents for (a) c-Si and (b) thin film technologies by country/collection [14].](image)

The development of cheaper and more environmentally friendly processing techniques will be imperative to the success of the industry. Currently the US is not investing much money into federal PV recycling R&D initiatives. Efforts from the BNL and the NREL have made valuable contributions to the understanding of recycling plant economics and panel life cycle analysis but
process R&D is lacking. In their recycling technology trends report, the IEA-PVPS outlines some of the most important process and materials R&D in the upcoming years [14]:

- Development of processes which recycle nearly 100% of module mass (current rates are between 90 and 95%)
- Recovery of high purity glass and silicon
- Integration of recycled products into the supply chain
- Scale up of promising laboratory scale processes
- Replacement of EVA as an encapsulant with a recyclable material

The NREL is the best equipped to spearhead projects on materials and design development as they have dedicated device design projects already. Efforts should be made to collaborate with industry in order to share device designs that are easily recyclable. Other federal R&D efforts on solar energy should look into adding recycling process R&D into their funding opportunities. One such example is explored below.

The DoE Solar Energy Technologies Office (SETO) can move to include PV recycling R&D into their funding opportunities directly and indirectly. For the 2018 fiscal year, funding opportunities by the office focused on increasing performance, reducing materials and processing costs, and improving the reliability of PV cells, modules, and systems in an effort to reduce panel cost [56]. Many of these initiatives touch on issues that affect recycling. As they fund projects to reduce materials and processing costs the recyclability of the panel should be considered. Materials that are easily recyclable and designs that facilitate automated recycling will be highly desirable 30 years from now as the panels reach their EOL. In future years SETO should look into adding an additional focus area on the development and scaling of recycling processes and incorporate recycling friendly principles into their funding decisions.

International efforts can also serve as inspiration for US R&D. As outlined earlier, Japan has invested into national R&D efforts with success. The US should look at the Japanese priorities for process development for guidance on how to move forward. China holds the most patents
related to solar recycling in large part due to their national c-Si R&D program. Without federal R&D efforts the US may continue to fall behind China and may need to rely on Chinese technologies to deal with the solar waste issue in the future. While concerning levels of solar waste in the US are still several years away, R&D initiatives also can take several years. If action is taken now the US can be technologically prepared to deal with the solar waste issue.

**Orphan and Historical Waste**

For states that pass mandatory recycling programs, orphan and historical waste will pose liability problems unless they are directly addressed. Orphan waste consists of PV panels that were produced by companies that are no longer in business [4]. Thus, they cannot be held liable for the disposal of their panels. This presents a problem for an industry with a very long lifespan for its products. Historical waste consists of PV panels that exist on the market and were installed before the waste management legislation was enacted [4]. The Italian method for dealing with orphan and historical waste is explained below.

On March 14th, 2014 Italy passed Legislative Decree No. 49 to implement the WEEE Directive [22]. This decree outlined the differences between new and historical waste as seen in **Error! Reference source not found.**. For historical residential systems, producers (in this case meaning manufacturers) are responsible for organizing the collection and transport of panels to recycling centers through a system of direct proportionality [22]. This direct proportionality approach assigns a percentage of historical waste to be managed by each manufacturer based on the weight percentage of new panels put into place the year the decree was passed. For new residential panels, manufacturers have the option to individually organize recycling efforts or utilize a collective system in order to meet their weight percentage recovery mandates [22]. Orphan waste sources are covered by the collective system. These EPR methods ensure that residential PV systems are properly disposed of.
Utility scale responsibility operates in a different manner. For historical utility waste the consumer is usually tasked with proper disposal and recycling at their own expense. Manufacturers of the panels that are used in existing solar farm are only responsible if they supply a replacement for a panel. This ensures that no orphan waste is generated. New utility scale waste is left to the responsibility of the manufacturer unless they are able to arrange a voluntary agreement with the utility solar farm to provide alternative methods of financing [22]. While the Italian method will not carry over directly to any US recycling method it can serve as inspiration for how to properly handle orphan and historical waste.

In the US the e-waste issue has also dealt with orphan and historical waste. Determining liability for these waste groups is important to ensure a level playing field for all entities designated as responsible for financing their recycling and disposal [57]. Maryland and California gets around the issue of orphan waste by collecting funds in through AFR. The ARF revenue goes into a fund to finance recycling [57]. It does not matter if a company goes out of business as the government can contract out transportation and recycling services with the money already collected. Maryland
started a pilot program in 2006 for the recycling of desktop computers, laptops, and computer monitors. Manufacturers were required to pay an annual fee of $5,000 unless they implemented a take back program in which case the fee was reduced to $500 [57]. The money generated went into a fund to help local governments finance collection and recycling. This method does not need to determine who manufactured the product and thus solves the orphan waste issue so long as they have sufficient funds.

Policy Recommendations to Promote PV Recycling

A federal mandate for PV recycling is unlikely when no mandate exists for e-waste. It will be up to the states in order to ensure that PV waste does not end up in the same situation of trying to adopt reactionary measures that do not solve the issue. States should adopt a mandatory, EPR recycling program approach. At a minimum, states that adopt PV specific recycling mandates should develop a recycling friendly atmosphere for industry, minimum collection standards at the current level of the WEEE Directive or higher, a landfill ban, a reporting system, and an informational system for the public’s benefit.

State policy makers should look to Washington’s SB 5939 as an example for how to finance and create a reporting program through their energy or environmental departments. States looking to educate the public on PV recycling should consider New York’s S2837B. Each state should examine the funding mechanisms available and select methods that work best for their needs. The top 10 states (CA, NC, AZ, NV, NJ, MA, TX, FL, UT, and GA, see Figure S-3) which represent roughly 80% of national capacity should prioritize developing a recycling framework that includes methods for dealing with orphan and historical waste. Funding mechanisms such as ARF and allowing manufacturers to join compliance schemes have proven to be effective.

When state mandates are not politically viable for a state, promotion of voluntary recycling programs is second best. Offering some economic incentive to utility and residential solar owners
to bring their panels to a recycling center could help curb waste. In all policy efforts a C2C approach should be prioritized. Where possible redesign and upcycling efforts should be incentivized alongside recycling.

Universal waste designation is likely to occur at the state level rather than the federal level as well. As the PV waste volume in the US is not large right now it makes economic sense for recycling centers to operate at limited times. Classification of intact EOL PV panels as universal waste would help waste handlers and recycling centers grow their infrastructure as less money would be wasted on administrative paperwork, allow for bulking and temporary storage of waste, and still properly treat PV panels. As California’s efforts have shown, states which want to give their industry an economic advantage with universal waste classification should start the process early.

Federal policy efforts can help assist state leadership. The EPA has served as a central authority for the e-waste issue by bringing together various stakeholders in the EPA Electronics Forum [58]. The EPA can organize a similar forum with stakeholders such as the SEIA, Recycle PV, solar manufacturers, NREL, BNL, academia, NGO recycling advocates, PV and non-PV recyclers, and states. The focus of the forum should be on how to grow the PV recycling infrastructure, encourage state adoption of recycling legislation, identify gaps in R&D, and encourage dialogue between the stakeholders.

Additional R&D funding for PV recycling is necessary for the US to stay competitive with the rest of the world. The NREL and BNL can spearhead research on process development and economic analysis while other organizations with renewable energy funding prioritize funding projects related to the following areas:

- Development of processes which recycle nearly 100% of module mass
- Recovery of high purity glass and silicon
- Integration of recycled products into the supply chain
- Scale up of promising laboratory scale processes
• Replacement of EVA as an encapsulant with a recyclable material
• Minimize recycling process cost and energy intensity

Proactive PV recycling policy measures can ensure that valuable materials are recovered, waste is diverted from landfills, solar moves towards a sustainable closed loop production standard, and manufacturers keep their green branding. While the US has some time before large quantities of waste are generated, now is the time to implement and iterate on solutions.
References


EPA, “Hazardous Waste Management Facilities and Units.”


North Carolina Clean Energy Technology Center, “State Regulation of Solar Decommissioning.”


legislation.aspx.


Figure S-1. Optimal site location and waste flows from utility scale power plants to recycling centers in central Germany [45].
Figure S-2. Optimal site location for recycling centers in New York depending on the mandated level of collection and processing. Scenarios A, B, and C correspond to a 100%, 50%, and 25% collection rate respectively [42].
Table S-1. Location and webpages to various PV recycling companies in the US.

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<td>Morgen Industries Inc</td>
<td>701 Penhorn Avenue, Building 7 Secaucus, NJ 07094</td>
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<td>Silrec Corporation</td>
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Figure S-3. Solar installed capacity by each state as a percentage of the national total of 55.9 GW. Data taken from SEIA.
Figure S-4. Schematic of automatic separation recycling of multiple types of panels developed by NEDO [4].