A COMPARATIVE ANALYSIS OF TECHNOLOGY AND POLICY OF HIGH-VALUE PV RECYCLING: THE UNITED STATES VERSUS THE EUROPEAN UNION

by:

Katherine Finley Collins

Departmental Honors Thesis

Appalachian State University

Submitted to the Sustainable Technology and the Built Environment Honors Program

in partial fulfillment of the requirements for the degree of

Bachelor of Science

December 2023

James Houser, Ph.D., Thesis Chair

Marie Hoepfl, Ed.D., Second Reader

Jeremy Ferrell, Ph.D., Second Reader

Rita Joyner, Ph.D., STBE Honors Program Director

Abstract

The global energy sector is amid a solar photovoltaic (PV) energy boom (International Energy Agency [IEA], 2023; Sharma et al., 2019). PV technologies are crucial for a clean energy future; however, in 2021, PV panels were the fastest growing stream of electronic waste (E-waste) (Majewski et al., 2021; Röpke, 2022). There is limited infrastructure and policy to manage End-of-Life (EoL) PV panels, and experts report that there will be an accumulated mass of 60 million to 80 million tons of EoL PV panels by 2050 (Aleid et al., 2023; Chowdhury et al., 2020; Ganesan & Valderrama, 2022; Majewski et al., 2021; Peplow, 2023). This study analyzed high-value recycling of crystalline silicon (c-Si) panels because they make up 95% of the global market (El-Khawad et al., 2022; Feldman et al., 2022; Majewski et al., 2021; Peplow, 2023). High-value PV recycling processes have been selected because they achieve higher rates of material recovery than other methods, via removal of the ethylene vinyl acetate layer (EVA), otherwise known as delamination (Chowdhury et al., 2020; Deng et al., 2022; El-Khawad et al., 2022; Ganesan & Valderrama). Three facilities performing high-value recycling of c-Si panels in the European Union (EU) and two facilities within the United States (US) were selected for comparison: Veolia of France; Tialpi Srl of Italy; FLAXRES GmbH of Germany; We Recycle Solar of Arizona; and SOLARCYCLE of Texas. The facilities were compared by handling capacity, delamination methods, and rates of recovery. PV EoL legislation was analyzed within the US, the EU, and selected states. This study found that only the EU has specific legislation addressing the PV panel lifecycle (Curtis et al., 2021; Ganesan & Valderrama, 2022). The gap in nationwide recycling rates for the EU and the US is wide, at just 10% in the US (Curtis et al., 2021; Echo Environmental, 2022; Hurdle, 2023; Kart, 2023; Peplow, 2023) compared to 80% in the EU (Majewski et al., 2021; Peplow, 2023; VCT Group, 2022; Weckend et al., 2016), but the

facilities within the US are comparable to those in the EU in terms of handling capacity and rates of recovery. However, the price difference to perform high-value PV recycling in the two nations is significant. In the US, the price range is $15 to $45 USD per panel (Curtis et al., 2021; Wallace, 2023), with SOLARCYCLE, Inc. charging $18 USD per panel (Hurdle, 2023; Wallace, 2023) and We Recycle Solar, Inc, charging $20 USD (Hurdle, 2023; O'Brien, 2022; Wesoff, 2022). The EU, on the other hand, has prices down to around $0.70 USD (California Solar + Storage Association [CSSA], 2020; Curtis et al., 2021). This study was unable to confirm why the price gap between the EU and the US is so wide but hypothesized that it is due to the lack of supporting policy and economic incentives within the US.

Table of Contents

Table of Abbreviations

Abbreviation	Definition
B2B	Business-to-Business
B2C	Business-to-Consumer
c-Si	Crystalline Silicon
EoL	End-of-Life
EPA	Environmental Protection Agency
EPR	Extended-Producer Responsibility
EU	European Union
EVA	Ethylene Vinyl Acetate
E-Waste	Electronic Waste
PTE	Polyethylene Terephthalate
PV	Photovoltaic
PVF	Polyvinyl Fluoride
RCRA	Resource Conservation and Recovery Act
RE	Renewable Energy
TCLP	Toxicity Characteristic Leaching Procedure
US	United States
USD	United States Dollar
WEEE	Waste Electrical and Electronic Waste

Introduction

My interest in photovoltaic (PV) panel recycling began during an internship for Moss & Associates in their solar division, where I spent five months working on a 75 MW fixed-mount PV site at the Kennedy Space Center. The client for this project was Florida Power and Light (FPL), and I was fortunate to spend much of my time working with upper management and FPL. During a quality control walk-through of a PV array, I began asking the attending members of FPL about who would be decommissioning the site 25 to 30 years down the road. Although decommissioning is not a part of Moss & Associates' responsibilities, I was expecting FPL to know some portions of the site's lifecycle and which contractors would be handling it. However, they were not sure, and this interaction got me thinking about the lack of discussion around solar PV panels' lifecycles. I realized that I could name quite a few solar manufacturers, installers, and utility companies, but none that provided decommissioning or recycling services. My curiosity in solar PV's lifecycle was reinforced when I returned to campus and studied Sustainable Resource Management with Professor Kevin Gamble. In this class I had the opportunity to learn more about the recycling of solar panels and the associated technical and economic problems, further sparking my interest. This study has allowed me to dive deeper into a subject that I am very passionate about and will hopefully allow others to learn about the necessity that is PV End-of-Life (EoL) management.

The management of solar panels' lifecycle is of rising importance as the number of PV installations continues to expand (Sharma et al., 2019). Now that solar can provide the cheapest new electricity generation for most parts of the world (Bojek, 2023), PV seems to be foundational in navigating our way toward a clean energy future with respect to greenhouse gas (GHG) emissions reductions. Yet we must take care to avoid creating a new environmental problem via mismanaged PV panels. Although higher grid penetration by PV will help combat the energy and climate crisis, the number of installed panels coming to EoL poses a problem with respect to E-waste, and subsequently a challenge for the global PV recycling infrastructure. As of 2021, PV waste was the fastest growing E-waste stream (Majewski et al., 2021; Röpke, 2022) and since then global PV capacity has only increased. There are varying predictions surrounding total numbers, but most experts have estimated that by 2050 around 60 million to 80 million tons of accumulated PV waste will need to be managed (Aleid et al., 2023; Chowdhury et al., 2020; Ganesan & Valderrama, 2022; Majewski et al., 2021; Peplow, 2023).

Problem Statement

Mismanagement of EoL PV panels has the potential to threaten the health of both the environment and people (Jain et al., 2023), and the growth of the PV industry will further burden our recycling and ecological systems if not controlled (Casey, 2023; Majewski et al., 2021). When a PV panel ends up in a landfill, it has the potential to leach its trace heavy metal to its surroundings (Casey, 2023; Majewski et al., 2021; Peplow, 2023). Furthermore, the lack of circularity in the lifecycle of PV panels will result in avoidable carbon emissions. PV EoL management must be a society-wide response and it is crucial to society's transition away from fossil fuels and into a clean energy future, with continuing expansion in PV adoption expected (Curtis et al., 2021). Therefore, techniques for reuse and recycling must be developed and/or improved worldwide.

Within the United States, current estimates report that less than 10% of PV panels are being domestically recycled (Curtis et al., 2021; Echo Environmental, 2022; Hurdle, 2023; Kart, 2023; Peplow, 2023). PV industry experts have reported that panels are being dumped in non-hazardous landfills or are just tucked away into storage facilities (Curtis et al., 2021; O'Brien, 2022; Wesoff, 2022). Some of this waste stream is also being exported overseas, usually to places that do not have solid waste regulations themselves (Echo Environmental, 2022). For the 10% that is recycled, the majority utilizes mass recovery processes, only removing the external components such as the aluminum frame and the copper wiring. High-value recovery processes, which retrieve silicon and other precious metals, are generally not performed (Curtis et al., 2021; Peplow, 2023). As of 2021, the National Renewable Energy Laboratory (NREL) reported that only two recycling facilities in the US were using high-value recovery processes and that they "found no federal statutes or regulations that expressly speak to recycling-based recovery of PV panels in the United States" (Curtis et al., 2021, p. 7). By comparison, the European Union (EU) has had PV-specific EoL regulations in place since 2012 and the export of waste to other countries has been prohibited. The EU has also banned the landfilling of PV panels and required 80% of PV panels to be recycled by weight since 2018 (Majewski et al., 2021; Peplow, 2023; VCT Group, 2022; Weckend et al., 2016).

Research Questions

This study was guided by two overarching goals: To investigate the status of PV panel recycling in the US and to contrast that with PV recycling practices in the EU. The study was specifically guided by the following research questions:

1. What legislation in selected EU and US states is facilitating EoL management of PV panels?
2. What delamination technologies are currently in use in high-value PV recycling facilities in these selected states?

3. What are the rates of recovery being achieved by these high-value PV recycling facilities?
4. What are the costs associated with the disposal of a PV panel in the selected states?
5. What strategies in use within these EU member states might be adopted within the US to expand the percentage of PV panels that are recycle domestically?

Significance of the Study

This study's purpose is to educate those involved in the fields of renewable energy (RE), recycling, solar PV, and environmental policy about the growing stream of EoL PV panels and the current state of PV recycling. As the solar industry continues to expand, the need to recycle solar panels becomes more pertinent. Society's transition into a zero-carbon future is reliant on solar technologies, alongside other RE solutions, and proper management of these resources is crucial to ensuring that they are, in fact, zero-carbon. Therefore, the recycling and recovery of valuable materials within PV panels is necessary to reduce carbon emissions associated with the extraction of materials, manufacturing, and EoL management of PV panels. A key step in achieving this reduction is to first inform individuals involved in the industry and policy of the problem. This study aims to be a steppingstone in bridging the gap between the PV EoL industry and the public.

Limitations of the Study

The main limitation for this study was the lack of publicly available information regarding US PV recycling facilities (Curtis et al., 2021; VCT Group, 2022) and their technological processes. Both facilities examined within the US do not release details surrounding their delamination processes, regarding this as proprietary information (Davis [We Recycle Solar], personal communication, October 9, 2023; Disruptive Investing & Saghei, A., 2023; Winicov [SOLARCYCLE], personal communication, October 13, 2023;). The gaps in data and the lack of research around the topic of PV recycling within the US (Curtis et al., 2021; VCT Group, 2022) created difficulties in comparing the US and the EU equally and on a year-by-year basis.

Another significant barrier to research and data collection was translating scholarly articles efficiently and effectively from French, Italian, and German into English. Google Translate and an AI translation software, DeepL, were utilized for this function where possible. However, these tools have their own limitations in scope, accuracy, and financial costs to the user.

The scope of the sample study focused on states within both nations that are operating high-value recovery PV recycling processes, along with their legislation around PV EoL management. Therefore, other states that may have stricter PV EoL legislation or many mass-recovery PV recycling facilities have been excluded from this study.

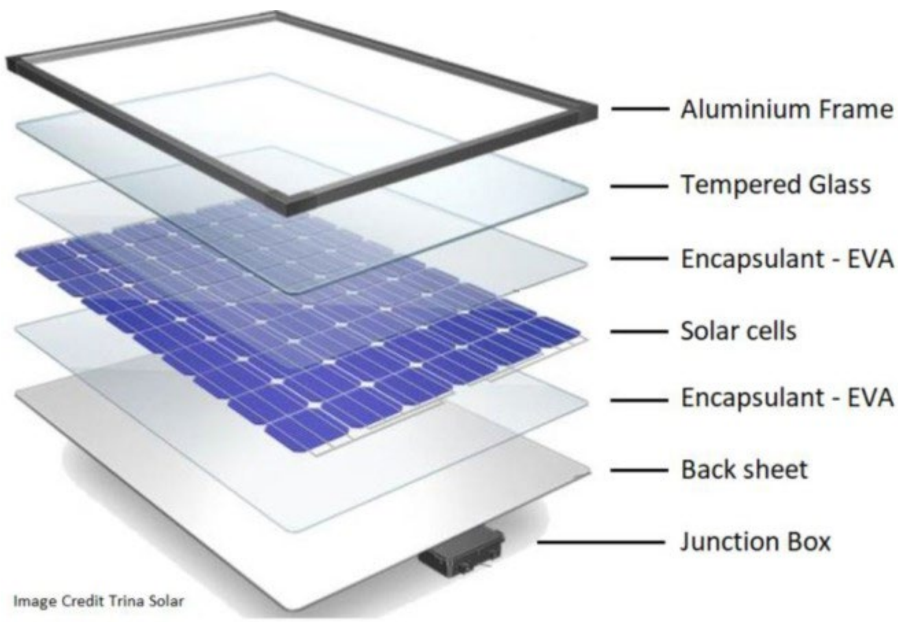
Review of Literature

Anatomy of a Crystalline Silicon PV Panel

This study is centered around the crystalline Si PV (c-Si) panel and its EoL management and recycling processes. Preliminary research revealed that c-Si panels have the highest market penetration, currently making up 95% of the global market share (El-Khawad et al., 2022; Feldman et al., 2022; Majewski et al., 2021; Peplow, 2023). Foundational to this topic is understanding the makeup of a c-Si PV panel. As shown in Figure 1, the major components of the panel are the front glass sheet, an encapsulant, silicon cells, copper wiring, a back sheet, an aluminum frame, and the junction box (Ecoprogetti, 2021; Peplow, 2023).

Figure 1

Components of a c-Si PV Panel (Deng et al., 2022, p. 2)



The encapsulant for the internal components consists of ethylene vinyl acetate (EVA) (El- Khawad et al., 2022; Ganesan & Valderrama, 2022; Majewski et al., 2021; Peplow, 2023). The back sheet is either polyvinyl fluoride (PVF), polyethylene terephthalate (PTE), or a combination of the two (El-Khawad et al., 2022; Majewski et al., 2021; Peplow, 2023). All three of these polymer products are different forms of plastic and help create the durable and watertight PV panels seen today (Peplow, 2023). Once all the components of the panel are put together, the panel goes through an air evacuation process and is heated until the EVA melts and fills the space between the front glass panel and the back lamination sheet (Majewski et al., 2021).

As per Majewski et al. (2021), the recyclable products from the panel can be broken down into an approximate weight percentage of the total:

- Glass, 68%wt
- Aluminum, 15%wt
- Silicon, 3%wt
- Copper cables, 1%wt
- Silver < 0.006%

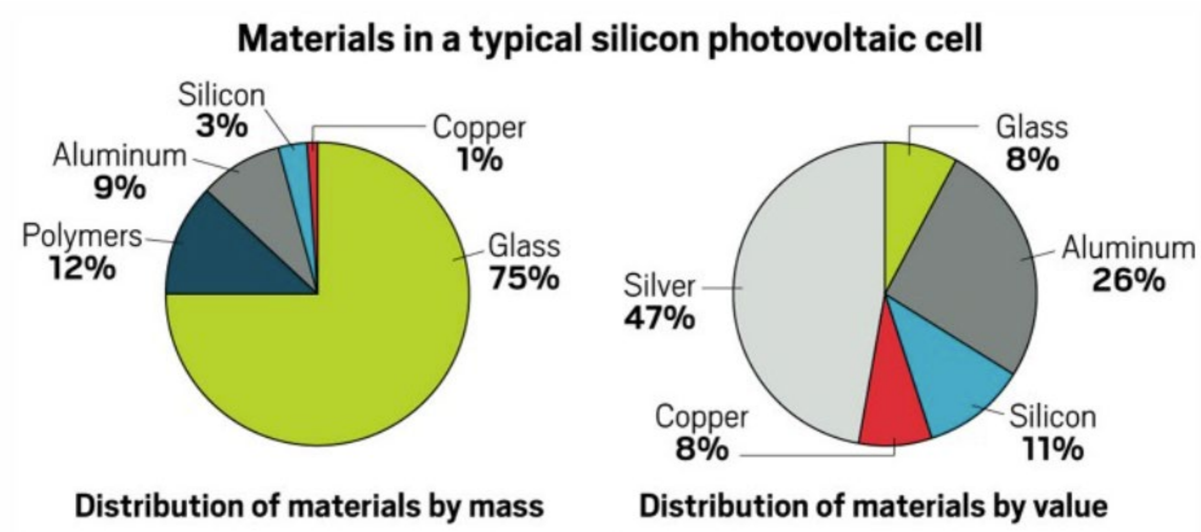
Even though silver has the smallest ratio of PV panel components by weight, it holds the most value, as shown in Figure 2. This research indicates that approximately 13% of the c-Si PV panel is not recyclable. The currently non-recyclable components are the EVA encapsulant, the PVF/PTE or PTE back sheet, and the trace elements of heavy metals (Majewski et al., 2021; Sah et al., 2023). According to Sah et al. (2023), the non-recyclable components within a c-Si PV panel comprise the following weight percentages:

- Tin, ≈ 0.12%wt
- Lead, < 0.1%wt
- EVA, ≈ 12.8%wt

It is the EVA that largely contributes to the technical difficulty of recycling the rest of the panel, due to its applications in the manufacturing process (Majewski et al., 2021). The lead and tin within the PV panel can create a health hazard in recycling processes if not managed appropriately (Casey, 2023; Jain et al., 2023 Majewski et al., 2021). Although these heavy metals represent a very small percentage of the PV panel, mass accumulation of panels in landfills should be avoided. One panel in a landfill may not pose a threat, but millions of tons of EoL PV panels will.

Figure 2

Material Distribution in a c-Si PV Panel (Peplow, 2023, para. 27)



Note: The calculations performed by Majewski et al. (2021) and Peplow (2023) differ at most by 7%.

PV Recycling Processes

There are two general methods for EoL recycling of c-Si PV panels: value recovery/ high-value recovery and mass recovery (Deng et al., 2022). Mass recovery results in a mix of unrefined materials through multiple stages of crushing the PV panel (Deng et al., 2022). The final products from a mass recovery process can only be used in low-value applications, such as sand blasting mixtures or aggregates for concrete and asphalt industries (Deng et al., 2022). High-value recovery refers to a recycling process that aims to recover the more expensive materials within the panel, such as silicon and silver (Deng et al., 2022). A high-value process does not downcycle the panel, and instead applies more complicated processes than its counterpart to produce refined materials that still have valuable applications (Chowdhury et al., 2020; Deng et al., 2022).

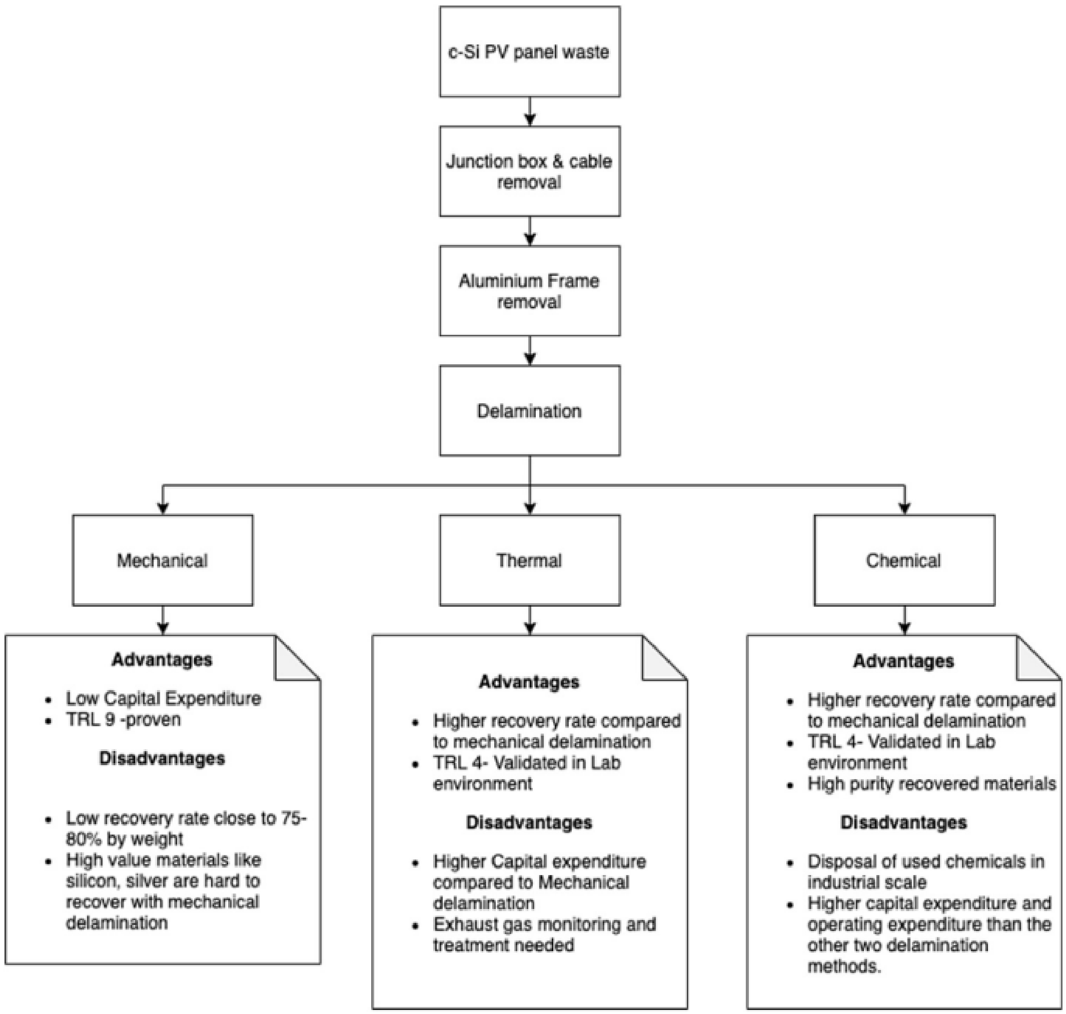
This study focused on high-value recovery because this methodology is the most effective in supporting a circular economy for PV panels (Deng et al., 2022; Ganesan & Valderrama, 2022; Peplow, 2023). The high-value recovery process can be broken into four main steps: (1) disassembly; (2) delamination; (3) material sorting; and (4) material extraction (Deng et al., 2022). Removing the EVA (delamination) is the most difficult stage of recycling a PV panel (Chowdhury et al., 2020; Deng et al., 2022), but is also the most critical step for high-value recycling (Ganesan & Valderrama, 2022).

Delamination Processes

The delamination process is imperative to achieving high rates of material recovery from the PV panel (Deng et al., 2022; El-Khawad et al., 2022; Ganesan & Valderrama, 2022), and as shown in Figure 3, can be approached via mechanical, chemical, or thermal methods (Chowdhury et al., 2020; Deng et al., 2022; El-Khawad et al., 2022; Ganesan & Valderrama, 2022). Research also indicates that a combination of methods can result in higher rates of recovery (Deng et al., 2022; El- Khawad et al., 2022). However, all three of the methods for removing the EVA encapsulant are energy intensive and can release a slew of toxic and hazardous materials (Chowdhury et al., 2020; Deng et al., 2022; Majewski et al., 2021; Tembo & Subramanian, 2023). Figure 3 illustrates the steps in high-value PV recycling, and breaks down the advantages and disadvantages of mechanical, thermal, and chemical delamination methods.

Figure 3

Comparison of Delamination Methodologies (Ganesan & Valderrama, 2022, p. 3)



Mechanical

Mechanical delamination is the most commonly used delamination method in commercial recycling facilities (Deng et al., 2022; Ganesan & Valderrama, 2022). There are a variety of different approaches utilized, such as high-voltage crushing, shredders, water jets, and vibrating knifes (Deng et al., 2022; Peplow, 2023). Usually, the first step is physical separation of panel components, such as removing the aluminum frame, junction box, and cables

(Chowdhury et al., 2020; Ganesan & Valderrama). The cables, junction boxes, and panels are then shredded, crushed, and tested for toxicity levels (Chowdhury et al., 2020). Typically, three to six runs through a series of shredders, crushers, millers, and grinders are necessary to fully break the panel's structure and EVA laminate (Deng et al., 2022). The crushing and shredding of panels produce toxic glass dust (Deng et al., 2022), because c-Si PV panels contain lead and tin (Chowdhury et al., 2020; Deng et al., 2022; Majewski et al., 2021; Sah et al., 2023). If not managed appropriately this can be a serious hazard to workers. Mechanical delamination processes by themselves are not linked to high rates of recovery, generally achieving around 75% to 80% recovery by weight (Ganesan & Valderrama, 2022).

Thermal

Thermal delamination uses extremely high temperatures to burn off the polymer-based EVA, PVF, and/or PTE (Deng et al., 2022; Majewski et al., 2021; Peplow, 2023). This process is very effective in facilitating clean separation of the remaining panel components (Deng et al., 2022). The complete removal of polymers results in high-purity glass, metal, and silicon free of polymer residue, better preparing these materials for secondary industries (Deng et al., 2022; Ganesan & Valderrama, 2022). However, thermal delamination processes require the highest energy inputs (Deng et al., 2022) and are subsequently more expensive to perform than mechanical processes (Ganesan & Valderrama, 2022). Thermal processes can also release toxic byproducts such as methane, carbon dioxide, carbon monoxide, lead, and hydrogen fluorides (Majewski et al., 2021; Deng et al., 2022; Shin et al., 2017). Proper exhaust, ventilation, and worker-protection mechanisms must be in place for thermal processes to be as non-hazardous to humans as possible.

Chemical

Chemical delamination relies on the application of a solvent to break down the EVA laminate (Deng et al., 2022; Peplow, 2023). There is significant research around the utilization of different chemicals. Chowdhury et al. (2020) explored trichloroethylene, toluene, and phosphoric acid paste for delamination. Shin et al. (2017) looked at the use of nitric acid, potassium hydroxide, and toluene to remove both EVA and lead from panel components. Deng et al. (2022) reiterated that trichloroethylene and toluene are effective EVA solvents, and listed hexane, d-limonene, chloroform, acetone, petroleum, benzene, ethanol, and isopropanol as possible delamination solutions. Of all three delamination methods, chemical approaches are the most expensive (Deng et al., 2022; Ganesan & Valderrama, 2022; Peplow, 2023). Like mechanical and thermal processes, there must be safety measures in place for those working within facilities performing chemical delamination. Appropriately disposing of used solvents is also crucial in further protecting those involved in the waste industry.

High-Value PV Recycling in Europe

Recycling facilities for this study were selected using the following criteria: that they perform high-value recycling processes, handle c-Si panels, and are operating commercially. For the EU, facilities in France, Italy, and Germany were identified.

Throughout the preliminary research one French facility was frequently mentioned, known as Veolia, which is located in Rousset (CSSA, 2020; Deng et al., 2022; Peplow, 2023; Tao et al., 2020; Tsanakas et al., 2020). Veolia opened in 2018 and was the first commercial recycling facility dedicated to c-Si PV high-value recycling (CSSA, 2020; Deng et al., 2022; Peplow, 2023; Tao et al., 2020; Tsanakas et al., 2020; Veolia, 2018).

The second facility that was also regularly mentioned in preliminary research is Sasil of Italy, which was founded in 2015 (CSSA, 2020; Deng et al., 2022; VCT Group, 2022). Sasil incinerated panels to delaminate them, and used other thermal processes to recover copper, silicon, and silver (Deng et al., 2022). Sasil was making advancements in electrostatic and gravimetric separation, using the differences in material density and conductivity to mechanically sort them (Deng et al., 2022). At the time, this facility was nearing 100% recovery rates (Deng et al., 2022), but further research into this facility revealed that it never made it past pilot-scale. Sasil was ultimately closed due to low demand for panels and economic limitations (CSSA, 2020; Tsanakas et al., 2020; VCT Group, 2022). Therefore, Sasil has been eliminated from further analysis because it did not meet the study's criteria.

However, another facility also operating in Italy was identified, known as Tialpi Srl (Bellini, 2022; Peplow, 2023). Tialpi Srl opened its high-value PV recycling facility in 2019 (Nekouaslazadeh, 2021) in Mottalciata of the Province of Biella (Frelp by Sun, 2023). Tialpi Srl only handles c-Si PV panels (Bellini, 2022), and like Sasil, is using thermal processes alongside mechanical ones (Frelp By Sun, 2023; Peplow, 2023).

Within Germany, Loser Chemie was the first high-value recycling facility that preliminary research revealed (Deng et al., 2022; Tsanakas et al., 2020). This facility mechanically delaminated and separated panels by crushing the panel, and then used a chemical process for enhanced material separation (Deng et al., 2022; Tsanakas et al., 2020). This facility, like Sasil, was closed and then taken over by a German chemical company LuxChemtech GmbH (CIRCUSOL, n.d.). Past this point, no further information on their processes was found, so this facility was eliminated from further study.

Another German high-value recycling facility was identified post-elimination of Loser Chemie, operated by the company FLAXRES GmbH. FLAXRES GmbH began experimental operation in 2017 (FLAXRES, n.d.) at a facility in Dresden, Germany. Their facility can handle both c-Si and thin-film panels, and they have begun developing mobile high-value recycling units in overseas shipping containers (Enkhardt, 2022; FLAXRES, n.d.; FLAXRES Press Release, 2022).

High-Value PV Recycling in the US

Facilities within the US were selected using the same criteria as those in the EU. Identified facilities must perform high-value recycling processes, handle c-Si panels, and be operating commercially. Three facilities were originally selected, operating in the states of Ohio, Arizona, and Texas.

The first recycling facility identified with high-value recycling operations in the US was First Solar, Inc. (Chowdhury et al., 2020; Curtis et al., 2021; Feldman et al., 2022; Majewski et al., 2021; Sharma et al., 2019; Tsanakas et al., 2020). Up until 2021 it was only one of two facilities in the US performing such processes (Curtis et al., 2021). First Solar, Inc. was originally a panel manufacturer with facilities in Ohio, Malaysia, and Vietnam (First Solar, Inc., 2023b). In 2005 they started an in-house recycling process in Ohio and have been achieving recovery rates of 90%+ (First Solar, Inc., 2023a; Peplow, 2023; Tsanakas et al., 2020). First Solar, Inc. is only manufacturing, and therefore recycling, thin-film panels, and, as of 2018, had no plans to move into c-Si panels (First Solar, 2023a; Peplow, 2023; Weckend et al, 2016). Despite the prominence and success of this company within the solar and EoL industry, it was eliminated from further investigation because it did not meet the criteria of this study.

The second company named by NREL that implements high-value recycling process is We Recycle Solar, Inc. (Curtis et al., 2021). This company was founded in 2019 and runs its recycling operations out of Yuma, Arizona (Casey, 2023; O'Brien, 2022). We Recycle Solar, Inc. has several panel collection centers across the United States, as well as in Japan, South Korea, Belgium, and Puerto Rico (We Recycle Solar, n.d.). We Recycle Solar, Inc. can process both c-Si and thin-film panels (Casey, 2023).

The final high-value PV recycling facility located in the US is SOLARCYCLE, Inc. It was founded in 2022, hence its exclusion from NREL's study (Curtis et al., 2021; Kart, 2023). SOLARCYCLE, Inc.'s recycling facility is located in Odessa, Texas and only handles c-Si panels, (Hurdle, 2023; Kart, 2023; SOLARCYCLE, n.d.; Wallace, 2023; Wesoff, 2022; Winicov [SOLARCYCLE], personal communication, October 13, 2023). SOLARCYCLE, Inc. began building a second high-value recycling facility in Mesa, Arizona in the fourth quarter of 2023, and plans to be fully operational by the second quarter of 2024 (Winicov [SOLARCYCLE], personal communication, October 13, 2023).

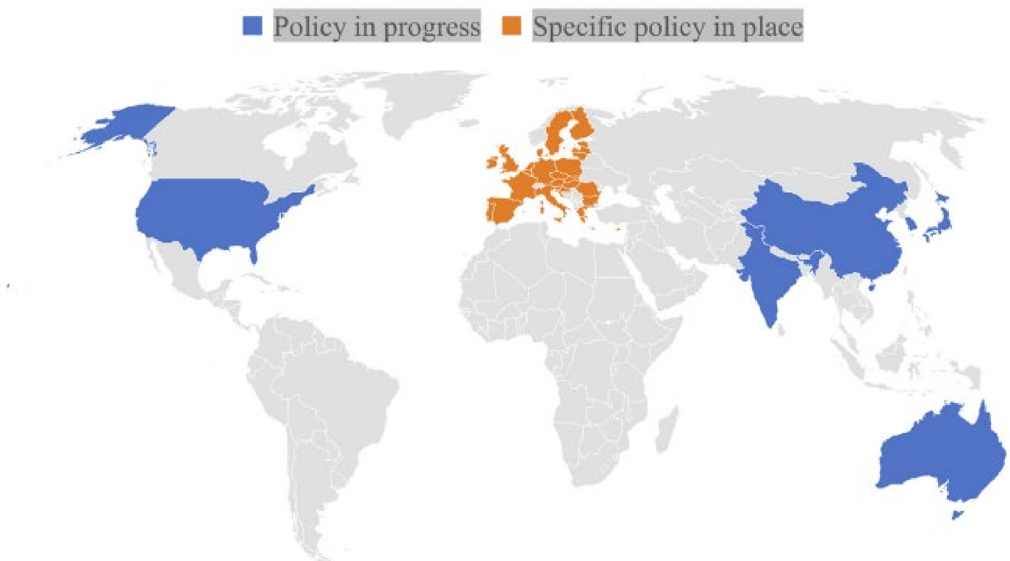
European Union PV EoL Legislation and Policy

The EU created a regulatory framework to deal with E-waste known as the Waste Electrical and Electronic Equipment Directive (WEEE). WEEE was first created in 2003 and was later modified in 2012 to specifically address PV EoL management (Chowdhury et al., 2020; Hurdle, 2023; Majewski et al., 2021; Sharma et al., 2019; Weckend et al., 2016). This 2012 modification of the WEEE directive officially classified PV panels as E-waste (Hurdle, 2023). The updated WEEE Directive came into force on August 13, 2012, and required implementation into national law by all 27 EU member states (GOV.UK, 2015) by February 14, 2014 (Röpke, 2022; Weckend et al., 2016). As shown in Figure 4, the EU is the only governing body that has put PV-specific regulations into place, but several other countries have legislation in progress (Ganesan & Valderrama, 2022).

The WEEE Directive addresses electronic life cycles and producer responsibilities within the EU, with an extended-producer responsibility (EPR) at its core (Weckend et al., 2016). Under an EPR framework, manufactures and retailers of PV panels assume financial responsibility and liability for proper management of EoL PV panels, whether they are domestically located or not (El-Khawad et al., 2022; Majewski et al., 2021; Sharma et al., 2019; Weckend et al., 2016). Compliance requires following regulations around the collection, transportation, and treatment of PV waste, including the financing of such (Majewski et al., 2021; Kummer et al., 2022; Weckend et al., 2016). The WEEE Directive also requires that each member state keep an up-to-date registry of all electrical equipment and products that enter the market with their corresponding manufacturers (Chowdhury et al., 2020; Röpke, 2022; Majewski et al., 2021; Weckend et al., 2016). PV panels that enter the EU market must be labeled in accordance with the WEEE Directive, providing information on the components, chemical makeup, hazardous materials, and best practices for handling (Röpke, 2022; Weckend et al., 2016).

Figure 4

Global Distribution of PV EoL Policies (Ganesan & Valderrama, 2022, p. 3)

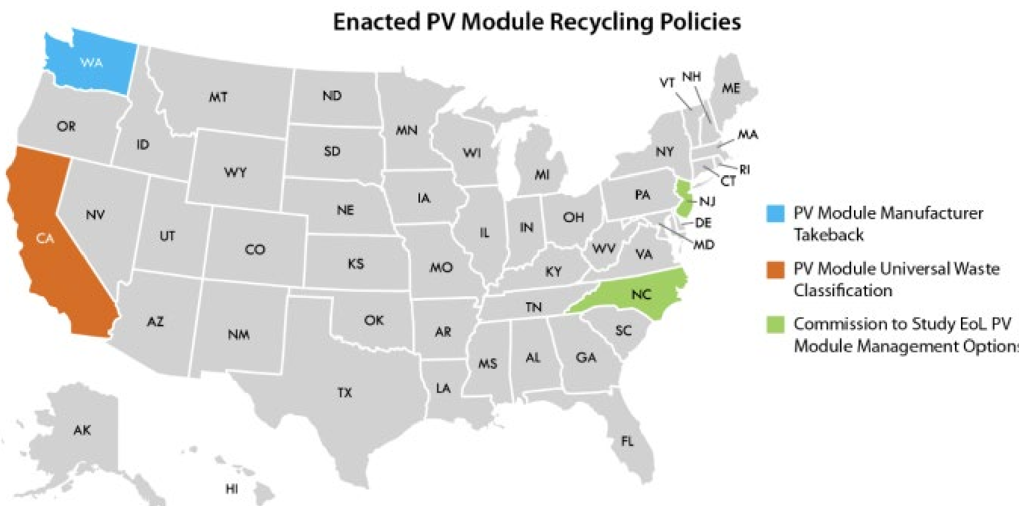


United States PV EoL Legislation and Policy

Unlike the EU, the US does not classify PV panels as E-waste (Hurdle, 2023). EoL management of PV panels is governed by the Resource Conservation and Recovery Act (RCRA) of 1976, which establishes regulations for managing non-hazardous and hazardous waste (Curtis et al., 2021; Solar Energy Industries Association, n.d.; US Environmental Protection Agency [EPA], 2023a; Weckend et al., 2016). According to Subtitle C of RCRA, the EPA has authority in the regulation of hazardous wastes, while Subtitle D grants states the authority to regulate non-hazardous waste (Curtis et al., 2021). As of 2021, the US had no federal policies or regulations that directly address the recycling of PV panels, nor federal or state legislation banning the disposal of PV panels into landfills (Curtis et al., 2021). As shown in Figure 5, there are very few existing policies that incentivize the recycling of PV panels, and none that require or incentivize manufacturers to label their PV panels with details on chemical makeup (Curtis et al., 2021).

Figure 5

US Enacted PV Panel Policies (Curtis et al., 2021, p. 23)



Research Methods

Overview of the Research Design

This study's purpose was to investigate the differences in policy around PV EoL management within selected states in the EU and the US and to compare rates of recovery between the nations' high-value recycling facilities. This research explored different aspects of the global PV industry and looked specifically at how the PV lifecycle, especially EoL, is approached within these two broad jurisdictions. In preparation for sample selection, a detailed analysis of c-Si panel composition and its recycling methods was performed for foundational understanding. Next, the study identified specific PV recycling facilities that use high-value recovery methods for c-Si panel recycling. Delamination methodology was then examined at each recycling facility, along with the corresponding rates of recovery. The third stage of research concerned PV recycling legislation within the EU and the US. The EU's PV related legislation was first examined as a whole, and then the identified EU countries were explored individually. The same process was done for the US; first federal legislation was analyzed, and then an analysis of policies was performed for the identified states. The final parameter of comparison was the average cost to recycle one c-Si PV in a high-value process at the selected facilities.

Study Sample

Three countries within the EU were selected for this study. Selecting the three countries within the EU to compare to the US was primarily based on identifying recycling facilities within the EU that are commercially performing high-value recycling of c-Si panels. The facilities for which published data were available and that met these criteria were Veolia, France (CSSA, 2020; Deng et al., 2022; Tao et al., 2020; Tsanakas et al., 2020; Veolia, 2018), Tialpi Srl, Italy (Bellini, 2022; Peplow, 2023), and FLAXRES in Germany (Enkhardt, 2022; FLAXRES, n.d.; FLAXRES Press Release, 2022).

The objective of this study was to compare three commercially operating, high-value recycling facilities within the EU to three within the US. However, only two facilities identified within the US met the criteria of using high-value recycling processes for c-Si panels. As shown in the *Review of Literature*, there were only two facilities that existed before 2021 that were performing high-value processes: First Solar, Inc. (Curtis et al., 2021; First Solar, Inc., 2023a; Peplow, 2023; Tsanakas et al., 2020; Weckend et al, 2016) and We Recycle Solar, Inc. (Casey, 2023; O'Brien, 2022; We Recycle Solar, n.d.). Of the two facilities, only We Recycle Solar, Inc. was handling c-Si panels (Casey, 2023; Curtis et al., 2021; O'Brien, 2022). The second facility, SOLARCYCLE, Inc., which opened in 2022, is the other selected facility for the study sample (Hurdle, 2023; Kart, 2023; SOLARCYCLE, n.d.; Wallace, 2023; Wesoff, 2022; Winicov [SOLARCYCLE], personal communication, October 13, 2023).

Data Collection

Data collection focused on four factors: (a) what facilities are performing commercial high-value recycling of c-Si panels, (b) the methods of delamination employed at each of the selected sites and their corresponding rate of recovery, (c) the legislation and policies in each country that support high-value PV recycling of c-Si panels, and (d) the cost for high-value recycling processes at the selected sites. This study relied heavily on academic and government databases, using third-party research and data to compare the US and the EU under the selected criteria. Google Translate and DeepL software were crucial tools in data collection for the selected EU member states, because many of the found sources were originally published in French, Italian, and German.

High-Value PV Recycling Facilities

The first stage of this study was identifying PV recycling facilities within the US and the EU. Initial research into this topic revealed that high-value processes are the ideal way to handle PV panels in terms of overall sustainability (Deng et al., 2022; Ganesan & Valderrama, 2022; Peplow, 2023). Therefore, this was the foundational criterion for the study. As shown in the *Review of Literature,* c-Si panels dominate the global PV market (El-Khawad et al., 2022; Feldman et al., 2022; Majewski et al., 2021; Peplow, 2023), hence its inclusion as a criterion for PV recycling facility selection. Commercial high-value recycling facilities from both the US and the EU were explored under this framework, and five in total were chosen for further comparison. The objective was to compare three facilities from each nation; however, this proved to be unfeasible due to the chosen criteria for PV recycling facilities and the small number of commercially operating high-value recycling facilities within the US.

Methods of Delamination and Rates of Recovery

The next stage in answering the research questions was to compare the delamination methodologies used by these selected high-value, c-Si commercial recycling facilities and their correlating rates of recovery. As shown in the *Review of Literature*, achieving high rates of recovery requires delamination of the panel to access the components underneath (Deng et al., 2022; El-Khawad et al., 2022; Ganesan & Valderrama). Using a combination of delamination methods is also linked to higher rates of recovery (Deng et al., 2022; El-Khawad et al., 2022). Consequently, this was chosen as a parameter for comparison of high-value, c-Si PV recycling facilities. The objective of this area of focus was to investigate a relationship between delamination methods used by the selected facilities, and how they might correlate to their rates of recovery.

Presence of Comprehensive Legislation

The third step of this stage was identification of comprehensive PV legislation in countries and states that met the aforementioned criteria. Comprehensive legislation was defined as policies affecting all parties within a location and addressing PV EoL management specifically. Comprehensive was further defined as providing regulations for all aspects of the PV panel lifecycle; from collection, to transportation, to handling, and finally to recycling. This study examined legislation on both a national and statewide level. For the US, comprehensive legislation meant an examination of federal policies that impact all 50 states. For the EU, this process was done by identifying legislation that impacted all 27 member states (GOV.UK, 2015). Legislation was analyzed within the EU, and then in the selected member states. For the US, federal legislation was first examined, followed by independent state-wide policies within selected states. Both nations were compared by their nationwide PV recycling rates as well.

Cost per Panel

The final metric for comparing these countries and plants was the average cost to process one PV panel in the selected high-value recovery facilities. For the US, the average cost to landfill a panel was also included. Because the EU has banned the landfilling of PV panels (VCT Group, 2022) this metric was not available for the selected member states. However, this parameter is crucial for understanding the presence, or lack thereof, of high-value PV recycling within the US. This economic metric comparison between price to recycle or landfill a panel identifies the barrier of economic viability within the US and can be directly correlated to lower rates of PV panel recycling compared to the EU (Curtis et al., 2021; Echo Environmental, 2022; Hurdle, 2023).

Findings

The findings for this study are presented in correspondence with the *Research Methods*. The collected data for each section of this study has a corresponding table to summarize the results.

High-Value PV Recycling Facilities

Veolia, France

As the first commercial c-Si PV recycling facility (CSSA, 2020; Deng et al., 2022; Peplow, 2023; Tao et al., 2020; Tsanakas et al., 2020; Veolia, 2018), Veolia has set the standard in many ways. Their process is fully automated, utilizing shredders, grinders, and optical sorters (Deng et al., 2022). Veolia is capable of processing one panel within a minute to a minute and a half, reaching 4,000 tons of panels per year (Deng et al., 2022; Tao et al., 2020). According to Deng et al. (2022), Veolia was processing 65% of all PV waste in Europe in 2019. Veolia has also established itself within secondary markets. All of their materials are separated and then redirected into other industries; two-thirds of the recovered glass is sent into the glass-making sector; the frames are sent to aluminum refineries; the EVA and PET/PVF are used as fuel in cement works; the recovered silicon is used by precious metal sectors; and the external cables and connectors are crushed and sold as copper shot (Veolia, 2018).

Tialpi Srl, Italy

The first step in Tialpi Srl's process is to remove the aluminum frame via automatic miter saws and pistons (Bellini, 2022). The external cables are manually cut from the polymer back sheet with a thin knife, then separated from the panel for later recovery (Bellini, 2022). Tialpi Srl employs thermal and mechanical processes for delamination, utilizing highly focused infrared rays at different wavelengths in conjunction with vibrating steel blades (Bellini, 2022; Frelp By Sun, 2023; Peplow, 2023). The glass can then be sorted, and the rest of the panel components can be recovered (Peplow, 2023). Optical sorters and screens are used to separate glass by its coarseness and transparency, and also to remove any panel materials that may be mixed in (Bellini, 2022; Frelp By Sun, 2023; Peplow, 2023). This facility only handles c-Si panels and can process them a panel per minute, or a rate of 60 panels per hour. They are currently reaching for the goal of 5,000 tons of panels per year (Bellini, 2022; Frelp By Sun, 2023; Peplow, 2023). However, this company recently reported that they will need to hit 20,000 tons per year to be cost effective (Bellini, 2022; Peplow, 2023).

FLAXRES GmbH, Germany

FLAXRES GmbH, like Tialpi Srl, utilizes "high-intensity at low-energy light pulses" (D'Souza, 2020, para. 1) to separate panel components and remove the EVA encapsulant (Enkhardt, 2022; FLAXRES, n.d.; FLAXRES Press Release, 2022). Their facility can process both c-Si and thin-film PV technologies and is currently achieving a rate of 10 tons of panels per day (Enkhardt, 2022; FLAXRES, n.d.). While in the pilot-scale phase, they tested their process on 7.5 tons of panels and recovered 200 kilograms of silicon, 4 kilograms of silver, and 4.9 metric tons of high-purity glass (Enkhardt, 2022; FLAXRES Press Release, 2022). FLAXRES GmbH has also been developing mobile PV panel recycling units, installing their proprietary technology within overseas shipping containers, and aiming to cut down on the costs of transporting PV panels to recycling facilities (FLAXRES, n.d.; FLAXRES Press Release, 2022). They are reporting a rate of one panel per 10 seconds, a capacity of 1,000 tons per year, and only using one kilo-watt hour to break apart one panel (Enkhardt, 2020; FLAXRES Press Release, 2022).

We Recycle Solar, Arizona

The second company named by NREL that implements high-value recycling process is We Recycle Solar, Inc. (Curtis et al., 2021). This company was founded in 2019 and runs its recycling operations out of Yuma, Arizona (Casey, 2023; O'Brien, 2022). We Recycle Solar, Inc. has a number of panel collection centers across the United States, as well as in Japan, South Korea, Belgium, and Puerto Rico (We Recycle Solar, n.d.). We Recycle Solar, Inc. can process both c-Si and thin-film panels (Casey, 2023), and has achieved significant milestones in the PV EoL sector. The company had processed 500,000 panels by 2023 and claims to be the only US solar recycler that is fully permitted by the EPA to handle the secondary hazardous materials within panels (Casey, 2023; Disruptive Investing & Saghei, 2023). Both the CEO of We Recycle Solar, Inc., Adam Saghei, and Casey (2023) report that the facility is capable of processing 7,500 panels (345,000 pounds) per day, and 69 million pounds per year (Disruptive Investing & Saghei, 2023). By 2028, We Recycle Solar, Inc. plans to increase their capacity to 522 million pounds (Casey, 2023), or 237,273 metric tons. However, the reported capacity requires further exploration. Equation 1 shows the conversion of pounds per day to pounds per year and Equation 2 breaks down the difference between reported daily and annual capacity.

$$\frac{345{,}000\ pounds}{day} \times \frac{249\ days}{year} = 85{,}905{,}000\ pounds\ per\ year \tag{1}$$

The number 249 was chosen as the average amount of workdays in the US, which is 252 to 260 days, with 11 Federal holidays observed annually in the US (EspoCRM, 2023). Information on We Recycle Solar, Inc.'s working schedule is not available, so this estimate was selected.

$$85{,}905{,}000\ pounds - 69{,}000{,}000\ pounds = 16{,}905{,}000\ pounds \tag{2}$$

Achieving maximum production on a day-to-day basis is not feasible, and a difference between daily capacity and annual capacity is to be expected. However, a difference of almost 17 million pounds is significant. This study was unable to confirm why the gap in reported daily and annual handling capacity is this wide due to the proprietary nature of We Recycle Solar, Inc.'s recycling operations (Davis [We Recycle Solar], personal communication, October 9, 2023; Disruptive Investing & Saghei, A., 2023).

SOLARCYCLE, Texas

The final high-value PV recycling facility located in the US is SOLARCYCLE, Inc., founded in 2022, hence its exclusion from NREL's study (Curtis et al., 2021; Kart, 2023). SOLARCYCLE, Inc.'s recycling facility is located in Odessa, Texas (Hurdle, 2023; Kart, 2023; SOLARCYCLE, n.d.; Wallace, 2023; Winicov [SOLARCYCLE], personal communication, October 13, 2023), and the company began opening a second facility in Mesa, Arizona in the fourth quarter of 2023 (Winicov [SOLARCYCLE], personal communication, October 13, 2023). Their facility only handles c-Si panels and utilizes a myriad of machinery, from a fully automated line that can remove the frame, junction box, and glass panel, to grinders and shredders, a series of electrically charged rollers to separate materials, and finally a patented process to extract valuable materials (Hurdle, 2023; Wesoff, 2022). Figure 6 provides a breakdown of SOLARCYCLE, Inc.'s recycling process. This facility's current panel-handling capacity is 500,000 panels annually, but they are reaching for a goal of 1 million panels per year by the end of 2023 (Kart, 2023).

Figure 6

SOLARCYCLE Recycling Process (Winicov [SOLARCYCLE], personal communication, October 13, 2023)

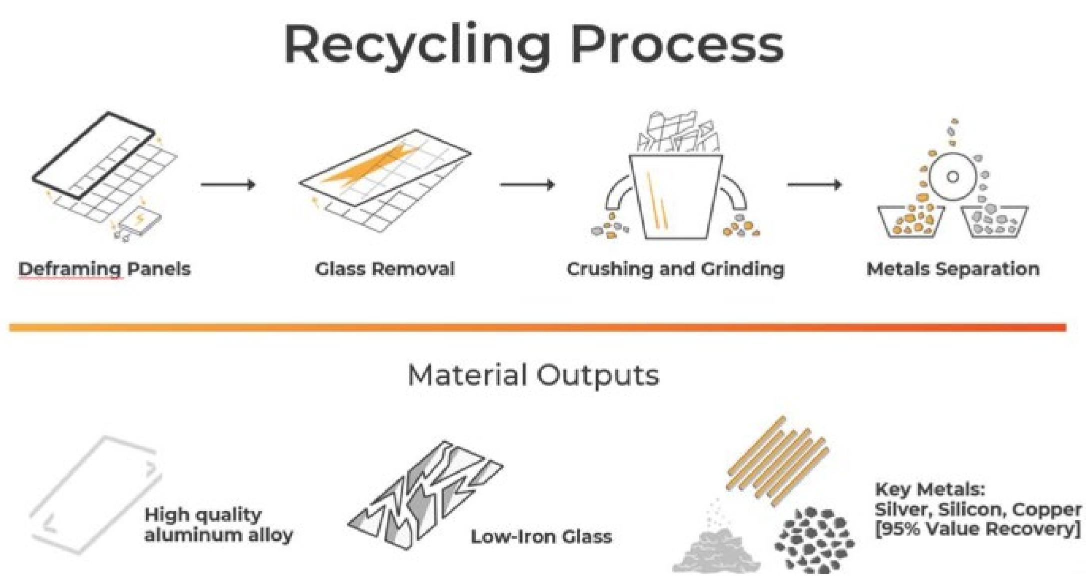


Table 1 and Table 2 summarize the findings for the selected facilities, comparing the panels accepted and the handling capacity. Table 1 summarizes the capacity and accepted panel types of the selected high-value recycling facilities. The EU facilities report in metric tons, while the US uses pounds. Every facility except for SOLARCYCLE, Inc. provided a metric involving weight. Instead, SOLARCYCLE, Inc. reports the number of panels processed per year. Calculations needed to be performed to compare these facilities equally: converting pounds to metric tons and a quantity of solar panels to weight. This study is using an estimate from Dearing (2023), which reports that the average solar panel is around 40 pounds. Equation 3, Equation 4, and Equation 5 convert the reported capacities from both US high-value PV recycling facilities to metric tons. The equivalent metrics are listed in Table 2.

$$1\ metric\ ton = 2{,}200\ pounds$$

$$1\ solar\ panel \approx 40\ pounds$$

(3) $$\frac{69{,}000{,}000\ pounds}{per\ year} \div \frac{1\ metric\ ton}{2{,}200\ pounds} = \frac{31{,}364\ metric\ tons}{per\ year}$$

(4) $$\frac{500{,}000\ panels}{per\ year} \times \frac{\approx 40\ pounds}{1\ panel} \approx \frac{20{,}000{,}000\ pounds}{per\ year}$$

(5) $$\frac{\approx 20{,}000{,}000\ pounds}{per\ year} \times \frac{1\ metric\ ton}{2{,}200\ pounds} \approx \frac{9{,}091\ metric\ tons}{per\ year}$$

Table 1

Comparison of High-Value Recycling Facilities in the US and the EU

Country	Source	Facility & Location	Accepted Panel Types	Metric	Capacity
France	(Veolia 2018; Tao et al., 2020)	Veolia: Rousset, France	c-Si	Metric tons/year	4,000
Italy	(Bellini, 2022)	Tialpi Srl: Mottalciata, Italy	c-Si	Metric tons/year	5,000
Germany	(FLAXRES, n.d.) (FLAXRES Press Release, 2022) (Enkhardt, 2022)	FLAXRES GmbH: Dresden Germany	c-Si & thin-film	Metric tons/year	1,000
United States	(Casey, 2023; Disruptive Investing & Saghei, 2023)	We Recycle Solar: Yuma, Arizona	c-Si & thin-film	Pounds/year	69,000,000
United States	(Hurdle, 2023; Kart, 2023, Wesoff, 2022; Winicov [SOLARCYCLE], personal communication, October 13, 2023)	SOLARCYCLE: Odessa, Texas	c-Si	# of panels/year	500,000

Table 2

Comparison of High-Value Recycling Facilities in the US and the EU with Equivalent Metrics

Country	Source	Facility & Location	Accepted Panel Types	Metric	Capacity
France	(Veolia 2018; Tao et al., 2020)	Veolia: Rousset, France	c-Si	Metric tons/year	4,000
Italy	(Bellini, 2022)	Tialpi Srl: Mottalciata, Italy	c-Si	Metric tons/year	5,000
Germany	(FLAXRES, n.d.) (FLAXRES Press Release, 2022) (Enkhardt, 2022)	FLAXRES GmbH: Dresden Germany	c-Si & thin-film	Metric tons/year	1,000
United States	(Casey, 2023; Disruptive Investing & Saghei, 2023)	We Recycle Solar: Yuma, Arizona	c-Si & thin-film	Metric tons/year	31,364
United States	(Hurdle, 2023; Kart, 2023, Wesoff, 2022; Winicov [SOLARCYCLE], personal communication, October 13, 2023)	SOLARCYCLE: Odessa, Texas	c-Si	Metric tons/year	≈ 9,091

Note: As shown in Equation 4, the capacity for SOLARCYCLE is an approximation derived from the average weight of a solar panel reported by Dearing (2023).

Delamination Methods and Rates of Recovery

Veolia, France

As previously mentioned, Veolia relies on a fully automated line of machinery for their high-value recycling processes. This facility employs machinery to separate panel components via crushing, shredding, and grinding, and then uses optical sorters to efficiently separate recovered materials. Their delamination and panel separation process are mechanical, and they have consistently been achieving a 95% recovery rate (Deng et al., 2022; Tao et al., 2020; Tsanakas et al., 2020; Veolia, 2018).

Tialpi Srl, Italy

Tialpi Srl utilizes both thermal and mechanical delamination methods in their high-value recycling processes. There is some variation in Tialpi Srl's reported recovery rates. According to Bellini (2022), this facility is promising 100% rates of recovery, but as of 2022 was only achieving 85%. A year later, Peplow (2023) reports that Tialpi Srl is still only recovering 85% of the panel. Only two months after Peplow's (2023) article was published, Frlep by Sun (2023) claimed both 97% and 98% on the same website page. It should be noted that Google Translate was necessary to read the article by Frlep by Sun (2023), and the process of translating Italian to English may be the cause of this discrepancy. Because of these inconsistencies, Tialpi Srl's rate of recovery has been starred in Table 3 to signify that deeper research and more advanced translation may be needed.

FLAXRES GmbH, Germany

FLAXRES GmbH also employs thermal and mechanical delamination methodologies (D'Souza, 2020; Enkhardt, 2022; FLAXRES, n.d.; FLAXRES Press Release, 2022).

Despite the success that FLAXRES GmbH has had within the PV EoL field, this study was unable to identify a reputable source for their recovery rate. One source reported that “all components of the panels would be completely recovered” (PHOTON, 2021, para. 1), implying that FLAXRES GmbH is achieving a 100% recovery rate. The only other place I was able to find confirmation of this recovery rate was in a LinkedIn comment thread (Buntrock, 2023). For these reasons this facility’s rate of recovery has also been starred in Table 3. It should be noted that the majority of third-party data and research for this facility was reported in German, and this may contribute to this gap in data.

We Recycle Solar, Arizona

Very little information has been released surrounding the recycling processes and machinery used by We Recycle Solar, Inc., because the company regards all this as proprietary information ((Davis [We Recycle Solar], personal communication, October 9, 2023; Disruptive Investing & Saghei, A., 2023). In an interview with Disruptive Investing (2023), CEO Adam Saghei reported that the first step is a recycling line that mechanically separates the panel, but whether this is the only process employed for delamination could not be confirmed. Because of this gap in data, the thermal and chemical categories in Table 3 have been flagged. Cronkite News also reported that a chemical reduction process is utilized to recover trace valuable metals, such as copper and silver (O’Brien, 2022), but past this no further information on recycling processes was found. The only place I located a reported recovery rate was in the Disruptive Investing (2023) interview with We Recycle Solar, Inc.’s CEO, Adam Saghei, who claims recovery rates of 99% (Disruptive Investing & Saghei, 2023) We Recycle Solar, Inc. declined to provide further information when contacted. “Due to overwhelming requests from academic institutions and research firms, the proprietary nature of our process, and general business concerns additional information isn't available at this time" (Davis [We Recycle Solar], personal communication, October 9, 2023). This study could not identify a reported recovery rate from a source other than the company itself, therefore, the recovery rate has been flagged in Table 3.

SOLARCYCLE, Texas

SOLARCYCLE, Inc. has released more information surrounding its high-value recycling processes than We Recycle Solar, Inc., despite being a younger company by three years. According to an environmental sustainability engineer for SOLARCYCLE, Inc. and Yale Environment 360, the EVA encapsulant is processed mechanically; the panels are crushed, ground, and shredded; and through their "multi-step patented process" the EVA is sorted out from the high-value materials (Hurdle, 2023; Winicov [SOLARCYCLE], personal communication, October 13, 2023). Whether or not SOLARCYCLE, Inc. is using thermal or chemical processes alongside mechanical ones could not be confirmed, hence the flagging of these categories in Table 3. Despite being a very young company, SOLARCYCLE, Inc. is already achieving 95% recovery of panel materials (Kart, 2023; SOLARCYCLE, n.d.; Wesoff, 2022; Winicov [SOLARCYCLE], personal communication, October 13, 2023). However, the referenced sources all report personal communications with members of the company. Due to the lack of non-company sources, the recovery rate has been flagged in Table 3.

Table 3

Comparison of Delamination Methods and Rates of Recovery

Country	Source	Facility & Location	Mechanical	Thermal	Chemical	Rates of Recovery
France	(Deng et al., 2022; Tao et al., 2020; Tsanakas et al., 2020; Veolia, 2018)	Veolia, Rousset	Yes	No	No	95%
Italy	(Bellini, 2022; Frelp By Sun, 2023; Peplow, 2023)	Tialpi Srl, Mottalciata	Yes	Yes	No	98%**
Germany	(Buntrock, 2023; FLAXRES, n.d. FLAXRES Press Release, 2022; Enkhardt, 2022; PHOTON, 2021)	FLAXRES GmbH, Dresden	Yes	Yes	No	100%**
United States	(Casey, 2023; O'Brien, 2022; Disruptive Investing & Saghei, 2023)	We Recycle Solar, Arizona	Yes	-	-	99%**
United States	(Hurdle, 2023; Kart, 2023; SOLARCYCLE, n.d.; Wesoff, 2022; Winicov [SOLARCYCLE], personal communication, October 13, 2023)	SOLARCYCLE, Texas	Yes	-	-	95%**

Note: Thermal and chemical delamination processes for US facilities have been marked to indicate that both facilities do not release detailed information on their delamination processes (Davis [We Recycle Solar], personal communication, October 9, 2023). This study could not confirm whether thermal or chemical processes are used by either We Recycle Solar, Inc. or SOLARCYCLE, Inc. (Davis [We Recycle Solar], personal communication, October 9, 2023; Disruptive Investing & Saghei, A., 2023; Winicov [SOLARCYCLE], personal communication, October 13, 2023).

Comprehensive Nationwide PV EoL Management Legislation

EU PV EoL Management Legislation

As shown in the *Review of Literature*, the EU has had regulations specifically addressing PV EoL management since 2012. Along with the EPR framework that the EU has put in place, high-value recycling approaches are also foundational to the WEEE Directive (Weckend et al., 2016). WEEE legislation ensures potentially harmful substances will be removed and contained during treatment, rare metals will be recovered and treated for future use, materials with high energy embodiment will be recycled, and that glass recycling processes should take quality of final products into account (Weckend et al., 2016).

The two established financial frameworks to enforce the proper collection, handling, and treatment of PV waste are Business-to-Consumer transactions (B2C) and Business-to-Business transactions (B2B) (Aleid et al., 2023; Sharma et al., 2019). The classification of B2B versus B2C depends on the size of the customer and whether they are a private household or not (Aleid et al., 2023; Weckend et al., 2016). Under both frameworks, the manufacturer or seller of the PV panel is responsible for the proper EoL management of said panels, assuring that both small and large-scale customers can dispose of their PV panels in compliance with WEEE (Aleid et al., 2023; Sharma et al., 2019).

The WEEE Directive also includes a strict labeling process for PV panels (Weckend et al., 2016). Labels must inform consumers that panels cannot be mixed with municipal waste streams and that take-back and recycling are free, along with information for waste-handlers on how to properly collect, store, transport, dismantle, and treat the panel (Weckend et al., 2016). The 2012 revision also put in place collection, recycling, and recovery by mass benchmarks, shown in Table 4 (Majewski et al., 2021; Peplow, 2023; Weckend et al., 2016).

Table 4

WEEE Directive Benchmarks (Taken from Weckend et al., 2016, p. 54)

	Annual collection targets	Annual recycling/Recovery targets
Original WEEE Directive (2002/96/EC)	4 kg/inhabitant	75% recovery, 65% recycling
Revised WEEE Directive (2012/19/EU) up to 2016	4 kg/inhabitant	Start with 75% recovery, 65% recycling, 5% increase after 3 years
Revised WEEE Directive (2012/19/EU) from 2016 to 2018	45% (by mass) of all equipment put on the market	80% recovered and 70% prepared for reuse and recycled
Revised WEEE Directive (2012/19/EU) from 2018 and beyond	65% (by mass) of all equipment put on the market or 85% of waste generated[13]	85% recovered and 80% prepared for reuse and recycled

US PV EoL Management Legislation

Within the US, the Resource Conservation and Recovery Act (RCRA) of 1976 acts as the regulatory scheme for PV EoL management (Curtis et al., 2021; Solar Energy Industries Association, n.d.; US Environmental Protection Agency [EPA], 2023a; Weckend et al., 2016). As shown in the *Review of Literature*, this framework relies on the distinction between non-hazardous and hazardous waste for subsequent handling procedures. The divide between what constitutes hazardous versus non-hazardous waste coupled with the divide in granted authority has ultimately created an environment of confusion for EoL management of PV panels (CSSA, 2020; Curtis et al., 2021; US EPA, 2023a). This confusion is further compounded by the lack of PV panel labeling requirements and mandates within the US (Curtis et al., 2021). Because determining if the panel is hazardous or not is crucial for subsequent handling under the RCRA, the absence of detailed chemical makeup labels makes this process much more difficult for waste handlers. Many panels end up undergoing a toxicity characteristic leaching procedure (TCLP) or other state-provided test to determine if they exceed toxicity limits (CSSA, 2020; Curtis et al., 2021; US EPA, 2023a; Weckend et al., 2016). This creates another barrier to effective PV EoL management because these tests can be expensive and vary widely between states (Curtis et al., 2021). If the PV panels are classified as hazardous, their management becomes more complicated. There are much stricter, and costlier, regulations around the collection, transport, storage, and treatment of hazardous waste, which again disincentivizes recycling a PV panel over landfilling it (CSSA, 2020; Curtis et al., 2021). As discussed in the Problem Statement, US industry experts are reporting that only 10% of solar panels are recycled domestically, and the gaps in legislation may heavily contribute to this low rate (Curtis et al., 2021; Echo Environmental, 2022; Hurdle, 2023; Kart, 2023; Peplow, 2023). Table 5 compares nationwide legislation for the EU and the US and illustrates the differences in legislation and recycling rates.

However, on October 23, 2023, the EPA announced that it is developing new guidelines to improve the recycling and management of solar panels (US EPA, 2023a). They are proposing that solar panels be added to Federal universal waste regulations (US EPA, 2023a), which should reduce confusion around PV EoL management, provide a more streamlined path for consumers and recyclers, and reduce associated costs.

Table 5

Comparison of Comprehensive Nationwide PV EoL Management Legislation

Country	Source	PV EoL Policies	Collection	Transportation	Handling	Recycling	Recycling Rate
European Union	(Majewski et al., 2021; Peplow, 2023; Weckend et al., 2016)	Yes	Yes	Yes	Yes	Yes	80%
United States	(Curtis et al., 2021; Echo Environmental, 2022; Hurdle, 2023; Kart, 2023; Peplow, 2023)	No	No	No	No	No	10%

Comprehensive Statewide PV EoL Legislation and Policy

France PV EoL Legislation and Policy

As a member of the EU, France must either comply with the WEEE Directive, develop its own legislation that still meets WEEE benchmarks, or implement a combination of the two (Aleid, 2023; Weckend et al., 2016). Unlike Italy and Germany, France classifies all PV panel waste as household waste (*France*, n.d.; Weckend et al., 2016), or B2C, eliminating the need to spend time classifying consumers. French WEEE law dictates that all producers and retailers must pay an up-front fee for every panel sold, and that fee must be clearly shown on every invoice for panels sold (*France*, n.d.). This fee finances the collection and treating of panels, and producers can either carry out the collection and treatment themselves or do so within a collective framework (*France*, n.d.). Furthermore, producers and retailers can only access the French market if they register with the Ministry of Environment and provide an accredited take-back scheme (*France*, n.d.).

Italy PV EoL Legislation and Policy

Italy has taken a different approach than France and Germany to ensure the EPR framework and WEEE compliance are upheld. Collection and treatment schemes are run through specific, non-profit consortiums that have been approved by Italy's Ministry for the Environment, Land, and Sea Protection (IR Global, 2014). As of 2020, there were 13 non-profit consortiums in operation managing the collection, transport, treatment, and recovery of E-waste (RAEE, 2020). The financial burden for PV panel producers is proportionate to their market share, and the consortia also reward local authorities, facilities, and managers who are excelling beyond WEEE benchmarks for collection and recovery (RAEE, 2020). Italy also reserves a portion of government supplied feed-in-tariffs from PV panel manufacturers to provide extra support in covering the costs associated with PV EoL management (Sharma et al., 2019) If panel manufacturers can prove that their panels were disposed of in alignment with WEEE within six months of collection, the held amount is repaid (Sharma et al., 2019)

Germany PV EoL Legislation and Policy

Within the EPR framework created by the WEEE Directive, Germany also runs two levels of operation and financing to keep the costs of EoL management from falling on the consumer (Aleid et al., 2023; Röpke, 2022). Level 1 covers the immediate, up-front costs of collection, handling, and recycling, while Level 2 covers the future costs associated with said steps of EoL management (Aleid et al., 2023). The amount of money that a producer must put aside to ensure that Levels 1 and 2 are funded depends on their market share, assumed return rate of PV panels, and assumed disposal costs (Aleid et al., 2023; Weckend et al., 2016). Producers, retailers, and others are not able to put their products on the German market if Level 2 financing has not been established with the National Register for Waste Electrical Equipment, known as Stiftung EAR (Aleid et al., 2023; Röpke, 2022; Weckend et al., 2016).

Along with being WEEE compliant, Germany also implemented its own national law: the German National Electric and Electronic Equipment Law, called Elektro-und Elektronikgerätegesetz or ElektroG (Kummer et al., 2022; Röpke, 2022; Weckend et al., 2016). This law introduces more specific legislation on the separation of PV panels from municipal waste streams, and details about their collection, handling, transport, and treatment (Kummer et al., 2022; Weckend et al., 2016).

Arizona PV EoL Legislation and Policy

In 2017, Arizona proposed a bill that would have established a committee to study PV EoL management and environmental effects (Curtis et al., 2021). Senate Bill 1309 advocated for the creation of a "renewable energy technology environmental impact study committee" that would examine lifespans of PV panels, environmental impacts associated with PV panels' lifecycles, and opportunities to bring recycling and reuse to the state (Curtis et al., 2021). However, this bill was never enacted (Curtis et al., 2021).

Arizona tried again to address PV EoL management in 2020 with House Bill 2828. This bill would have required manufacturers and retailers of PV panels to bear the burden of PV EoL management and would have banned PV panels from being disposed of in non-hazardous landfills (Curtis et al., 2021). House Bill 2828 also proposed that any manufacturer or retailer should have to pay a fee of $5 per panel sold to the Department of Revenue, which would then be deposited into a Specialty Environmental Component Fund to assist in covering associated costs with PV EoL management (Curtis et al., 2021). Like its predecessor, House Bill 2828 was also never enacted (Curtis et al., 2021).

Texas PV EoL Legislation and Policy

This study was unable to identify any legislation or policy, proposed or not, that addresses PV EoL management within the state of Texas. NREL's *Solar Photovoltaic Module Recycling: A Survey of US Policies and Initiatives* (Curtis et al., 2021) has no information regarding Texas, and the EPA confirms that no laws, regulations, or policies affecting PV panel waste or EoL management are currently in place (US EPA, 2023a). Table 6 illustrates the difference in statewide PV EoL legislation between EU member states and US states, and the lack of such policy in both Arizona and Texas.

Table 6

Comprehensive Statewide PV EoL Management Legislation

State	Source	PV EoL Policies	Collection	Transportation	Handling	Recycling
France	(Majewski et al., 2021)	Yes	Yes	Yes	Yes	Yes
Italy	(Majewski et al., 2021)	Yes	Yes	Yes	Yes	Yes
Germany	(Majewski et al., 2021)	Yes	Yes	Yes	Yes	Yes
Arizona	(Curtis et al., 2021; US EPA, 2023a; ERCC, n.d.)	No	No	No	No	No
Texas	(Curtis et al., 2021; US EPA, 2023a; ERCC, n.d.)	No	No	No	No	No

Cost to High-Value Recycle versus Landfill for PV Panels

Cost to Perform High-Value Recycling in the EU

As discussed in the *Review of Literature*, PV manufacturers and retailers in the EU absorb the cost of EoL management and treatment depending on their market share via the EPR framework established by the WEEE Directive (El-Khawad et al., 2022; Majewski et al., 2021; Sharma et al., 2019; Weckend et al., 2016). Because the WEEE Directive has required PV recycling since February 14, 2014 (Röpke, 2022; Weckend et al., 2016), the EU has had sufficient time to get costs down for all associated aspects of PV EoL management (CSSA, 2020). According to Curtis et al. (2021) and the 2020 California Solar + Storage Association (CSSA) webinar, the cost to recycle one panel in a high-value process is around $0.70 in the EU. The landfilling of PV panels has directly been banned (Hurdle, 2023; VCT Group, 2022); therefore, there is not an associated cost for this option as there is in the US.

Cost to Perform High-Value Recycling in the US

PV EoL management is not required by the US, landfilling of panels has not been banned, and there are only two facilities performing high-value recycling. Therefore, the responsibility to deal with EoL panels largely falls on the customer or independent recyclers (Curtis et al., 2021; Hurdle, 2023; Wesoff, 2022). High-value recycling processes are very capital intensive (Curtis et al., 2021; Disruptive Investing & Saghei, 2023), especially if not supported by the government, manufacturers, or retailers. There is some variation in the reported costs for high-value recycling in the US and within the selected facilities. Curtis et al. (2021) of NREL reported a range of $15 to $45 per panel throughout the US while Wesoff (2022) stated that the cost is around $20 to $30. However, the cost to landfill panels is drastically less expensive. Prices are around $1 per panel for non-hazardous landfilling, and about $5 per panel for hazardous landfilling (Curtis et al., 2021; Hurdle, 2023; Wallace, 2023; Wesoff, 2022). Currently, SOLARCYCLE, Inc. is charging $18 per panel (Hurde, 2023; Wallace, 2023) and We Recycle Solar, Inc, charges $20 (Hurdle, 2023; O'Brien, 2022; Wesoff, 2022)**.** Table 7 illustrates the wide gap in PV EoL high-value recycling costs between the EU and the US and shows the lack of economic feasibility for US customers to use such processes.

Table 7

Comparison of Cost to High-Value Recycle or Landfill for PV Panels

Country	Source	Facility & Location	Metric	Cost to High-Value Recycle	Cost to Landfill (Non-Hazardous)	Cost to Landfill (Hazardous)
USA	(Curtis et al., 2021; Hurdle, 2023; Wallace, 2023; Wesoff, 2022)	SOLARCYCLE, Texas	$US/Panel	$18	$1-$2	$5
USA	(Curtis et al., 2021; Hurdle, 2023; O'Brien, 2023; Wesoff, 2022)	We Recycle Solar, Arizona	$US/Panel	$20	$1-$2	$5
France	(CSSA, 2020; Curtis et al., 2021)	Veolia, Rousset	$US/Panel	$0.70	-	-
Italy	(CSSA, 2020; Curtis et al., 2021)	Tialpi Srl, Mottalciata	$US/Panel	$0.70	-	-
Germany	(CSSA, 2020; Curtis et al., 2021)	FLAXRES GmbH, Dresden	$US/Panel	$0.70	-	-

Discussion

The study's findings are discussed in the following order: Facilities Eliminated from Study; High-Value PV Recycling Facilities; Delamination Methods and Rates of Recovery; Presence of Comprehensive Legislation; Cost per Panel; and Future Considerations.

Facilities Eliminated from Study

The most interesting, yet disappointing, discovery from research and data collection was the closing of two successful high-value recycling facilities, Sasil of Italy and Loser Chemie of Germany. Sasil was approaching 100% recovery (CSSA, 2020; Deng et al., 2022; Tsanakas et al., 2020; VCT Group, 2022), but as discussed in the *Review of Literature*, was closed due to economic limitations and lack of EoL PV panels (CSSA, 2020; Tsanakas et al., 2020; VCT Group, 2022).

However, Italy is a leader in the EU for installed PV capacity (Feldman et al., 2022; Majewski et al., 2021), which does not directly correlate to lack of EoL PV panels, in my opinion. This study could not confirm a closing date for Sasil, which would be useful to compare to the collection, recycling, and recovery benchmarks established by the WEEE Directive (Majewski et al., 2021; Peplow, 2023; Weckend et al., 2016). If the closing date was before 2018, when it became required that 85% of materials be recovered and 80% were prepared for recycling (Majewski et al., 2021; Peplow, 2023; Weckend et al., 2016), then the lack of panels could make sense; a high-value process this advanced would have been more expensive than processes that could recover 80% of materials and prepare 70% for recycling (Majewski et al., 2021; Peplow, 2023; Weckend et al., 2016).

In the case of Germany, the PV industry in Germany has been strong since the late 1990's (Brachert & Hornych, 2010). This country is not only a leader in PV installations in the

EU, but also dominates a large share of the global installation share (Aleid et al., 2023; Feldman et al., 2022; Majewski et al., 2021; Veolia, 2018). Little information was found on Loser Chemie, including this facility's reason for closing, but it seems like the domestic market would have been suitable for a high-value PV recycling facility to thrive.

First Solar, Inc., a global manufacturer that runs its recycling operation out of Ohio (First Solar, Inc., 2023b), had to be eliminated for different reasons than the EU facilities. Because First Solar, Inc. only manufactures and recycles thin-film panels (First Solar, 2023a; Peplow, 2023; Weckend et al, 2016), this facility did not fit into the criteria of this study. While c-Si panels make up 95% of the global PV market (El-Khawad et al., 2022; Feldman et al., 2022; Majewski et al., 2021; Peplow, 2023), they do not dominate the installations in the US. Instead, thin-film type panels comprise around 40% of total PV deployment within the US (CSSA, 2020). This could explain why First Solar, Inc. has no plans to move into c-Si recycling (Peplow, 2023; Weckend et al., 2016). Between the manufacturing side of this company and the large quantity of thin-film panels within the US, First Solar, Inc. is likely not economically motivated to enter the c-Si recycling field.

High-Value Recycling Facilities

One of the most challenging aspects of this study was identifying facilities within the US that were performing high-value recycling processes commercially. Publicly accessible information is limited (Curtis et al., 2021; VCT Group, 2022), especially concerning technical processes. Many facilities were weeded out throughout multiple stages of preliminary research because they proved to not perform high-value processes. It is possible there are high-value PV recycling facilities within the US that are on the cusp of opening, are in the process of developing high-value recycling practices, or perhaps have not released information surrounding their PV recycling methods. Consequently, the data pool for the US is very small, with only We Recycle Solar, Inc. and SOLARCYCLE, Inc. fitting the criteria for this study. This challenge was not the case in the EU; however, there were still dead ends in the research process, namely Sasil and Loser Chemie.

When first beginning this study, the hypothesis was that the EU would be outperforming the US in every parameter explored, including the handling capacity of the selected facilities. This proved to not be the case. In fact, both We Recycle Solar, Inc. and SOLARCYCLE, Inc. have significantly higher handling capacities, especially We Recycle Solar, Inc. As shown in Table 1 and Table 2, the handling capacities for the selected facilities are as follows: Veolia, 4,000 metric tons/year; Tialpi Srl, 5,000 metric tons/year; FLAXRES GmbH, 1,000 metric tons/year; We Recycle Solar, 31,364 metric tons/year; SOLARCYCLE, 9,091 metric tons/year. Even with the estimated conversion to metric tons for SOLARCYCLE, Inc. this company is handling about 4,000 metric tons more than the highest performing EU facility in terms of capacity. We Recycle Solar, Inc. is in a league of its own, handling about six times the capacity of the EU's highest performer, Tialpi Srl.

Therefore, no conclusions can be drawn about the lack of US PV EoL legislation and the higher costs to perform high-value recycling processes influencing the handling capacities of facilities operating such processes. The high-value PV recycling US facilities, We Recycle Solar, Inc. and SOLARCYCLE, Inc., might have a much higher PV handling capacity than the selected EU facilities due to the small quantity of facilities operating in the US. With only three high-value recycling facilities (including First Solar, Inc.) available to US customers, the amount of PV EoL panels available to We Recycle Solar, Inc. and SOLARCYCLE, Inc. for recycling versus the amount available to EU facilities might be substantial. The significantly higher cost to recycle a PV panel in the US may also demand large-scale processes. A small-scale facility is most likely is not cost-effective enough to be viable.

Delamination Methods and Rates of Recovery

As stated, this study's original hypothesis was that the EU would outperform the US in every parameter of high-value PV recycling. This hypothesis was rejected following examination of facility rates of recovery. As shown in Table 3, the recovery rates for the selected facilities are as follows: Veolia, 95%; Tialpi Srl, 98%; FLAXRES GmbH, 100%; We Recycle Solar, 99%; SOLARCYCLE, 95%. All five facilities can achieve very high rates of recovery, even SOLARCYCLE, Inc., which just opened in 2022 (Kart, 2023). It is interesting that Veolia, the first dedicated c-Si PV recycling facility (CSSA, 2020; Deng et al., 2022; Peplow, 2023; Tao et al., 2020; Tsanakas et al., 2020; Veolia, 2018), has the lowest rate of recovery out of the selected facilities, tied with the youngest facility (SOLARCYCLE) out of the five. From this data pool, no correlations can be made about the lack of supporting PV EoL legislation and high costs to perform high-value recycling in the US influencing the rates of recovery achieved by PV recycling facilities.

As shown in the *Review of Literature*, mechanical delamination processes can allow a facility to process panels at a much faster rate than chemical or thermal delamination, but they are linked to recovery rates of only 75-80% (Ganesan & Valderrama, 2022). However, Veolia only utilizes mechanical delamination methods, and has been consistently reaching a 95% recovery rate. Although it could not be confirmed if We Recycle Solar, Inc. and SOLARCYCLE, Inc. use delamination methods other than mechanical, both recovery rates are considerably higher than the stated benchmark for mechanical delamination. This difference between the reported benchmark and what facilities are actually achieving could be due to advancements in automated optical sorting, or increased effectiveness of panel separation machinery and technologies.

Both US facilities were flagged for the lack of reported data outside of company sources, as shown in Table 3. Further information on both companies recycling processes and rates of recovery are needed to verify the accuracy of the reported data, and more publicly available information from sources other than the company are essential.

Presence of Comprehensive Legislation

As shown in the *Review of Literature* and Findings, the EU has specific legislation regarding the PV panel lifecycle, including policy dictating the labeling, collection, transportation, handling, recycling, and recovery of PV panels (Aleid et al., 2023; Majewski et al., 2021; Peplow, 2023 Sharma et al., 2019; Weckend et al., 2016). The US, on the other hand, has yet to develop federal or statewide legislation that bans PV panels from landfills or mandates their recycling (Curtis et al., 2021; Hurdle, 2023). As Figure 5 in the *Review of Literature* illustrates, a handful of states have begun establishing a framework for PV EoL management.

Washington State was the first in the US to enforce that PV manufacturers and retailers operating or selling panels within the state must finance a panel takeback scheme (Curtis et al., 2021). After July 1, 2023, parties cannot sell PV panels within or into the state without obtaining approval of a stewardship plan from the Washington State Department of Ecology (Curtis et al., 2021).

In 2021, California classified PV panels under their own category as a Universal Hazardous Waste (Curtis et al., 2021; Deng et al., 2022; Hurdle, 2023). This lessened regulations around the handling, transporting, and storing of panels, but prohibited the use of heat and chemical treatment in recycling processes (Curtis et al., 2021). If PV panels are exported out of state, this classification no longer applies and PV panels must be determined as non-hazardous or hazardous (Curtis et al., 2021).

The only other states that have established legislation surrounding PV EoL management are North Carolina and New Jersey. In 2019, both states passed legislation which created commissions to study management options (Curtis et al., 2021; Hurdle, 2023). As of 2021, 15 state bills addressing PV EoL management had been proposed and failed (Curtis et al., 2021). As per Curtis et al. (2021), the associated states and the dates the bills were proposed are as follows:

- Arizona, 2017
- Arizona, 2020
- Hawaii, 2014
- Hawaii, 2020
- Maryland, 2018
- Maryland, 2019
- Maryland, 2020
- Maryland, 2020
- Minnesota, 2014
- Minnesota, 2018
- New York, 2016
- New York, 2017
- New York, 2019
- North Carolina, 2019
- Washington, 2020

The political environment around PV EoL legislation is interesting. This study hypothesized that the US had made no efforts to establish a regulatory PV EoL framework, and I was surprised to find that several states had tried, some multiple times. Even more interesting is that the CEO of SOLARCYCLE, Inc. is not in favor of establishing EPR mandates in the US. In an interview with SOLARCYCLE, Inc.'s CEO, Suvi Sharma (Wallace, 2023), Sharma stated that he generally does not support EPR legislation on a state or federal level. "As a recycling company, you would think we would want EPR that would force recycling. I think there could be a place and time for it; I don't think now is the time and place for it" (Wallace, 2023, para. 31). I find this to be confusing, as I imagine that an EPR framework would only increase the product and revenue flow for both companies. More research is needed to investigate the public's perception of PV EoL management in the US, and why government attempts to address the issue keep failing. Deeper investigation is especially needed to examine the attitude of the operating US high-value recycling facilities towards more strict PV EoL management.

Cost per Panel

The final metric of comparison, the average cost to perform high-value recycling processes on one PV module, is the parameter with the most significant information gap. In the EU, where PV EoL legislation has been in place since 2012 (Majewski et al., 2021; Peplow, 2023; VCT Group, 2022; Weckend et al., 2016), the costs across the nation are reported at around $0.70 (CSSA, 2020; Curtis et al., 2021). In the US this price is much, much higher. NREL reports a range of $15 to $45 per panel (Curtis et al., 2021), and both We Recycle Solar, Inc. and SOLARCYCLE, Inc. charge about $20 per panel (Hurde, 2023; O'Brien, 2022; Wallace, 2023; Wesoff, 2022). Even the prices to landfill a PV panel are more expensive than high-value recycling in the EU, costing customers about $1 per panel for non-hazardous landfilling and about $5 per panel for hazardous landfilling (CSSA, 2020; Curtis et al., 2021; Hurdle, 2023; Wallace, 2023; Wesoff, 2022).

This wide gap in prices between the EU and the US may be due to the lack of supporting PV EoL legislation in the US and/or the fact that the EU has required such recycling practices since 2012 (Majewski et al., 2021; Peplow, 2023; VCT Group, 2022; Weckend et al., 2016). The facilities operating within the EU have had more time to refine their processes, increase their efficiencies, and cut associated costs. Because high-value PV recycling in the US is still in its infancy (EPA, 2023b; Hurdle, 2023), this price gap might take a couple of years to decrease as the US expands its high-value PV recycling portfolio, and advances in technology and efficiency facilitate a decrease in prices. However, it seems that all the odds are against We Recycle Solar, Inc. and SOLARCYCLE, Inc. Neither company has legislation to support it and their current prices are significantly less wallet-friendly than landfilling. Further investigation is necessary to analyze how both companies are able to operate capital intensive recycling processes (Curtis et al., 2021; Disruptive Investing & Saghei, 2023) despite the very wide price gap between high-value recycling and landfilling.

I believe that the associated costs of high-value PV recycling within the US are the main reason that only 10% of PV panels get recycled domestically (Curtis et al., 2021; Echo Environmental, 2022; Hurdle, 2023; Kart, 2023; Peplow, 2023). With landfilling options being considerably cheaper than that of high-value PV recycling, the economic environment does not currently favor the more sustainable path for PV EoL management. In conjunction with the wide price gap between landfilling and recycling, both We Recycle Solar, Inc. and SOLARCYCLE, Inc. do not cater to small-scale customers (SOLARCYCLE, n.d.; We Recycle Solar, n.d.).

Therefore, a wide range of potential customers are limited from using high-value PV recycling practices in the US, both by accessibility of available facilities and by cost.

Future Considerations

To increase PV recycling rates across the US, strategies from the EU should be considered. Some have proposed that a fee be added to PV panels to finance a national PV recycling program (CSSA, 2020). However, this tactic would still make consumers the financially responsible party for PV EoL management. Shifting the responsibility to manufacturers, like the EPR framework utilized by the EU, could further incentivize manufacturers to produce PV panels that are easier to recycle, or perhaps use a non-polymer-based substance for encapsulation.

Another factor in improving nationwide recycling rates is accessibility for small-scale customers. Customers of all scales should be able to responsibly manage their waste, and the lack of accessibility may disincentivize the adoption of PV systems in the future. One option to increase access for small-scale customers would be to implement more collection facilities across the US. Recycling facilities could independently establish PV panel-specific facilities for customers to bring their EoL panels to or collaborate with existing landfills.

Also worth consideration is the implementation of standardized, detailed labeling of PV panels for the US PV market. This strategy could increase the efficiency of non-hazardous versus hazardous classification and recycling processes. Hazardous component identification and a breakdown of contained materials would benefit retailers, customers, installers, and waste management.

Furthermore, the PV recycling industry has the potential to generate significant amounts of revenue. While sustainability and a circular lifecycle of the PV recycling industry might be a prime motivator for some, this sector should not be thought of as non-lucrative. Majewski et al. (2021) reported that $450 million could be generated by 2030, and $15 billion by 2050, by investing in and developing PV panel recycling industries.

Further Research Considerations

More research and analysis of the PV EoL industry within the US is necessary to aid in informing both the public and government officials of the issue that is on the rise. The gaps in reported data regarding the recycling process of both We Recycle Solar, Inc. and SOLARCYCLE, Inc. require further investigation. While keeping this knowledge as trade secrets may give these companies a competitive edge, collaboration in the PV EoL field could strengthen the industry's framework within the US.

Especially crucial to moving forward is further investigation of the public's attitude towards PV EoL-specific legislation. It is discouraging that 15 state bills aiming to do just that failed, and surprising that one of the leaders in the US high-value recycling industry is not in support of establishing an EPR framework. It is possible that the lack of publicly available information regarding high-value PV recycling influences the pace at which such legislation is adopted. Therefore, this relationship requires deeper analysis, and the barriers between industry-knowledge and public-knowledge need to be bridged.

Failure to address the rising quantity of EoL PV panels could create hazardous environmental and public health conditions. In conjunction with squandering valuable resources, the lack of circularity in the PV panel lifecycle will tarnish the solar industry's reputation of being a renewable and sustainable energy option. Communication and collaboration between industry, the public, and government officials is going to be necessary to ensure lifecycle circularity.

Conclusion

PV technologies are, and will continue to be, a crucial factor in society's transition away from fossil-fuels. The solar industry has largely been built around the promise of green energy (Peplow, 2023), and upholding this promise is dependent on a circular lifecycle. Without PV EoL management, precious resources such as silver and high-purity silicon are squandered and natural resources become at risk for contamination (Casey, 2023; Jain et al., 2023; Majewski et al., 2021; Peplow, 2023). As it stands, the rest of the world has much to learn from the EU, because it is the only governing body that has put PV EoL legislation into place (Curtis et al., 2021; Ganesan & Valderrama, 2022; Weckend et al., 2016). With 60 million to 80 million tons of EoL PV panels looming on the horizon (Aleid et al., 2023; Chowdhury et al., 2020; Ganesan & Valderrama, 2022; Majewski et al., 2021; Peplow, 2023), adopting policies that support a circular lifecycle for PV panels is a necessity. Although this study can draw no conclusions regarding the influence of PV EoL legislation on PV recycling facility handling capacity or rates of recovery, there does seem to be a direct correlation between legislation, costs to recycle PV panels, and nationwide recycling rates. In order to bring associated costs down for both recyclers and customers and increase the US PV recycling rate from the current 10%, adoption of PV EoL policy should be strongly considered.

References

Aleid, A., Ali, A., & Shafiullah, M. (2023). *Solar photovoltaic end-of-life waste management policies in leading countries and the lessons learned for the Kingdom of Saudi Arabia*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4449901

Bellini, E. (2022). New industrial plant concept for end-of-life PV panel recycling. *PV Magazine International*. https://www.pv-magazine.com/2022/10/24/new-industrial-plant-concept-for-end-of-life-pv-panel-recycling/

Bojek, P. (2023). *Solar PV still dominates renewable energy capacity additions*. https://www.iea.org/energy-system/renewables/solar-pv

Brachert, M., & Hornych, C. (2010). Entrepreneurial Opportunity and the Formation of the Photovoltaic Industry in Eastern Germany, 50th Congress of the European Regional Science Association: *Sustainable Regional Growth and Development in the Creative Knowledge Economy*, 19-23 August 2010, Jönköping, Sweden, European Regional Science Association (ERSA), Louvain-la-Neuve.

Buntrock, K. (2023). Something that FLAXRES GmbH has achieved years ago. Its first units are already in action! [Comment on the online forum post *Engineers at the University of New South Wales (UNSW) have developed a new, more effective method to recycle end-of-life solar panels. The technique allows them to quickly and efficiently separate 99% of PV cell component materials.*] LinkedIn. https://www.linkedin.com/posts/pv-magazine_australian-team-claims-99-recovery-rate-activity-7087700431346225152-6uKn/?trk=public_profile_like_view

Casey, J. (2023). *We Recycle Solar expands operation in Arizona*. Energy Global. https://www.energyglobal.com/solar/17052023/we-recycle-solar-expands-operation-in-arizona/

Chowdhury, S., Rahman, K. S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, D., Tiong, S. K., Sopian, K., & Amin, N. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. *Energy Strategy Reviews*, *27*, 100431. https://doi.org/https://doi.org/10.1016/j.enpol.2020.112062

CIRCUSOL. (n.d.). *New Horizons for LuxChemtech*. Circusol. https://www.circusol.eu/en/nieuws/68/new-horizons-for-luxchemtech

California Solar + Storage Association [CSSA]. (2020). *New regulations for end-of-life PV modules webinar*. California Solar + Storage Association. Retrieved November 11, 2023, from https://register.gotowebinar.com/recording/3084273463311327760

Curtis, T. L., Buchanan, H., Heath, G., Smith, L., & Shaw, S. (2021). *Solar Photovoltaic Module Recycling: A Survey of US Policies and Initiatives.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-74124. https://www.nrel.gov/docs/fy21osti/74124.pdf

Dearing, P. (2023). *Solar panel size and weight explained: How big are solar panels?* Solar Energy World. https://www.solarenergyworld.com/solar-panel-size-and-weight-explained-how-big-are-solar-panels/#:~:text=On%20average%2C%20solar%20panels%20weigh,add%20to%20your%20roofing%20system

Deng, R., Zhuo, Y., & Shen, Y. (2022). Recent progress in silicon photovoltaic module recycling process. *Resources, Conservation, and Recycling*, *187*. https://doi.org/https://doi.org/10.1016/j.resconrec.2022.106612

Disruptive Investing, & Saghei, A. (2023). *Solving solar panel recycling: We Recycle Solar interview*. YouTube. https://www.youtube.com/watch?v=26VtWa1hxUk

D'Souza, A. (2020). *FLAXRES sets a new benchmark in recycling photovoltaics*. EIT RawMaterials. https://eitrawmaterials.eu/flaxres-sets-a-new-benchmark-in-recycling-photovoltaics/

Echo Environmental. (2022). *Solar Panel Recycling*. Echo Environmental. https://echoenvironmental.com/solar-panel-recycling/

Ecoprogetti. (2021). *What is raw material that composes a photovoltaic module?* Ecoprogetti - Specialist in photovoltaic production process. https://ecoprogetti.com/the-structure-of-photovoltaic-module/

El-Khawad, L., Bartkowiak, D., & Kümmerer, K. (2022). Improving the end-of-life management of solar panels in Germany. *Renewable and Sustainable Energy Reviews*, *168*, 112678.

Enkhardt, S. (2022). Industrial process for "mobile" solar module recycling. *PV Magazine International*. https://www.pv-magazine.com/2022/07/22/industrial-process-for-module-recycling/

ERCC. (n.d.). *Map of states with legislation*. Electronics Recycling Coordination Clearinghouse. https://www.recycleclearinghouse.org/contentpage.aspx?pageid=10

EspoCRM. (2023). *How many work days in a year?* EspoCRM. https://www.espocrm.com/blog/how-many-work-days-in-a-year/

Feldman, D., Dummit, K., Zuboy, J., Heeter, J., Xu, K., & Margolis, R. (2022). *Spring 2022 solar industry update.* National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/82854.pdf

First Solar, Inc. (2023a). *Leading the industry in environmental stewardship*. Responsible Solar | Environmental | First Solar. https://www.firstsolar.com/en/Responsible-Solar/Environmental

First Solar, Inc. (2023b). *Manufacturing Locations*. About Us: Locations. https://www.firstsolar.com/About-Us/Locations

FLAXRES. (n.d.). *A new era of photovoltaic recycling*. https://www.flaxres.com/de/flaxres-photovoltaik-recycling-neu-gedacht/

FLAXRES Press Release. (2022). *Flaxres achieves breakthrough in Photovoltaic Module Recycling*. FLAXRES. https://www.flaxres.com/en/flaxres-achieves-breakthrough-in-photovoltaic-module-recycling/

France. Solar Waste / European WEEE Directive. (n.d.). http://www.solarwaste.eu/in-your-country/france/

Frelp by Sun. (2023). *Full Recovery End of Life Photovoltaic: BY the energy of the SUN*. https://www.frelp.info/

Ganesan, K., & Valderrama, C. (2022). Anticipatory life cycle analysis framework for sustainable management of end-of-life crystalline silicon photovoltaic panels. *Energy*, *245*. https://doi.org/10.1016/j.energy.2022.123207

GOV.UK. (2015). *Countries in the EU and EEA*. GOV.UK. https://www.gov.uk/eu-eea#:~:text=The%20EU%20countries%20are%3A,%2C%20Slovenia%2C%20Spain%20and%20Sweden.

Hurdle, J. (2023). *As millions of solar panels age out, recyclers hope to cash in*. Yale E360. https://e360.yale.edu/features/solar-energy-panels-recycling

International Energy Agency [IEA]. (2023). *Renewable power on course to shatter more records as countries around the world speed up deployment.* IEA. https://www.iea.org/news/renewable-power-on-course-to-shatter-more-records-as-countries-around-the-world-speed-up-deployment

IR Global. (2014). *Legislative decree n. 49/2014 – photovoltaic panels classified as "raee" - Italy*. IR Global. https://irglobal.com/article/legislative-decree-n-492014- photovoltaic-panels-classified-as-raee-italy-4116/

Kart, J. (2023). SOLARCYCLE plans to recycle 1 million panels a year with help from $30 million in financing. *Forbes*. https://www.forbes.com/sites/jeffkart/2023/03/15/solarcycle-plans-to-recycle-1-million-panels-a-year-with-help-from-30-million-in-financing/?sh=19a32f905406

Kummer, S., Löhle, S., & Schmiedel, U. (2022). Consumer survey on the final consumer behavior concerning the disposal of WEEE in Germany. *Waste Management & Research*, *40*(5), 538-544.

Majewski, P., Al-shammari, W., Dudley, M., Jit, J., Lee, S. H., Myoung-Kug, K., & Sung-Jim, K. (2021). Recycling of solar PV panels-product stewardship and regulatory approaches. *Energy Policy*, *149*, 112062.

Nekouaslazadeh, A. (2021). *Recycling Waste Solar Panels (c-Si & CdTe) in Sweden*. https://www.diva-portal.org/smash/get/diva2:1568855/FULLTEXT01.pdf

O'Brien, H. (2022). *Recycling solar panels is complicated. how We Recycle Solar approaches it*. Cronkite News. https://cronkitenews.azpbs.org/2022/03/22/recycling-solar-panels-complicated-yuma-company-we-recycle-solar/

Peplow, M. (2023). *Solar Panels Face Recycling Challenge*. Chemical & Engineering News. https://cen.acs.org/environment/recycling/Solar-panels-face-recycling-challenge-photovoltaic-waste/100/i18

PHOTON. (2021). *European consortium to develop photovoltaic recycling on an industrial scale*. The World of Information in the World of Solar Electricity. https://www.photon.info/en/news/european-consortium-develop-photovoltaic-recycling-industrial-scale

RAEE. (2020). *Annual report 2020: Collection and treatment of waste electrical and electronic equipment in italy*. Raee Italia. https://www.raeeitalia.it/en/report/

Röpke, N. (2022). *The WEEE EU directive: distribution and disposal of electrical appliances in the EU and Europe*. Deutsche Recycling. https://deutsche- recycling.com/weee-eu-directive/

Sah, D., Chitra, Upadhyay, N. K., Muthiah, S., & Kumar, S. (2023). Growth and analysis of polycrystalline silicon ingots using recycled silicon from waste solar module. *Solar Energy Materials and Solar Cells*, *261*. https://doi.org/10.1016/j.solmat.2023.112524

Sharma, A., Pandey, S., & Kolhe, M. (2019). Global review of policies & guidelines for recycling of solar pv modules. In *International Journal of Smart Grid and Clean Energy* 8(5), 597–610. Engineering and Technology Publishing. https://doi.org/10.12720/sgce.8.5.597-610

SOLARCYCLE. (n.d.). *Full solar panel recycling services*. https://www.solarcycle.us/

Solar Energy Industries Association [SEIA]. (n.d.). *Recycling & end-of-life considerations for photovoltaics*. https://www.seia.org/initiatives/recycling-end-life-considerations-photovoltaics

Tao, M., Fthenakis, V., Ebin, B., Steenari, B. M., Butler, E., Sinha, P., Corkish, R., Wambach, K., & Simon, E. S. (2020). Major challenges and opportunities in silicon solar module recycling. *Progress in Photovoltaics: Research and Applications*, *28*(10), 1077–1088.

Tembo, P. M., & Subramanian, V. (2023). Current trends in silicon-based photovoltaic recycling: A technology, assessment, and policy review. *Solar Energy 25*, 137–150. Elsevier Ltd. https://doi.org/10.1016/j.solener.2023.05.009

Tsanakas, J. A., van der Heide, A., Radavičius, T., Denafas, J., Lemaire, E., Wang, K., Poortmans, J., & Voroshazi, E. (2020). Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification. In *Progress in Photovoltaics: Research and Applications, 28*(6), 454–464. John Wiley and Sons Ltd. https://doi.org/10.1002/pip.3193

US EPA. (2023a). *End-of-life solar panels: Regulations and management.* https://www.epa.gov/hw/end-life-solar-panels-regulations-and-management

US EPA. (2023b). *Solar Panel Recycling*. Hazardous Wastes. https://www.epa.gov/hw/solar-panel-recycling

VCT Group. (2022). *Recycling Solar.* https://vctgroup.com/recycling-solar/

Veolia. (2018). *Veolia opens the first European plant entirely dedicated to recycling photovoltaic panels*. News. https://www.veolia.com/en/newsroom/news/recycling-photovoltaic-panels-circular-economy-france

Wallace, J. (2023). *Solarcycle CEO, fresh off $31.5M in public and private funding, discusses solar recycling's future*. Waste Dive. https://www.wastedive.com/news/solarcycle-ceo-sharma-solar-panel-recycling pv/648247/#:~:text=Right%20now%20we%20have%20a,processing%20equipment%20and%20technologies%20there

Weckend, S., Wade, A., Heath, G. (2016). *End-of-life management: Solar photovoltaic panels.* International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems. IEA-PVPS Report Number T12-06:2016. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf?rev=49a75178e38c46288a18753346fb0b09

We Recycle Solar. (n.d.). *About Us*. https://werecyclesolar.com/about-us/