SCHOOL FOR ENVIRONMENT AND SUSTAINABILITY
UNIVERSITY OF MICHIGAN

Final Project Report

Investigate technical, policy and business approaches to addressing stewardship and circularity for end-of-life for PV system

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Client**:** Michigan Energy Options

A practicum submitted in fulfillment of the requirements for the Master of Science degree at the University of Michigan School for Environment and Sustainability

April 2021

Acknowledgements

I would like to thank Dr. John A. Kinch (Michigan Energy Options) and Henry Love (Elevate) to give me an opportunity to work on this project and guiding me throughout the project. Many thanks to my advisor, Prof. Geoffrey McD. Lewis, for being flexible and providing continued support in my research and academic career. I additionally extend my gratitude to Michael J. Larson (Michigan Energy Options) and Dr. Dwarakanath Ravikumar (NREL).

Thanks to my family and friends in Ann Arbor as well as in India for continuously supporting me throughout my graduate studies and helping me face homesickness.

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Executive Summary

There has been exponential growth in the PV market around the world in the last decade. Although this growth is needed to reduce carbon emissions of energy production, this growth has resulted in a growth in PV waste as well. With the estimated global PV capacity of 4500 GW by 2050, PV waste would also accumulate to 78 million tons by 2050 for early loss and 60 million tons for regular loss scenarios. By 2020, Crystalline Silicon (c-Si) panels, which are first generation PV panels, accounted for 73% of total PV market share. This research studies global PV end-of-life (EOL) management policies, available technologies and business models for c-Si panels with the aim of proposing a policy, technology and business solution for the state of Michigan. Literature review was the main research approach used.

Most of the countries in the world and many major PV installers do not have PV EOL management policies. With the revision of the Waste Electrical and Electronic Equipment directive in 2012, the EU became the first entity in the world to have a PV EOL management policy. This directive is based on the extended-producer responsibility (EPR). Based on the different PV EOL management policies, guidelines and waste amount, the UK, Italy, Germany, Japan, China, Taiwan, and the United States are the countries focused on in this policy review. On the technology side, Full Recovery End of Life Photovoltaic (FRELP), a process developed at Arizona State University (ASU), and Photovoltaic Panel Mobile Recycling Device (PV-MoReDe) are analyzed due to their recycling rate, economic value of recycling materials and PV waste availability in Michigan. For the business side, centralized and decentralized models are considered.

Introduction

Solar, as a form of renewable energy, offers many advantages.[1] It has almost no environmental impact in terms of producing electricity.[2] It is viewed as a reliant and a clean energy source to combat climate change.[3] Furthermore, the decreasing cost of solar panels has fueled the growth of the solar industry around the world with China leading the market.[4] Global installed PV capacity reached 586.4 gigawatts (GW) at the end of 2019 and is expected to rise further to 4,500 GW by 2050.[5] As shown in Figure 1, particularly high cumulative deployment rates are expected by that time in China (1,731 GW), India (600 GW), the United States (US) (600 GW), Japan (350 GW) and Germany (110 GW).[6]

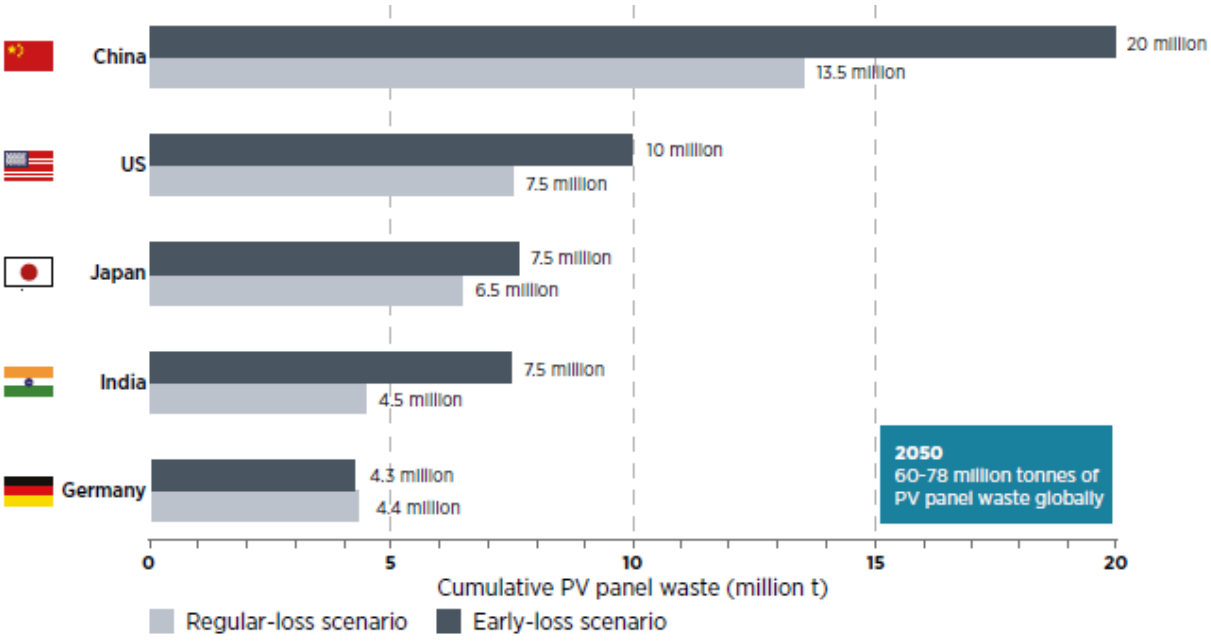

Figure 1. Cumulative waste volumes of top 5 countries for EOL of PV panels by 2050[6]

(This figure is directly taken from Figure on pp. 12 in [6])

However, this growth has also created a new landfill problem.[7] Photovoltaic panels have a life of 20-30 years, and they lose productivity over time.[8] As per the International Renewable Energy Agency (IRENA) estimates, there were about 43,000-250,000 metric tons of solar panel waste by the year 2016, which is projected to accumulate to 78 million tons by 2050 for early loss and 60 million tons for regular loss scenario.[6] Previous years have seen tremendous growth in solar energy. In the US itself, solar energy capacity increased by nearly 3149% in the last decade.[9] As a result, as shown in Figure 2, waste PV to new PV ratio will increase due to the

high projected growth rate of PV in the future.[6] PV panels contain many toxic chemicals and elements such as cadmium and lead that generally cannot be removed without breaking apart the entire panel.[10] Recycling solar panels has potentially huge economic value, the International Renewable Energy Agency estimates that recoverable materials from decommissioned solar panels could be worth up to $450 million, and possibly $15 billion by 2050.[6]

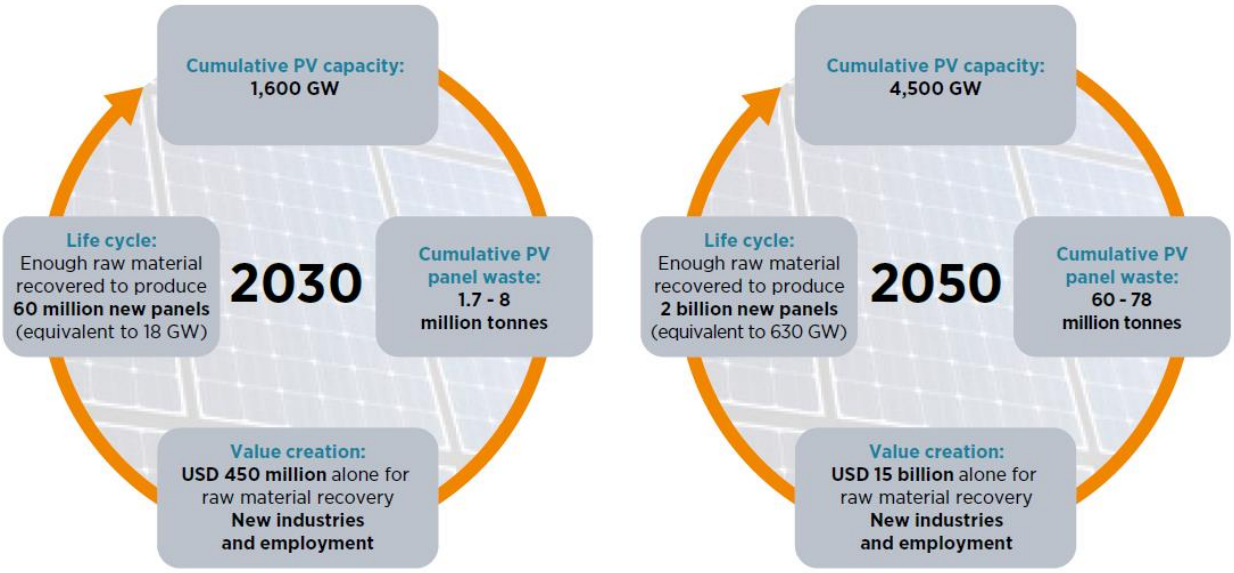

Figure 2. Potential value creation through PV EOL management and PV waste as percentage of total installed capacity in 2030 and 2050[6]

(This figure is directly taken from Figure on pp 13 in [6])

Solar panels contain large amounts of aluminum and glass, both of which can be easily reclaimed.[11] Additionally, recycling solar panels prevents the loss of rare metals, such as indium, gallium, and germanium.[12] Research by the Electric Power Research Institute does not recommend disposal of panels in landfills because toxic materials can leach into the soil.[13] A study commissioned by the Ministry of Economic Affairs reveals that pollutants such as lead and cadmium can be washed out of the fragments of the panels by rainwater over a period of several months.[14] In the absence of proper recycling, processing, and reusing systems, the heavy metals embedded in EOL PV panels will pose significant threats to human health and the environment by polluting land and water[15] .Lead can affect our central nervous system (headache, tremors, irritability, hallucinations, memory loss, coma, etc.), as well as to the cardiovascular system, the

endocrine system, kidneys, etc.[16, 17] The amount of lead present in a crystalline silicon (c-Si) module varies from 1.64 to 11.4 g for different panels.[17]

Currently, the solar industry is focusing on installations of solar panels, not decommissioning of these assets. Many local jurisdictions see a parallel between past resource extraction and manufacturing industries that once were economic engines but now are legacy brownfields and toxic sites within communities. We need to make sure this is not the unintended consequence of renewable energy development, which is critical to addressing climate change. The cost of recycling solar panels is currently more than the economic value of recovered materials in most markets.[18] This is one of the reasons most of the solar panels end up in the landfill.

Types of PV panels

PV panels can be classified into three types by technology: First generation (c-Si), second generation (thin-film) and third generation (concentrating solar PV, organic PV, etc.). C-Si are the oldest and most popular panels in the market due to high efficiency and they make up around 73.3% of the PV market, as shown in Table 1.[6] These cells are made up of silicon wafers, which are the highest cost component in these panels. Much research has been performed to separate intact wafers from panels during recycling. Thin-film panels have lower efficiency and cost compared to c-Si panels. Examples of these types of panels are cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), which makes up around 10.4% of the PV market.[6] Third generation PV panels are advanced emerging technologies.

Table 1. PV Panels market share by technology group[6]

Technology		2014	2020	2030
Silicon-based (c-Si)	Monocrystalline	92%	73.3%	44.8%
	Poly- or multicrystalline			
	Ribbon			
	a-Si (amorph/micromorph)			
Thin-film based	Copper indium gallium (di)selenide (CIGS)	2%	5.2%	6.4%
	Cadmium telluride (CdTe)	5%	5.2%	4.7%
Other	Concentrating solar PV (CPV)	1%	1.2%	0.6%
	Organic PV/dye-sensitised cells (OPV)		5.8%	8.7%
	Crystalline silicon (advanced c-Si)		8.7%	25.6%
	CIGS alternatives, heavy metals (e.g. perovskite), advanced III-V		0.6%	9.3%

(This table is directly taken from Table 7 on pp. 37 in [6])

Second and third generation PV panels still have small market share. A major producer of CdTe thin-film PV panels (First Solar) responsibility manages their panels at EOL, which reduces the risk of contamination by hazardous materials. This research has focused only on c-Si panels.

Composition of c-Si panels

Figure 3 gives the general layout of c-Si panels and the material composition of c-Si panels is shown in Table 2. By weight, nearly 85% of the c-Si panel materials (i.e., glass and aluminum) are easily recyclable. However, the major economic value of panels is in silicon wafers and silver, which constitute a small percentage of overall materials. To decrease the cost of PV panels over time, manufacturers have decreased the thickness of silicon wafers from 400µm to 180µm.[19,20] Additionally, silver content in panels has also decreased by more than 70% in last decade, which is expected to continue to further reduce the cost of panels.[6] These changes have resulted in wafers being more fragile and the smaller amount of silver providing less economic benefit, which has disincentivized PV recyclers.

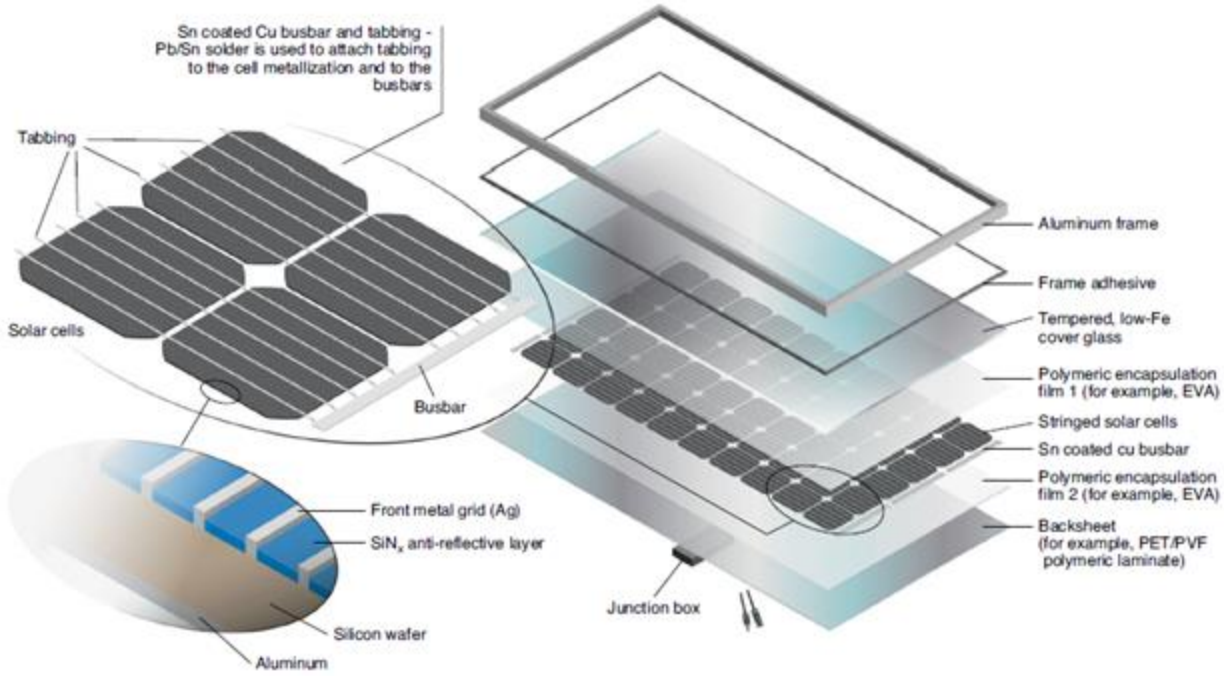

Figure 3. c-Si components[21]

(This figure is directly taken from Box 2 in [21])

Table 2. c-Si panel composition, by mass[6]

Materials	**Composition**
Glass	76%
Polymer (encapsulant and backsheet foil)	10%
Aluminum	8%
Silicon	5%
Copper	<1%
Silver, tin, lead	<0.1%

End of life management pathways for PV panels

Technologies for PV recycling

Three key steps in recycling PV panels are:[21]

- Removal of frame and junction box by mechanical process
- Separating the sandwich of EVA, wafer, and glass through thermal, mechanical or chemical processes
- Separation and further purification of silicon wafers and heavy metals such as silver, tin, lead, and copper, through electrical and chemical techniques.

Through mechanical separation, glass, aluminum and copper can be recovered with a cumulative yield of greater than 85% but recycling only these materials does not recover the cost of recycling.[22,23] In c-Si, two most valuable materials are solar-grade Si and Ag.[21] The challenging part in recycling photovoltaic waste is the removal of the encapsulation layer.[24] Over the years, many methods of c-Si panels recycling/reuse have been proposed:

1. Thermal and/or chemical process to remove EVA polymer layer. Researchers have tried different methods for removing EVA layers such as pyrolysis at variable heating rates, use of organic solvents such as trichloroethylene and nitric acid. Several field experiments are also being conducted by companies including Deutsche Solar (mix of thermal and chemical process) and Soltech (pyrolysis with microwave, dissolving panels in chemical reactors with triethylene and immersion in hot nitric acid).[25,26] In Japan, a pilot project funded by NEDO was based on pyrolysis of the polymers in a furnace.[27] Enterprises in Taiwan are nowadays using 'hot knife method' to separate glass and battery sheets and reuse them.[28]
2. In 2011, researchers proposed using c-Si PV panel waste in concrete.[29]
3. Recycling of panels by physical and thermal operation. As opposed to chemical processes, this method does not generate process-waste.[30]

A module using recycled wafers consumes 40% less energy than using new materials.[26] Many research projects have focused on recovering intact c-Si wafers, but some researchers have recommended deemphasizing R&D in this field for several reasons.[21] First, most cells at their EOL are broken and intact wafers are likely to represent a very small percentage of total

decommissioned PV waste. Second, to decrease the cost of panels, wafer thickness has decreased over time, and these thinner cells are more fragile. Third, cell efficiencies are increasing every year and manufacturers would be unlikely to be interested in old cells with lower efficiency.

Based on the recycling rate, value of recycling materials and PV waste availability in Michigan, three pioneer processes for recycling PV panels are: Full Recovery End of Life Photovoltaic (FRELP), the Arizona State University (ASU) developed process, and Photovoltaic Panel Mobile Recycling Device (PV-MoReDe).[31,32,33,21]

FRELP

The aim of this process is to recover the highest mass percentage of materials with the least waste. This study was supported by SASIL, PV Cycle and Stazione Sperimentale del Vetro (SSV). PV Cycle, a non-profit organization, was founded in 2007 to address PV EOL management issues.[34] SASIL is a mining and recycling company, and SSV is a researched center based in Italy.[35,36] The aim of the project was to design an operational pilot-scale plant, followed by an industrial-scale plant to treat 7000 tons of PV waste annually.[31] A pilot facility with the capacity to process 1300 panels/ per was built, though it is not currently operational owing to the insufficient quantity of PV waste.[21,23]. Process diagram of FRELP is given in Figure 4.

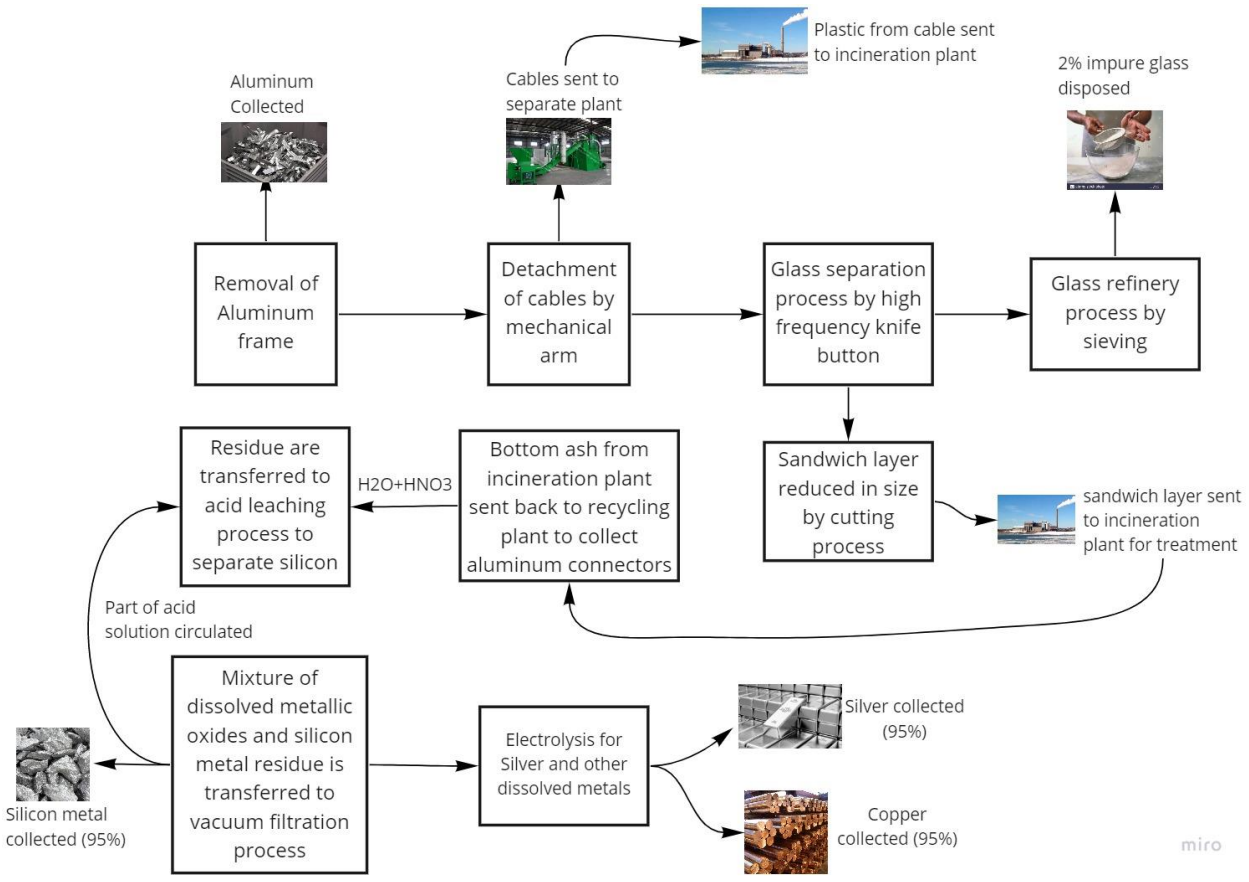

Figure 4. Process diagram of FRELP[37]

As per LCA study conducted for the FRELP process, transport is the biggest contributor to emissions associated with the whole process. In the freshwater ecotoxicity and human toxicity impact categories, incineration of PV sandwich, incineration of plastics from cable and disposal of fly ash have the biggest impact.[37]

ASU developed process

The ASU process is a 3-step process aimed at achieving highest recovered material value.[21] In this process, two new technologies (sequential electrowinning and sheet resistance monitoring) are demonstrated.[32] It is possible to recover solar-grade Si from this process, which significantly reduces the energy consumption for making new solar-grade Si while increasing revenue generation. This recycling process can generate a material value of nearly $16-17/module, which is a huge step towards making PV recycling profitable in the USA. The

recycling cost per panel in the USA is $15-45.[38] Therefore, this process has the potential to generate positive revenue for recyclers.

The recovery rate and purity for selected materials recovered by both processes is summarized in Table 3.

Table 3. Recovery rate and purity of recovered materials from FRELP and ASU processes[21]

Recovery rate and purity of recovered materials for FRELP and ASU module recycling processes			
Product	Recovery Rate		Purity
	FRELP	ASU	
Insulated cable	100%	100%	NA
Silver metal	94%	74%	99%
Copper metal	97%	83%	99.993%
Silicon	97%	90%	Metallurgical grade
Glass cullet	98%	99%	98%

(This table is directly recreated from Table 1 in [21])

Photovoltaic Panel Mobile Recycling Device (PV-MoReDe)

PV-MoReDe is a joint collaboration among La Mia Energia (Italy), PV Cycle (Belgium), the University of Florence (Italy), and the Leitat Technological Centre (Spain).[39] In late 2013, this project received funding from the EU through the 12th edition of the European Union's Eco Innovation Programme.[39] In 2020, they successfully developed a mobile PV recycling system that can recover up to 99% raw materials with silicon purity of 45-65%.[40]

This device can be set up inside a 13m container and is able to operate on a truck, which gives it flexibility to treat small scale PV panels on-site.[41] This system is capable of disassembling a standard panel in 40 seconds. Unlike the many other PV recycling systems in the world, this device uses only mechanical separation, and thus eliminates the pollution caused by

using chemicals. For small PV markets such as Michigan, where the expected amount of PV waste in the near future will not be large, a mobile recycling plant may prove to be more effective compared to a centralized recycling plant.

PV EOL management policies around the world

The EU was the first to recognize this growing PV waste problem. PV Cycle, a non-profit organization, was founded in 2007 to address these issues.[34] Finally, in 2012, the EU revised its waste regulation and included solar under the recast WEEE (Waste Electrical and Electronic Equipment) directive, placing the extended producer responsibility principle at its core.[42] As from 14th February 2014, every country in the EU needs to regulate the collection, transport and treatment of PV panels. Within the EU, this research highlights the policies of the UK, Italy, and Germany due to their different financial mechanisms for the EOL management of PV panels. This research also briefly highlights the PV recycling markets of Japan, China, Taiwan, and the United States. Major PV policy development across the world (except USA) is shown in Figure 5.

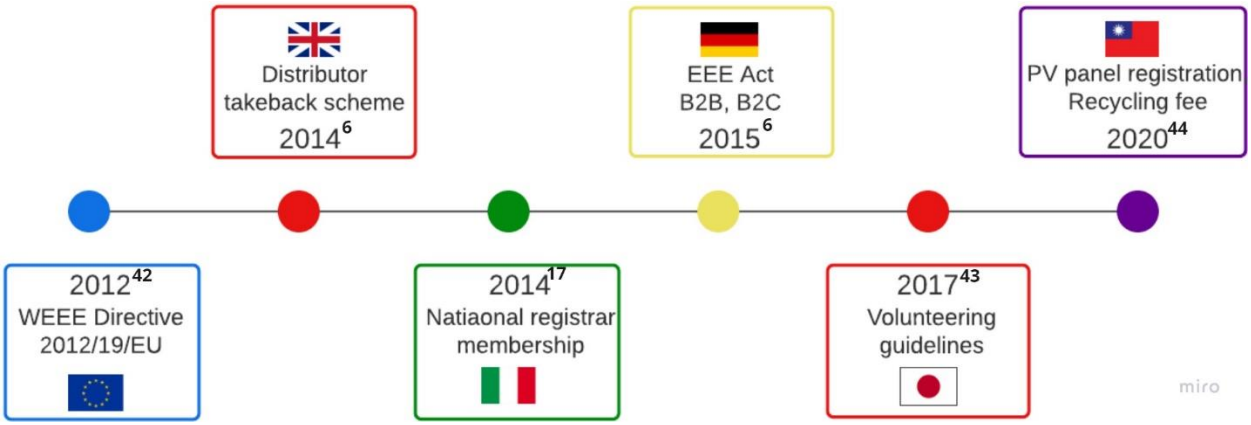

Figure 5. Major PV policy development around the world

European Union (EU)

PV deployment in the EU started in the early 1990s with significant growth from 2005.[45] European Union has been a forerunner in regulating waste electrical and electronic equipment (WEEE) with the aim of contributing to sustainable production and consumption. With the goal of managing WEEE sustainability, the EU Commission passed the WEEE Directive in 2003 (Directive 2002/96/EC).[46] This directive did not include PV panels and was also not efficient in tackling diverse and growing amounts of E-waste.[47] To tackle these issues, the EU commission

revised the original directive in 2012 (2012/19/EU) and the EU became the first in the world to regulate PV waste.[42] This directive is based on Extended Producers Responsibility (EPR), where producers are responsible to at least finance the collection, treatment and recovery and disposal of PV wastes.

Each of the 28 EU states needed to implement this directive in their country by 14 February 2014. WEEE legislation sets up a minimum target for the disposal of PV waste and members are free to further refine or strengthen the rules. The UK was the first country to officially implement this directive on 1 January 2014.[48] Currently, each of the 28 states have begun to implement this directive through their national legislation. As per the definition of producers in the directive, producers can be manufacturers, distributors, resellers, importers and internet or distance sellers of photovoltaic panels, or: any natural or legal person, established in a specific Member State, and putting PV panels onto this market for the very first time. Consumers are also responsible for returning their PV waste at the end of life at no cost. In addition to the treatment of PV waste, this directive also prevents illegal shipments, which prevents dumping of PV waste in underdeveloped countries.

As per this directive, for PV panels coming out of service up to 2016, 75% of all PV waste should be recovered with a recycling rate of at least 65%, which needs to be increased by 5% 3 years after implementing the directive. From 2016 to 2018, at least 80% waste needs to be recovered with a minimum 70% recycling or reuse rate. After 2018, 85% of waste should be recovered with a recycling/reuse rate of 80%.

Due to revised WEEE Directive, research and development of solar panel recycling methods has increased significantly.[49] The WEEE Directive provides environmental benefits far beyond the EU because it forces global producers who want to sell solar panels on the European market to comply with WEEE Directive requirements.

United Kingdom (UK)

Although the UK is not an EU member anymore, it was the first country in the EU to adopt a revised WEEE Directive in their national legislation on 1 January, 2014.[48] Contrary to other EU countries such as Germany and Italy, major PV deployment in the UK started only from 2011.[9] Therefore, the UK PV waste market is still very nascent. However, as shown in

Figure 6, the UK has strong PV waste growth projection, which necessitates its EOL management.

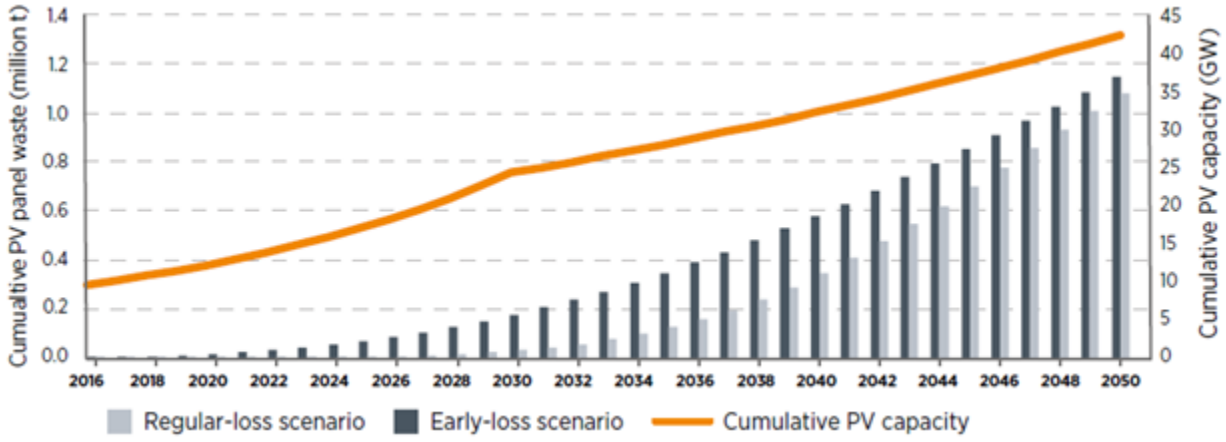

Figure 6. EOL PV panel waste volume projection for UK through 2050[6]

(This figure is directly taken from Figure 15 on pp. 64 in [6])

The UK has set out a different definition for PV producers, which they have defined as:

- UK manufacturer selling PV panels under its own brand;
- Importer of PV panels into the UK market;
- UK business selling PV panels manufactured or imported by someone else under its own brand.

These producers must register under a producer compliance and distributor takeback scheme, and submit relevant data for consumer (B2C) as well as business (B2B) product transactions. There are two different financial schemes for B2C and B2B transactions, which is explained in Table 4.

B2C	B2B
Producers collect waste PV panels based on their market share of placed PV panels in the previous year The year when they were first introduced on the market will be ignored.	PV producers must finance the handling and recycling of non-household (B2B) PV modules carrying the wheelie bin symbol and old modules without symbol will be exchanged by new ones.

Table 4. B2C and B2M financial system[24]

Germany

Germany is one of the earliest and biggest solar power markets in Europe. PV installation in Germany dwarfs the installation in other European nations. In the first half of 2020, solar provided 27.9 TWh into the public grid, which is nearly 11.4% of total electricity generation.[50] Germany's solar capacity will increase from over 50 GW in 2020 to about 415 GW by 2050.[51] Nearly 95% of total solar capacity installed in Germany in 2017 was c-Si cells.[52] Due to this strong growth, the amount of PV waste in Germany is projected to be more than any other EU member.

In 2018, nearly 8000 tons of PV waste was collected and processed in Germany. In 2020, most of PV recycled in Germany was damaged or malfunctioning PV and not panels reaching the end of their service life.[53] However, given the massive amount of installed capacity, Germany will see significant PV EOL waste by 2030, which is shown in Figure 7.

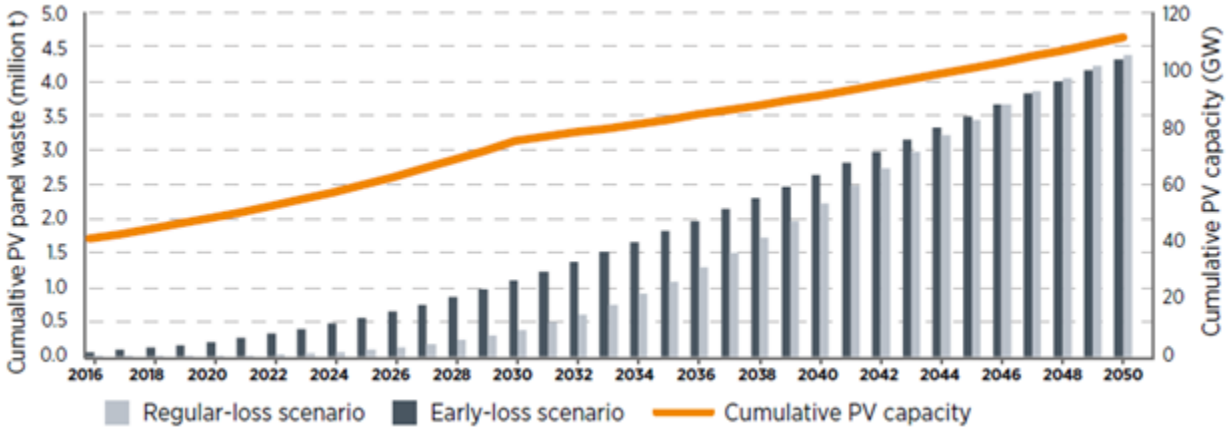

Figure 7. EOL PV panel waste volume projection for Germany through 2050[6]

(This figure is directly taken from Figure 13 on pp. 60 in [6])

A revised WEEE Directive was adopted into national law in Germany in Oct 2015.[6] A national registrar (Stiftung Elektro-Altgeräte Register or Stiftung EAR), which was founded after the adaptation of the original WEEE Directive is responsible for regulating PV waste in the country.[6] This agency is responsible for registering producers, collecting data on PV waste placed on the market, reporting annual flow of materials to the Federal Environmental Agency etc. Before selling panels in the market, each producer must provide some financial guarantee, which is calculated based on many factors such as presumed return rate, presumed disposal costs, etc. This financial guarantee also depends on which type of financing option the producer is choosing. Currently, there are two types of financing mechanism for implementing recycling policies in Germany focused on B2C and B2B transactions

Business-to-consumer (B2C) transactions

German law ensures that producers are responsibly managing the end-of-life waste associated with panels sold to households or users other than private households but with similar demand, i.e., dual use e-waste. For B2C transactions, Germany has implemented a collective producer compliance system (Figure 8), which has two levels: level 1 is the cost of immediate collection and recycling of products, including historic product put on the market before PV was included in WEEE Directive, and level 2 to finance the management of future PV waste.[6]

Costs of level 1 are covered using pay as you go (PAYG) model, where the producer takes responsibility for level 1 costs depending on their market share. They also need to register

with the clearing house to show that they have made arrangements to cover level 2 costs. After receiving this information, the clearing house provides a register number to the producer, which needs to be printed on each module and invoice. Producers are able to decide whether they want to recycle panels on their own (like First Solar) or they want to join a group collection scheme such as PV Cycle. In case a producer leaves the market, its market share, along with financing collection and recycling accountability, will be distributed among current market players.

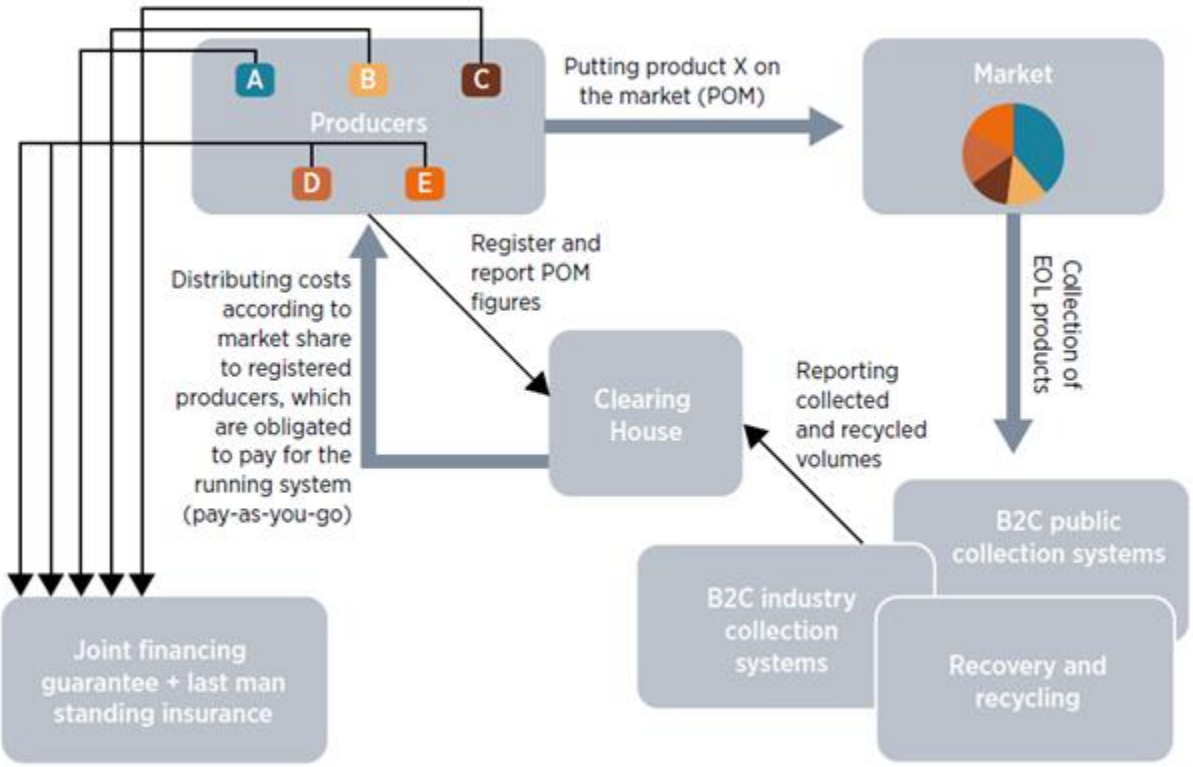

Figure 8. Collective producer responsibility system for EOL management of B2C PV panels[6]

(This figure is directly taken from Figure 14 on pp. 62 in [6])

Business-to-business (B2B) transaction

Financing of B2B transaction is significantly different from B2C transactions. In this transaction, the producer and final PV installation owner can execute a contract between them to manage PV waste. There is more flexibility to agree on a funding/financing mechanism. In case of industrial or commercial scale PV installations, this financing will most likely result from creative economic models that create funds for collection and recycling from near-commercial end-of-life project cash flows.

Italy

Various efforts taken by the Italian Government to increase the PV installation through feed-in-tariff, market-based mechanisms, capital account funding, tax concessions, etc. has resulted in significant PV deployment over the last decade.[17] Established in 2010, National Action Plan for Renewable Energy Sources, also played a crucial role in this growth. Based on the growth projection of PV waste, recycling of silver and lead present in C-Si panels represent a huge saving potential by 2050. With the projected price of $1617/kg for silver, recycled silver represents a market of nearly $1.2 billion.[54] Furthermore, the cost relating to pollution caused by the leaching of improper disposal of lead ($1409/kg) would be over $2.4 billion.[54] Therefore, EOL management of PV panels provides a cost-saving benefit for the longer term in Italy.

A revised WEEE Directive was adopted in Italy by the implementation of Decree No. 49 on 14 March 2014.[55] This decree classified panels based on the power of the plant to which they belong; less than 10 kWp is considered household waste and equal or more than 10 kWp are considered as professional. Panels are also classified based on the period in which they were placed on the market. PV waste coming from plants installed before the implementation of Decree No. 49 are defined as ‘historical’ and ones after the implementation of decree are defined as ‘new’ waste. So PV waste in Italy can be broadly classified into four categories: historical household, new household, historical professional, and new professional. Financial arrangements for the management of EOL of all these categories are shown in Figure 9:

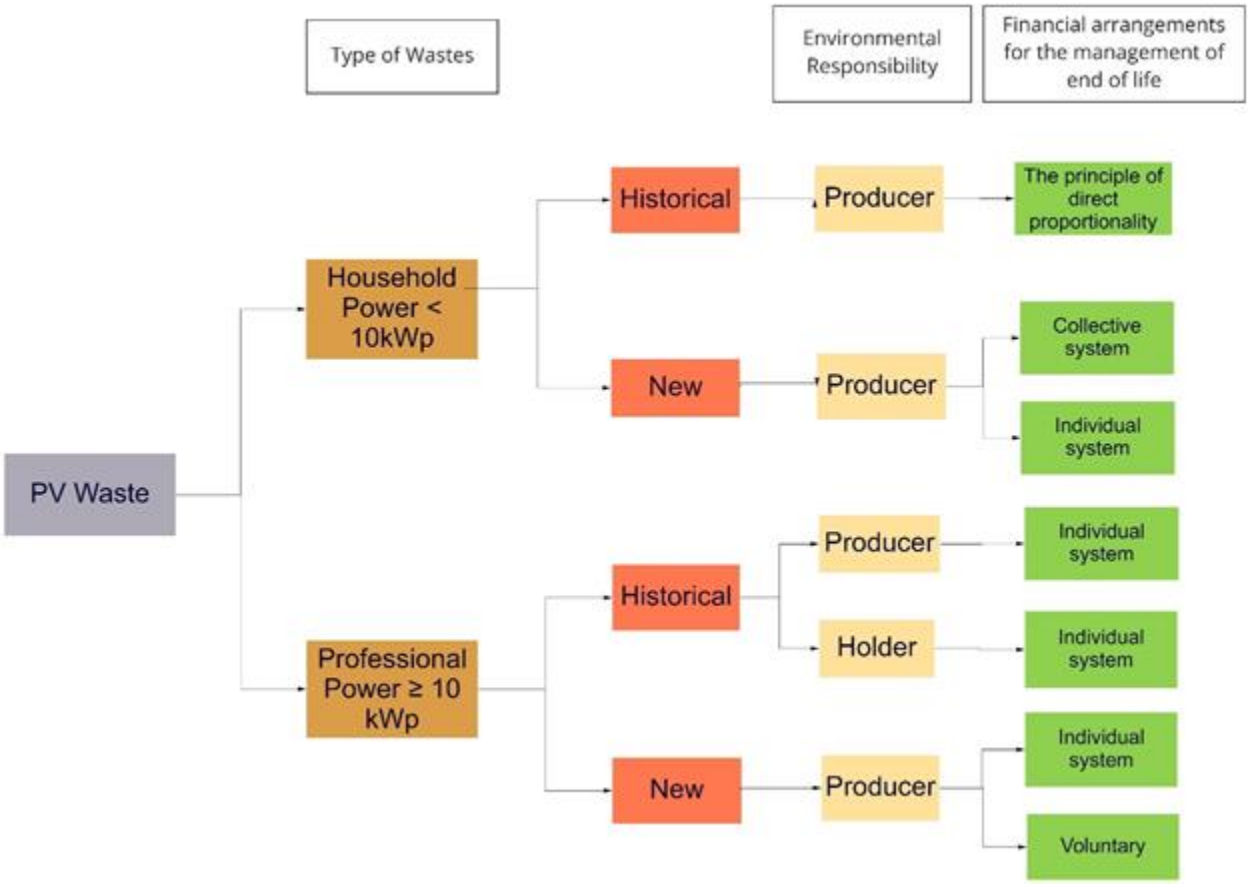

Figure 9. PV waste types and their respective financial arrangements[17,]

(This figure is directly recreated from Figure 1 in [17])

Legislative decree no. 49 also sets a minimum target (by weight) of at least 75% recovery and 65% recycling until 14 August 2015 and at least 80% recovery and 70% recycling until 14 August 2018. However, even before the introduction of a revised WEEE in 2012, Italy took steps to address the stewardship and circularity for end-of-life for PV panels through the Fourth Feed-in Scheme (Ministerial Decree 5 May 2011).[56] Through this system, manufacturers of PV panels were required to send a certificate to the Manager of Energy Services (GES) to ensure the recovery and recycling of panels. In case of non-compliance, holders of the plants were excluded from the financial incentives provided by the Fifth Feed-in Scheme.

Japan

Japan is one of the leading countries in PV deployment. In 2019, Japan installed nearly 7GW of PV capacity and with the cumulative capacity of 63 GW, it ranked 3rd in the world.[57] With the 497/capita, Japan also ranks 3rd in terms of solar installation per capita.[57] Major solar installation in Japan started after the introduction of feed-in-tariff in 2012 and with the projected waste capacity of 6.5-7.5 million tons, it will be the third largest producer by PV waste.[6] Japan's PV waste projection and cumulative PV capacity is shown in Figure 10:

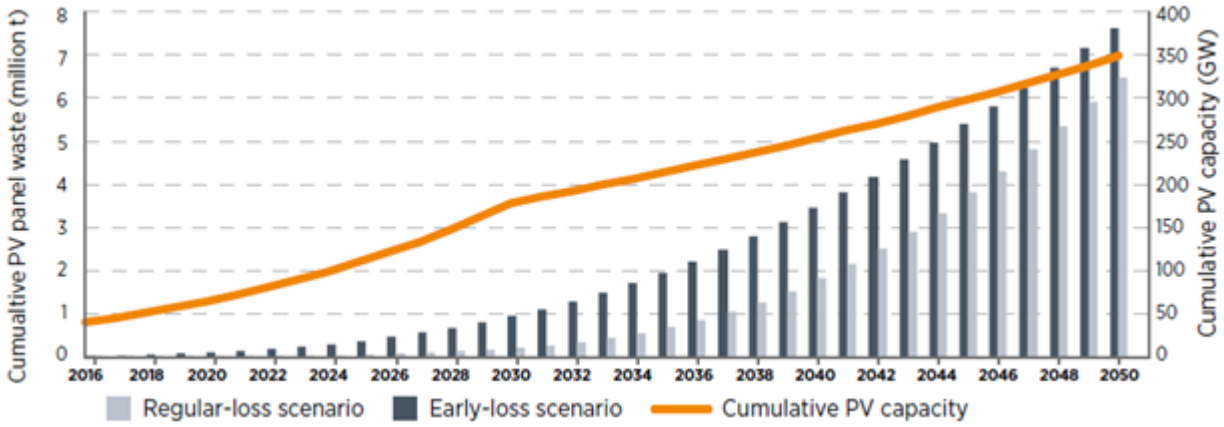

Figure 10. EOL PV panel waste volume projection for Japan through 2050[6]

(This figure is directly taken from Figure 16 on pp.66 in [6])

Currently, Japan has no regulation for PV EOL management and therefore, it must be treated under the general Waste Management and Public Cleansing Act.[58] However, the Ministry of Environment (MOE) and Ministry of Economy, Trade and Industry (METI) have jointly worked to address the EOL management of decommissioned energy equipment such as PV panels and wind turbines. In 2015, they also prepared a report with the roadmap for promoting collection, recycling, environmentally friendly design, guidelines for dismantling, transportation and treatment of waste.[58,59] This roadmap led to the launch of the first set of guidelines in 2016 for promoting EOL of PV.[60] These guidelines also push for reusing PV in places like Africa, where electricity grids are underdeveloped.

In Dec 2017, the Japan Photovoltaic Energy Association (JPEA) published voluntary guidelines on managing EOL PV panels.[61] Although these guidelines are not binding, JPEA strongly recommends industry to follow these guidelines. As observed by a survey conducted by

the Ministry of Public Management, Home Affairs in 2017, there has been strong support to know more about PV disposal methods among waste disposers and local governments.[61]

Japan has seen some strong growth in R&D activities regarding PV recycling technologies. From 2014, the National Institute of Advanced Industrial Science and Technology (NEDO) and Environment Agency, together with private companies, are working to develop recycling technologies to pry the sandwich of glass, EVA and cells apart.[62]

A company, named NPC incorporated, developed a hot knife process to separate cells of a panel from glass in just 40 seconds.[62] In this method, panels are placed on two roller, which moves panels along and hold them steady. To separate glass and cells, these panels are then cut with a hot knife, which is a 1 meter long, 1 centimeter wide steel blade, heated to 180-200°C.

JPEA has listed 29 organizations, which can accept and property treat PV panels in Japan.[63] However, one of these companies (NPC Incorporated) specialized in PV module recycling and as of January 2021, it has treated a total of 25,587 panels.[64] Recycling process used by NPC Incorporated is shown in Figure 11.

Figure 11. Process used by NPC Incorporated[27]

(This figure is directly taken from Figure 9 in [27])

China

China is the biggest PV market in the world.[57] In 2019, it installed 30.1 GW of PV capacity, which is more than the combined installation of the EU and USA.[57] China will be the

biggest PV panel recycling market with the projected waste capacity of 13.5-20 million tons.[6] China's PV waste projection and cumulative PV capacity is shown in Figure 12.

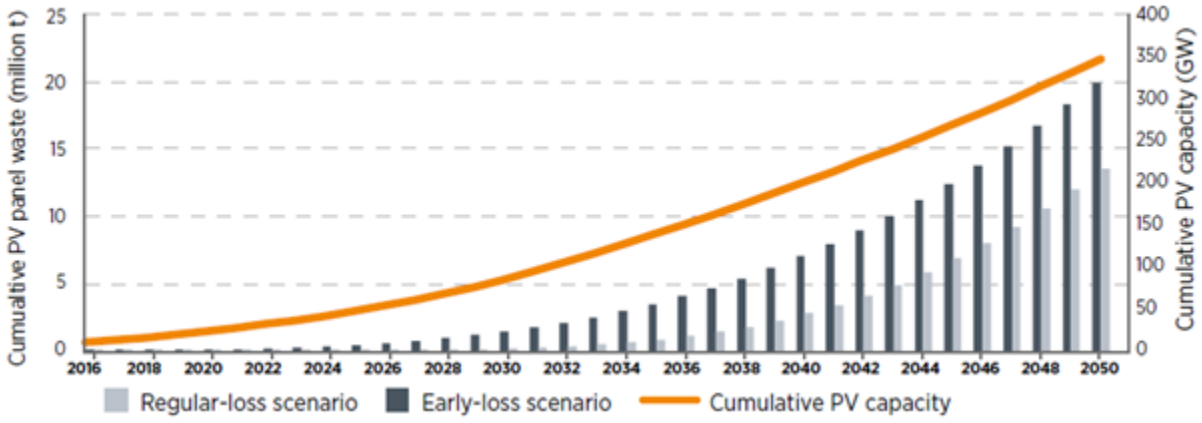

Figure 12. EOL PV panel waste volume projection for China through 2050[6]

(This figure is directly taken from Figure 20 on pp. 71 in [6])

Due to yearly descending feed-in-tariff and special programs such as Photovoltaic Poverty Alleviation Initiative, political pressure of completing projects in a timely manner, and demand of high-quality PV panels exceeding the supply, some developers have expected to install low quality PV panels from smaller PV manufacturers. These panels might need to be replaced much before the expected service life has ended, further increasing projected PV module waste in China.

Because of the rapidly growing PV industry, PV module EOL management is receiving attention from the Chinese government and PV producers. In 2011, Waste Electrical and Electronic Product Recycling Management Regulation came into effect, which requires e-waste to be collected and recycled in a centralized processing system.[65] Producers are given freedom to either collect and recycle e-wastes by themselves or make an arrangement with the seller for proper recycling/disposal. However, this regulation does not list PV panels as e-waste. Directions for accelerating EOL management of PV panels are described in the 13th 5-Year Plan for 2016-2020.[66] In 2017, China Photovoltaic Industry Association (CPIA) published a PV module recycling standard, but it does not clearly clarify who is obliged for PV recycling.[67]

Due to the concern surrounding managing PV panels waste, China sponsored R&D on PV recycling technologies under China's National High-tech R&D Programme for PV Recycling and Safety Disposal Research.[68] This research primarily focused on two recycling methods for c-

Si panels by physical and thermal recycling. The physical method achieved a recycling rate of nearly 90% by mass without the recycling of silicon. Thermal methods successfully recycled silicon, silver, and aluminum.

Taiwan

Major PV deployment in Taiwan started in just the last decade.[5] By 2019, cumulative PV capacity in Taiwan was just 4.1 GW.[5] However, this is projected to increase to 20 GW by 2025, which could lead to annual PV waste of nearly 100,000 tons starting from 2035.[28] Taiwan government is taking a proactive approach to address this issue. In 2020, the Environmental Protection Agency (EPA) of Taiwan and the Ministry of Economic Affairs Bureau of Energy (BOE) jointly established a recycling, clearance and disposal system, which is currently run by Taiwan Photovoltaic Industry Association.[28] In this system, before putting any solar panel in the market, along with registering the serial number of each PV panel with BOE, large scale PV power generating companies must pay the recycling and clearing costs. Even during the EOL of panels, enterprises must register online and dispose of the old panels as per the regulations. This online registration during disposal is matched with a serial number of panels to make sure that each decommissioned panel is properly disposed of. Failure to do so or illegal disposal of PV module waste can result in penalties of up to NT$ 3 million.

Businesses are free to choose either to dispose of their panels by themselves or by commissioning certified publicly or privately run waste clearance enterprises. There are several drawbacks of this regulation.

- It covers only large-scale developers. Households and small developers are encouraged but not required to dispose of their panels as per these regulations.
- By registering each panel, this regulation attempts to achieve a 100% recovery rate, but it does not set any minimum recycling rate.
- This regulatory system does not promote or provide details on reusing of panels.

In Taiwan, the recycling cost of a panel and revenue from recycling panel waste is estimated to be around NT$ 23.89/kg and NT$ 5.25/kg, which makes recycling an unprofitable business.[69]

United States

The USA is an established PV market with rapid growth since the mid-2000s. In 2019, the USA installed 13.3 GW of PV with cumulative capacity of 75.9 GW.[57] The US will be the second biggest PV waste market by 2050, with a cumulative waste volume of 7.5-10 million tons (Figure 13).[6] Currently, the USA lacks recyclers, incentives and regulatory drivers specific to PV recycling at national and state scales (except Washington).[21] Currently, the cost of recycling PV panels in the USA is greater than the economic value gained from recycling.[21,38] This economic infeasibility makes it difficult to promote solar panel recycling.

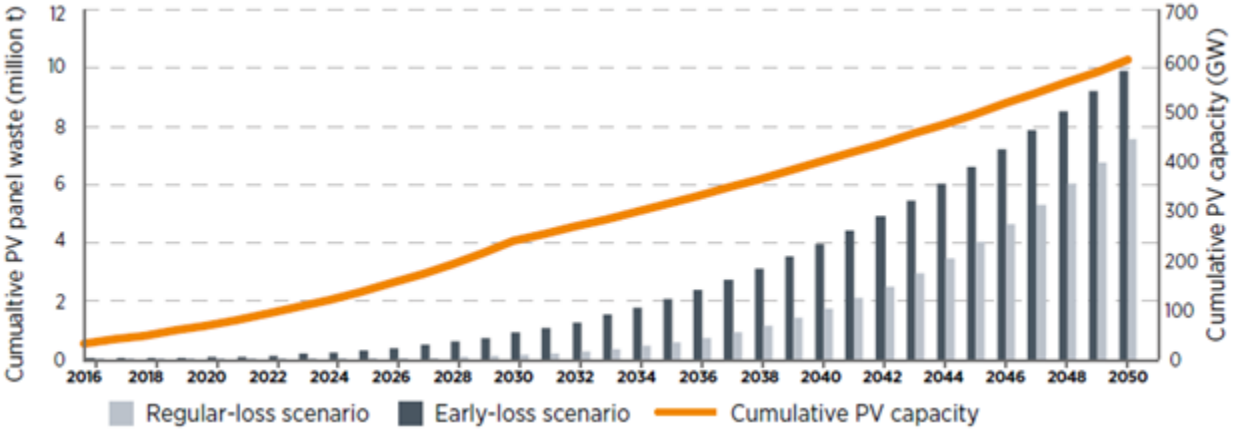

Figure 13. EOL PV panel waste volume projection for the USA through 2050[6]

(This figure is directly taken from Figure 19 on pp. 69 in [6])

The USA regulates e-waste through the federal Resource Conservation and Recovery Act (RCRA).[47] With a variety of state regulations and in the absence of any national PV waste law, PV panels are also regulated through RCRA. As the amount of decommissioned solar panels increases, this lack of a national standard will become problematic. RCRA is for handling hazardous waste and it requires producers of hazardous waste to comply with management standards to ensure the safe handling of hazardous waste. The four characteristics of hazardous waste are ignitability, corrosivity, reactivity, and toxicity. To test toxicity, RCRA requires a Toxicity Characteristics Leaching Procedure (TCLP) test to be performed on products. Many solar panels have been shown to leach toxic substances, and therefore they must be disposed of according to RCRA. However, RCRA is an insufficient vehicle for EOL management of PV panels. There are two major drawbacks in RCRA regarding solar panel EOL management. It does not include household waste, and therefore homeowners can legally dispose of their solar

panels in the regular trash. PV panels that fail the TCLP test will end up in hazardous waste landfills, which is not the best option for PV EOL management. PV panels that pass the TCLP test will not be subject to RCRA, even if toxic substances are present.

Enacted PV laws in the United States

In the absence of national policy, few states have enacted PV module recycling policies, as shown in Figure 14.

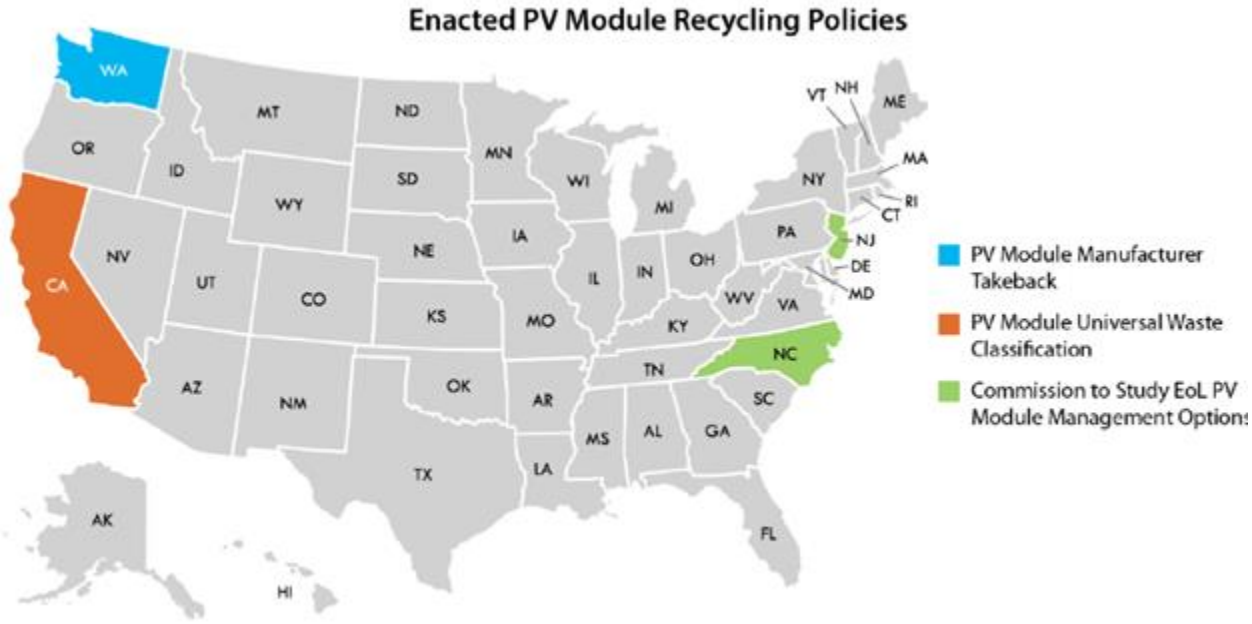

Figure 14. Enacted PV module recycling policies[70]

(This figure is directly taken from Figure 3 in [70])

Following states are listed in the order of when the policy was enacted.

Washington

In 2017, Washington became the first state in the USA to pass a PV recycling law. It passed SB 5939 (2017) for Photovoltaic Module Stewardship and Takeback Program.[71] As per this bill, manufacturers are responsible for financing the PV takeback program. This program provides an opportunity for consumers to send EOL PV panels back to manufacturers for recycling, without any cost to the consumer. This plan states that a manufacturer may join in a national program if its purpose meets the objective of the state program. As per one of the requirements of the bill, after July 1, 2017, all manufacturers are responsible to provide financing

to the recycling program. After January 1, 2021, producers who do not provide their recycling plan details were to be barred from selling solar panels. However, due to difficulties associated with implementation of the law, this date has been pushed to 2023. This bill only covered household PV waste, therefore HB 2645 was passed in 2019 to also include commercial and utility scale PV waste under the manufacturer take back scheme.[72]

Each manufacturer is required to submit their plan and subsequent annual report to the Department of Ecology. In addition, the Department of Ecology may also charge a flat fee for the administrative costs of the program and an annual fee based on the manufacturer's pro rata share of the preceding year's PV module sales in Washington state. This program has several advantages, such as creating a revenue stream to fund the program, improving material circularity, and creating jobs by promoting recycling of PV panels. However, this program is not the best method for EOL management of PV panels because it takes back only panels purchased after July 1, 2017. Additionally, this program does not mandate consumers to recycle decommissioned solar panels and even in the presence of a manufacturer take-back scheme, customers can choose to dispose of PV panels in a landfill.

North Carolina (NC)

In 2019, North Carolina passed House Bill 329, which intended to study and consider the adoption of regulations to govern EOL PV panels used in utility scale projects.[73] This bill requires the Environmental Management Commission to establish a regulatory program for the management of EOL PV panels before Jan 1, 2022. This bill tasked the commission to complete study of various aspects such as characterization of PV waste under federal and state law, its hazardous solid waste characteristics, the expected economically productive life cycle of different types of PV panels, and a global survey of PV EOL management.

A stakeholder group, established by The Department of Environmental Quality (DEQ) submitted 5 quarterly joint interim reports between Dec 2019 to Dec 2020 and a final report in Jan 2021.[74,75,76,77,78,79] Key findings of the final report are summarized in the following paragraph.

Currently, approximately 500,000 tons of PV panels are installed in North Carolina and this is expected to double in the next 5 years.[79] Of the current PV facilities, nearly half of them will be decommissioned between 2036 and 2040.[79] The DEQ report recommends using the 3R

(Reduce, Repair, Recycle) principle for the EOL of panels before disposal. However, it also highlights that PV module recycling capacity in NC is still developing and it needs sufficient infrastructure to support future module waste EOL management. Following in the footsteps of California, the report recommends DEQ consider defining PV waste as universal waste. For utility scale plants, instead of establishing a network of collection and consolidation points, anticipation of collection and transportation of EOL PV panels during decommissioning planning phase would be a better approach. Advantages and challenges associated with HB 329 are given in Table 5.

Table 5. Advantages and challenges/drawbacks of HB 329[70,79]

Advantages	**Challenges/ Drawbacks**
Provided details study of current PV EOL situation as well as future pathways	Does not enforce adoption of rules and regulations
Emphasizes the benefits of recycling	Only covers utility scales PV installation
Determined when decommissioned EOL PV panels constitute solid or hazardous waste	Does not provide roadmap for policy development
Emphasized the need for future investment in infrastructure to support recycling of EOL PV panels	Does not recommend immediate investment in infrastructure to support cost effective and efficient recycling options for EOL PV panels
Advocates classifying PV module as universal waste	

New Jersey (NJ)

In 2019, New Jersey passed Senate Bill 601, which requires the establishment of the New Jersey Solar Panel Recycling Commission (consisting of 9 voting members) to investigate options for recycling and EOL management of PV waste and development of recommendations for legislative, administrative, or private sector action.[80] The commission must submit their

report to the Governor and post it on the Department of Environmental Protection's (DEP) website before August 2021. Going one step beyond North Carolina's law, NJ's bill also authorizes the DEP to implement the rules and regulations for the EOL management of PV panels based on the final report of the commission. Advantages and challenges of this bill are given in Table 6.

Table 6. Advantages and challenges/drawbacks of SB 601[70,80]

Advantages	**Challenges/ Drawbacks**
Give authority to the DEP to implement rules and regulation based on the commission's report.	Does not mandate adoption of rules and regulations by DEP.
Addresses barriers to PV recycling	Does not identify a funding source to satisfy the Act's requirements
May create new jobs by promoting	Does not classify PV waste
Requires details study of current PV EOL situation as well as future EOL management pathways	

California

California is the biggest PV market in the USA with a cumulative installed capacity of 31,288 MW by 2020.[81] California has realized the problems associated with the EOL management of PV panels and passed SB 489 in 2015, which authorized the California Department of Toxic Substances Control (DTSC) to change PV waste from hazardous to universal waste.[82] Universal waste comes under the category of hazardous waste that is often produced by households and not industry and it does not pose as much of a threat to the environment and human health. Universal waste must be brought to a recycling facility or disposed of safely as per the regulation. However, DTSC required the approval of EPA to change the PV waste to universal waste category. Five years after SB 489 was passed, EPA authorized California to change PV panel waste to the universal waste category.[83] After getting approval

from EPA, the DTSC enacted regulation R-2017-04 in Sep 2020, which allows for decommissioned PV panels to be managed as universal waste in California.[84] It also helps universal waste handlers, who do not have permits for a hazardous waste facility, to successfully treat PV panel waste. DTSC regulations clarify that refurbished and reused PV panels do not come under universal waste regulations.

This regulation allows the disposal of PV panels waste only at a universal waste destination facility. With a separate prior authorization from DTSC, this regulation also allows universal waste handlers to intentionally break the PV module's glass to process the waste panels. Each handler that accepts more than 100kg of PV module waste from an external source and handlers that generate more than 5000 kg of PV module waste and handlers that treat PV panels must report annual to DTSC. This regulation also directs that PV panels should be managed in a way that prevents releases of any constituent to the environment. As per DTSC analysis, this regulation is expected to save nearly $11 million for state businesses and individuals, who do not have to treat PV panels as hazardous waste anymore.

This regulation is a positive step towards PV stewardship. However, this regulation does not go far enough. It does not require recycling, and therefore decommissioned solar panels could still end up in hazardous waste landfills. A list of advantages and drawbacks and challenges associated with this regulation is given in Table 7.

Table 7. Advantages and challenges/drawbacks of SB 489[70,82]

Advantages	**Challenges/ Drawbacks**
Cost saving for business and individuals	Does not allow for processing PV panels by heat or chemicals in California
Promote EOL management options as opposed to abandonment of PV panels	Regulates PV panels destined for recycling in the same manner as those being disposed of
Complement state's goal of 100% clean energy by 2050	May result in more disposal of PV panels until the accessibility and economics of recycling are more favorable

Specifies management standards to safely handle and treat PV panels	Does not mandate recycling to preserve resources
Clarifies regulatory standard for EOL PV panels destined for recycling-based resource recovery	Restricts transport unless transported to another universal handler, an authorized waste destination facility, or a foreign destination

Proposed PV module recycling legislation

Apart from PV module recycling policies enacted in these states, other states have proposed legislation. A map of these states is shown in Figure 15.

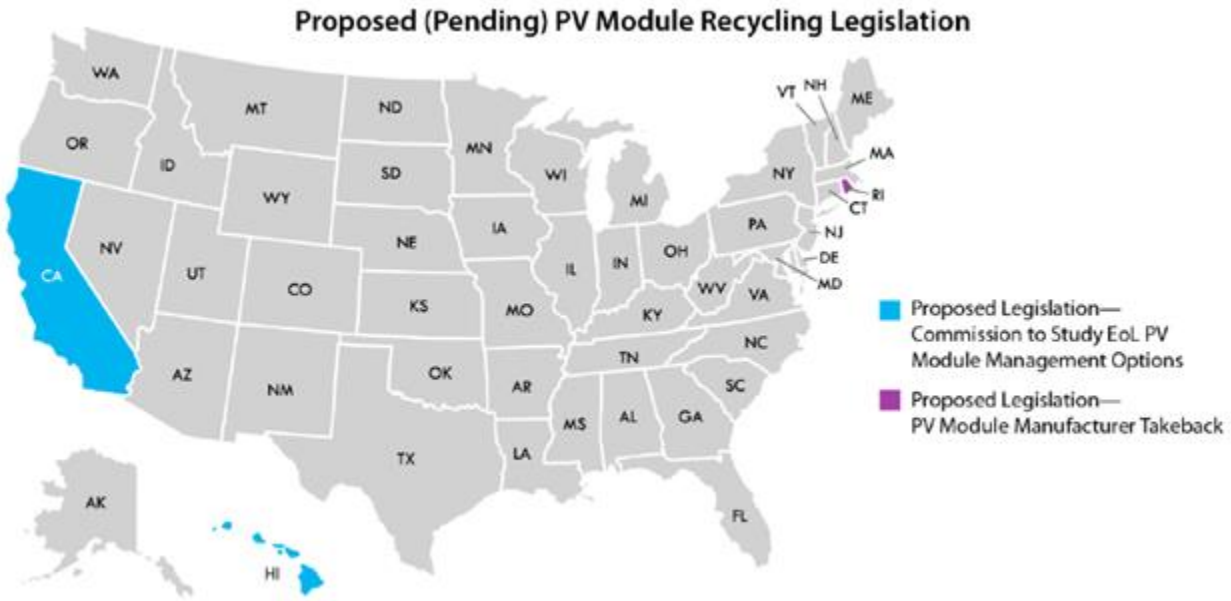

Figure 15. Proposed PV module recycling legislation[70]

(This figure is directly taken from Figure 3 in [70])

California

In Jan 2021, Senate Bill 207 was introduced in California, which would require the Secretary for Environmental Protection to convene the Photovoltaic Recycling Advisory Group, consisting of a diverse group of 9 members ranging from manufacturers to recyclers and enforcement agencies, on or before April 1, 2022.[85] The task of this group would be to advise the

Legislature on photovoltaic panel recovery and recycling policies. With the aim of reusing or recycling nearly 100% of PV panels at EOL, the advisory group will be tasked with developing policy recommendations and submitting them to the Legislature on or before April 1. 2025.

Hawaii

In January 2021, House Bill 1333 was introduced in Hawaii.[86] If passed, then this bill would require the Hawaii State Energy Office to work with the Department of Health to conduct a study to determine the best practices for the disposal and recycling of energy products during the decommissioning stage. This study will address research questions, including the amount of aging PV panels that need to be disposed of or recycled, best practices for collection, and recycling and disposal of clean energy materials.

The Hawaii Energy Office would be required to submit an interim progress report and final report to the legislature no later than 20 days prior to the regular session of 2022 and 2023.

Rhode Island

In February 2021, House Bill 5525 was introduced in Rhode Island, with the aim of finding a convenient, safe and environmentally friendly system for recycling of PV panels, minimization of hazardous waste, and increasing the recovery of commercially viable materials.[87] Similar to the Washington PV EOL management legislation, Rhode Island's proposed bill also makes manufacturers fully responsible to finance and implement a takeback scheme to increase recycling or reuse stewardship of PV panels sold in or into the state after July 1, 2021. This bill discusses that responsibility of this system must be shared among all stakeholder, with the Department of Environmental Management (DEM) supporting manufacturers by developing and implementing guidance in preparing and implementing self-directed stewardship plans by July 1, 2022. Just like in the Washington legislation, the state body (i.e., DEP) can collect a fee from every participating manufacturer to cover the administrative costs of this program.

This bill has support from the Product Stewardship Institute, which is a national producer responsibility advocacy group. However, this bill has faced significant opposition from the state's solar developers and installers, who believe that it will negatively affect their business.[88]

A short summary of enacted and proposed bills in the US states is given in Table 8.

Table 8. Summary of enacted and proposed legislation in the US states

Enacted Policies				Proposed Legislation	
Washington[71,72]	North Carolina[73,79]	New Jersey[80]	California[82,83]	Hawaii[86]	Rhode Island[87,88]
SB 5939 (2017) for Photovoltaic Module Stewardship and Takeback Program Manufacturer will pay the cost burden of this program to the department HB 2645 (2019) will cover utility scale PV waste Take back program will only apply to panels purchased after July 1, 2017 Consumers are not mandated to recycle	HB 329 (2019) requires Environmental Management Commission to establish regulatory program for the management of EOL PV modules before Jan 1, 2022 A stakeholder group established by DEQ submitted final report in Jan 2021 Only covers utility scale PV installation	SB 601 (2019) requires to establish the New Jersey Solar Panel Recycling Commission to investigate options for recycling and EOL management of PV The owner of PV energy generation facilities would be responsible for recycle of facility Does not mandate adoption of rules and regulations by DEP.	SB 489 (2015) authorizes the California Department of Toxic Substances Control to change PV waste from hazardous to universal waste In 2020, EPA authorized California to change PV panel waste to universal waste category This regulation do not mandate recycling	HB 1333 (2021) to conduct a study to determine the best practices for the disposal and recycling of energy products during decommissioning stage. The Hawaii Energy Office would be required to submit final report to the legislature no later than 20 days prior to the regular session of 2023.	HB 5525 (2021) (in house committee)would require solar panel manufacturers to recycle their equipment. The bill requires manufacturers to fund a program that collects and processes old panels and recovers rare earth elements and toxic materials like lead Bill is opposed by PV develops in the state

PV EOL management voluntary groups around the world

PV Cycle

Founded in 2007, PV Cycle is a non-profit, member-based organization, which is primarily based in Europe but also provides collective and tailor-made EOL management and legal compliance services for companies and waste processors around the world.[34] PV Cycle is an example of a volunteering scheme, which is established and financed by leading PV manufacturers to provide better service to end-users. Over the decade, PV Cycle has been involved in research and development projects for recycling of PV panels. With the help of more than 300 collection points around Europe, it has collected more than 35,773 tons of PV panels since the start of its operation in 2010 to 2019.[89] In 2019 alone, it collected 11,514 tons of waste, which is a 35% increase from the previous year.[89] In the same year, it partnered with Recycle PV Solar, a US PV recycling company, to promote PV module recovery in the US.[90]

Solar Energy Industries Association (SEIA)

Founded in 1974, SEIA is a trade association for solar and solar+storage industry in the United States.[91] It works with over 1000 member companies around the US to promote solar energy. SEIA has a national program to promote PV recycling in the USA. Based on evaluation criteria, SEIA chooses preferred recycling partners to manage PV waste.[92] SEIA is also actively involved in supporting PV EOL legislation in various US states.

PV recyclers in the United States

Figure 16 shows the map of all current (2020) PV recyclers in the USA. There are 19 recycling facilities in the USA that accepts PV waste only a handful of them are specialized PV recyclers.[93,94] Cleanlites Recycling, which is a SEIA recycling partner, has a recycling center in Mason, MI. A list of facilities, that accepts PV in the United States is given in appendix 1.

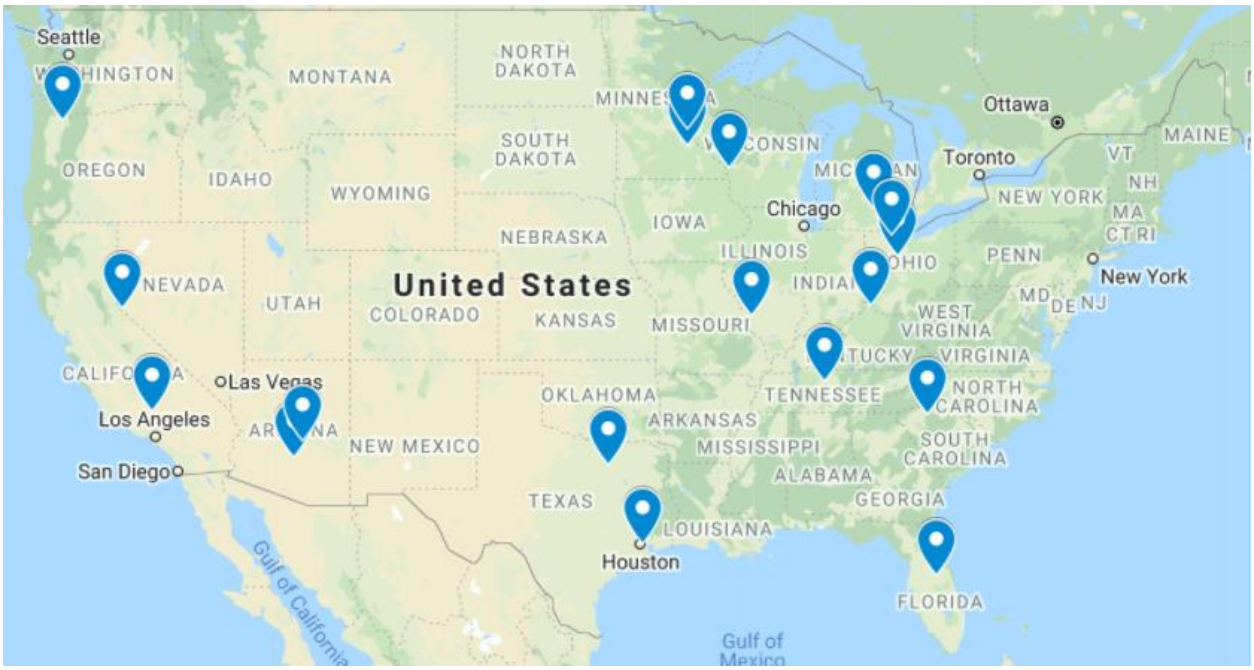

Figure 16. Location of US PV Recyclers[93,94]

Current status of PV in Michigan

Michigan is not one of the top states for installing solar power in the USA due to its moderate solar resource. In 2020, Michigan has a total installed PV capacity of just 290.7 MW, which is expected to grow to 1,594 MW by 2025.[95] As per installed PV capacity, Michigan ranks 34th in the USA.[95] Several large companies located in Michigan have invested heavily in solar generation in the past several years. Ford has two solar generation sites owned and operated by DTE in Michigan totaling 1.54MW.[96] General Motors has a 900kW solar generation plant owned and operated by DTE, and in 2020 announced a deal to purchase 800,000MWh electricity through DTE's MIGreenPower (500,000MWh from solar, 300,000MWh from wind).[97] In 2016, IKEA expanded its store-top solar site to now total 1.22 MW.[98] IKEA fully owns and operates this project. Currently, there is no PV EOL management policy in Michigan nor any law has been introduced in the senate or house.

Proposed PV EOL management policy in Michigan

Extended producer responsibility has an excellent track records with the products that pose a risk to community.[99] EU has successfully implemented EPR for PV EOL. Jigar Shah, Director of Loan Program Offices at the U.S Department of Energy also advocated for EPR in 2020.[100] He said "It's far more cost effective for manufacturers to be forced to work together, to own recycling facilities in a joint fashion, where they try to greatly reduce the cost of all that collectively. That happens through policy. It doesn't happen through people opting in,". Considering all these, Michigan PV EOL management should be based on an extended producer responsibility scheme with producer financing and managing photovoltaic waste at the EOL.

In HB 2645, Washington has defined manufacturer as "any person in business or no longer in business but having a successor in interest who, irrespective of the selling technique used, including by means of distance or remote sale.[72]

(i) Manufactures or has manufactured a PV module under its own brand names for use or sale in or into this state;

(ii) Assembles or has assembled a PV module that uses parts manufactured by others for use or sale in or into this state under the assembler's brand names;

(iii) Resells or has resold in or into this state under its own brand names a PV module produced by other suppliers, including retail establishments that sell PV module under their own brand names;

(iv) Manufactures or has manufactured a co branded PV module product for use or sale in or into this state that carries the name of both the manufacturer and a retailer;

(v) Imports or has imported a PV module into the United States that is used or sold in or into this state. However, if the imported PV module is manufactured by any person with a presence in the United States meeting the criteria of manufacturer under (i) through (vi) of this subsection, that person is the manufacturer;

(vi) Sells at retail a PV module acquired from an importer that is the manufacturer and elects to register as the manufacturer for those products; or

(vii) Elects to assume the responsibility and register in lieu of a producer"

This definition provides a descriptive information about manufacturer. Therefore, Michigan should adopt this definition and define ‘Producer’ just like ‘Manufacturer’ is defined in HB 2645.

House Bill 2828, introduced in Arizona in 2020, proposed banning disposal of PV panels in solid landfill.[101] Senate Bill 568, introduced in North Carolina in 2019, also proposed banning disposal of PV panels in landfill.[102] Michigan should also ban the dumping of PV panel waste in landfill, which may increase the recycling rate.

Enacted in 2017, SB 5939 of Washington provides manufacturers nearly 5 years to develop recycling or reuse plan before restricting placing restriction on those manufacturers without a recycling/reuse plan.[71] After a certain date, producers in Michigan should be required to register with the Michigan Department of Environment, Great Lakes, and Energy (EGLE) before placing any PV module in the market. EGLE should provide a registration number, which needs to be placed on each module and invoice. This will help in tracking the decommissioned panels at their EOL.

Legislative Decree no. 49 of Italy classified based on the period in which they were placed on the market.[55] This helped responsibility managing the historical panels placed in the market. Based on this, Michigan should classify PV panel waste as following:

PV waste coming from plants installed before the implementation of the bill should be defined as ‘historical’ and ones after the implementation of the bill should be defined as ‘new’ waste. Based on this, PV waste in Michigan can be broadly classified into four categories: historical household, new household, historical professional, and new professional.

- For historical household waste, producers will collect PV waste based on their market share of PV installation in the previous year. If a producer leaves the market then the share of that producer will be taken by other producers.
- For new household PV waste, producers should inform EGLE and keep a separate escrow fund to finance the EOL management.
- For historical professional PV waste,
- For new professional PV waste, there can be flexibility in financing. However, an agreement needs to be established between producer and consumer to declare who would be responsible for PV EOL management.

Revised EU WEEE Directive set a min target for recovering and recycling panels to encourage material circularity.[42] Based on this, Michigan should also set a min. target. For the first three years after the implementation of law, there must be a recovery and recycling rate of 80% and 75% respectively, 90% and 85%.

Producers should only be allowed to send decommissioned panels out of the state for the purpose of reuse/recycling. In the lack of a federal PV recycling policy, this will ensure the sustainable EOL management of PV panels.

Producers should be mandated to disclose PV material composition to ease the recycling process.

SB 5939 of Washington does not mandate household consumers to return PV waste to recyclers/ producers.[71] Taiwan EPA also encourage but does not mandate households for proper recycling of PV panels.[28] These policies and laws left a huge portion of PV waste unregulated, which can end up in landfill. Therefore, in Michigan, households should be mandated to return PV waste to collection points/recyclers/producers for free of cost.

Since the PV waste quantity in Michigan is likely to remain small over the years and the absence of similar regulations in other states might discourage sale of PV in Michigan. Therefore, an effort should be made to form a coalition with other states such as Illinois, Minnesota and Wisconsin. As of 2020, Minnesota has installed solar capacity of 1586.6 MW (almost 5.4 time of Michigan) and has already proposed several bills (HB 2909, SB 2698, HB 3333) for PV EOL management.[70,103] In Illinois, Institute of Sustainable Center at the University of Illinois launched a Solar Panel Recycling Initiative in 2017 to prepare Illinois for a glut of EOL of panels.[104] Furthermore, Rhode Island is facing a stiff challenge from PV producers in response to the introduction of H.B. 5525.[87] Therefore, joining a coalition would likely to give Michigan an upper edge to implement PV EOL management policies.

Proposed business model

The basic viability of any recycling program often hinges on the geographic concentration of the goods and their proximity to appropriate recycling facilities, and on their content of valuable materials. PV are not at present very concentrated neither by geography, nor by content. Also, the total amount, concentration, and value of reclaimable material are low. Owing to low historic installation of PV panels, a centralized PV recycling system would not be the best choice for Michigan. Therefore, near-terms need of recycling can be a mobile technology such as PV-MoReDe or a centralized plant covering other states as well. For the longer term, once the amount of PV waste generated each year would be considerate, a centralized plant can be chosen.

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Appendix 1

List of PV panel recycling companies in the USA

Sr. No	Company	Location
1	Cascade Eco Minerals	Upper Sandusky, OH
2	Cleanlites Recycling	Cincinnati, OH
3	Cleanlites Recycling	Lakeville, MN
4	Cleanlites Recycling	Mason, MI
5	Cleanlites Recycling	Spartanburg, SC
6	Cleanlites Recycling	Wauseon, OH
7	CMK Recycling	Houston, TX
8	Dynamic Lifestyle Innovations	Onalaska, WI
9	Dynamic Lifestyle Innovations	Nashville, TN
10	Echo Environment	Carrollton, TX
11	Fabtech Enterprises Inc	Gilbert, AZ
12	First Solar	Perrysburg, OH
13	Green Century Recycling	Portland, OR
14	Green Lights Recycling	Blaine, MN
15	Interco Trading Company	Madison, IL
16	Recycle PV Solar	South Lake Tahoe, NV
17	Solar Recycling Experts	Tehachapi, CA
18	Solar Sun’s Recycling	Orlando, FL
19	We Recycle Solar	Phoenix, AZ