



STANDARDS RESEARCH

Photovoltaic (PV) Recycling, Reusing, and Decommissioning

Current Landscape and Opportunities for Standardization

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Executive Summary

Photovoltaic (PV) modules are used worldwide as a source of renewable electricity. They can play a significant role in reducing the use of fossil energy sources. In recent years, technology advancement and increased manufacturing capacity have led to the falling cost of PV modules and have made solar energy costs comparable to other sources of electricity. This has resulted in an exponential growth in solar energy adoption globally.

In North America, the cumulated installation of PV modules was approximately 80 GW by the end of 2019 [1]. It is estimated in this report that the installation could increase up to 437 GW by 2030. With an average lifespan of 30 years for each PV module, a significant amount of waste is expected to be generated and could reach 27,000,000 tonnes in the years to come. Therefore, end-of-life management of PV modules is an essential part of making sure clean solar energy is a sustainable solution for the future energy economy.

Most of the PV modules in the North American market are made of crystalline silicon solar cells encapsulated in a polymer matrix behind glass and framed with aluminum, and the waste would mostly include glass, polymer, aluminum, copper, silicon, and silver. Without treatment, there is risk that these materials will leak into the ground if PV panels are landfilled, which will have a negative impact on the environment. Additionally, it is expected that up to 70% of used modules may still be functional, though some degradation might have taken place, and could still be reused or refurbished to give them a second life. The main markets are expected to be outside North America. However, even if panels are sold for reuse, sound decommissioning processes and transportation will be important to avoid leakage of materials into the environment.

Currently, specific legislation to manage the recycling and treatment of end-of-life PV modules in North America does not exist, but some federal states in the United States have introduced PV module regulations or have initiated a regulatory process. The regulations differ between states and the regulatory framework is rather fragmented. There is a similar situation in Europe which has a waste electronic electrical directive and individual national transpositions that require detailed knowledge to ensure full compliance with the rules but often through different processes. A fragmented framework can have a negative impact on recycling. For instance, in the United States, modules can be transported from one state that has regulations in place to another state that does not have regulations and that will allow the modules to be landfilled without treatment. Harmonized legislation and common standards could help to establish sound and equal rules and thus save overhead and compliance costs.

The PV industry, the waste treatment industry, and governments and authorities should develop the necessary policies and legal frameworks together to tailor solutions for the development of the PV market and waste industry in North America. Environmentally friendly renewable energy technologies can utilize modern approaches like Eco-Design, Product Environmental Footprint, and stewardship standards that include a sound circular economy strategy to save valuable resources and meet zero waste demands as much as possible.

There are only a few standards related to PV modules, and the most comprehensive one is NSF/ANSI 457 *Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters*. It provides sustainability performance criteria and corporate performance metrics to create high sustainability in the PV market. It helps the purchaser to identify sustainable and environmentally friendly products. However, there are still more opportunities for the development of standards as this standard does not cover the whole PV recycling and reusing process. Standardization and international harmonization of standards and best practice guidelines will contribute to improving PV waste management and to saving costs.

For instance, it has been identified in a recent study that there is no consistency of data pertaining to PV modules put in the market in Europe leading to the recommendation to harmonize international data reporting [6]. Adequate and consistent tracking of the renewable energy system transformation can support the development of sound cradle-to-grave or even cradle-to-cradle solutions, and can also provide reliable statistical data for not only governments and authorities but also for stakeholders of the value chain, including manufacturers, installers, and plant operators, and repair and refurbishment, waste collection, and recycling plants.

The conclusion discussed the gaps that have been identified and support a more sustainable use of PV modules. They include standardization of decommissioning, collection, pretreatment, waste treatment processes, and monitoring and quality control. These standards can help encourage investment into value-retaining high-quality recycling and reusing processes to be established with a good eye to meeting both the growing demands of the waste market and the environmental protection targets.

ABBREVIATIONS

ANSI	American National Standards Institute	ORAMA	Optimising Data Collection for Primary and Secondary Raw Materials
BIPV	Building-integrated PV	OSHA	Occupational Safety and Health Administration
CCR	California Code of Regulations	PEFCR	Product Environmental Footprint Category Rule
CENELEC	European Committee for Electro Technical Standardization	POP	Persistent Organic Pollutants
CFR	Code of Federal Regulations	PV	Photovoltaic
CLP	Classification, Labeling and Packaging Regulation	RCRA	Federal Resource Conservation and Recovery Act
CPSA	Consumer Product Safety Act	REACH	Registration, Evaluation, Authorisation of Chemicals
DOE	Department of Energy	ROHS	Restriction of Hazardous Substances
DOT	Department of Transportation	SEIA	Solar Energy Industries Association
DTSC	Department of Toxic Substances Control	STLC	Soluble Threshold Limit Concentration
ECHA	European Chemicals Agency	SVHC	Substances of Very High Concern
EEE	Electrical and electronic equipment	SVTC	Silicon Valley Toxics Coalition
EHSMS	Environmental, Health and Safety Management System	TCLP	Toxicity Characteristic Leaching Procedure
EPA	Environmental Protection Agency	TCO	Transparent conductive oxide
EPRI	Electric Power Research Institute	TSCA	Toxic Substances Control Act
EU	European Union	TTLC	Total Threshold Limit Concentration
HW	Hazardous waste	UW	Universal waste
IEA	International Energy Agency	UNU	United Nations University
IEA-PVPS	International Energy Agency Photovoltaic Power Systems Programme	VDMA	Verband Deutscher Maschinen- und Anlagenbau e. V (German Mechanical Engineering Industry Association)
IPCC	Intergovernmental Module on Climate Change	WFD	Waste Framework Directive
IRENA	International Renewable Energy Agency	WEEE	Waste electrical and electronic equipment
ITRPV	International Technology Roadmap for Photovoltaic	WET	Waste Extraction Test
NREL	National Renewable Energy Laboratory		
NSF	National Science Foundation		
OECD	Organisation for Economic Co-operation and Development		
OEFSR	Organisation Environmental Footprint Sector Rule		



“As the PV market increases in the US and Canada, the volume of decommissioned PV modules is expected to increase as the modules reach their end-of-life.”

1.0 Introduction

Photovoltaic (PV) modules are widely used as a source of renewable electricity at costs that are comparable to other electricity sources¹. PV modules have become a worldwide commodity and, to a large extent, have a very high potential for substituting fossil energy sources in the future. In North America, the cumulated installation of PV modules was approximately 80 GW by the end of 2019.

The manufacturing process for PV modules includes a number of hazardous materials, and the amount and type of chemicals used depends on the type of cells used in the modules. Thin-film PV cells contain more toxic materials, like gallium arsenide, compared to materials used in the more common silicon photovoltaic cells. Once PV modules have reached their end-of-life use, they become waste and, if disposed in landfills without proper treatment, they can harm the environment and human health due to leaching of hazardous metals (such as lead and cadmium) or through the loss of conventional resources (such as glass and aluminium and rare metals). In addition, addressing the growth of PV waste and enabling related-value creation will not be easy in the absence of legally binding end-of-life standards specific to PV modules and the used PV module trade. The development of PV-specific collection and recycling regulations, including recycling

and treatment standards for PV modules, will help to consistently, efficiently, and in an environmentally friendly way, deal with increasing waste volumes. Furthermore, waste regulations or policies can promote more sustainable life-cycle practices and improve resource efficiency.

1.1 Scope of the Study

This study covers an analysis of the PV market development in North America and a projection of the amount of waste that can be expected until the year 2030. The major PV technologies are summarized and a short review of existing standards and regulations in comparison to the existing European framework is presented. PV module recycling is mandatory in Europe, and the early experiences of the mandatory European PV collection and recycling system are discussed.

Aspects of the protection of the environment and associated economic challenges are investigated to promote sound waste-treatment solutions with growing PV waste streams.

1.2 Motivation and Objectives

As the PV market increases in the US and Canada, the volume of decommissioned PV modules is expected to increase as the modules reach their end-of-life. Due to difficulties related to the end-of-life management of

¹Information about PV modules can be found at <https://energyhub.org/cost-solar-power-canada/>

the modules and the lack of incentive to find a solution, there is no regulation or requirement for PV module decommissioning and recycling in Canada today. The end-of-life disposal of solar products in the US is governed by the Federal Resource Conservation and Recovery Act (RCRA) [2], [3] and state policies that govern waste disposal or other regulations.

The need for an appropriate framework of standards in North America to support a sound circular economic strategy is identified with respect to the following:

- The amount of PV waste;
- The best recycling technologies available; and
- New business opportunities by establishing value-preserving recycling systems.

Recommendations are made to support the development of incentives, policies, and regulations tailored to the demands of a growing PV market. Suggestions for potential resource and cost savings achievable with the support of internationally harmonized PV waste system models are included.

2.0 Methodology

The following approaches were used to carry out the work:

- Online survey and literature search;
- Stakeholder and expert interviews from PV and waste associations, manufacturers, non-governmental organizations (NGOs), governmental organizations, researchers, waste treatment companies, PV plant operators, certification organizations, insurance companies;
- A Weibull waste model similar to the one used in the International Renewable Energy Agency (IRENA) and the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS)² study [1] published in 2016;

- Material and technology data extraction from the 2019 VDMA version of the International Technology Roadmap for Photovoltaic (ITRPV) [5]; and
- Review of relevant standards, e-stewardship approaches, IRENA and IEA-PVPS studies, and the work of IEA-PVPS task 12, including recent statistical European Union (EU) reporting on PV waste and results of EU-funded projects like ORAMA [6] and others [4] to identify best practices.

An extensive literature review was carried out on the following topics:

- Canadian and US PV waste module market (based on the technology), including the economical aspect of PV recycling for Canada and the US;
- Review of current Canada, US, and EU PV regulatory requirements and waste classifications; and
- Standards and codes relevant to PV recycling.

2.1 PV Waste Module Market and Economical Aspect of PV Recycling for Canada and the US

Using the Weibull waste model developed for IRENA and IEA-PVPS [1] as a foundation, the installation data of PV modules was updated for the cumulated installations of all major technologies: crystalline silicon (c-Si), cadmium telluride (CdTe), copper indium gallium selenium (CIGS), and new technologies like perovskites and organic PV³. The data were gathered from the analysis of published market and installation data and statistics per region by contacting PV associations and institutes such as the International Energy Agency (IEA), IRENA, Solar Energy Industries Association (SEIA), the National Renewable Energy Laboratory (NREL), and through interviews with experts working with PV companies. The data were correlated with recent publications on module quality and lifetime to adjust the waste model data for regular and early losses and validated by the expert interviews. Data were collected and updated throughout the project with contributions from associations and companies.

²IRENA and IEA-PVPS published a comprehensive study on end-of-life treatment of PV modules in major markets [1].

³An overview on PV technologies can be found at <https://en.wikipedia.org/wiki/Photovoltaics>

The installation and damage data are included in the Weibull waste model.

2.2 Current Canadian, US, and EU Regulatory Requirements

The major and waste-relevant PV technologies were assessed for their potential waste and classified for their potential environmental risks in the event that they are not properly waste-treated at their end-of-life. Aspects of mandatory takeback and responsible recycling, and toxic reduction and elimination were included. A value analysis was carried out to identify potential business opportunities in PV waste recycling depending on volumes expected for the recyclers to bring down costs and encourage investments in collection systems and PV-specific recycling technologies.

A survey of current and forthcoming legislation and standards concerning the end-of-life for PV modules was carried out for the US and leading federal states (e.g., California, Washington, New York, New Mexico) and for Canada, and was compared with European waste legislation.

2.3 Standards Relevant to PV Recycling

Standards relevant to PV recycling were reviewed but only a few were found, such as the National Science Foundation (NSF) 457-2019 *Sustainability Leadership*

Standard for Photovoltaic Modules and Photovoltaic Inverters and the European Committee for Electro Technical Standardization (CENELEC) EN50625-1-4 (2018) [7] on collection, logistics, and treatment requirements for waste electrical and electronic equipment (WEEE).

2.4 Stakeholder and Expert Interviews

Stakeholder discussions were prepared by curating a list of potential contacts from PV companies, agencies, institutes, associations, recyclers, PV plant operators, and insurance companies. Questionnaires were tailored for the different stakeholders interviewed (see Appendix A). An overview of the stakeholder contacts and interviews is presented in Table 1.

The overall response to the interview requests was good, although some organizations declined for confidentiality reasons. In the recycling sector, it was only possible to discuss general trends, as the interviewees were reluctant to disclose details about the modules processed and their treatment. Approximately 16 recyclers mention their PV recycling services on the homepages of their websites, but provide few details about them. The results of the interviews are included in the discussion of the topics in the appropriate sections of the report. The statements are anonymized at the request of several interviewees.

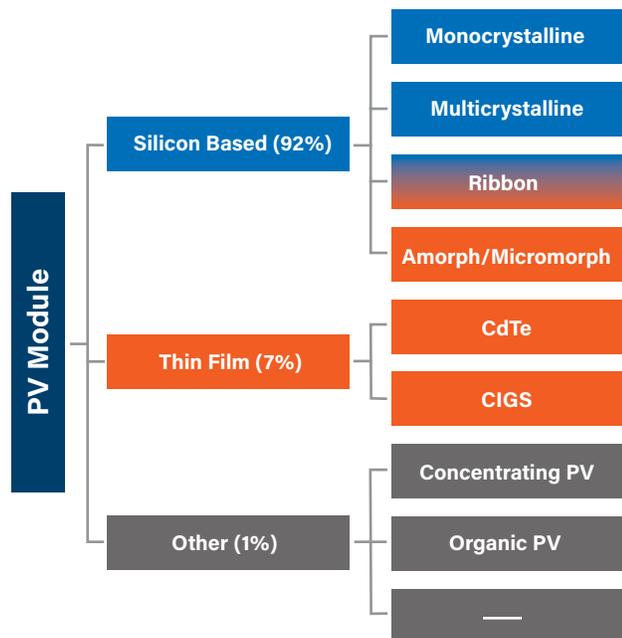
Table 1: Overview of stakeholder contacts and interviews

Category	Contacted	Interviewed	US	Canada	Other Country
Industry Experts, Companies	14	8	3	3	2
Organizations	18	5	4	0	1
Associations	5	5	1	2	2
Institutes	10	5	5	0	0
Recyclers	16	2	2	0	0
Operators	7	1	1	0	0
Financial & Insurance	5	2	0	0	2

3.0 Relevant PV Technologies

PV products can be classified according to Figure 1, which shows the major product types on the market. The market share of crystalline silicon modules was roughly 92% in 2016 [1]. The thin-film technologies are represented predominantly by cadmium-telluride (CdTe), copper indium gallium selenium (CIGS), and amorphous silicon (a-Si), which added up to about 7%. The category “other” comprises, for example, concentrating PV and organic PV, which have low market shares.

Figure 1: Recommended classification of PV modules with market shares of the three main product groups based on the IRENA and IEA-PVPS study [1]



3.1 Crystalline Silicon (c-Si) Modules

About 76% of the module weight is glass (soda lime glass with low iron content for better light transmittance), 10% are polymers like ethylene vinyl acetate (EVA) as encapsulant, - Polyethylene terephthalate (PET) and other as backsheet, and 8% is aluminum frame.

The solar cells contribute about 3% and the copper interconnectors between the solar cells about 1% to the total module weight. Small amounts of toxic or precious materials like lead, tin, and silver might also be present.

The quest for higher efficiencies, power, and cost saving is linked to the rapid introduction of new technologies and materials associated with significant material savings and cost reductions. Many different module types have already been installed and this can be expected to continue in the future; only technologically robust, large-scale recycling plants will be able to handle the waste in a cost-efficient way.

3.2 Cadmium Telluride (CdTe) Modules

Modules with CdTe have been commercially available in large quantities since 2002 and show the second largest installation base after c-Si technologies. A typical configuration is shown in Figure 2. The transparent conductive oxide (TCO)⁴, intermediate cadmium sulfide (CdS), and CdTe layers are deposited on soda lime glass in superstrate configuration, meaning that the cell is deposited with the photoactive layer facing the front of the glass. The back contact layer is frequently a metal, e.g. molybdenum, nickel-aluminum, copper/gold (Cu/Au), Cu/graphite, or graphite doped with Cu. An encapsulant like EVA is used to laminate the back glass to the cell.

3.3 Copper Indium Gallium Selenium (CIGS) Modules

The term “chalcopyrite” (the name of a crystalline structure) is used for solar cells with absorbers with the general formula Cu(In,Ga)Se₂. These modules contain a layer of about 10% copper (Cu), 28% indium (In), 10% gallium (Ga), and 52% selenium (Se) deposited on a molybdenum back side electrode layer and a glass substrate (steel or polymer substrates are also possible). A schematic drawing is presented Figure 3. Small quantities of CdS may be present as an intermediate layer. Zinc oxide (ZnO) is used as a transparent front contact. Some producers apply a nickel/aluminum (Ni/

⁴Transparent conductive oxides (TCO) can be SnO_x:F (preferred), indium-tin-oxide (ITO), ZnO:Al, or CdSnO₄.

Figure 2: Example of a CdTe Cell based on the NREL study [8]

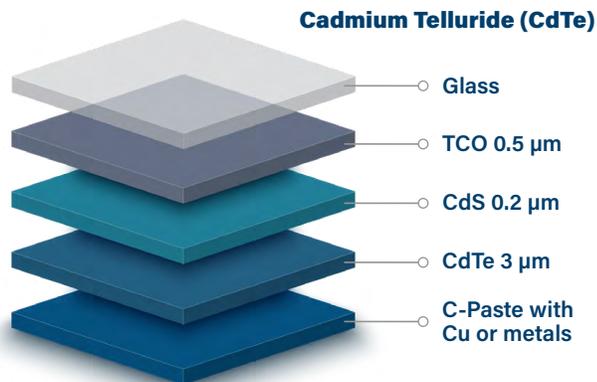
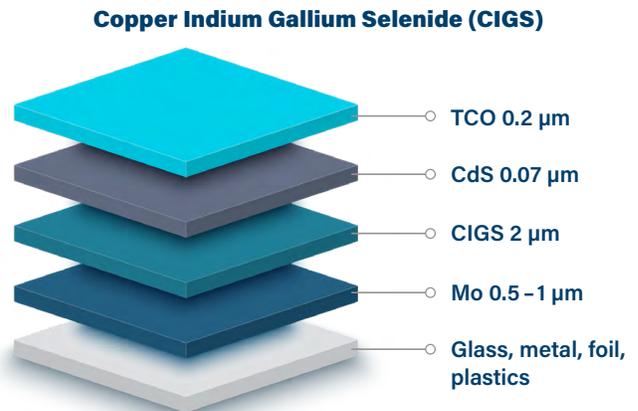


Figure 3: Example of CIGS cell based on N. Romeo et al. [10]



Al) grid as a front side conductor [9]. The front glass is glued with EVA to the substrate. The materials used for the frame, the ribbons, the glass, and the encapsulant and backsheet foils are similar to those of the crystalline silicon modules.

3.4 Other Modules

Other modules like organic PV or concentrating PV have a different design and might contain other valuable or some hazardous materials in small quantities. Novel PV cells may use perovskites (e.g., as a top layer on crystalline silicon cells), and are designed as quantum dots, dye-sensitized cells, organic cells, or thermoelectric devices [5]. They could offer excellent new applications in the future but they still require further development for power systems. The market share of the novel devices will grow, but the commonly used products (silicon based, thin-film) will dominate the market at least until 2030 [11].

4.0 Results and Discussion

4.1 Assessment of PV Waste Market

With PV market deployment, PV module waste streams will increase ten to 30 years after installation. The approach to model the waste streams is similar to the

one used in the IRENA and IEA-PVPS study [1]. It is used here to estimate the potential PV module waste streams for the US and Canada until 2030. Historical, present, and future solar PV growth rates from 1985 to 2030 are the primary inputs to waste volume estimation.

4.1.1 PV Market Development in the US

The projection of the PV growth for the US up to the year 2030 is based on data from IEA [12], [13], IRENA [14]–[16], Quaschnig [17], and SEIA/Wood Mackenzie [18].

As shown in Figure 4, PV growth deployment in the US reached an initial peak in 2016 with 14.8 GW installed. SEIA/Wood Mackenzie predict further market growth at a similar level for the years 2019 to 2024. An accelerated growth rate beginning in 2025 has been calculated based on exponential growth, resulting in a cumulated installed PV capacity of 437 GW for the total region of North America in 2030 (IRENA REmap case 2030 [15]⁵). In 2030, it is estimated that the annual PV installation will reach 74.6 GW.

Large PV installations (utility scale) dominate the market growth. Residential systems have a market share of approximately 20% with reference to recent developments (see Figure 5). Some of the US and

⁵ Using the 2019 SEIA/Wood Mackenzie forecast data for the US [18], the reference case for North America (153 GW) will almost be reached in 2024. This case does not apply to further processing in this study and only the REmap case is used.

Figure 4: Projected annual PV installation in the US, based on IEA, IRENA, Quaschnig, NREL, EPRI, and SEIA/Wood Mackenzie studies [12]–[15], [17]–[19]

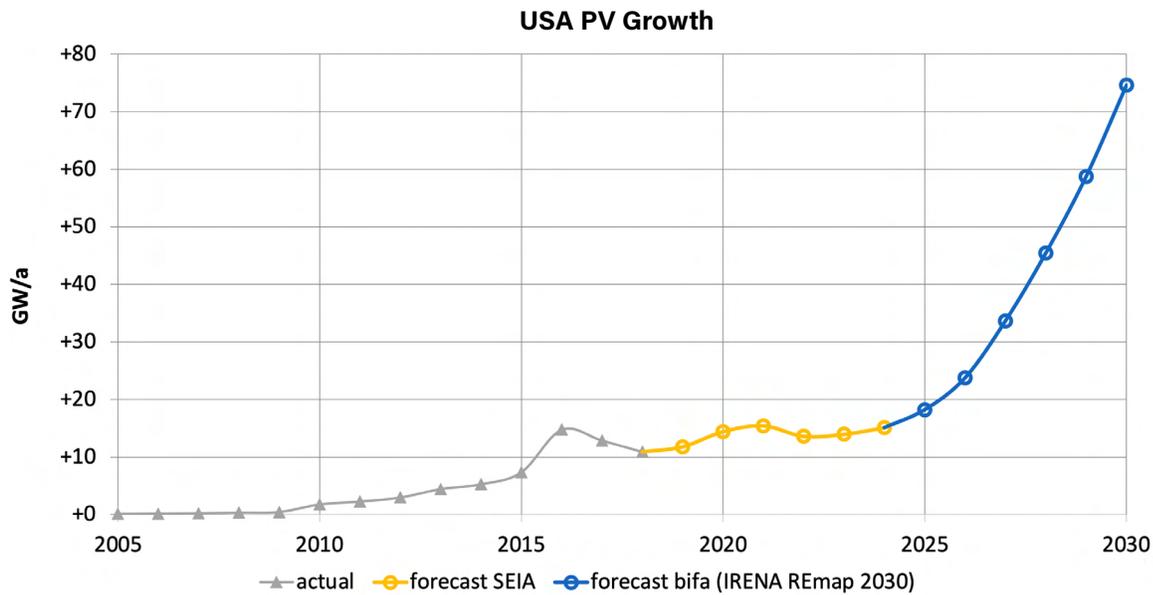
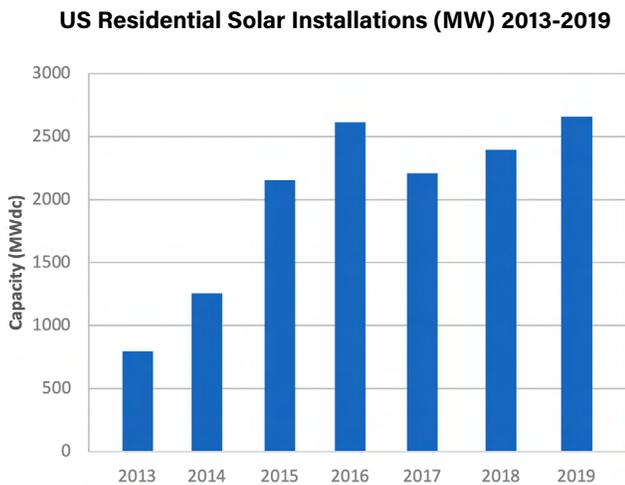


Figure 5: Residential PV system installations in the US in 2013–2019; the 2019 numbers are estimated [18]



Canadian manufacturers interviewed recommended putting the focus on the residential market for stable growth forecasts. One interviewee expressed the opinion that the utility scale PV market will be predominantly served by cheap modules imported from Asia.

4.1.2 PV Market Development in Canada

The projection of the PV growth for Canada is based on 2018 and 2019 data from IEA [12], [13], IRENA [14]–[16], and Quaschnig [17]. Canada’s average share of the North American market is in the range of 8% of the US market. As shown in Figure 6, PV growth deployment in Canada reached a first peak in 2015 with 0.7 GW installed capacity. Based on exponential growth, resulting in a cumulated installed PV of 437 GW for the total region of North America [15] (REmap case 2030⁶), an accelerating growth rate beginning in 2019 has been calculated. In 2030, the annual PV installation is estimated to reach 5.6 GW.

⁶ Using the 2019 SEIA/Wood Mackenzie forecast data for the US [18], the reference case for North America (153 GW) will almost be reached in 2024. This case does not apply to further processing in this study and only the REmap case is used.

4.1.3 Cumulative PV Capacity and Potential Waste

Taking into account a 64.2 GW installed capacity in 2018 in the US [19] and a yearly mean growth of about 14 GW [18], PV installed in the US is predicted to reach a capacity of nearly 150 GW in 2024. Based on 2008 to 2018 data for Canada and 2008 to 2024 data for the US, an exponential trend was used to match the forecast of the IEA's PV Technology Roadmap 2030 for North America (437 GW) [15]. Figure 7 summarizes the projected cumulative PV capacity for the US and Canada.

Most of the PV modules on the North American market are made of crystalline silicon solar cells encapsulated in a polymer matrix behind glass and framed with aluminum to fix the modules in a system. As a commodity, the PV installations build a large anthropogenic material stock representing a cumulated installed PV capacity of 437 GW for the total region of North America in 2030. This is equivalent to a material stock of 27 million tonnes (Table 2).

Table 2: Material stock of North American modules in 2030 based on the IRENA and IEA-PVPS and IRENA studies [1], [15]

Material	Amount (metric tonnes)
Module	27,000,000
Glass	20,600,000
Polymers	2,800,000
Aluminium	2,100,000
Copper with solder	239,000
Silicon	1,270,000
Silver	11,000
Other	170,000

Figure 6: Projected annual PV installation in Canada based on IEA, IRENA, and Quaschnig studies [12]–[17]

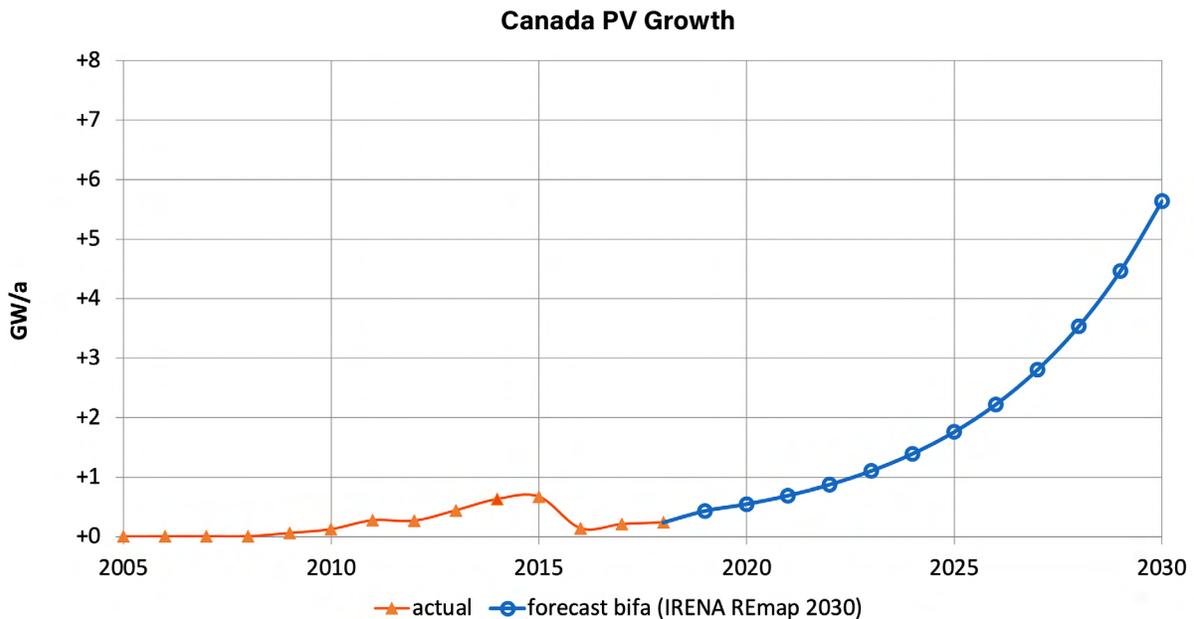
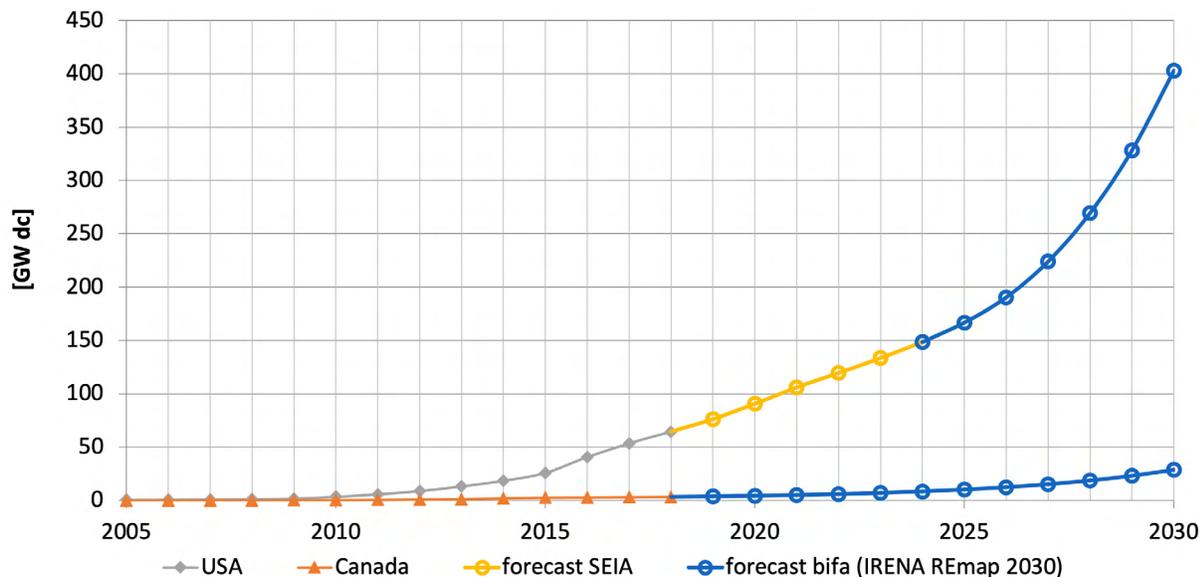


Figure 7: Projected cumulative PV capacity for the US and Canada [12]–[17]



4.1.4 Review of Reliability and Time of Use of PV Systems

Most PV waste is typically generated during four primary life-cycle phases. These are:

- 1) Module production;
- 2) Module transportation;
- 3) Module installation and use; and
- 4) End-of-life disposal of the module.

The Weibull waste model [1] covers all life-cycle stages except production⁷, which accounts for the high import rate of PV modules compared to domestic manufacturing. Since most PV production takes place abroad, this production waste will not enter the waste stream in North America.

Correspondingly, future PV module waste streams can be quantified according to the model described as follows:

- **Step 1:** Conversion of installed PV capacity to installed PV module mass (from gigawatts to metric tonnes)

- **Step 2:** Calculation of probability of PV module losses with Weibull model function in two different scenarios

- a) Regular loss, assuming an average lifetime of 30 years
- b) Early loss, as above, but including early damages:
 - Installation/transport damages: 0.5%
 - Within first 2 years: 0.5%
 - After 10 years: 2%
 - After 15 years: 4%

Details of the model applied and the parameters used are listed in Table B.1 in Appendix B.

4.1.5 Forecast of PV Waste and Model Limitations

4.1.5.1 Results

By significantly increasing the number of PV installations, the amount of waste from PV modules will grow over the coming years with significant time offset after the installation of the PV systems. The time offset should be more than 25 years but some early losses will likely generate a waste stream even in the first years after installation.

⁷ Assumption: Production waste is managed, collected, and treated by waste treatment contractors or manufacturers themselves.

The Weibull model results for the North American market for both scenarios are presented in Table 3 and Figure 8. This steep increase of waste amount in the early-loss scenario results from the assumption that a higher percentage of early PV module failures will occur during transport, installation, or storms as compared with the regular-loss scenario. Figure 8 shows the cumulative PV module waste results per year up to 2030.

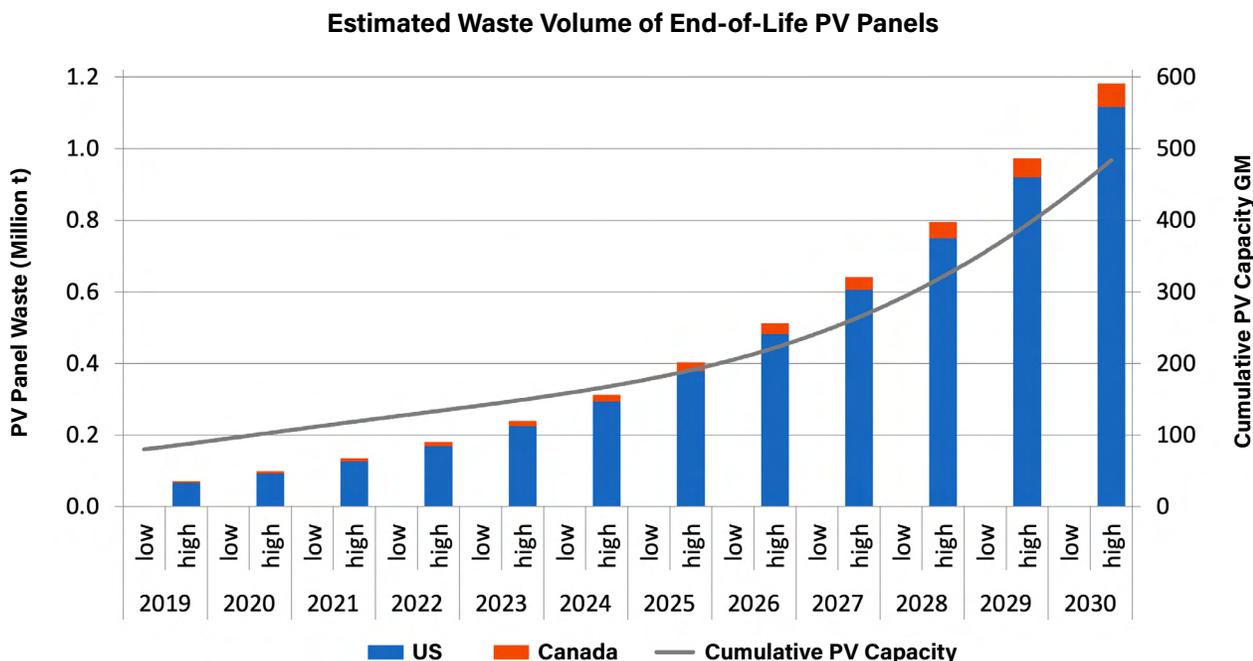
The expected PV module waste amount in North America will increase from 12,000 metric tonnes in 2019 to 214,900 metric tonnes in 2030 in a regular loss scenario (Table 3). While in an early loss scenario, the total waste amount of PV modules is 71,000 metric tonnes in 2019 and will increase to 1,200,000 metric tonnes in 2030, representing a material value of about USD\$385 million based on the IRENA and IEA-PVPS study [1].

Table 3: Weibull waste model results in two scenarios

Year	2019 (Metric Tonnes)	2030 (Metric Tonnes)
Regular Loss	12,000	214,900
Early Loss	71,000	1,200,000

Since no statistical data are available on the actual waste amounts (as confirmed by the interviewees), the early loss numbers in the model results shall be taken as a worst-case scenario. Holm et al. report that US recyclers have processed approximately 100 metric tonnes of PV, which equates to a few thousand tonnes in the US per year [20]. Total annual e-waste in the world today accounts for 49.8 million tonnes [20] for comparison.

Figure 8: Estimated cumulative waste volumes of end-of-life PV modules in North America



NOTE: Low = regular loss scenario (Weibull exponent $\alpha = 2.4928$), high = early loss scenario ($\alpha = 5.3759$).



“The forecast for the amount of PV module waste is subject to a very high uncertainty because it can be assumed that a significant portion of modules may be still functional, though some degradation might have taken place, and could be sold into secondary use applications.”

— 4.1.5.2 Decommissioning and Reusing

The decommissioning of large power plants, including the pickup of the modules, is frequently ordered after tendering the best price and service and is therefore expected to be well organized at moderate costs [21]. Interview results about the current decommissioning practices revealed that recently, the PV panels are often sold as used panels for export without entering the waste regime at all after decommissioning, but little statistical data are available.

Also, in order to save on costs, owners of PV plants might decide to store the modules at the plant site for some time or leave them installed even after the shutdown or decommissioning of the plant. This will create a stock of secondary materials as the modules will not have entered the waste stream. This will reduce the waste stream of modules versus the model results significantly.

The forecast for the amount of PV module waste is subject to a very high uncertainty because it can be assumed that a significant portion of modules may be still functional, though some degradation might have taken place, and could be sold into secondary use applications. The interviewees estimate that up to 70% of the value of new modules could be achieved for good quality used modules. Since no statistical data are available, the experts interviewed assume that on average 25% of the modules dismantled are prepared for reuse and export to other countries. This will further reduce the waste streams in North America.

The residential or building-integrated PV (BIPV) installations may require different collection mechanisms than for the decommissioning of utility size PV power plants, such as pickup on request or bring-in systems to collection points, because relatively small quantities have to be transported and the collection of end-of-life modules from highly dispersed homes or buildings will increase the logistics costs. Additionally, the disassembly of rooftop and façade BIPV requires additional efforts and safety precautions according to building decommissioning standards, which do not include electrical aspects of PV modules such as preparing a Decommissioning Plan Report with the details of procedures for managing excess materials and waste. The reusability of customized BIPV modules is expected to be lower because they have different shapes, dimensions, and glass thicknesses to fit with specific buildings, which create significant obstacles for further use.

A very long life cycle is desirable to minimize the product's environmental footprint. The establishment of rules or requirements would help to distinguish functional modules from module waste so those that are still functional could be reused. A documented quality inspection should ideally take place prior to any trade of used modules to provide clear evidence that these modules are still functional, avoiding any illegal shipments of defective modules and potential dumping in other countries.

The demand for used modules for repair and replacement of defective panels in PV installations in North America

is expected to be rather small because used modules provide lower efficiencies while the cost of new modules would be higher but more efficient. Therefore, used modules would only be used for repair or replacement purposes.

In North America, as the demand is moving towards the use of high-power modules with the lowest possible price, which is mainly materialized by using new modules, there is no significant demand for used modules at the moment. According to interview results, the primary markets for used modules are expected to be outside North America, e.g., in Africa, Pakistan, Afghanistan, and other countries. More details about the preparation for reuse are presented in Sections 4.3 and 4.6.

— 4.1.5.3 Monitoring of Waste Streams

The uncertainties identified in the waste and reusable product streams make it difficult to predict developments in the waste and reuse markets. A better understanding of the actual waste would help support the development of sound PV waste policies and encourage investment in efficient recycling solutions to preserve the value of the secondary materials.

For this reason, recommendations for the harmonization of international data reporting are under development by several working groups in EU, e.g., Wagner *et al.* [6]. The objective is to improve the quality of reporting and monitoring of reusable product and waste streams. A harmonized coding relying on the United Nations University (UNU) Key 0002 PV Panel [6] was proposed to differentiate module types and materials used (Table 4). This would help with the monitoring and reporting of products put on the market; PV panel waste collected, treated, recovered, recycled, and prepared for reuse in tonnes; trade data on new and used modules; and information on materials used from international shipments, installations, decommissioning, and waste treatment.

4.2 Review of Current Canada, US, and EU Regulatory Frameworks

4.2.1 Principles of Waste Classification

The overall goal of classification principles is to identify risks to the environment and human health that a product could cause during end-of-life management,

although risk assessment may differ by country and jurisdiction. The management of end-of-life PV modules has to comply and follow the principles of general waste classification, whether the modules have to be classified as hazardous or as non-hazardous waste. Classification is based on material composition by mass or volume and accounts for the properties of the components and materials used (e.g., solubility, flammability, and toxicity). Any potential mobilization pathways of components and materials are assessed for the reuse, recovery, recycling, and disposal scenarios (e.g., materials leaching to groundwater, admission of particulate matter into the soil).

Table 4: Recommendations for harmonized international data reporting based on Wagner *et al.* [6]

Stakeholders	National registries, statistical institutes, data providers (e.g., public authorities, industries, collection systems, and recyclers)
Coding (internationally standardized)	e.g., UNU Key 0002 PV Panel with more elaborate subcoding
Regular Loss	Monitoring and reporting of products put on market; PV panel waste collected, treated, recovered, recycled, and prepared for reuse in tonnes; trade data on new and used modules; information on materials used

4.2.2 US Regulation and Legislation

On a national scale, there is no legal framework for managing end-of-life PV modules covering handling, transporting, storing, accumulating, treating, or recycling in the US. General federal, state, or industry-led policies that require or incentivize PV recycling and resource recovery do not exist everywhere [19]. Where there are no specific regulations on PV modules in a state, waste solar modules are governed by the RCRA (Code of Federal Regulations, Title 40: Protection of the Environment) as the principal federal law in the US governing the disposal of solid and hazardous waste. State regulations must at a minimum meet RCRA requirements. The toxicity classifications must take into account federal limits according to the Toxic Characteristic Leaching Procedure (TCLP) test. In general, the waste is divided in “universal waste” (UW)

with lower limitations for collecting, transport, and recycling, and “hazardous waste” (HW), which can be “listed” or “unlisted.” UW can contain hazardous waste (e.g., batteries) if collecting and recycling is properly organized. “Listed HW” is sorted by origin of the waste and contains known waste streams. It is included in one of four lists below:

1. **F-list:** Waste from non-specific sources;
2. **K-list:** Hazardous wastes from specific sectors of industry and manufacturing, and considered source-specific wastes;
3. **P-list:** Acute hazardous wastes from discarded commercial chemical products; and
4. **U-list:** Hazardous wastes from discarded commercial chemical products.

A waste can be a hazardous waste if it is solid and can be assigned to one of the four lists. A waste can also be considered as hazardous if specific criteria on ignitability, corrosivity, reactivity, or toxicity (Part 261, Subpart C of the RCRA) are met, otherwise the waste is considered non-hazardous solid waste. Disposing and recycling of such waste is regulated by each state, but if no state regulations exist, then RCRA is applied [2], [22].

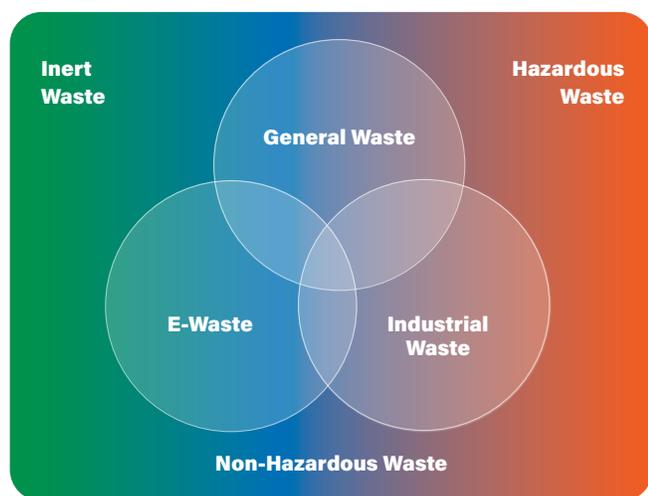
Under the actual legal framework, end-of-life PV modules may be classified as hazardous or non-hazardous, depending on the used module materials and on the test methods (Figure 9).

Based on data by SEIA [18], the top ten states with their corresponding installed capacity megawatt (MW) of 2019 are shown in Table 5. It is interesting to note that the presence of state regulations (or regulatory initiatives started) for modules does not always correlate with the installed PV capacity in the state. It is worth noting that Hawaii is not part of the top ten states with PV installations but has significantly increased its installations in 2019 [19].

It seems that TCLP tests are mostly accepted based on the definition of waste by leaching tests. The thresholds can vary from state to state, but they are not allowed to be less stringent than the RCRA requirements. California has adopted more stringent testing with the Soluble Threshold Limit Concentration (STLC) test and the Waste Extraction Test (WET). TCLP and WET are methods used to determine whether a waste is a toxic hazardous waste. The main differences between TCLP and WET are in the laboratory analysis methods and in the regulated chemicals that are tested. Further tests according to California Title 22 STLC and TTLC also require different methods with other criteria and threshold limits.

The photovoltaic module wastes are not listed under RCRA regulation. By knowing the composition of the photovoltaic modules, a further investigation of the criteria in Part 261, Subpart C of the RCRA for ignitability

Figure 9: Legislation and reasons for different characterization relevant for end-of-life PV modules based on the IRENA and IEA-PVPS study [1]



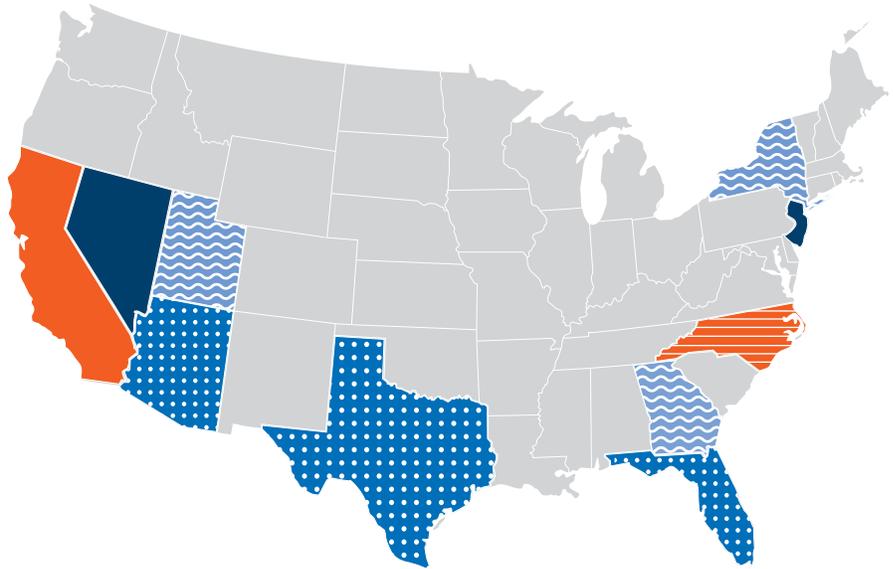
PV modules may contain trace amounts of hazardous materials such as lead, tin, zinc, cadmium, selenium, indium, gallium and others.

Different waste characterisation tests and methods can lead to different classifications of PV module waste according to the legal requirements.

Standardized leaching tests and material concentration limits determine the classification and minimum requirements for waste treatment and disposal.

Table 5: Top ten states by installed capacity by September 25, 2020 [18]

State	Installed Capacity (MW)
California	27,897
North Carolina	6,435
Arizona	4,708
Florida	4,649
Texas	4,606
Nevada	3,587
New Jersey	3,320
Georgia	2,659
New York	2,311
Utah	1,786



(D001), corrosivity (D002), reactivity (D003), or toxicity (D004–D043) is done. The criteria for ignitability (D001), corrosivity (D002), and reactivity (D003) might not always be fulfilled. The fourth criterion “toxicity” can be checked by carrying out a TCLP test. There could be matches for the substances cadmium, chromium, copper, lead, mercury, molybdenum, selenium, silver, and zinc. According to the test results, older solar modules might have to be determined as hazardous waste under the RCRA regulation because they might fail the leaching tests. The material savings applied for cost reductions and new developments usually reduce the content of hazardous substances in new module generations.

Table 6 shows the results of the regulatory review of enacted or pending law, policy, or program that was conducted by NREL and the Electric Power Research Institute (EPRI) [19]. This review also revealed that, in addition to official regulations, there are some state-led initiatives in California [23], Illinois, and Minnesota that address end-of-life PV management.

4.2.3 Canada Regulation and Legislation

An online search that included the websites of the ministries of environment in all the Canadian provinces did not provide any specific end-of-life PV regulations, which was confirmed by the Canadian interviewees. Common waste legislation in Canada regulates waste for PV modules. The control of waste management activities on federal lands and the international and interprovincial movement of hazardous waste and hazardous recyclable materials are the responsibility of the Government of Canada.

According to the Government of Canada [24], waste management is applied as follows:

- The collection, recycling, composting, and disposal of hazardous materials and hazardous recyclables falls under municipal jurisdictions;
- Establishing measures and criteria for licensing hazardous-waste generators, carriers, and treatment facilities, in addition to controlling movements of waste is in provincial and territorial governments jurisdictions;

Table 6: Review of Actual regulation, policy, or program specific to PV waste modules

State	Enacted or Pending Law, Policy or Program
Arizona	No specific regulation found, other than common waste regulation
California	Proposed regulations: Photovoltaic (PV) Modules – Universal Waste Management; DTSC Reference Number: R-2017-04, OAL Reference Number: Z-2019-0409-04, Public Comment Period: (12/24/19 – 01/08/20)
Florida	No specific regulation found, other than common waste regulation
Georgia	No specific regulation found, other than common waste regulation
Hawaii	HI HR126, resolution adopted in final form 2019-04-04
Illinois	Solar Module Recycling Initiative in 2017, still ongoing
Minnesota	Minnesota Solar Module Recycling Strategy Working Group 2019
Nevada	Seems to be regulated actually by common waste regulation
New Jersey	Senate Bill 601, passed on 2019-08-09
New York	Proposed Legislation S.B. 942, current status: notice of committee consideration requested, 2019-05-06
North Carolina	N.C. H329, currently passed on 2019-07-19
Texas	No specific regulation found, other than common waste regulation
Utah	No specific regulation found, other than common waste regulation
Washington	<p>Wash. Rev. Code §70.355: Photovoltaic module stewardship and takeback program: July 2019 guidance for manufacturers released HB 2645 - 2019-20, Concerning the photovoltaic module stewardship and takeback program:</p> <ul style="list-style-type: none"> ▪ Requires that no manufacturer, distributor, retailer, or installer may sell, or offer for sale, a PV module for which a recycling plan has not been approved, beginning July 1, 2023, rather than January 1, 2021. ▪ Each manufacturer must submit a recycling plan due July 1, 2022, rather than January 1, 2020. ▪ Defines PV modules covered in the program to include those directly connected to the grid or utility service.

- Transboundary movements of hazardous waste and hazardous recyclable material, in addition to negotiating international agreements related to chemicals and waste, is the task of the federal government.

Transportation across Canadian borders must follow processes established under the Basel Convention, the Canada-USA Agreement on the Transboundary Movement of Hazardous Waste [25], and the Organisation for Economic Co-operation and Development (OECD).

Under the Canadian Environmental Protection Act, 1999 [26], the Government of Canada has the authority to intervene when there is a potential for release of

toxic substances into the air, land, or water. This act specifies what is considered to be “hazardous waste” and “hazardous recyclable material,” and a “Toxic Substances List” is available [27]. This list contains specific regulations for substances Canada has determined to be toxic or potentially toxic.

A waste classification is done based on the composition of the PV modules, which may contain small amounts of toxic materials such as lead or cadmium. In Canada, the “Export and Import of Hazardous Waste and Hazardous Recyclable Material Regulations” [79] and the “Toxic Substances List” [27] have to be taken into consideration if the PV waste modules are classified

as hazardous waste; if so, they have to be checked to determine if they contain substances in the above list and if any specific action is required. As an example, a classification of three types of modules (CdTe, CIGS), and c-Si) is carried out according to the "Export and Import of Hazardous Waste and Hazardous Recyclable Material Regulations."

For cadmium, according to the risk assessment report done by the Government of Canada [27], photovoltaic modules were not identified as one of the sources of cadmium in Canada, as "inorganic cadmium compounds" are present in CdTe- and in CIGS-modules. The risk management tools developed to manage risk associated with cadmium only cover guidelines and codes for the base metals smelting sector, electric power generation sector, and steel manufacturing sector.

For lead, according to the risk assessment report done by the Chemicals Management Division of Government of Canada [27], based on the tools developed to manage risks associated with lead in Canada, the "Export and Import of Hazardous Waste and Hazardous Recyclable Material Regulations" seems to be applicable for an assessment of waste photovoltaic modules [27]. Lead found in the list as "lead" may be contained in c-Si modules.

Since 2014, all provinces in Canada have established programs to manage end-of-life electronics and electrical equipment. Alberta has established a product stewardship model, and all the other provinces have legislated programs. The Northwest Territories has reviewed options for the management of electronic and electrical equipment while the Yukon has considered amendments to its regulation that would create a stewardship program for these materials [28]. In addition, the waste management industry provides services under contract to industrial, commercial, and institutional waste generators [28], [29].

In the survey on the waste management legislation of each province conducted for this report shows that the provinces refer to the federal dangerous goods regulation in the management of hazardous waste materials. The TCLP test is applied as a standard test to determine leachate toxic waste, but the threshold concentrations can vary from province to province.

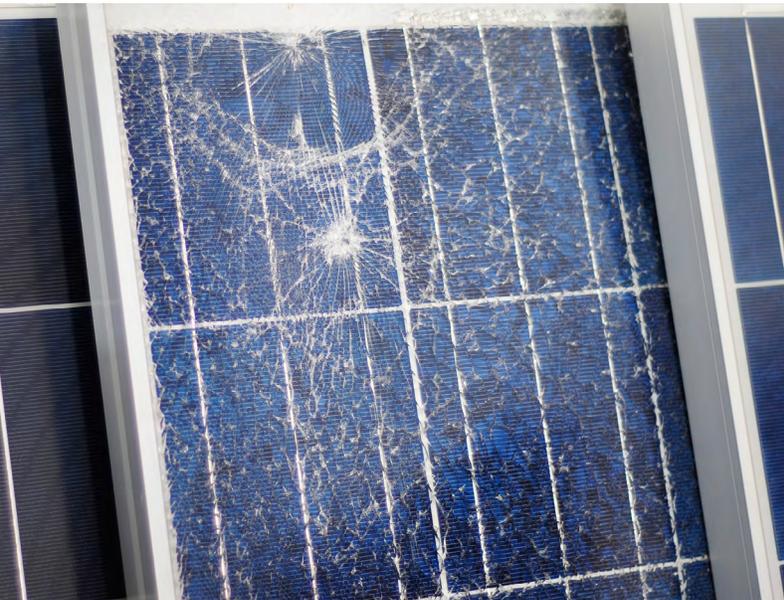
4.2.4 EU Legislation

The recycling of PV modules is already mandatory in Europe and the EU. The Waste Electrical and Electronic Equipment (WEEE) Directive [30] covering waste treatment and recycling has been transposed into national law by the member states. Policy development and several regulations in Europe are based on the producer's responsibility principle, energy and resource savings, and product environmental footprints. Regulations relevant for PV modules and the end-of-life treatment are as follows:

- Waste Electrical and Electronic Equipment (WEEE) Directive [30];
- European Waste Framework Directive 2008/98/EC [31] (WFD);
- Commission Decision 2000/532/EC [32] established the List of Waste;
- Classification, Labelling and Packaging (CLP) Regulation [33];
- Persistent Organic Pollutant (POP) Regulation [34];
- Restriction of Hazardous Substances directive (ROHS) [35];
- Battery Directive [38];
- Eco-Design Directive [36]; and
- Product Environmental Footprint (PEF) [39].

The European Waste Framework Directive (WFD) 2008/98/EC [31] is the key legislative document on waste at the EU level. This directive specifies properties that render waste hazardous and provides information about handling waste and end-of-waste criteria.

The Commission Decision 2000/532/EC [32] established the European List of Waste (LoW), which is the key document for classification of waste. As an EU decision, the LoW is binding in its entirety; it addresses all member states and does not require transposition. The LoW provides further provisions for the assessment of hazardous properties and the classification of waste. It provides the list of wastes, categorized into chapters, subchapters, and entries. Full and compliant classification enables businesses and competent authorities to determine whether the waste is hazardous or not. In this respect, the LoW has three types of entries:



“The recycling of PV modules is already mandatory in the EU.”

- **Absolute hazardous entries:** Waste that is hazardous without any further assessment;
- **Absolute non-hazardous entries:** Waste that is non-hazardous without any further assessment;
- **Mirror entries:** Waste from the same source that might be allocated to a hazardous entry or to a non-hazardous entry under the LoW, depending on the specific case and on the composition of the waste. Hazardous waste is signed with an asterisk after the six-digit number [37].

The waste assessment process of the PV modules has to account for the WFD [31], CLP Regulation [33], POP Regulation [34], the composition (processing), and the substances in the waste.

The WFD [31] defines 15 hazardous properties (HP1 to HP15) and specifies rules for the classification of or limit on values for hazardous substances of the different hazardous characteristics of waste in Europe. The reference modules plus their defined waste streams are assessed according to the requirements of the WFD. When intact, the classification of a photovoltaic module as non-hazardous waste is possible according to the results of the waste assessment. The CLP Regulation [33] is also applied to identify the hazardous properties.

The aim of the POP Regulation [34] is to protect the environment and human health from persistent organic pollutants. The hazardous classification is based on the relevant threshold listed in the Annex of the POP Regulation [34], but none of the substances used in

PV modules are listed there. Based on the extended-producer responsibility principle, the EU WEEE Directive [30] requires all producers supplying PV modules to the EU market (wherever they may be based) to finance the costs of collecting and recycling end-of-life PV modules put on the market in Europe. The legal framework of the WEEE Directive has to be transposed into a national law by the member states of the EU that may add more requirements into their national laws. The WEEE obliges member states to take measures to ensure that producers provide free information about preparation for reuse and treatment, and about the location of hazardous substances and mixtures in electrical and electronic equipment (EEE). Annex VII of the directive contains a list of substances, mixtures, and components that have to be removed as a minimum requirement (e.g., mercury containing components, printed circuit boards, external electric cables) by selective treatment of any separately collected waste electrical or electronic equipment. Another part of the WEEE Directive requires electronic-waste (e-waste) to undergo proper treatment, which means the removal of the listed items as a minimum requirement. The directive also sets the recovery rate targets that are to be achieved.

The Restriction of Hazardous Substances Directive (ROHS) [35] is closely linked to the WEEE Directive and lays down rules on the restriction of the use of hazardous substances in EEE with a view of contributing to the protection of human health and the environment, including the environmentally sound recovery and

disposal of EEE waste. Mitigating the use of hazardous substances in photovoltaic modules intended to be used in systems that are designed, assembled, and installed by professionals for permanent use at defined locations to produce energy from solar light for public, commercial, industrial, and residential applications are not (yet) in the scope of this directive [35].

The Battery Directive [38] covers the handling of batteries, accumulators, waste batteries, and waste accumulators. By decommissioning a PV plant, the requirements of that regulation apply if batteries are used as energy storage systems.

The Eco-Design Directive [36] establishes a framework for the setting of eco-design requirements for energy-related products. This directive obliges the supplier or the manufacturer to assess possibilities for reuse, recycling, and recovery of materials or energy. The supplier has to provide information about treatment facilities concerning disassembly, recycling, or disposal at the end-of-life. A similar regulation may be developed for PV modules in the future.

The Product Environmental Footprint (PEF) [39] is a harmonized methodological approach to assess, display, and benchmark the environmental performance of products, services, and companies by doing an assessment of the environmental impacts over the life cycle. The life-cycle approach includes resource extraction and preprocessing, design, manufacturing, and retail, distribution, use, collection and reuse, recycling, energy recovery and disposal. The PEF is part of a resource-efficient European strategy, which is one of seven flagship initiatives of the Europe 2020 strategy. Its goal is to decouple economic growth from use of resources and environmental impact. For the pilot phase, the European Commission released a PEF guide in 2012 [39] that provided a method for modelling these environmental impacts.

One of the pilots targeted PV modules used in power systems for electricity generation. The results successfully isolated the impacts of usage from the impacts caused in the other life-cycle stages (raw material acquisition and preprocessing, distribution and storage, production of the main product, end-of-life).

4.2.5 Summary of Enacted or Pending Legislation Referring to End-of-Life PV Modules

Compared to Europe, there are very few federal rules in North America for end-of-life PV modules or even general requirements for the treatment of hazardous substances or recovery rates of valuable materials. End-of-life PV modules are regulated as any other waste. Depending on the technology (crystalline silicon, CdTe, CIGS or other) and the substances present in the panel (and on the test procedures applied for waste assessment), they are classified as hazardous or non-hazardous waste. The threshold values and test procedures vary so that PV modules may be classified as non-hazardous waste in some countries but as hazardous waste in others. Valuable materials are recovered if the modules are recycled properly and offer value retention rather than being disposed of.

There is a lack of detailed and harmonized rules for reporting on PV modules, such as:

- The number of modules put on the market in a year;
- Module materials;
- Collection of end-of-life modules;
- Reuse;
- Recycling;
- Recovering; and
- Disposal.

As a result, the availability of public data for valuable or hazardous materials referring to end-of-life PV modules and treatment results is poor [6].

In the EU, specific requirements for treatment and recovery rates for end-of-life panels are established in the European directives. These requirements are based on the principle of extended producer responsibility and work in combination with the framework for waste management, as described in Section 4.2.4 above. For managing the waste stream of EEE, producers have the following responsibilities:

- **Financial and operational responsibility:** Producers have full financial and operational responsibility for their products and packaging at the end-of-life.

- **Reporting, auditing, and record-keeping responsibility:** Producers are required to provide an annual mass balance and record keeping on the quantity and weight of WEEE supplied to the market. Unfortunately, the reporting is not harmonized between member states and numbers cannot be fully compared. New harmonized international standards may help to obtain more reliable data [6].

4.3 Dismantling, Collection, and Recycling in North America

In this section, the current practices for dismantling, collection, and recycling of PV modules are described based on the interview results obtained and the research carried out for this project. Two cases are distinguished for the dismantling of modules: (1) PV power plants (large scale), and (2) BIPV and small home system applications (small scale).

4.3.1 PV Power Plants

As discussed in Section 4.1, the utility size PV plants dominate the installed capacity in North America. The building, operation, and decommissioning of such PV power plants is solely driven by economic factors. The plants are usually well monitored and maintained to maximize the electricity output. Repowering is generally allowed if the plant has to be repaired after damages due to environmental events such as storms or a tornado, for example. Repowering can also take place when an economic benefit can be expected by replacing PV modules with more efficient ones and even by adding more modules onto the existing structure. Although the technical lifetime of a PV module is well above 25 years, some interviewees estimate the economic lifetime is between eight and 15 years. Local rules may exist that depend on the contracts, permits, funding and financing of the PV systems; local rules may also prohibit repowering to optimize the power output of the plant, in which case the PV plant would require a new permit.

The decommissioning costs of a plant usually have to be estimated before it is built to secure financing, insurance, and permits from local authorities. In addition, the ground conditions often have to be restored to the current land use prior to development of the project, for instance, a full recultivation of the area may be required.

The detailed costs of the decommissioning of PV power plants were estimated by EPRI [40]. The revenues of the metals, inverters, transformers, and the modules make up a large part of the total decommissioning costs. PV plant owners try to minimize the efforts and reduce costs of decommissioning by introducing new support structures, saving fundaments, concrete, buildings, and roads that are known to be costly, in addition to the labour costs. Often, it is requested by financing institutions and insurance companies that money be set aside as a surety so that the decommissioning can be financed even in case of a bankruptcy. The risk assessment and calculation methods to do this are not yet fully standardized and the calculation rules may differ significantly. The same applies to the decommissioning process itself. No standards or guidelines are available yet for the proper management of this process, including monitoring rules.

Only skilled workers should carry out the decommissioning and any unnecessary damage to the modules should be avoided. Modules can be prepared for pickup by stacking them on pallets, in boxes, in big bags, or in containers. It is expected that the plant operators monitor and collect data on the performance of each module, as well as its position on the string data, and that the data be made available. The data may include electroluminescence or infrared measurements taken via drones. It is also possible to measure I-V curves at the decommissioning site via handheld equipment or mobile sun simulators. A pre-sorting of the modules, including a preliminary visual inspection with documentation, is recommended to classify the modules for reuse or for recycling. Costs for a pre-treatment at another location and logistics can then be saved. For more details about preparation for reuse or recycling, see Section 4.6.

4.3.2 Building-Integrated PV (BIPV) and Home Systems

BIPV and home systems are much smaller than PV power plants and frequently have capacities that range between one single module and 10 kW. Access to the modules may require scaffolds if installed in a façade or on a roof. Only skilled workers should perform the work, e.g., PV installers or decommissioning specialists, and they must avoid damaging the panels by, for instance,

throwing them from the roof into the containers. Modules should be packed in the same way as they are when decommissioning utility-scale plants. Considering the size and scattered locations of home systems, the proper dismantling may bear significant costs, and the collection of a full truckload might require longer transport distances. In the case of very small systems, a bring-in system (e.g., to an e-waste collection site) could help to save costs. Since the dismantling process is not yet standardized, general standards for construction, demolition, and electrical installations can be applied.

4.3.3 Module Recycling

Based on the results of the expert interviews and the research conducted at the time this report was prepared, 16 recyclers in the US were found to be active in collecting and recycling PV modules with a clear focus on crystalline silicon modules, but no recyclers in Canada were identified. First Solar has established its own high-value recycling program and takes back its own modules. The process is described, for example, in the IRENA and IEA-PVPS study [1].

The number of modules collected and treated and the associated technologies and results are not publicly reported. Only limited information could be found on the recyclers' website pages.

From the interviews, it was determined that the terms and conditions established by recyclers vary greatly. Gate fees of up to USD\$25 per piece were reported in the US compared with average costs of around USD\$60 for recycling plus USD\$150 for logistics per metric tonne in Germany. Other recycling costs were reported to be USD\$0.04/Wp with a reduction target of about USD\$0.02/Wp.

Despite the very small quantity of waste modules, several recyclers were identified but the processes they apply to recycle the PV panels were not disclosed. Several interviewees were of the opinion that, in most cases, only the frames and cables are removed and sold to recyclers for aluminum and copper prior to the landfill of the laminate (glass, encapsulant and solar cells) while, in some cases, the modules are shredded and the glass is separated for recycling. The silver and silicon are usually lost.

The waste panels are sometimes transported to a neighbouring state to be landfilled if a state's legislation does not allow this process, as observed in California where modules were transported to Nevada for disposal [41]. Some recyclers use processes similar to the ones described in Figure 10 (described in Section 4.4) and have the polymer fraction incinerated or landfilled. One recycler reported using a state-of-the-art thermal process to combust the polymers and separate glass, cells, and metals, including silver.

The interviewees estimated that the number of modules processed by a recycler could be up to 500 metric tonnes per year with an average of 200 tonnes. They also mentioned that research institutes and universities have expressed interest in developing recycling processes for PV modules, but they were unaware of any research taking place on this.

4.4 Mandatory Takeback and Recycling in Europe

As mentioned in Section 4.2.4, the major applicable directives in the EU are the Waste Framework Directive (WFD) 2008/98/EC [31] and the WEEE Directive [30].

The WFD includes the following definitions [31]:

- **Reuse:** Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived;
- **Treatment:** Recovery or disposal operations that include preparation prior to recovery or disposal;
- **Recovery:** Any operation that results in waste serving a useful purpose by replacing other materials that would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy; and
- **Recycling:** Any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for as an original product or for other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.

The WEEE Directive [30] was amended in 2012 and PV modules were included then in a product category.



“Today, the recycling of PV modules is dominated by existing mechanical recycling processes that are currently in use for laminated glass, metal, and WEEE recycling.”

Article 16.4 of the WEEE Directive states: “Member States shall collect information, including substantiated estimates, on an annual basis, of the quantities and categories of EEE placed on their markets, collected through all routes, prepared for re-use, recycled and recovered within the Member State, and on separately collected WEEE exported, by weight.” In 2016 in the EU, 55.6% of the total WEEE collected was from large household appliances, while the second and third largest categories were IT and telecommunications equipment (14.8 %), and consumer equipment and photovoltaic modules (13.5%) [42].

Table 7 shows an example of how WEEE monitors the quantity of PV modules in tonnes put on the market, collected as waste in different ways, and reused and treated for three European member states (Germany, France, and the United Kingdom). Limited data are available and they are subject to different national reporting practices. Therefore, data are not sufficient for statistical analysis. Interviewees indicated that not all modules from decommissioned plants enter the waste stream or are reported.

The waste streams are still rather small and there is very little investment in specialized PV recycling plants. According to the interviewees, metal and glass recyclers are starting to show interest in PV waste and see it as a future business case. The waste is processed predominantly in discrete batches using the free capacities in existing metal or laminated glass recycling

plants. It is expected that this will be sufficient to recycle the waste stream in the coming years, but investments will be required with the expected increase in the volumes to be treated and to develop better recycling processes to obtain good quality output of the materials. For instance, the polymer fraction still contains a significant amount of glass, metals, and silicon that are currently lost if treated in waste incineration plants because the materials cannot be extracted from the ash.

Today, the recycling of PV modules is dominated by existing mechanical recycling processes that are currently in use for laminated glass, metal, and WEEE recycling. The process has to be adjusted to the input material and the PV modules are usually collected at the recycling plant until there is a significant amount to allow for optimized batch sizes to be recycled. The advantage is that hardly any investment is required to obtain sufficient recycling results in full compliance with the law. It also helps to fill excess capacities and gain experience at low-waste streams.

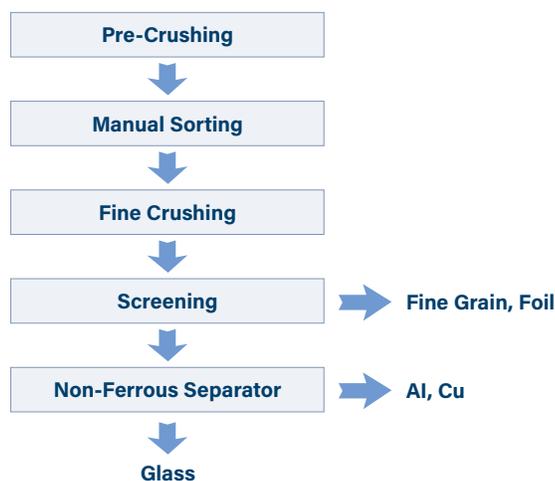
Figure 10 shows an example of the process flow. Extraneous material is manually sorted out after pre-crushing. The polymer fraction is extracted by screening after fine crushing. Aluminum and copper are removed with eddy-current separators from the glass to be reused as a secondary metal in the metallurgical industry. The residue is glass that can be added to road construction material or concrete or can be used for foam or glass fiber production.

Table 7: PV statistics according to WEEE monitoring in Germany, France, and the United Kingdom 2017 [42]. Units are in metric tonnes.

	Germany	France	United Kingdom
Products put on the market	155,539	83,621	33,813
Waste collected	3,595	1,885	106
Waste collected from households	1,000	1,885	106
Waste collected from other sources	2,595	0	0
Waste treatment	3,595	1,885	106
Waste treated in the member state	3,568	99	106
Waste treated in another state of the EU	26	1,786	0
Waste treated outside the EU	1	0	0
Recovery	3,560	1830	106
Reuse	270	0	0

Figure 11 shows a comparison of recycling results obtained in five different European plants [43]. The green lines mark the cumulated yields of the glass and metal fractions. These can vary significantly because the recyclers optimize the best economical results using the technology installed in their plants as long as their plants are in full compliance with the laws. Thus, this graph does not provide any information concerning the quality of the output and the processing costs.

Figure 10: Example of a Mechanical PV Module Recycling Process [43].

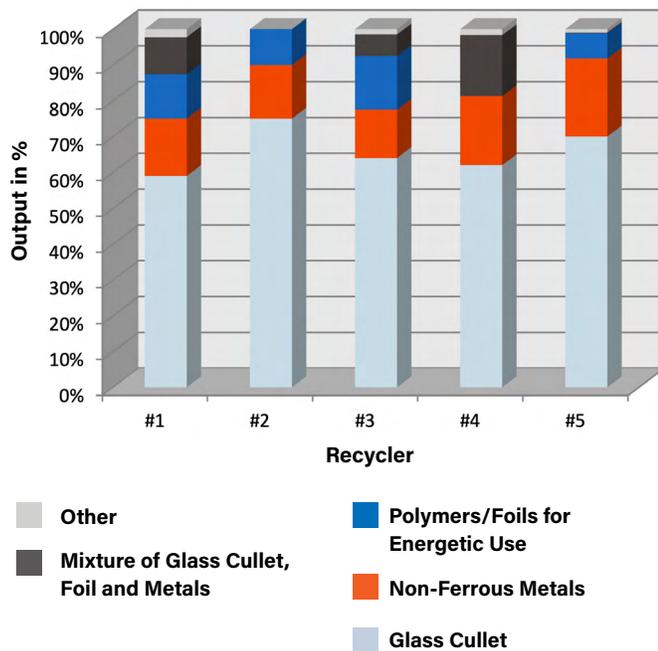


Collection and waste treatment of the different PV products should be carried out separately in order to obtain the highest possible quality of the recycling result and reduce the number of separation process steps needed to remove extraneous materials, which would minimize processing costs. For instance, PV modules could contain different levels (usually small amounts) of hazardous substances that have to be taken into account for safe handling and processing. Some modules contain small amounts of precious or rare materials (i.e., tellurium, gallium, indium, silver), which should be recovered to protect the environment and save valuable resources, even though the current metal prices hardly justify the efforts today.

More specifically, PV modules made of crystalline silicon and thin-film modules require at least some different processing steps of the whole sequence to recover the semiconductor materials and metals properly. They should be collected separately to facilitate the waste treatment process.

On the other hand, amorphous or micromorphous silicon modules usually do not contain significant amounts of hazardous or valuable materials; therefore, these can easily be treated in state-of-the-art glass recycling processes, for example, laminated glass removed from frames, junction boxes and cables.

Figure 11: Comparison of recycling processes in Europe [43]



4.5 Materials in PV Modules

The PV industry utilizes significant amounts of semiconductor materials, glass, silver, and polymers. The industry is trying to reduce costs by using smaller amounts of materials in the panels and by introducing new and less expensive materials, but also by achieving higher module efficiencies with the development of better solar cells. An overview of upcoming technologies is presented in the ITRPV Roadmap [5]. The modules of the year 2030 will offer higher efficiencies, lower weight, less toxic material consumption, and the replacement of costly components and critical substances compared with the standard modules of today. However, PV waste for new technologies will be offset in time, therefore the focus here is on past and current PV module designs that are reaching their end-of-life now and in the coming years.

4.5.1 Polymers

The main encapsulant used in PV modules is ethylene vinyl acetate (EVA), which is reasonably priced, easily available, and known for having good performance. EVA is a duroplastic polymer that melts at high temperatures and decomposes. It is cured with peroxide radical

starters in a vacuum lamination process during module production. EVA contains several UV-absorbers to optimize long-term light stability. The absorbers consume over time and become yellowish rapidly when they are at their end-of-life. EVA is a common source of the “snail trails” defect in PV modules. The formation of “snail trails” can be observed as discolourations above cracked cells in a module. The cracks allow ions like silver or elements from the glass (such as sodium and magnesium) to migrate in the polymer matrix causing degradation such as potential-induced degradation (PID) effects and corrosion.

There are alternative materials to EVA. One is polyvinyl butyral thermoplastic (PVB) that is used to require an autoclave process for lamination, but autoclave-free lamination of PVB is now possible. Other encapsulants are polyolefines, ionomers, polyurethane, and silicones.

The backsheets of modules are usually made of a polyethylene terephthalate (PET) foil with one or more layers of polyvinyl fluoride (PVF). The colour of the foils can be modified with inorganic fillers (TiO₂, CaCO₃, Al₂O₃, SiO₂, and others) and UV stable pigments and stabilizers. A big share of the PET foils can contain up to a few hundred parts per million (ppm) of antimony used as polymerization catalyst. Antimony may be present in some flame-retardants and the glass as well.

4.5.2 Glass

Glass thickness ranges from 2 to 4 mm in most PV modules, which may be manufactured as single-glass or double-glass modules; the latter is frequently used in combination with bifacial solar cells or for BIPV applications.

Antimony may be present in some types of glass used in solar application in concentrations of about 100 to 300 ppm in casted and rolled (textured) glass. In 2010, round robin tests were carried out according to Standard EN 12457-4 *Characterization of Waste - Leaching* with different glass types and showed that there was no leaching above the allowed threshold limits in the common concentration range of below 200 ppm of Sb [44]. The results depend on the cullet size of the glass with more leaching for the finest cullets due to the increased surface area and a change in the pH-value.

Therefore, it is recommended in Standard EN 12457-4 that the material should not be finely ground or milled down.

4.5.3 Metallization Pastes

Several pastes for screen-printing, dispensing systems, or ink jet technologies are used for the metallization of the cells. Silver and glass frit containing pastes are printed for the front contacts and gridlines, the backside is aluminum with small silver pads for better soldering. The composition of the pastes is not normally disclosed by manufacturers but lead, cadmium, thallium, bismuth, tin, and other heavy metals might be present. Where possible, it is expected that manufacturers will aim to further reduce the amount of toxic materials.

4.6 Processing of Used PV Modules

Information from the expert interviews revealed that repair of PV modules already takes place in production. The modules can be repaired quite easily for simple things like changing components such as cables, bypass diodes, and junction boxes. The repair of a frame or a defective backsheet, or even the replacement of a solar cell is more challenging and is carried out in a workshop or in a manufacturing plant. Some companies have mobile workshops for repairs and also for quality inspections and measurements. Repaired modules are remounted in the PV installation in the best case or are sold to third parties for reuse (secondary use).

There is very limited information about the reuse market, but experts mentioned that export of the modules for reuse in other countries (e.g., Africa, Pakistan, Afghanistan) does take place. The modules might come from manufacturers takeback and from decommissioning or collection companies already present at the global level.

Two cases can be distinguished:

1. The used module is still a working product and can be sold as a product;
2. It has to be proven that the waste module can become a product again by adequate quality testing and documentation. End-of-waste criteria are set in the European Waste Framework Directive (WFD). In summary, they are:

- The module is functional;
- Quality inspection documents can be shown;
- A market and a price exist for the module;
- A purchase contract can be shown;
- It is packed like a product.

According to the interviews carried out with authorities, manufacturers, certification organizations, and installers, and based on bifa Umweltinstitut's research [4], the following steps are recommended:

- A visual inspection and cleaning should be carried out;
- A current-voltage (IV)-curve should be recorded;
- For product and electrical safety reasons, a ground-continuity and an electrical isolation test should be performed and the system voltage of future applications should be limited according to the test results;
- The results shall be documented and a new label with the results should be placed on the back of the module;
- A warranty of 6 or 12 months should be provided at minimum.

Additional demands may be present according to local regulations.

The experts interviewed estimated that up to 80% of the dismantled modules could be reused in optimum cases, with 25% on average considering some PV installations have had significant damages due to environmental events such as storms. Specific procedures and guidelines do not seem to exist specific to the testing of end-of-waste criteria for PV modules.

A potential and simple test sequence is proposed in Figure 12 to prepare a module for reuse. The process starts with the documentation of the general module data such as dimension, type, number of cells, nominal electrical data, and serial number. Most information should be found in the data sheet. Then the module is subjected to a visual inspection and electrical tests and results are recorded on the data sheet that is delivered with the module to the buyer. The document can also be presented to authorities as a proof that it is a usable product and not waste.

The visual inspection can be based on international testing guidelines for module acceptance inspections [45], [46]. For time and cost reasons only the most important tests can be carried out and existing information (e.g., from a plant monitoring) should be used where possible.

According to the experts interviewed, the capacity of landfill sites in North America is sufficient for the disposal of the small PV module waste streams and hardly any known investments are made into recycling plants. Considering the dispersion of PV modules in various sites and the associated long-transportation distances, the recycling costs are predominantly determined by the costs of the logistics. Several recyclers seem to charge about USD\$25/module for recycling versus USD\$1-\$2/module to landfill, according to the interview results.

An example of recycling costs was presented by the German e-waste takeback system Take-E-Way at the trade fair Intersolar in Munich, Germany, in 2014 [47]. The modules were recycled in a fully mechanical separation process at a metal recycler. The data can be found in Table 8. The data clearly show that only efficient procedures with large quantities will result in sufficient revenue to cover the costs for recycling. In the EU, landfill disposal is banned, but if such legislation does not exist, like in North America, PV module recycling will compete with landfill disposal since costs are often lower. The value of secondary material is expected to decrease as manufacturers develop modules using less material or less expensive material to reduce the

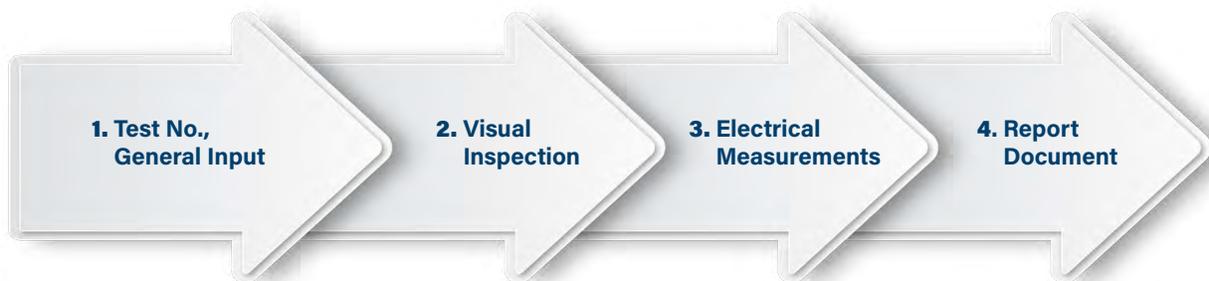
production costs of new modules [1]. The recycling processes have to be as fast and as economical as mass processes to achieve acceptable cost and to meet excellent and certified environmental standards.

Table 8: Treatment cost breakdown of module recycling in Germany [47]. Negative amounts refer to costs related to treatment. Positive amounts refer to revenue received from materials.

	Best Case Efficient procedure, large quantity (Cost/tonne in Euros)	Worst Case Inefficient procedure, small quantity (Cost/tonne in Euros)
Treatment Costs	-170.00	-250.00
Revenue from Materials	193.40	193.40
Total Treatment Balance	23.40	-56.60

The recycling costs in the EU are much higher than in North America where landfill costs are low and the disposal of PV modules in landfills is allowed. Also, the regulatory framework is different and there is a lack of industrial-size recycling facilities of PV modules. In Europe, PV recycling is mandatory, modules must not be landfilled (at least in most EU countries), and recycling is carried out in discrete batches in the industrial plants of laminated glass recyclers, metal recyclers, or WEEE recyclers.

Figure 12: Example of a test sequence to prepare for reuse of a module





“It can be expected that the recycling costs will come down with increasing waste streams and investments into large-scale recycling plants in North America.”

It can be expected that the recycling costs will come down with increasing waste streams and investments into large-scale recycling plants in North America.

5.0 Standards and Guidelines

5.1 Examples of Existing Documents

No standards on end-of-life PV modules were found for North America, though several related activities have been observed, such as growth forecast (SEIA [18]), surveys of policies (NREL [19]), decommissioning cost estimates (EPRI [21]), and standard on responsible recycling of electronic equipment (NSF [48]). Some state-led (in the US) and industry-led initiatives have been launched in order to develop concepts for PV waste management as discussed in Section 4.2.2. Currently, international and national industry standards exist that promote environmentally sustainable end-of-life management decisions. These voluntary standards, which are not exclusive to PV, provide guidelines for the PV industry that can develop a sustainable recycling and resource recovery of end-of-life PV modules and stewardship approaches. Documents relevant to PV recycling are as follows:

- EU Product Environmental Footprint Category Rules (PEFCR) [49];
- ANSI/NSF 457 Sustainability Leadership Standard for PV Modules [48];
- Responsible Recycling Standard (R2) [50];

- EN 50625 Standard Series on Collection, Logistics and Treatment Requirements for WEEE [7]; and
- Silicon Valley Toxics Coalition (SVTC) Solar Scorecard [51].

These are described in the following subsections.

5.1.1 EU Product Environmental Footprint Category Rules (PEFCR) [49]

In 2013 the European Commission implemented the “Single Market for Green Products Initiative” and established and recommended methods to measure the environmental performance throughout the life cycle that is the Product Environmental Footprint Category Rule (PEFCR) and the Organisation Environmental Footprint Sector Rule (OEFSR). The methods include communication principles like transparency, reliability, completeness, comparability, and clarity. The PEFCR for PV modules was published in 2019 [52] and major parts were implemented in NSF/ANSI 457 (section 2).

An extended life-cycle analysis shall cover the full life cycle of a product, including the mitigation potential of emissions by identified optimization measures related to PV electricity generation following the current PEFCR PV document. The life-cycle stages are included in a cradle-to-grave approach, which are the raw materials, transportation, production, distribution, use, and end-of-life. For PV systems, it includes the balance of system components, e.g., mounting structures and electrical cabling.

The use of a standardized methodology with high-quality data shall provide a comprehensive analysis with improved international comparability.

5.1.2 ANSI/NSF 457 Sustainability Leadership Standard for PV Modules

This standard provides sustainability performance criteria and corporate performance metrics in order to create high sustainability in the PV market. This includes a framework and standardized set of performance objectives for manufacturers and the supply chain in the design and manufacture of PV modules and PV inverter components. It helps to identify sustainable and environmentally friendly products by providing scalable criteria to measure their level of sustainability throughout the life cycle. The products are awarded points if they meet several requirements based on the following:

- Management of substances;
- Preferable materials use;
- Life-cycle assessment;
- Energy efficiency;
- Water use;
- Responsible end-of-life management and design for recycling;
- Product packing; and
- Corporate responsibility.

In the EU, in order to fulfill the requirements for management of substances, the manufacturer has to list all declarable substances in the product as well as all declarable substances that are used during the manufacturing process of the product according to the European Chemicals Agency (ECHA) database. The manufacturer is required to avoid or reduce gas emissions of gases with high global warming potential. The products also have to comply with the substance restriction requirements of the European Union RoHS Directive.

A declaration of recycled content in the product is required in order to promote recycled materials as preferable materials use. The manufacturer must commit

to conduct a life-cycle assessment in accordance with ISO 14040/14044 that includes all stages of the product life cycle from extraction of raw materials to the end-of-life and the quantifying of several impact indicators. The manufacturer shall identify the biggest environmental impact factor and reduce its contribution. The products are awarded additional points if they outperform according to the EU PEFCR [49] screening study results.

Implementation of the following are other examples of how additional points can be earned:

- An energy management system;
- A water management policy and inventory;
- Product take back services for recycling;
- Environmental, health, and safety management systems; and
- Conflict materials sourced only from validated conflict free smelters and participation in region conflict-free sourcing programs [48].

The complete list is provided in the standard.

5.1.3 Responsible Recycling Standard (R2)

The Responsible Recycling ("R2") Standard [50] is a comprehensive guideline for establishing the responsible recycling of electronics. Although voluntary, recycling companies should be certified by a third party so that the purchasers of the recycling services have a guarantee that the end-of-life of electric equipment is carried out in an environmentally responsible manner, preserving resources and protecting people (health and safety of workers and the public) and data throughout the entire reuse and recycling chain of used electronic products.

According to the R2 Standard, the following requirements must be met by electronic recyclers:

Implementation of an Environmental, Health and Safety Management System (EHSMS) in order to plan and control its environmental, health, and safety practices;

- Treatment of end-of-life equipment based on reuse and recovery as key for responsible management;

- Compliance with all applicable environmental, health and safety, and data security legal requirements as well as all applicable importing, transit, and exporting according to the country's laws;
- Where possible, repairing and refurbishing components;
- Before reuse, proper testing and packaging of components to ensure continued use;
- Documentation of the flow of equipment, components, and materials that accumulate at the facility in order to provide business data;
- Erasure of the data on all media that pass through the facility by using generally accepted data-destruction procedures;
- Appropriate storage of items and materials that can cause harm to the workers' health and safety or to the environment before reuse;
- Security measurements appropriate for the equipment handled and for the customers;
- Appropriate insurance to cover potential risks and liabilities associated with type and size of the facility's operation as well as potential closure of the facility;
- Transportation of all equipment, components, and materials that are under regulatory authorization in a protective manner to public health and the environment; and
- Maintenance of documentation in order to demonstrate conformance to the R2 Standard.

5.1.4 EN 50625 Standard Series on Collection, Logistics and Treatment Requirements for WEEE

In 2018, Europe enforced the EN 50625 Standard [7] that supports the requirements of Directive 2012/19/EU (WEEE) [30] for collection, logistics, and treatment of waste of electrical and electronic equipment. The standard concerns all operators handling, sorting, and storing WEEE until the end-of-waste status is fulfilled or the WEEE is prepared for reuse or is recycled, recovered, or disposed of.

The standard includes the following requirements:

- Implementation of a management system for all activities in the sphere of health, safety, environment, and quality, and continuous improvement of all activities;
- Implementation of a risk management process that includes hazard and risk assessment, elimination or reduction of the risk, documentation of the process, and identification of locations and activities that require the use of personal protective equipment;
- Informing staff members of the treatment facility about the environmental, health, and safety policies;
- Suitable infrastructure and technologies for all activities executed on the operator site;
- Recording of the origin of each consignment of WEEE accepted at the treatment facility as well the downstream treatment and fraction thereof until end-of-waste status is reached or until WEEE is prepared for reuse or is recycled, recovered, or disposed of;
- Handling WEEE in a way that no release of hazardous substances in to air, water or soil takes place;
- Destruction of confidential and personal data in the permanent memory of WEEE either by shredding or grinding, or by deleting through secure data erasure;
- Storage of the amount of WEEE at the treatment facility shall not exceed the annual processing capacity of WEEE;
- Ability of the treatment operator to identify hazardous WEEE items and to store these separately before proper treatment (hazardous waste shall be only treated by designated facilities);
- Use of appropriate methodology for depollution;
- Maintenance of documentation demonstrating compliance with legal and regulatory obligations and with the process diagrams.

After the WEEE treatment process, the resulting fractions can reach end-of-waste status or be further recycled, treated, or disposed of.

5.1.5 Silicon Valley Toxics Coalition (SVTC) Solar Scorecard

The SVTC Solar Scorecard [51] rates manufacturers on many aspects, including extended producer responsibility, emissions reporting, worker rights, health and safety, supply chains, module toxicity and materials, energy and greenhouse gas emissions, water and conflict minerals. The ratings provide purchasers with information on the sustainability, safety, and environmental health of products. For instance, PV manufacturers get points for extended producer responsibility by establishing fully funded collection and recycling for end-of-life PV modules. Further points can be earned by publicly describing on a manufacturer's website how the customer can responsibly return PV modules. The recycling has to take place at a facility with a documented environmental management system according to ISO 14001 and by offering environmental friendly design. Points (non-exhaustive) are awarded if the following criteria are met:

- Information about all categories of emissions like chemical and hazardous waste, air pollutants, ozone depleting substances, landfill disposal, and any sanctions related to non-compliance with environmental regulations is provided;
- Workers' rights, health, and safety beyond compliance with the local laws and regulations are protected and have the same commitment from their suppliers;
- Modules are produced free from toxic heavy metals or with concentrations below the regulations;
- The requirements for energy and greenhouse gas emissions are fulfilled;
- The volume of water use and the amount of generated wastewater according to several water quality indicators are reported.

5.2 Standardization Opportunities

Regulations about PV modules are not very developed in North America when compared with the standards in Europe. Examples of the few standards and guidelines that exist (as described in Section 5.1) are either general or not specific to PV recycling. Still, they provide a broad collection of best practices for a more sustainable and environmentally friendly PV industry, which can help

achieve a better quality of end-of-life modules and feedstock for recycling, and a more level playing field for all stakeholders. These best practices can be followed even if a legal framework for PV has not yet been established. However, the lack of laws and regulations to enforce the recycling and treatment of end-of life PV modules in North America have a negative effect on recycling. For instance, while some states in the US have requirements, PV modules can be easily transported to neighbouring states, where there are no special requirements for PV modules and they are landfilled instead of being recycled. The PV industry, the waste treatment industry, and governments and authorities have the opportunity to develop the policies and legal frameworks to improve the recycling of PV modules. This would create many new job opportunities in the sectors of installation, monitoring and maintenance, decommissioning, reuse, and recycling in the PV value stream.

There are many opportunities for standards as well. For instance, there are few procedures detailing how manufacturers must prepare samples to be analyzed in order to identify substances that are hazardous to human health and the environment and to detoxify the waste. An analysis is carried out by tests like TCLP and WET but interviewees have noted that the outcomes depend on the preparation of the test samples. As such, a detailed guideline on how to prepare samples to perform these leaching tests and to provide standardized results to classify end-of-life PV modules would be useful.

PV manufacturers develop their own products and practices and to date they have installed more than 50,000 different module types worldwide. The module designs are optimized for long product life cycles, high-power conversion efficiencies, and low production costs but rarely for recycling. The PV recycling industry would benefit from the development of a database of materials with standardized properties used in PV modules in order to determine the right course of action to detoxify the waste and determine the recycling process outputs. High-quality components and raw materials obtained from recycling can be reused in production.

In order to guarantee suitable recycling for end-of-life PV modules, a standardized approach for the calculation and risk assessment of decommissioning costs would

facilitate comparisons for authorities, investors, insurance companies, and banks and support better management.

The digitalization of plant planning, erecting, monitoring, and decommissioning with predictive maintenance tools and cost/benefit optimizations and full tracking of modules throughout the whole lifetime promise big business opportunities.

Renewable energy technologies shall implement modern approaches like Eco-Design, Product Environmental Footprint, and stewardship standards that include a sound circular economy strategy to save valuable resources and meet zero waste demands. These targets can be realized with a good eye on the growth and needs of the PV and waste industry in North America.

Eco-Design involves integrating environmental protection criteria over a product's life cycle. The main object is to anticipate and minimize negative environmental impacts, and at the same time keep a product's quality level according to its ideal usage.

The Product Environmental Footprint is a multi-criteria measure of the environmental performance of a good or service throughout its life cycle. It is a new method for measuring sustainability performance developed by the European Commission in cooperation with companies and sustainability experts. The aim is to improve the validity and comparability of the environmental performance evaluation compared to existing methods [39].

Proper international monitoring and harmonized datasets are required to track the renewable energy system transformation from cradle to grave and to provide reliable statistical data for not only governments and authorities but also for stakeholders of the value chain like manufacturers, installers, plant operators, repair and refurbishment, and waste collection and recycling. To ensure high-quality recycling, the use of the outputs and their quality should be included as well. A first approach has been made in Wagner et al. [6] but further standardization efforts in data collection are needed.

The examples just described here, along with a more comprehensive list of standardization opportunities, are identified in Table 9.

Early international harmonization of standards can help establish a level playing field with significant cost savings for global PV manufacturing, and support the application of a sound circular economic strategy.

6.0 Conclusions

The North American PV market is dominated by installations in the US, with Canada contributing less than 10%. Crystalline silicon modules with heterojunction cells, CdTe and CIGS modules are the preferred technologies to be installed in the coming years. Perovskite or organic modules are expected to cover niche applications only. The major applications are utility size PV power plants, large installations, and rooftop systems. Building-integrated PVs require building-specific designs and are used much less frequently.

According to the industry assessment survey results, early damage to several PV power plants and systems have been observed, but there is little statistical data available on this. A waste model is developed with an early and a regular loss scenario for US and Canada based on the model published by IEA and IRENA and IEA PVPS [1] using Weibull statistics.

Although there are not any specific PV regulations in North America, several working groups have been established for research funding programs, e.g., SEIA is in discussions with DOE. In the US several states have passed or are preparing regulations on managing PV waste.

For the most part, recycling takes place by the removal of cables and frames and the disposal of the rest of the module in landfills. In some cases, the glass is recycled but silicon, silver, and copper interconnectors are not being recycled. Therefore, more research and development as well as pilot projects are required to establish advanced recycling solutions and to retain value of the materials.

Standardization and international harmonization of standards and best practice guidelines will contribute to improving PV waste management and to saving costs.

Table 9: List of standardization opportunities identified

Issue		Opportunity
1	Lack of global approach to the PV industry	Global harmonization of standards for materials, product properties, documentation, packaging, collection, and treatment; this would be a huge benefit expected by producers, associations, and agencies
		Safety standard for packing, storage, logistics, and handling
		Eco-Design aspects
		Product Environmental Footprint
2	Repair and reuse of modules (product safety, warranties)	Standard for materials database
		Quality standard, measurement standard
3	There is no procedure on how to decommission PV power plants to ensure proper dismantling of PV modules for optimal reuse and recycling	Develop best practice guidelines/standards for the decommissioning of PV power plants
4	Lack of proper financial analysis practices on decommissioning	Standards for calculation and risk assessment of decommissioning costs, and revenues associated with sell or recycling of equipment
5	Recycling of modules	Collection and recycling standards (best available technologies)
		Takeback and treatment
6	Monitoring and statistics	Market data
		PV use, PV plants and maintenance, defect prediction and statistics
		PV decommissioning, collection, repair and reuse (used modules, non-waste)
		Modules put on market
		Modules installed
		Module damages
		Module repair and reuse (from waste collection)
		Shipments of used modules by destination (import, export)
		Module collection
		Recycling and recovery results, recycling quota, output material quality and quantity
		Waste incineration and landfill
		Use of output fractions
		Treatment quotas, yield, and quality data of output

Issue		Opportunity
7	Lack of skilled workers for the PV industry	Develop education programs for workers to become expert in monitoring, measurement, repair, reuse, decommissioning, waste treatment, end-of-waste documentation for PV industry
8	Standards for sampling, waste classification and eluate test	Standards for leaching tests (TCLP) with improved sampling and analytical technologies dedicated to PV products
9	Demands on collection points, proper operation	Standardized module and material database including valuable, critical, conflict and toxic materials
10	End-of-waste criteria	Harmonizing international activity

This can be established by better management of materials, product properties, documentation, packaging, collection, and treatment. Producers, associations, and agencies expect huge benefits from such initiatives. Adequate tracking of the renewable energy system transformation can develop sound cradle-to-grave or even cradle-to-cradle solutions and provide reliable statistical data for not only governments and authorities but also for stakeholders of the value chain, including manufacturers, installers, and plant operators, and repair and refurbishment, waste collection, and recycling plants.

The PV industry, the waste treatment industry, and governments and authorities should develop the necessary policies and legal frameworks together to tailor solutions for the development of the PV market and waste industry in North America. Environmentally friendly renewable energy technologies can utilize modern approaches like Eco-Design, Product Environmental Footprint, and stewardship standards that include a sound circular economy strategy to save valuable resources and meet zero waste demands as far as possible. First approaches have already been initiated in Europe and the US.

In summary, the following standardization opportunities are identified:

- Standardizing module and material databases that include valuable, critical, conflict, and toxic materials;
- Standards for calculation of decommissioning costs and revenues;

- Standards for sampling, waste classification, and eluate tests;
- Standardized data monitoring for:
 - Materials used in a module provided by international databases;
 - Modules put on market;
 - Modules installed;
 - Module damages;
 - Module repair and reuse;
 - Shipments of used modules by destination;
 - Module collection;
 - Recycling and recovery results, recycling quota, output material quality and quantity;
 - Waste incineration and landfill;
 - Use of output fractions.
- Demands on collection points, proper operation;
- Packing and transport;
- End-of-waste criteria; and
- Qualification for reuse.

Early development and international harmonization of standards can help establish a level playing field for global PV manufacturing and application, contribute to a sound circular economy, and reduce the distribution and administration costs.

7.0 Glossary

Amorphous silicon - A non-crystalline silicon formed by using silicon vapour which is quickly cooled.

Building-integrated photovoltaics - Building-integrated photovoltaics (BIPV) are photovoltaic materials that are used to replace conventional building materials in parts of the building envelope such as the roof, skylights, or facades.

Directive (EU) - A "directive" is a legislative act that sets out a goal that all EU countries must achieve. However, it is up to the individual countries to devise their own laws on how to reach these goals.

Eco-Design - The integration of environmental aspects into the product development process, by balancing ecological and economic requirements [80].

Electrical and electronic equipment - The term electrical and electronic equipment (EEE) is defined as equipment designed for use with a voltage rating not exceeding 1,000 volts (V) for alternating current and 1,500 V for direct current, or equipment dependent on electric currents or electromagnetic fields in order to work properly, or equipment for the generation of such currents, or equipment for the transfer of such currents, or equipment for the measurement of such currents.

Extended producer responsibility - Extended producer responsibility (EPR) is an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle. An EPR policy is characterized by (1) shifting responsibility (physically and/or economically; fully or partially) upstream towards the producers and away from governments, and (2) the provision of incentives to producers to take into account environmental considerations when designing their products.

I-V curve - An I-V curve (short for "current-voltage characteristic curve") is a graphical representation of the relationship between the voltage applied across PV modules and the current flowing through it shows the possible combinations of current and voltage output of a PV module.

Monocrystalline silicon - Silicon manufactured in such a way that it forms a continuous single crystal without grain boundaries.

Raw material - Basic material that has not been processed, or only minimally, and is used to produce goods, finished products, energy, or intermediate products which will be used to produce other goods.

Thin-film - Technology used to produce solar cells based on very thin layers of PV materials deposited over an inexpensive material (glass, stainless steel, plastic)

Watt peak (Wp) - Watt peak (Wp) stands for solar module peak power under full solar radiation (under set standard test conditions, solar radiation of 1,000 watts per square metre).

Weibull statistics - Weibull statistics is a method used to make predictions about the life of all products in a population by fitting a statistical distribution to life data from a representative sample of units. It can be used to estimate product life characteristics that include reliable or failure probabilities.

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Appendix A – Questionnaires

The questionnaires were intended to initiate the discussion and were complemented by additional questions that depended on the information provided during the interviews. Therefore, these were used as a guide through the interview process. The interviews were carried out within 30 to 60 minutes. The questionnaires varied according to the target group.

Financial Services:

1. Is a constant increase in solar energy production required to invest in production installation of a new photovoltaic power station?
2. Is data on use time and early losses relevant for investments?
3. Are you interested in the reuse of PV plants? What kind of reuse do you foresee/prefer?
4. Does an existing recycling economy increase the willingness for investments?
5. Are policies on feed in of solar electricity or recycling a driving factor? Do you have any ideas/wishes?
6. Which commitments from photovoltaic power station operators do you expect, e.g. maintenance?
7. Do you consider a technical or an economical life period of a photovoltaic as useful?
8. What should happen with a photovoltaic power station after shutdown? Who is liable for dismantling it?
9. Which developments in the recycling technology or policies do you expect?
10. Which standards should be introduced for photovoltaic recycling?

Additional Questions:

11. Which strengths do you expect from a PV plant? Which weaknesses do you fear?
12. Are innovations a driving factor for investments?
13. What is in your opinion a suitable PV plant to invest in?
14. Which rate of return is necessary in order for you to invest?
15. Is there a maximum amount you are willing to invest?
16. Is there a minimum plant size you would invest in?
17. Which developments in the PV market can slow down investments?

PV Plant Operators:

1. Do you think that the installed power will increase in Northern America in this way in the future?
2. Which situations could slow down this development, which ones could accelerate it?
3. Is there data available on use time, early and regular losses, damages and root causes?
4. Do you already use emerging technologies? Can you tell us something about funded research projects for this issue?
5. Do you invest in repowered plants? Which are the conditions for repowering a plant (modules, financing, replacement, disposing of waste modules)?

6. Are there value analyses of repair and reuse of waste PV modules?
7. How is decommissioning of plants actually done? Which plans or special requirements like mandatory takeback of components, e.g., wires, do you know?
8. Several standards and codes relevant to PV recycling exist or are upcoming. Do you think that there should be more regulation or requirements for PV module decommissioning and recycling? Which aspects should be addressed in your opinion? How do regulatory measures affect the market?
9. Would harmonized regulation or requirement be helpful? Which aspects should be addressed in your opinion? How can the collection of PV Modules be improved? What are the obstacles to an effective recycling of PV modules?
10. In the EU the 3R principle is used. That means reduce-reuse-recycle. The first step is to reduce either the amount or the hazard potential of waste. Next step is looking for a possibility to reuse the waste material in the same manner or in another way. After that the different recycling options has to be proved before a waste material has to be disposed. Could such a principle be used in Northern America in your opinion?

PV Recyclers:

1. What types of PV modules do you recycle? What is the average lifetime of the recycled modules?
2. How do you recycle PV modules? What are your outputs?
3. Should the design of PV modules and their input materials be improved for greater recyclability? How?
4. What can the following parties do to improve recycling:
 - a. Manufacturers? (What information do you need – from the manufacturer – to improve your recycling process?)
 - b. Consumers/operators?
 - c. Logistics?
 - d. Government?
5. What can recyclers do to improve the viability of recycling (networks, database)?
6. Should recycling be the responsibility of the manufacturer?
7. How do regulatory measures affect the market?
8. What are the obstacles to an effective recycling of PV modules?
9. How can the collection of PV modules be improved?
10. What are the biggest environmental issues in the recycling process? How can the environment be protected from harm during the recycling process?
11. How can the recycling process be made more profitable?
12. How can the recycling of PV modules in North America be improved?
13. What is the future of recycling PV modules: Specialized recycling technologies just for PV modules or existing recycling processes (e.g., e-waste)?
14. How can standards or guidelines improve the recycling or collection process?

Research Institutes:

1. Which technologies will dominate the market for the next ten years?
2. What is the composition of the modules?
3. Which environmental aspects have to be addressed?
4. Which materials should be replaced?
5. Which designs should be preferred?
6. How should the decommissioning, reverse logistics and treatment be organized?
7. Which technologies are needed?
8. What are your expectation to obtain sound results?
9. Which research opportunities result from this?
10. Which standards exist or should be developed to obtain the best possible results?

Associations and Organizations:

1. Do you think, that the installed power will augment in Northern America in this way in the future?
2. Which situations could slow down this development, which one could accelerate it?
3. Are there surveys and/or available data of use time, early and regular losses, damages and root causes?
4. Do you know other emerging technologies? Can you tell something about funded research projects for this issue, please?
5. Do you know about repowered plants? Which are the conditions for repowering a plant (modules, financing, replacement, disposing of waste modules, ...)?
6. Are there value analyses of repair and reuse of waste PV modules?
7. Which licence does a company have to apply, if it would like to build up a plant? Does the company need to have plans for the day after the plant will be decommissioned?
8. What' about the financing or funding of a plant, either new or repowered? Do decommissioning costs play a role in it?
9. How will the decommissioning of plants actually be done? Which plans or special requirements like mandatory takeback of components (e.g., wires) are you aware of?
10. Several standards and codes relevant to PV recycling exist or are upcoming. Do you think that there should be more regulations or requirements for PV module decommissioning and recycling? Which aspects should be addressed in your opinion?
11. Would harmonized regulations or requirements be helpful? Which aspects should be addressed in your opinion?
12. In the EU the 3R principle is used. That means reduce-reuse-recycle. The first step is to reduce either the amount or the hazard potential of waste. The next step is looking for a possibility to reuse the waste material in the same manner or in another way. After that the different recycling options have to be proved before the waste material is disposed of. Could such a principle be used in Northern America in your opinion?

Appendix B – Description of Weibull Waste Model Parameters

Table B.1: PV module loss model methodology for step 1 and steps 2a and 2b

Model	Data input and references
Step 1: Conversion of capacity to PV module mass (from gigawatts to metric tonnes)	
<ul style="list-style-type: none"> The model's exponential regression function converts gigawatts of PV capacity to metric tonnes of module mass For each year, the annual conversion factor is calculated 	<ul style="list-style-type: none"> Standard module 1990-2013 data sheets [53] are used to extract supporting data for the exponential fit. Typical module data were used in five-year periods from the biggest producers (Arco Solar, BP Solar, Kyocera, Shell Solar, Sharp, Siemens Solar, Solarex, Solarworld, Trina and Yingli). Standard module data are predicted using the 2019 International Technology Roadmap for Photovoltaic (ITRPV) as a baseline [5] as well as other literature [11], [54]–[58].
Step 2a: Probability of PV module losses	
<ul style="list-style-type: none"> Infant failure Midlife failure Wear-out failure 	<ul style="list-style-type: none"> Assumptions on early losses were based on reports by TÜV, Dupont, SGS, and others [59]–[62].
Step 2b: Scenarios for annual waste stream estimation (regular-loss and early-loss scenarios)	
<p>Regular-loss scenario input assumptions:</p> <ul style="list-style-type: none"> 30-year average module lifetime 99.99% probability of loss after 40 years Extraction of Weibull model parameters from literature data ($\alpha = 5.3759$) [63] <p>Early-loss scenario input assumptions:</p> <ul style="list-style-type: none"> 30-year average module lifetime 99.99% probability of loss after 40 years Inclusion of supporting points for calculating non-linear regression: <ul style="list-style-type: none"> Installation/transport damages: 0.5% Within first 2 years: 0.5% After 10 years: 2% After 15 years: 4% Calculation of Weibull parameters ($\alpha = 2.4928$) 	<ul style="list-style-type: none"> The 30-year average module lifetime assumption was taken from literature [64]. A 99.99% probability of loss was assumed as an approximation to 100% for numerical reasons using the Weibull function. The 40-year technical lifetime assumption is based on depreciation times and durability data from the construction industry [65]. The early-loss input assumptions were derived from different literature sources [59]–[62]. Weibull shape factors reported in literature [63], [66]–[68].

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

