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International Energy Agency
Photovoltaic Power Systems Programme

Task 12 PV Sustainability Activities

PVPS

Status of PV Module Take-Back and Recycling in Germany 2024

Report IEA-PVPS T12-27:2024

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The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme comprises 6,000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (PVPS) is a TCP within the IEA; it was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." To achieve this, the programme's participants have undertaken a variety of joint research projects in photovoltaic (PV) power systems applications. The overall programme is headed by an executive committee, comprising one delegate from each country or organization member, which designates distinct tasks, which may be research projects or activity areas.

The 25 IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance, the Solar Energy Industries Association, the Solar Energy Research Institute of Singapore and Enercity SA are also members.

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What is IEA PVPS Task 12?

Task 12 aims to foster the international collaboration in safety and sustainability that are crucial for ensuring that PV integration increases to levels high enough to make it a major contribution to the energy needs and emissions reductions of the member countries and the world. The overall objectives of Task 12 are to (1) quantify the environmental profile of PV compared to other energy technologies, (2) investigate end-of-life management options for PV systems as deployment increases and older systems are decommissioned, and (3) define and address environmental health and safety and other sustainability issues that are important for market growth. The first objective of this task is well served by life cycle assessments that describe the energy, material, and emissions flows in all stages of the life of PV. The second objective is addressed through the analysis of including recycling and other circular economy pathways. For the third objective, Task 12 develops methods to quantify risks and opportunities on topics of stakeholder interest.

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COVER PICTURE

Pretreated PV modules at recycling plant; Michael Held, Fraunhofer IBP, Germany, 2013

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Federal Ministry
for Economic Affairs
and Climate Action

LIST OF ABBREVIATIONS

2N	material purity of 99%
5N	material purity of 99.999%
Ag	silver
Al	aluminium
B2B	business to business
B2C	business to consumer
BMUV	Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (German: Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz)
Cd	cadmium
CdTe	cadmium telluride
CIGS	copper indium gallium selenide
CIS	copper indium selenide
c-Si	crystalline silicon
Cu	copper
DUH	Environmental Action Germany (German: Deutsche Umwelthilfe; nongovernmental organization for environmental and consumer protection)
EAR	German WEEE register (German: Stiftung Elektro-Altgeräte-Register)
EBA	certified treatment facilities (German: Erstbehandlungsanlage)
EEE	electrical and electronic equipment
EEG	Renewable Energy Sources Act (German: Erneuerbare Energien Gesetz)
ElSi	Industrial Scale Recovery and Reuse of all Materials from EOL Si-based Photovoltaic Modules
ElektroG	Electrical and Electronic Equipment Act (German: Elektro-Gesetz; implementation of the WEEE directive into national law)
EOL	end of life
EVA	ethyl vinyl acetate
Fe	iron
GWp	gigawatt peak
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISE	Institute for Solar Energy Systems
kg	kilogram
KrWG	Circular Economy Act (German: Kreislaufwirtschaftsgesetz)

kWp	kilowatt peak
LAGA	German task force of the environmental ministers to ensure the best possible harmonization of waste legislation across the federal states (German: Bund/Länder-Arbeitsgemeinschaft Abfall)
mg	milligram
mm	millimetres
OECD	Organisation for Economic Co-operation and Development
örE	public waste management authority (German: Öffentlich-rechtlicher Entsorgungsträger)
PV	photovoltaic
PVPS	Photovoltaic Power Systems Programme
Se	selenium
Si	silicon
t	tons
TCP	Technology Collaboration Programme
UBA	Federal Environment Agency (German: Umweltbundesamt)
WEEE	Waste Electrical and Electronic Equipment

EXECUTIVE SUMMARY

Photovoltaics (PV) is one of the key technologies needed for transforming Germany's energy system and meeting the targets of a low-carbon electricity generation system. Germany is one of the top five countries in terms of installed PV capacity, together with China, the United States of America, Japan, and India [1]. According to an estimate from Fraunhofer Institute for Solar Energy Systems (ISE), approximately 67 GWp of cumulative PV power were installed in Germany by the end of 2020 [2]. Further, with the update to Germany's Renewable Energy Sources Act [3] in 2023, the PV expansion targets were significantly increased to the cumulative installed PV power of 215 GWp in 2030 and 400 GWp in 2040. During this period, the first larger PV plants will also reach the end of their life (EOL) and will need to be gradually replaced. Because Germany was the first country to install large numbers of PV modules, it will be the first country that will need to handle large numbers of EOL modules. The current returns of EOL PV modules are still comparably low in number but will start to significantly increase by the end of the decade. The 2016 study of the International Renewable Energy Agency and the International Energy Agency Photovoltaic Power Systems Programme Task 12 on the EOL management of PV panels estimated that the waste streams in Germany for 2030 will range from 400,000 to 1,000,000 tons and estimated that the expected waste volume will significantly increase in the following years [4]. With regard to PV as part of a sustainable energy system, it is necessary to provide appropriate treatment and recycling processes for returned PV waste streams to ensure the circularity of used materials. Additionally, the recycling capacities need to be expanded to meet future demand. Further, professional coordination and infrastructure for the take-back and collection of PV module waste are required to ensure that EOL modules are treated via the intended recycling routes.

The main intention of this report is to provide insights into the current situation of PV EOL management in Germany, both its structure and the current practical experience of the stakeholders involved in the take-back and recycling system. For this purpose, two workshops were held in 2021 and 2022 with experts from both industry and research representing stakeholders along the entire treatment chain of EOL PV modules. The workshop covered the whole EOL process chain of module treatment—from collection and take-back coordination to the initial treatment and recycling of recovered materials. On this basis, this report discusses the problems, challenges, and identified necessary measures for improving the current waste management system.

This report is divided into two parts. The first part gives a short introduction on the main legal framework of the European Waste Electrical and Electronic Equipment (WEEE) directive [5] and Germany's implementation into law with the Electrical and Electronic Equipment Act (ElektroG) [6]. Further, it provides a brief introduction to the recorded statistics of PV module waste volume prepared for the reporting of collection and recycling rates to the European Commission. The second part describes the current situation of established recycling infrastructure and take-back coordination and discusses identified challenges and problems in the present system according to the practical experiences of the stakeholders involved in the take-back and recycling system.

In short, the discussions at the expert workshops on the current situation of Germany's take-back system and the recycling infrastructure indicate that Germany, as a pioneer in PV expansion and one of the first countries to be confronted with larger volumes of waste PV modules, has already introduced a number of measures to ensure the proper collection and recycling of PV modules. Yet, improvement potential was identified along the whole treatment chain of PV modules to be well prepared to enhance take-back and recycling with regards to the strongly increasing future EOL module flows. The practical experience and lessons learned will in turn generate valuable information for other countries to prepare for large volume flows of EOL PV-modules and to enable targeted measures for the successful implementation into the end-of-life management and recycling of PV modules.

The main indicated improvement potentials of the current take-back and recycling system in Germany are described as follows.

Regarding the significantly increasing PV module waste volume in the near future, an urgent need to expand recycling capacities was identified. Even though there have been several development activities in the past concerning the recycling of PV modules, most have not made it into commercial application at the industrial scale—mainly because of currently low volumes of processed EOL modules. Today, PV recycling plants with large recycling capacities in Germany are operated by Reiling [7] (silicon-based modules) and First Solar [8] (cadmium telluride thin-film modules) using mechanical or, in the case of First Solar, combined mechanical and wet chemical treatment. These processes are comparably easy to scale, easy to operate, and independent from PV module dimensions. The main challenges of these processes, however, are that glass cullet currently fails the quality requirement to be recycled for high-quality applications; hence, they are used for foam glass products or other applications with lower quality requirements. In terms of silicon module recycling, not all valuable material fractions (e.g., silicon) can be economically recycled with current processing. In the First Solar process, approximately 90% of the semiconductor material is recovered and can be recycled in a quality to produce new modules, but also with this processing, cullet from front and back glass are mixed and cannot be recycled for high-quality glass products.

Currently, there are also no commercial- or industrial-scale operating recycling plants for other module types; however, there are some promising approaches that are close to implementation or have taken an important step toward commercial applications using alternative technologies. These technologies enhance the recycling rate of valuable materials from different module types and allow for mobile operation, e.g., based on processes using high-energy light-impulses [9] to separate material composites.

The stakeholder convened in the workshops currently have the opinion that German's current take-back system is very complex: The take-back coordination applied to PV modules differs for business-to-business (B2B) or business-to-consumer (B2C) use. This leads to higher administrative expenses for the stakeholders involved in the collection and take-back. Further, the need was expressed for better communication of the responsibilities and obligations of manufacturers, distributors, and stakeholders along the take-back and recycling system. One major problem for the take-back coordination is the missing or insufficient sorting of the modules at the public collection points, which leads to the permanent redirection of PV modules to suitable initial treatment plants; thus, a high share of the recycling costs is related to avoidable transport [10]. This could be overcome if the personnel at the public collection points and initial treatment facilities could be properly trained to sort, and if the modules could be labeled with the correct module type at the module manufacturer sites.

Other challenges identified by the stakeholders include the improper handling, storage, and transport of EOL modules, which leads to high breakage rates. Because every EOL module should have been tested in functionality for reuse, there are still higher shares of functional modules that are destroyed during handling and must be recycled. Additionally, broken modules are sometimes harder to recycle, depending on the kind of recycling process, and they carry risk for human health and the environment. Training personnel who handle and prepare modules for transport could solve these problems, too.

In addition, workshop attendees expressed the need to better inform private end users about the obligation to return old modules to the public collection points instead of storing them in barns, etc. Currently, workshop attendees felt that EOL modules owned by consumers are not being sent to recycling because take-back is not free of charge if a consumer owns more than 20-30 modules. The total number of modules that can be returned free of charge is depending on the collection provider. Waste module volume could be increased for B2C modules if this restriction were removed.

Further, workshop attendees see the need that the monitoring and tracking of PV module waste streams must be improved, especially with a view toward the expected increasing waste volume in the near future. During the workshops, attendees notes that the current reported volumes from the official reporting system and statistics have been found to be significantly less than the expected waste volumes, and it can be assumed that higher volumes are disposed apart from the take-back system, e.g., as illegal exports or via alternative storage or disposal routes. Thus, the complete monitoring and tracking of PV waste streams along the whole EOL process chain—from the collection of PV modules to the final treatment of the recovered materials—could be necessary to ensure transparency and to gain a better understanding of the EOL system.

It is noted that the identified challenges and improvement measures of the coordination of the take-back system are based on discussions that were conducted in expert workshops between 2021 and 2022 on the practical experiences of the involved stakeholders; hence, no practical experiences on the impact of the most recent updates, e.g., ElektroG3 (2022), were available.

Taken together, this report provides an in-depth analysis and stakeholder-experiences of the current system for end-of-life treatment of PV modules in Germany. It is important to analyze the situation in Germany because it is the first country to support widespread adoption of PV modules, and therefore is expected to be the first to experience larger EOL volumes. While specific to an analysis of the situation in Germany, this report is hoped to offer useful lessons for other countries in advance of their own expected rise in EOL volumes.

1 INTRODUCTION

Electricity generation from photovoltaic (PV) technologies is a key component in the transformation of Germany's energy system to achieve the targeted climate goals. Together with China, the United States, Japan, and India, Germany is among the top five countries in terms of total installed PV capacity [1]. Germany had its first PV installation boom from 2007–2013. Although the growth in PV installations flattened in the following years, the installed PV capacity significantly increased again in 2018. According to estimates from Fraunhofer ISE [2], approximately 7.2 GWp of PV power was installed in 2022, leading to a total installed PV capacity in Germany of approximately 67 GWp, which is distributed among more than 2 million PV power plants.

The recent update of the Renewable Energy Sources Act (Erneuerbare Energien Gesetz [EEG]) [3], which took effect on January 1, 2023, targets an expansion of installed PV capacity to 215 GWp in 2030 and 400 GWp in 2040. To reach these goals, annual additions of net PV capacity up to 22 GWp/year are expected in the next few years.

Figure 1 presents the development of installed PV capacity from 2010 and the projected annual additions as recommended by EEG 2023 to reach the targeted cumulative PV capacities in 2030 and 2040.

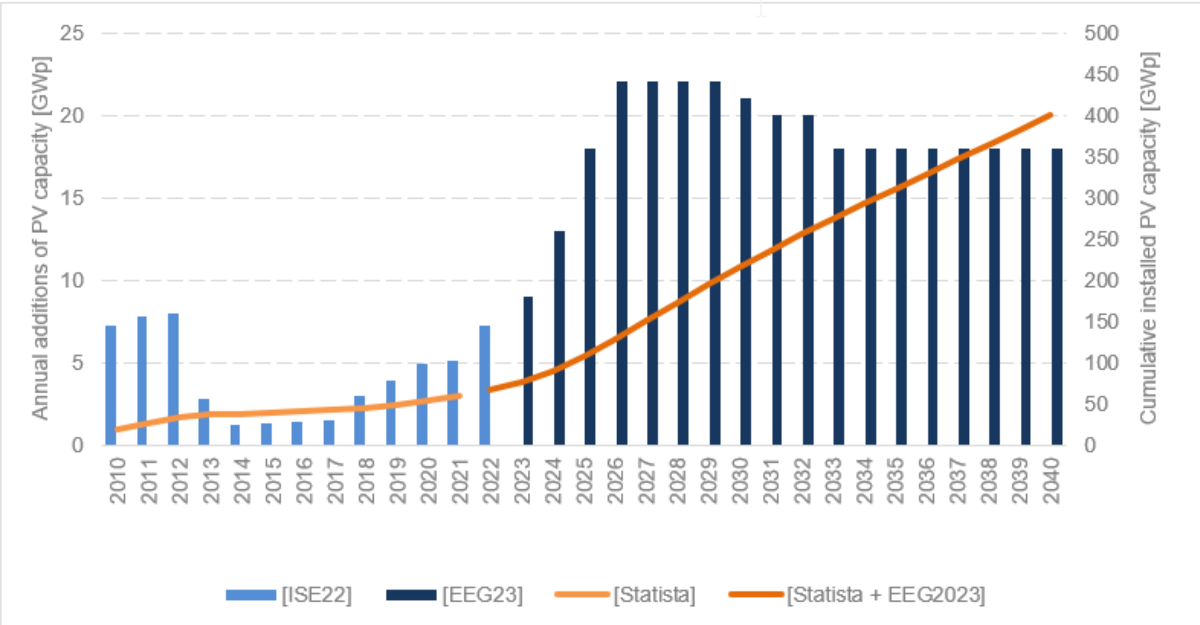

Figure 1. Development of annual additions and cumulative PV capacity in Germany according to Fraunhofer ISE [2], EEG [3], Statista [11]

Also during this period, the first large PV systems will reach their end of life (EOL), and they will need to be gradually replaced. The expected lifetime of PV modules is approximately 20–30 years, so the current volume of EOL PV modules is still comparably low, but it will start to significantly increase as a result of the installation boom in 2007.

In 2016, the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS) Task 12 published development scenarios on future PV waste streams on a global level and for countries and regions with relevant installed PV capacities [4]. Figure 2 presents the estimates for PV waste streams in Germany for the years from 2016–2050. The authors included two scenarios to represent PV waste development in cases of regular losses and early losses of PV modules. The development paths of PV waste were calculated using Weibull distributions from historical data on early failure modes of PV modules. Based on these data, future development trends of PV waste quantities were determined.

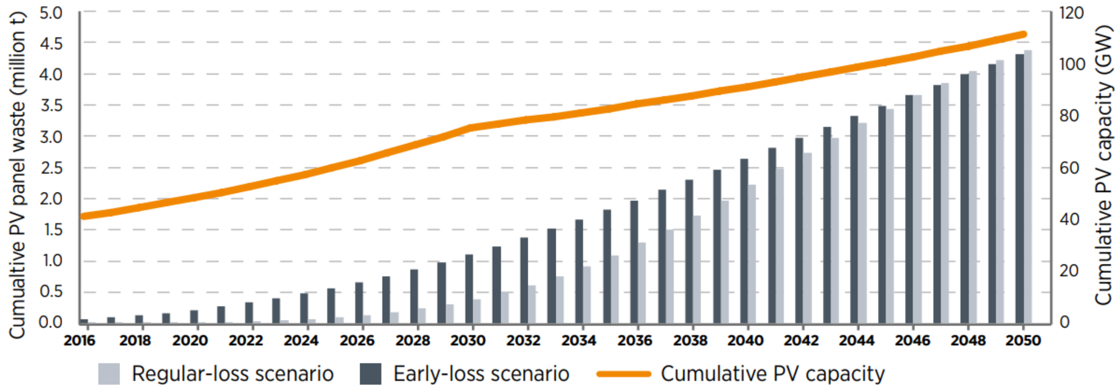

Figure 2. Estimated cumulative PV waste volume in Germany according to the 2016 IRENA and IEA Task 12 report [4]

Figure 2 shows that a significant increase in PV module waste volume is expected in the coming years. Further, it shows the high uncertainty of PV module waste quantities for the period from 2023–2040. For instance, in 2030, between 400,000 tons (regular loss scenario) and 1 million tons (early loss scenario) of PV panel waste are expected. Both scenarios converge to approximately 4.3 million tons of PV waste in 2050.

In addition, Figure 3 presents a comparison of PV waste volume for the years 2016–2020 in Germany based on the actual recorded volume (Eurostat) [12] and installed cumulative PV capacity (Statista) [11]. The official reported collected waste volume in Germany from 2016–2020 totals 42,300 tons, which is about twice the estimated volume of the IRENA regular loss scenario (20,000 tons) but still considerably less than the estimate for the early loss scenario (200,000 tons) (compare to Figure 2). Even in the regular loss scenario, however, waste volume will increase twentyfold by 2030, and it will continue to exponentially increase from there.

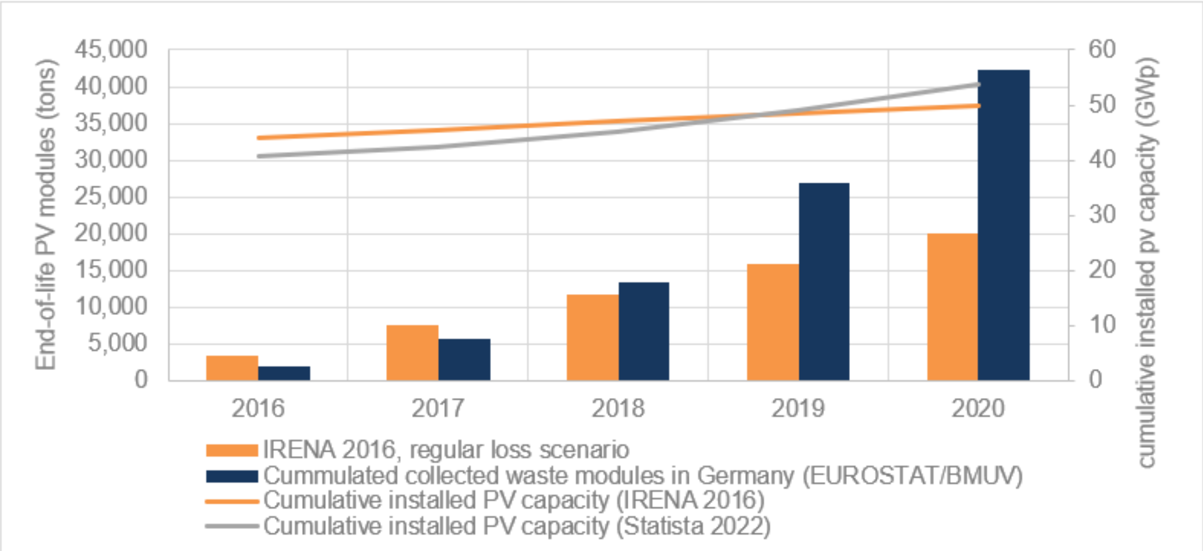

Figure 3. Comparison of estimated PV waste volume to the IRENA regular loss scenario with recorded waste volume in Germany for the years 2016–2020 [4], [11], [12]

Further, a comparison of the cumulative PV capacity of the IRENA study to the current development targets for Germany of the recent EEG (2023) of 400 GWp in 2040 [3] (Figure 1) shows that a significant increase in PV power plants must be expected for the future; hence, the waste stream from EOL PV modules will also accordingly increase in the mid and long term.

With regard to PV as part of a sustainable energy system, it is necessary to provide suitable treatment and recycling processes for returned PV waste streams and to expand the recycling capacities to meet future demand. Because PV modules are made from valuable materials, which differ in their material systems depending on the PV technology used, suitable recovery and recycling are important to ensure the long-term supply of the required resources and raw materials in the sense of a circular economy. With the increasing complexity of the material systems of future PV technologies and module designs, suitable recycling and recovery of rare materials will become more important.

This makes it important to establish a working take-back and recycling system for PV module waste. The system must provide the necessary recycling capacities and treatment processes at an early stage, and it should be expandable according to expected waste module streams.

In view of the current situation of the waste management system and recycling infrastructure in Germany, there is still a high demand for the implementation of industrial-scale PV recycling plants but also for plants that reliably treat the diverse materials from different PV technologies and recover valuable materials to produce new modules or other high-value products. In addition to the technological and infrastructural challenges, it must be ensured that PV module waste is collected via a take-back and recycling system that enables the tracking of waste streams from return and collection to the end of the process. Further, clear processes and responsibilities in the coordination of the recycling system across all treatment stages are of great importance to ensure that modules are collected via the designated collection and recycling channels.

1.1 Goal of This Report

The main intentions of this report are to provide insights into the current situation and framework of the EOL management of PV modules in Germany and to provide an assessment based on the current practical experiences of the stakeholders involved in the take-back and recycling system. For this purpose, two workshops were held in 2021 and 2022 with approximately 20–25 experts per workshop from 26 different institutions.

The goal of the workshops was to present and discuss the current situation and challenges of the EOL management of PV modules in Germany covering the different perspectives of the involved stakeholders. Potential solutions and optimization measures were discussed based on the stakeholders' experience with the systems and the associated regulations. In addition, the workshops provided a platform for networking and strengthening the exchange of information among the stakeholders.

The participants included stakeholders along the full treatment chain of EOL PV modules—from production, collection, and take-back coordination to the initial treatment and recycling of recovered materials. The stakeholders contributed knowledge and experience from the following areas (acknowledging that some experts fit into more than one area):

- Research and consulting (4)
- PV module manufacturing (4)
- Development of recycling processes of PV modules (5)
- Take-back coordination (2)
- Recycle yard operators (1)
- PV module recycling (4)
- Material recycling (3)
- Policy, Waste Electrical and Electronic Equipment (WEEE) registration, and project funding (3).

The first part of this report gives a brief introduction on the main legal framework and recorded statistics for the take-back and recycling of PV module waste in Germany. The second part describes the current situation of the established recycling infrastructure and take-back coordination, and it discusses the challenges and problems of the current EOL management system in Germany according to the experiences of involved stakeholders. Further, potential measures for improving the system are discussed.

2 LEGAL FRAMEWORK AND REGISTRATION OF END-OF LIFE PV FLOWS IN GERMANY

This chapter gives a brief introduction of the framework of the WEEE directive and Germany's implementation into law with the Electrical and Electronic Equipment Act (ElektroG). Further, this chapter briefly discusses the requirements and hierarchies of waste flows according to Germany's Circular Economy Act (Act to Promote Circular Economy and Safeguard the Environmentally Compatible Management of Waste, Kreislaufwirtschaftsgesetz [KrWG]).

2.1 Legal Framework for Take-Back and Recycling of PV Modules

In Europe, PV modules that reach their EOL are classified as electrical and electronic waste. The take-back and treatment of EOL PV module waste in Europe is covered by the legal framework of the WEEE directive [5].

The first version of the WEEE directive, enacted in 2002, did not include PV waste; this was added in an updated version in 2012, 2012/19/EU [5]. The deadline for transposition into national legislation was 2014, but it wasn't until the beginning of 2016 when every member state implemented it into national law; therefore, statistical data specifically on PV module waste streams are available only from the year 2016 on (see Section 2.6).

The requirements of the WEEE directive are implemented into Germany's legislation by ElektroG [6]. The first version of ElektroG was enacted on March 15, 2005, with a major update (ElektroG2) on October 24, 2015, which became obligatory for manufacturers to follow on February 1, 2016. With this update to ElektroG, electrical and electronic equipment manufacturers must take more responsibility throughout the life cycle of their products.

The recovery and recycling rates of WEEE were adopted by ElektroG. For PV modules, the minimum recovery rate is 85%. In this context, the recovery rate includes the preparation for reuse and refurbishment, the recycling of material, and the energy recovery from thermal treatment, e.g., waste incineration. The recycling rate for PV module waste is 80% of mass. These minimum quotas—the 85% recovery rate and the 80% recycling rate of PV mass—are applied as target quotas for Germany.

Since the implementation of the revised WEEE directive into national law, all manufacturers or authorized representatives that place PV modules on the German market must register the modules with the German WEEE register, Stiftung Elektro-Altgeräte-Register (EAR) [13]. Stiftung EAR, as a joint body of manufacturers, has been assigned sovereign tasks by the Federal Environment Agency (Umweltbundesamt [UBA]) to ensure the implementation of ElektroG. According to ElektroG, manufacturers of PV modules bear responsibility for the products they place on the market, i.e., the manufacturers are responsible for the products' return, logistics, sorting, dismantling, recovery, and recycling. To this end, the manufacturers must provide financial guarantees. Stiftung EAR records the quantities placed on the market and coordinates the provision of waste containers at public locations of the waste management authorities (öffentlich-rechtliche Entsorgungsträger örE) [13].

In Germany, PV modules are classified as business-to-consumer (B2C), dual-use products. Depending on their application—either commercial (business-to-business [B2B]) or private (B2C) use—different regulations apply for the collection and take-back of PV modules.

In Germany, PV modules are classified as Collection Group 6, "photovoltaic modules," and they are assigned to either WEEE Category 4 ("large equipment": any external dimension more than 50 cm) or Category 5 ("small equipment": no external dimension more than 50 cm), depending on their size. The local authorities are responsible for sorting the waste equipment into containers for the respective groups. Small PV modules that are embedded in electronic products, such as calculators, belong to the respective collection groups of the main product.

PV modules from private households can be handed in free of charge at collection points of municipal waste management authorities or points registered by Stiftung EAR. In Germany, however, these are limited to typical quantities that are customary for households, which is defined by the German task force of environmental ministers to ensure the best possible harmonization of waste legislation across the federal states (Bund/Länder-Arbeitsgemeinschaft Abfall [LAGA]) for a maximum of 20–50 modules [14]. The collection and further treatment of residential volumes are coordinated by the public legal waste management authorities. The collection of larger quantities is organized by the manufacturers, which can commission haulers to collect the EOL modules directly from the end user and transport them to the appropriate treatment facilities.

2.2 Relevant Stakeholders of Take-Back Logistics and Their Authorizations and Obligations Under ElektroG

Public waste management authorities, distributors, manufacturers, and authorized representatives of the manufacturers are entitled to collect and take back WEEE, according to ElektroG, including PV modules, and third parties can also participate in the collection process; however, commercial collection without a commission from the authorized players is not permitted. A distinction is made between B2C PV modules (PV modules from private households—the PV modules originate from private households and are present in household quantities) and B2B PV modules (PV modules from commercial use—the PV modules do not originate from private households and are present in larger quantities). PV modules that can be used in residential and commercial applications are referred to as B2C modules. PV modules that are for commercial use only, and for which the manufacturer can demonstrate that they are not usually used in residential applications, are referred to as B2B modules [6].

The public waste management authorities have an obligation to take back PV modules from "private households." For this purpose, they must set up municipal collection points, called bring systems. Currently, approximately 1,700 collection points exist in Germany [15], which can be supplemented by collection systems. The PV modules can come either directly from the end user or from a distributor that has set up collection points. Distributors that have a sales area or, in the case of mail-order companies, a storage area of at least 400 m^2 for electrical and electronic equipment are obliged to take back old electrical or electronic equipment when selling a similar one.

Distributors that are not obliged to do so may carry out the take-back on a voluntary basis. WEEE must be collected in containers that are separated into six collection groups, of which Collection Group 6 includes PV modules [14].

Manufacturers whose PV modules are distributed in Germany are responsible for taking back and disposing of their PV modules. Manufacturers that do not have a branch in Germany must appoint an authorized representative to fulfill this obligation; otherwise, their PV modules may not be distributed. The manufacturers must set up collection containers at the transfer points of the local authorities. Once the collection containers are full, the manufacturers must transport the container to certified primary treatment facilities (Erstbehandlungsanlage [EBA]), where either the contents are prepared for reuse, or a depollution and separation of recyclable materials is carried out. To perform this step, manufacturers can contract with third parties, such as private logistics or waste management companies. Manufacturers can set up an individual take-back system or join a collective take-back system, such as PV Cycle. A manufacturer can also set up private collection points [16].

For primary treatment, the preparation for reuse has priority over the depollution and separation of recyclables. For this initial treatment, the facilities must be certified, and the corresponding treatment processes may only be carried out in these facilities. PV modules must be sorted for further treatment into silicon (Si)-based and non-Si-based PV modules (Figure 4). After sorting, the PV waste must be transported to the correct recycling plant. WEEE volume that is delivered to the initial treatment plants must, if economically reasonable and technically feasible, be tested to determine whether it is suitable for reuse and, if so, must be sent to an appropriate treatment facility. In an initial treatment, pollutants (e.g., lead or cadmium [Cd]) or valuable materials (e.g., aluminium [Al] or copper [Cu]) must be separated if technical feasible before the modules are shredded for recycling. Si-based and non-Si-based modules must be treated separately. The Al frames and Cu-containing cables are removed during an initial treatment. Regarding pollutants in recovered materials, in Si-based modules, the limit value for lead is 100 mg/kg, and the limit value for selenium (Se) and Cd is 1 mg/kg. For non-Si-based modules, the limit value for lead is 10 mg/kg (except semiconductor material), and the limit value for Se and Cd is 1 mg/kg [17]. The initial treatment can be carried out in several stages in different plants. Further treatment of the recovered materials, after the initial treatment and after pollution removal, are carried out in secondary treatment plants [14].

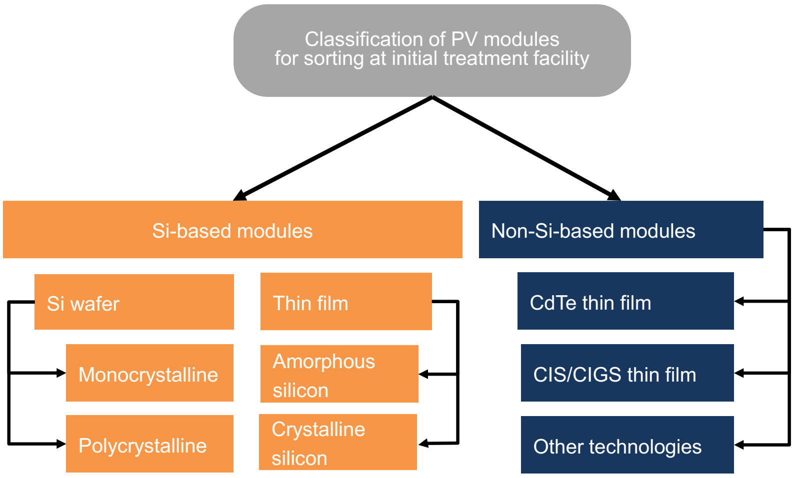

Figure 4. Classification of PV modules for sorting at initial treatment facilities [14], [18]

The public authorities, manufacturers, and distributors of PV modules and the operators of the initial treatment facilities have obligations to provide information, notification, and reporting, as well as verification and registration. The most important obligations are summarized as follows:

- Module manufacturers must provide treatment facilities free of charge with information on the treatment of their products, including hazardous substances contained therein.
- All participants involved in the take-back of WEEE have reporting obligations to Stiftung EAR. They must report the quantities of electrical and electronic equipment that are placed on the market, collected, recovered, or disposed according to the collection group and category.
- Module manufacturers, distributors, and operators of collection points and initial treatment facilities are listed in registers of Stiftung EAR.
- The transport of WEEE from the collection point to the initial treatment facilities and recycling sites require accompanying documentation.
- WEEE volume or associated parts leaving the initial treatment plant are considered hazardous waste, so verification obligations must be fulfilled in accordance with the Circular Economy Act (KrWG [19]) for their transport to waste treatment facilities [14].

Financing System of Take-Back Logistics and Recycling

In Germany, there are two mechanisms for financing the take-back and recycling of PV modules: (1) In the B2C mechanism, PV modules are sold directly to private households or users with similar requirements. (2) In the B2B mechanism, product responsibility is transferred to the end owner of the PV modules for commercial use [4], [6].

In the B2C mechanism, there are two levels of financing: Level 1 and Level 2. Level 1 covers collection operations and direct collection and recycling costs. Costs for legacy EOL PV modules, i.e., EOL modules from manufacturers that no longer exist, are included here. Level 2 ensures funding for the collection and recycling of future waste. When a manufacturer registers with Stiftung EAR, it assumes the Level 1 costs according to its current market share, and it declares covering the Level 2 costs of its products placed on the market. Manufacturers can operate their own take-back and recycling system or join a cooperative. Among these cooperatives, PV Cycle [16] and take-e-way [20] are the most relevant associations. If a manufacturer leaves the market, other manufacturers must take over its market share [4].

In the B2B mechanism, manufacturers or authorized representatives must take over the costs for the take-back and recycling of modules that were placed on the market after October 24, 2015. In the case of legacy modules, end users are responsible for the take-back and recycling costs. The B2B mechanism applies to operators of solar parks [4], [6].

Recent Updates of the ElektroG3

The latest update to ElektroG, ElektroG3, took effect on January 1, 2022. Despite the previous updates, this revision was not based on new WEEE requirements but on a national revision. Among other points, ElektroG3 provides stronger liability for online markets. These updates should ensure that online vendors have authorized representatives and are registered with Stiftung EAR, and hence they are responsible for the consequential obligations for financing, take-back, and recycling. Online vendors and fulfilment service providers are committed to regularly reviewing that their offered products are registered and comply with the current regulation. In addition, from January 2023 on, online traders from other countries must designate an authorized representative for the German market, and they must register with Stiftung EAR. Further, traders are committed to informing users and customers about the options of free returns of WEEE, and they must ensure that the return collection points are located within a reasonable distance to end users [21].

Further, the initial treatment facilities (EBA) can now also be collection points, thus extending the availability of return points for private end users. A new uniform logo should give WEEE collection points better visibility. As part of the initial registration, manufacturers of B2B products must present a take-back and recycling concept to Stiftung EAR. These concepts must be reviewed and accepted by the manufacturers [21].

ElektroG3 also sets new take-back obligations in commerce, such as the possibility for end users to return WEEE to grocery stores that sell electronic products; and even occasionally for stores within an 800-m^2 sales area, which were previously exempt from the 400-m^2 rule, to allow the free return of up to three old appliances to the store, even if no new goods are purchased, or obligations for free-of-charge take-back in online trade [21].

Further updates to ElektroG3 are related to providing better information and communication to customers and end users on the return options, the use of hazardous substances (e.g., in light bulbs), and the chemical systems of used batteries in products. Batteries in products must be removable with standard tools without damaging the product, and information must be provided for this purpose [21].

2.3 Germany’s Circular Economy Act (KrWG)

In addition to ElektroG, the Circular Economy Act (KrWG) [19]) provides a legal framework for the treatment, recovery, and disposal of waste. The Circular Economy Act took effect on June 1, 2012, and it implemented the requirements of the European Union Waste Framework Directive (2008/98/EC) into national law. According to paragraph §1 of the KrWG, “the purpose of this Act is to promote circular economy in order to conserve natural resources and to ensure the protection of human health and the environment in the generation and management of waste” [19].

The KrWG regulates the point at which products receive a waste status (§3) and the point at which the status is revoked (end of waste status) (§5). According to paragraph §5 of the KrWG, the waste status of a product or substance ends when it has been treated in a suitable recovery process; there is a use, demand, or market for the substance; and certain technical and legal requirements are met. In addition, the use of the substance must be harmless.

In paragraph §6, the KrWG defines a five-level waste hierarchy that follows the basic principle of recovery before recycling and determines the order of waste management measures (see Figure 5).

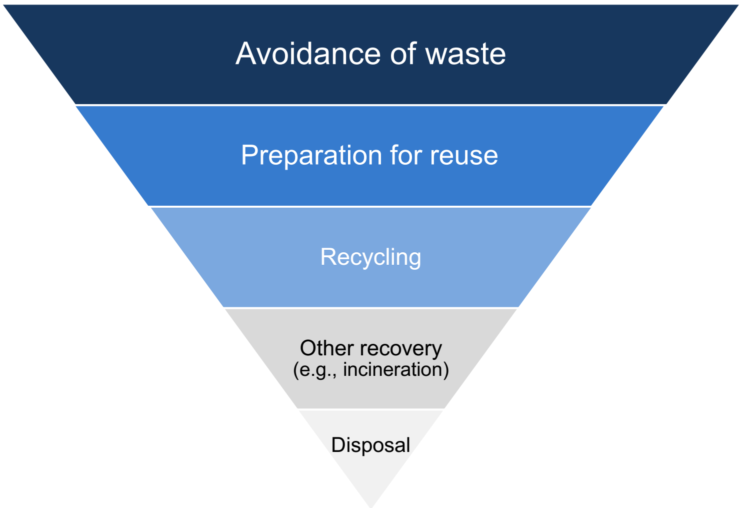

Figure 5. Waste hierarchy of the Circular Economy Act [19]

For PV module owners, there are legal obligations for both the disposal and the sale of used modules, which are briefly outlined next.

Disposal of PV Modules

According to the Circular Economy Act (KrWG), a product receives a waste status from the moment the product is no longer used and the owner wishes to dispose of it or when a product is no longer used for its originally intended purpose. The waste status ends when a product has completed the designated recovery or recycling process.

Owners must ensure compliance with all waste regulations that are required to dispose of waste. The return and disposal of PV modules is carried out in accordance with the regulations for PV modules in ElektroG. In paragraphs §20 and §21 of ElektroG, the basic principle of recovery before recycling (KrWG paragraph §7) applies. Accordingly, reuse and recycling have priority over waste disposal. To ensure this, nondestructive dismantling and transport of the modules is mandatory. Upon receipt of the EOL modules at the primary treatment facility, the modules must first be tested for reuse. If the tested modules are suitable for reuse, they must be marketed under the requirements of ElektroG paragraph §23 (certificate of origin, test certificate, appropriate packaging). If the test determines that the modules are not suitable for reuse, they must be sent for recycling, material recovery, and/or waste disposal via the designated disposal system. The waste hierarchy shown in Figure 5 also applies here.

In case PV owners want to sell used modules via a secondary market, PV modules continue to be treated as a product. Prior to the sale, the owners must ensure that the modules are still functional for their originally intended use. Also, in this case, modules must be dismantled, transported, and tested in a nondestructive manner before they are supplied to a secondary market. Further, the obligations to provide evidence according to paragraph §23 of ElektroG apply.

An overview of testing facilities for old modules is given in Section 3.1.2.

2.4 Monitoring and Statistics on the Provision of Evidence in ElektroG

Manufacturers and authorized representatives that place PV modules on the German market must register with Stiftung EAR (WEEE register) and report the monthly quantities of PV modules sold as well as the EOL modules that will be disposed via the take-back system.

On this basis, Stiftung EAR compiles the annual statistics for WEEE, and they are also reported to the European Commission to demonstrate compliance with the specified collection and recovery targets, which are accessible via the statistical database Eurostat [12].

Stiftung EAR publishes the statistics once per year. Manufacturers and authorized representatives must report the annual statistics of the previous year (reporting year) to Stiftung EAR by April 30. The data are evaluated by independent experts and forwarded to the German Federal Environment Agency (UBA). If necessary, the data are further processed before they are forwarded to the European Commission.

All manufacturers and authorized representatives that were registered in the reporting year are obliged to report.

With the reporting obligation to Stiftung EAR, the following quantities are queried [13]:

Input quantities:

- **Products put on the market:** Total amount of PV modules that were put on the German market in the reporting year.

Output quantities:

- **PV modules prepared for reuse:** Includes PV modules that were initially reported as waste but after testing are prepared to be reused for their originally designated use without further pretreatment
- **Recycled PV modules:** Represents the share of PV modules or fractions from EOL treatment from which materials or substances have been used for the manufacture of new PV modules or another purpose. Here, the summarized weight of EOL modules along the treatment chain is decisive. All quantities of modules recycled in Germany, within the European Union, and outside the European Union are reportable, provided they were recycled according to European standards.
- **Recovered PV modules:** Describes the proportion of PV modules or fractions from treatment that are prepared for reuse, recycled, and/or sent for other recovery. Here, too, the quantity includes the modules recycled in Germany, within the European Union, and outside the European Union, provided compliance with the European standards. The evaluation quantity is the weight that is fed into the last plant in the treatment chain and whose output is the successful preparation, recycling, or recovery of the device or the recovered materials.
- **Disposed PV modules:** Includes the share of PV modules or fractions from the treatment that were not fed into any of the previously mentioned types of use or recovery but were disposed of as waste—for example, landfilled or disposed of via waste incineration plants. Here, too, the quantity includes the modules disposed of in Germany, within the European Union, and outside the European Union.
- **PV modules exported for treatment:** Total quantity of PV modules exported for treatment. The decisive factor is in which country the first treatment step of depollution, separation of recyclables, or preparation for reuse was carried out. If the initial treatment was subcontracted, the metric is counted as an initial treatment in the corresponding state only if it included the first treatment step.

In addition, the query of the input/output volumes at the initial treatment points as well as the allocation of the type of take-back via the disposal system are carried out, the modules are subdivided into B2C modules via public waste management authority (Öffentlich-rechtlicher Entsorgungsträger [örE]) and B2B modules, and the modules are organized via the manufacturer's own take-back and collection coordination program.

2.5 Registered Manufacturers at Stiftung EAR

In January 2023, 336 different manufacturers and authorized representatives were registered via Stiftung EAR. The list can be accessed via the Stiftung EAR website [22]. The following registrations were made for PV modules in different categories:

- 297 registrations for PV modules in Category 5, "large devices over 50 cm"
- 72 registrations for PV modules in Category 4 "small devices less 50 cm"

- 71 registrations for PV modules that can be used in private households
- 1 registration for PV modules with exclusive use in something other than private households.

Twenty-five of the registrations are companies registered as agents for 77 manufacturers/distributors of PV modules.

2.6 Annual Statistics and Reported Quantities to the European Commission

PV modules have been listed in the ElektroG statistics as separate subgroups in Category 4 (large appliances), Category 5 (small appliances), and Collection Group 6 since 2016.

The annual statistics of Stiftung EAR provide information on the input [23] and output [24] quantities of B2B and B2C modules as well as on the collection routes of EOL PV modules. The statistics include information on the quantities of manufacturers and distributors; on the take-back quantities of modules via collection coordination, the manufacturers' own take-back programs, WEEE accepted at initial treatment facilities, and WEEE modules collected via public waste management authorities. This information, however, is currently only available in aggregated form for categories 1–6, so a specific evaluation of PV modules is not possible.

Table 1 shows the current annual statistics for the reporting year 2021. According to the Stiftung EAR statistics, a total of 442,531.283 tons of PV modules were placed on the German market in 2021, and 4,676 tons of EOL modules were collected via the designated take-back routes through the disposal system. It is noticeable that, according to these statistics, only a small portion (1,256 tons) was taken back via collection coordination.

Table 1. Input/Output Flows of PV Modules of the Stiftung EAR Annual Statistics for the Reporting Years 2016–2021 (the authors' compilation based on [23], [24], rounded values)

Year	Input Quantities (Metric Tons)				Output Quantities (Metric Tons)			
	Category 4		Category 5	Categories 4 and 5	Collection Group 6			
	PV modules that can be used in private households	Big PV modules, can be used in private households	Small PV modules, can be used in private house-holds.	Total	Output (take-back coordination)	Output (volun-tary own take-back)	Output (public waste ma-nage-ment authori-ties)	Total
2016	106 894.64	-	-	106 894.64	144	621	-	765
2017	155 539.26	-	-	155 539.26	367	186	-	553
2018	-	210 528.62	0.01	210 528.64	598	922	-	1 520
2019	-	272 421.73	37.27	272 459.32	882	773	-	1 655
2020	-	320 433.73	82.26	320 515.97	980	919	-	1 899
2021	-	442 441.44	89.84	442 531.28	1 256	3 420	-	4 676

The structure of the data prepared by the Federal Environment Agency (UBA) differs from the annual statistics of Stiftung EAR in the reporting of the output flows: The Stiftung EAR statistics record the collection quantities via the various collection routes, whereas the Federal Environment Agency (UBA) provides information on the collection quantities, recovery, and disposal routes of EOL PV modules because they must be reported to the European Commission for verification purposes.

The input quantities of PV modules during the reporting years of the statistics can also slightly differ. One difference results from the fact that detailed statistics of the import quantities of PV modules in the Federal Environment Agency (UBA) are only available for Category 4 (large appliances). Older appliances in Category 5 (small appliances) are not further subdivided, so a separate list of PV modules in this category is not possible.

Table 2 shows the processed figures of the Federal Environment Agency (UBA)/Federal Ministry for the Environment, Nature Conservation, Nuclear Safety, and Consumer Protection (Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz [BMUV]) for the reporting years 2016–2020. The values for the reporting years 2016–2018 can also be found in the Eurostat statistics [12].

Table 2. UBA/BMUV Statistics of the Input/Output Quantities of PV Modules (the authors' compilation based on [12], [25]–[30])

PV Module (Category 4b) (Metric Tons)	2016	2017	2018	2019	2020
Input					
Products put on the market	106,895	155,539	211,142	272,422	320,434
Waste collected	2,032 *(9,167[a])*	3,595	7,865	13,362	15,396
Waste collected from households	2,032 *(9,167[a])*	1,000	2,259	2,603	4,445
Waste collected from other sources	0	2,595	5,606	10,758	10,951
Output					
Waste treatment (only in Eurostat)	2,032	3,595	7,865		
Waste treated in the member state	1,970 (9,105[a])	3,568	7,865	13,362[c]	15,396[c]
Waste treated in another member state	60 (61[a])	26	0	-[c]	-[c]
Waste treated outside the European Union	2	1	0	-[c]	-[c]
Recovery	1,914	3,560	7,708	13,154	15,240
Recycling and preparation for reuse	1,723	3,385	6,896	11,953	14,155
Preparation for reuse	436	270	909	N/A[b]	N/A[b]
Recycling (not in Eurostat)	-	-	-	11,953	14,155

[a] The 2016 values were corrected in Eurostat in the following year; hence, they differ from the initial report of the BMUV numbers. [b] Values are not listed because they are subject to statistical confidentiality and can be traced to individual reporters. [c] Statistical confidentiality applies if the statistics can be attributed to a reporting party. In this case, the quantities are considered in the data point "WEEE treated in the member state."

Note that the originally reported value in the UBA/BMUV statistics on collection quantities and recovery routes of a total of 9,167[a] tons in 2016 was corrected in subsequent years in the Eurostat database to 2,032 tons.

In addition, the values of the output quantities "preparation for reuse" in the reporting years 2019 and 2020 are not listed because as these are subject to statistical confidentiality and can be traced to individual reporters.[b] These quantities are included in the data point "recycling."

For the data points "WEEE treated in another member state" and "WEEE treated outside the European Union," statistical confidentiality applies if the statistics can be attributed to a reporting party. In this case, the quantities are considered in the data point "WEEE treated in the member state".[c]

2.7 Summary of Main Findings of the DUH White Paper on PV Sector Circularity in Germany

In March 2021, the nongovernmental organization Environmental Action Germany (Deutsche Umwelthilfe [DUH]) published a white paper addressing the challenges and opportunities for improving the circularity in the PV sector in Germany [31]. This white paper is based on expert interviews and stakeholder surveys. The white paper summarizes and discusses the main challenges and opportunities for strengthening the circular economy of PV along its life cycle—from product design; to market placement; to the collection, repair, and reuse; to the recycling of PV modules at their EOL.

To this end, DUH defines the main targets for improving the circular economy of PV modules [31] as follows:

- Waste prevention: PV modules have comparably long lifetimes, from 20–30 years; hence, appropriate use and maintenance is necessary.
- Preparation for reuse: In case of early exchanges of intact modules, e.g., for repowering PV plants, the repair or the reuse of intact modules must be ensured.
- Recycling: Broken or unfunctional modules must be recycled by modern, advanced processing to recover rare materials and to avoid contaminations of pollutant substances.

The white paper highlights the need for improvements to the current collection of used PV modules and PV module waste with regard to the collection process but also in terms of transparency and economic aspects. Due to improper treatment, the repair and reuse of used modules is not always ensured. Further, improper collection might lead to the disposal of modules. Also, there is the need for better communication and information to the relevant stakeholders as well as the public regarding the collection and take-back processes and responsibilities in the recycling and disposal of used PV modules or PV module waste. In this regard, public collection systems must be improved to ease the return of PV module waste for private users, e.g., when returning larger amounts of modules. An additional challenge for B2B modules describes the extended producer responsibility of ElektroG that requires PV module manufacturers to provide possibilities to return and recycle used modules that were placed on the market after October 24, 2015. On one hand, it must be ensured that all producers comply with these requirements; on the other hand, under currents conditions, the collection and recycling costs are expensive. Currently, there is no similar regulation addressing modules that have been placed on the market before October 24, 2015; hence, the cost for collection and recycling were not included in the pricing of modules sold before that date, and owners could incur return fees. As a result, owners might try to find more cost-effective solutions to dispose of used modules, so there is a higher risk that these modules are not placed in the proper recycling systems.

The white paper also states that the amount of collected modules as reported to WEEE of the European Union is still low compared to the expected volume of used and waste modules, but it is not clear whether the lifetime of the modules is higher than expected or whether used modules bypassed the collection system, e.g., by being resold on secondhand markets or illegally exported. This shows the need for increased transparency of the disposal of used and waste PV modules. If PV modules have left the German market and been sent to countries with less developed waste collection or waste management systems, there is a risk that PV waste modules are not being properly recycled or disposed; thus, there is a need to enhance the possibilities for the repair and reuse of used PV modules while also stopping illegal exports to improve circularity.

Further, the white paper states that valuable materials are often downcycled for other applications or get lost because of the complexities of PV recycling, so there is a high potential to develop better technical solutions for better recycling (e.g., for glass and Si recycling); however, investments in recycling require security, which will be improved with increased volume streams of used or PV module waste. Specific recycling requirements could also provide incentives for introducing better suitable technologies. Finally, better repairability and recyclability of modules must be implemented in product development, which could be enhanced by eco-design regulations. With this in regard, improvements of future PV modules must include recycling-oriented module design and avoid/reduce the use of pollutants.

3 EVALUATION OF THE CURRENT SITUATION OF PV TAKE-BACK AND RECYCLING IN GERMANY

This chapter describes the evaluation of the current situation of PV module take-back and recycling in Germany. The evaluation is based on the observed problems and challenges from the experiences of experts from research and industry that were discussed during two recycling workshops. The workshops were held in 2021 and 2022 with approximately 20–25 experts per workshop from 26 institutions. The participants were stakeholders along the full treatment chain of EOL PV modules—from production, collection, and take-back coordination to the initial treatment and recycling of recovered materials. Then the chapter discusses the stakeholder-identified needs for actions and measures to improve the current system considering the expected increase in PV module waste volume during the coming years.

3.1 PV Recycling Plants and Technologies

3.1.1 Active Recycling Plants and Applied Process Schemes

In recent years, several companies and research projects have developed PV module recycling processes and operated them in pilot demonstration plants. PV module recycling processes are based on mechanical, wet chemical, thermal, and optical mechanisms, or combinations of these. Most pilot recycling plants, however, have not made it to commercial implementation on an industrial scale or have been discontinued after a short time. One main reason has been the comparably low and unstable mass flow of EOL PV modules, which makes the operation of the recycling plants financially difficult.

Currently in Germany, the recycling of Si-based modules uses schemes that are partially adapted from other industries, mainly based on mechanical process schemes from flat glass recycling. These mechanical process schemes can differ in individual process sequences and in the applied process steps, but they share a principal sequence, as shown in Figure 6. First, EOL PV modules undergo a pretreatment in which the frames, cable, and junction boxes are removed. Subsequently, the EOL PV modules are shredded in single- or multistage processes, for example, by using shredders or hammer mills. In the next steps, material fractions are separated. Ferrous metals are collected by magnetic separators, and nonferrous metals are collected by eddy-current separators. The shredded material is then screened. Depending on the adapted process sequence, this is done before or after the metal separation. In this process, the larger polymer film pieces are separated from the glass fragments, whereas the solar cell fragments remain mostly stuck to the films. Further, manual separation by handpicking can be included between the process steps to remove impurities and contaminants. In addition, multistage screening is possible. The separation of the polymer fraction can be supplemented by suction. The recovered glass fraction can be further purified by optical color sorters. For further reading, we recommend the following reports by PVPS Task 12: [32], [33], [34], [35].

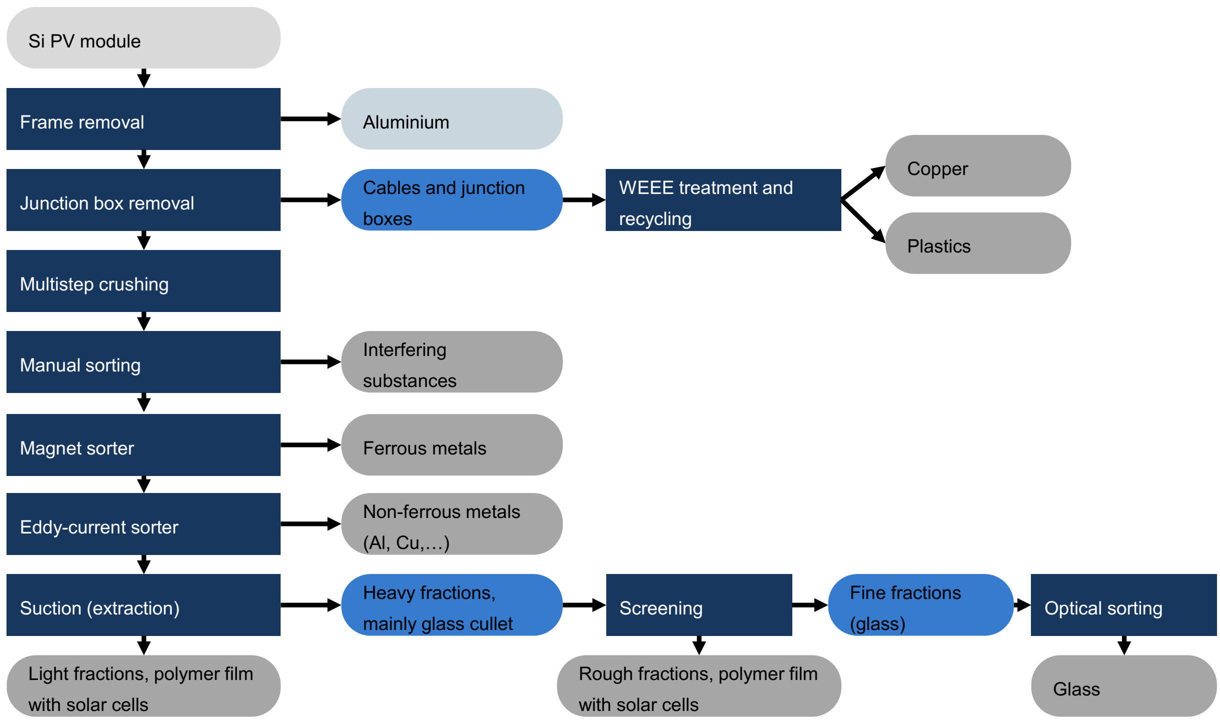

Figure 6. Diagram of the general process for recycling c-Si modules based on flat glass recycling (based on [32], [33], [40])

The Reiling company group is the most relevant player for the treatment and recycling of Si-based PV modules in Germany. Reiling operates 19 recycling sites internationally, with a focus on flat glass and container glass recycling, polyethylene terephthalate plastics, wood, and PV modules.

PV modules are recycled at three recycling sites in Germany—Sülzetal (Osterweddingen), Marienfeld, and Torgau—which currently have a total PV module recycling capacity of approximately 10,000 tons/year [36], [37]. Reiling estimates that currently approximately 6,000 tons of PV modules are recycled per year at these recycling sites [37].

Furthermore, in June 2023, Reiling started operating a recycling plant that exclusively recycles Si-based modules. The recycling plant is located at the competence center of PV module recycling in Münster. The Münster recycling site is intended to process the majority of the crystalline silicon (c-Si) PV modules [37] and should recycle more than 10,000 tons/year [36]. In contrast to the recycling sites in Sülzetal, Marienfeld, and Torgau, where PV modules are processed in batches, the recycling plant in Münster will be operated by continuous processing and is designed for recycling capacities of up to 50,000 tons/year to treat increasing EOL PV module volumes in the future [38], [39]

For the recycling plants in Sülzetal, Marienfeld and Torgau, Reiling uses a process scheme similar to that as described in Figure 6, which is divided into three main process steps: the initial treatment, in which modules are prepared for reuse or modules containing hazardous substances are sorted out; the shredding or crushing of the modules to open the glass laminate; followed by different fractioning and sorting steps to separate interfering materials from the glass cullet. The fractioning and separation processes are based on physical principles, like magnet and eddy-current separators, wind sifter, optical separation and induction sorters.

The main advantages of this mechanical process scheme for Si PV module recycling are that they can be applied independently from module size, type, or design. Further, these processes are robust and proven in industrial-scale applications and can be easily scaled to EOL PV module streams. This type of process, however, also faces some challenges. Currently, the quality of the recovered glass cullet does not fit the requirements for recycling in flat glass or container glass products. In particular, the residual shares of nonferrous metals, an elementary Si, are problematic for high-quality glass recycling; hence, only downcycling into alternative glass products with lower-quality requirements is possible, e.g., for foam glass. Another challenge is that there are still valuable material fractions that cannot be economically recycled with the current process, e.g., the recovered composites of lamination foil and the Si itself [18].

The research project ReModul [41], a cooperation between Reiling and the Fraunhofer Center for Silicon Photovoltaics, demonstrated the technical feasibility of separating the inorganic materials—such as silver (Ag), Si, lead, and Cu—with high purity. Passivated emitter and rear contact cells from 100% recycled Si from mechanical treatment were manufactured, and demonstrator modules were made. The recycling of Si, however, is still at a low technology readiness level [6].

To make the recycling of PV materials worthwhile in the future, the volume of PV module waste must increase, which is expected soon, as shown in Figure 2, and the recycling cost must be reduced while the value of the recovered materials is increased. Today's process development of module recycling is strongly focused on the economic efficiency of the processes. One way to make recycling more affordable is to incentivize new module designs (design-for-recycling approaches). For example, the disposal fee could be more closely linked to material recovery, or the recycling quota requirements could also be based on the material value or the carbon dioxide footprint of the recycling process [6].

For non-Si-based thin-film modules, the only existing commercial/industrial-scale recycling plant in Germany is First Solar's recycling plant in Frankfurt Oder, which specializes in recycling cadmium telluride (CdTe). Other First Solar recycling plants are in Ohio (USA), Vietnam, and Malaysia [8]. First Solar's Germany recycling plant has been operating since 2010, with a recycling capacity of 10,000 tons/year, and it recycles CdTe modules from other European countries too. Approximately 95% of the recycled modules are First Solar modules. With the current annual mass streams of waste modules, the recycling process is not economic. The main reason is the high share of transport costs, which account for at least 30% of the recycling costs. With volumes increasing to approximately 100,000 tons/year, which are expected for the years 2028–2030 for European PV module waste streams, the German recycling plant could be economically operated [42]. In this case, scaling the recycling capacity could be achieved by simultaneously operating several recycling lines. The Frankfurt Oder recycling plant has space for 10 or more recycling lines.

The process scheme of the Frankfurt Oder plant represents the first generation of First Solar's recycling process and is based on a combined mechanical and wet chemical process. The newer generations of the recycling process follow the same principles but have been optimized regarding the transport of glass cullet and in chemicals during the wet chemical process steps. The most recent generations of the recycling process are operated at the CdTe production site in Vietnam and Malaysia. Figure 7 presents a simplified flowchart of the Frankfurt Oder recycling process. First, the modules are crushed to a size of approximately 5 mm in a two-stage crushing step using a shredder and a hammer mill. This generates a large edge area for the succeeding etch process, which breaks the composite of the lamination foil (ethyl vinyl acetate [EVA]) and glass and dissolves the semiconductor material. Dust is extracted via a ventilation system equipped with a high-efficiency particle filter. The CdTe semiconductor layer is dissolved in a mixture of sulfuric acid and hydrogen peroxide. The recycling plant in Frankfurt Oder uses a screw dehydrator for transporting the glass cullet through the chemicals. In the next step, the liquid, loaded with Cd and tellurium, is separated from the solid. With the newer generations, this step has been replaced by a batch process in which the glass is fixed, and the liquids are moved through the material. The remaining solid fraction is separated in a classifier and a vibrating screen. In this process, the EVA flakes are enriched in the coarse fraction and the glass pieces in the fine fraction. In the glass and EVA fraction, residual process medium is washed off with water. Cd and tellurium are precipitated from the acid by raising the pH value and filtering. Cd and tellurium are concentrated in a filter cake. This is passed to specialized smelters, such as 5N Plus [43] in Eisenhüttenstadt, where it can be further processed into starting materials for semiconductors. With this process, more than 90% of the semiconductor materials are recycled and are used for the CdTe module production [42].

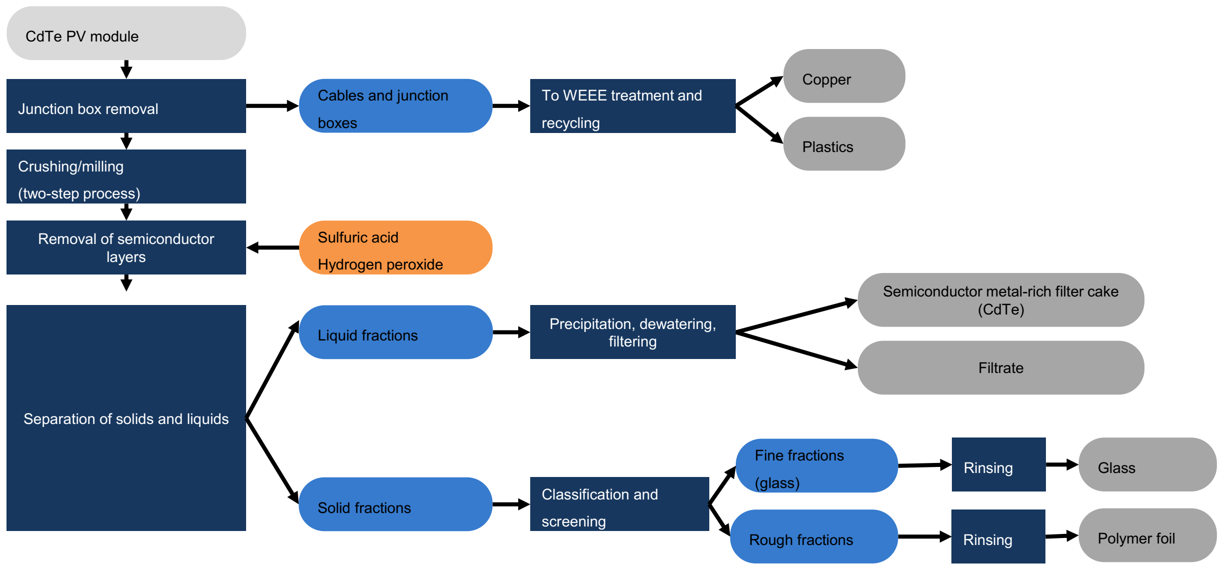

Figure 7. Diagram of First Solar's recycling process of CdTe modules (based on [42], [33], [32])

To reduce the freshwater demand of the recycling process, the Frankfurt Oder recycling plant runs a closed-water circuit; hence, only losses from water evaporation must be replaced.

Currently, the recovered glass cullet can be used for other glass products with lower-quality requirements, such as foam glass. The CdTe modules use different types of glass for the front and back sides of the module (flat glass and solar glass), which would require a separation step to achieve the quality of flat glass recycling. This is not possible with the current process scheme because the cullet is mixed during the processing.

In Europe, recovered plastic foil is put to incineration/thermal treatment. In Malaysia, approaches for further use of waste foils for rubber soles are developed.

3.1.2 Other Activities and Process Developments

In addition to First Solar's currently operating PV module recycling plant, there are further developments and activities that have the potential to extend the available recycling technologies and infrastructure in Germany.

In 2018, Suez GmBH [44], together with Geltz-Umwelttechnologie [45], started operating a recycling plant in Knittlingen, southern Germany, for Si-based PV modules. The processing was developed and tested in the European research project ElSi [46] (Industrial Scale Recovery and Reuse of all Materials from EOL Si-based Photovoltaic Modules) together with Fraunhofer IGB. The developed process scheme is a combination of mechanical, thermal, and electrolytic processes. Pyrolysis (700°C) is used to break down the glass/polymer foil composite. The target of this recycling scheme was to recycle a minimum of 95% of all PV module materials. After separating the frames, cable, and junction boxes, the modules are shredded, followed by a pyrolytic process step to remove the foil. An electrochemical process is used to separate Si, Cu, and Ag from the glass. Elsi's [46] [47] initial goal of the recycling plant in Knittlingen was to recycle 1,000 tons/year of waste modules [45]; however, the plant stopped operating in 2020–2021, when Suez sold the division of waste management to PreZero [48].

LuxChemtech [49] develops and tests recycling processes for PV by using a combined chemical-physical processing. Within the European Union-funded research project Photorama [50], LuxChemtech, together with other partners, is developing a pilot line for recycling PV from dismantling and delamination to metal recovery on an industrial environment. The pilot line includes a three-steps process to manage the c-Si-based waste stream and a two-step process to manage the thin-film CIGS waste stream, which allows for recycling valuable materials—Ag, Si (and indium for heterojunction technology), and gallium [51], [52].

Further, the companies ImpulsTec [53] and FLAXRES [9], [54], [55] are developing alternative processes for breaking up the material composites of PV modules based on physical treatment. The approach of ImpulsTec uses shock wave fragmentation technology (electrohydraulic fragmentation), whereas FLAXRES uses high-intensity light pulse technology [56].

Both technologies show high potential for improving the recycling of various PV technologies because they can be used universally, independent of module type and size.

The ImpulsTec process includes a mechanical pretreatment for crushing the PV modules, followed by the contact-free shock wave processing to separate the front glass, Si, and back foil or lamination foil. Currently, recovery rates of 7 mass-% of EVA, approximately 3 mass-% of Si, and approximately 1 mass-% of Cu are achieved. Based on this processing, 75–200 kg of PV modules can be treated per hour [56].

No mechanical pretreatment is applied for the FLAXRES process. The module layers are separated using high-intensity light pulses. Because the modules are not crushed, the glass panes remain in one piece, and the front and back glass can be collected separately, which enhances the potential for recycling higher-quality glass products; hence, materials can be collected and sorted by type after the separation step. After lifting one glass layer, the semiconductor layer can be withdrawn by suction from the glass underneath. The polymer fraction is also a pure fraction and can undergo recycling for plastics. During a mass test with 7.5 tons of PV modules in the pilot production equipment FLAXTHOR, more than 200 kg of Si, 4 kg of Ag, as well as 4.9 tons of glass of the highest quality were recovered [57]. Currently, the light-impulse process consumes less than 1 kWh of electrical energy per module to break it down into its major components [57]. The recycling plant is designed to fit into a cargo container. In case of successful commercial implementation, this could be an important complement to stationary recycling plants because the initial treatment could take place directly at the power plants. This would save transport costs for take-back and collection because the recovered materials could be directly forwarded to the respective recycling companies.

The FLAXRES process is currently being tested together with Veolia, ROSI Solar, Evonik, and other partners[1] in the European Union, and it is funded by the EIT Raw Materials project ReProSolar [55], [58].

According to FLAXRES, five mobile plants will be built for the European market in 2023 and should be available by 2024 [54]. By 2030, FLAXRES plans to build 400 recycling plants for worldwide operation.

[1] Additional partners include the Grenoble Institute of technology (INPG), France; TECNALIA Research and Innovation, Spain; and Triade Electronique, France.

Three of the mobile plants will be operated in Germany, and the other two plants are planned to operate in France and in the Netherlands. The recycling plants will have a recycling capacity of 1,000 tons per plant per year [57].

The startup Solar Materials [59] is focusing on recycling technologies of Si-based PV modules using physical-mechanical processing. It was founded in the year 2021. Currently, no further information on the processing or planned market introduction is available.

There are also other recycling companies where it is not clear whether or not they are operating, how much they are recycling if they are operating, or which materials they are recycling. For example, Envaris [60](Berlin) and SolarGermanCells [61] (Leipzig) do not specialize in PV module recycling, but they do manage EOL processes for PV, such as the disassembly of PV plants and waste disposal. SiC Processing [62] (Bautzen) specializes in recycling Si kerf losses and Si slurry from PV production. ROTH International [63] (Wernberg-Köblitz) deals with the recycling and recovery of used PV modules. Further, they plan to develop new recycling processes for all PV module technologies at low costs. Rinovasol (Weiden) [64] deals with recycling, reuse, repair, and refurbishment. The French company ROSI Solar [65] is planning a recycling plant in Germany for Si-based PV, but currently there is no information regarding the location and schedule.

Further, in recent years, concepts for reuse and second-life markets of used PV modules have gained attention. 2ndlifesolar [66] is a service provider for the disassembly of PV power plants as well as the functional testing and coordination of the further treatment of used modules. A mobile testing facility allows functionality and reusability tests of used modules directly at the disassembly site. Several companies, such as SecondSol [67] or Solardoo [68], provide marketplaces for second-life modules from different manufacturers.

3.1.3 Further Challenges for Material Recycling

Regarding the recycling and further treatment of recovered materials from PV, there are several challenges that need to be addressed to improve PV module circularity. The wide variety of PV technologies and available products will further increase in the future with the development of the next generation of PV (e.g., perovskites, tandems, organics, and others); hence, distinguishing among them, sorting, and further treatment will become increasingly complex. Solutions at an early stage are needed to align the EOL system. Because PV modules can contain small amounts of rare, valuable, critical, or toxic materials, specific treatments for recycling and disposal are required. In addition to the different semiconductor materials in PV modules, a wide variety of substances and elements are used as interlayers, contact materials, or encapsulation materials. For example, hazardous substances in PV modules include lead from solder or metallization pastes, Cd used in CdTe thin-film PV, or lead used in perovskites, as well as other organic compounds. In addition, the polymer films used as laminate films or back sheets can differ depending on the manufacturer or product series, which can complicate material recycling. Further, contaminants or interfering substances introduced into the product, e.g., antimony content of polymer films from the manufacturing processes or in flat glass, can be a problem for further downstream use.

Considering recyclability at an early stage of product development and ensuring that appropriate recycling processes for next generation PV are already developed when entering the market, could give competitive advantages to module manufacturers.

Other possible measures to improve recycling conditions would be finding solutions to provide the relevant material information for initial treatment and recycling on or with the modules e.g. barcodes or labels attached to the modules that allow to access the material specifications of the modules.

One general challenge in recycling (not exclusively for PV) is also a risk of improper treatment or disposal—for example, if modules are exported to countries that do not have appropriate take-back and recycling infrastructure [69]. Expanding the recycling technology and take- back system for PV will reduce this risk of illegal EOL module exports and could improve circularity as a whole.

Regarding better recycling of Si from PV modules, ensuring the purity of the recovered Si from module recycling or from the production process is critical. A global player in Si production stated that the purity must be >95% for metallurgy and >99% (2N) for Si synthesis. For Si synthesis, there are tolerance ranges for impurities that must be met because they directly affect the reactivity and quality of the product. For example, critical parameters are Al impurities, which must be within the range from 0.1%–0.2%. Metallurgical Si, which is sold on the market, has typically impurities ranging from 0.1%–0.5% for iron (Fe) and Al and from 0.01%–0.3% for Ca, depending on the Si grade. In addition, there are more stringent requirements for surface impurities from organics, heavy metal impurities, and concentrations of dopants, and a shelly or flat morphology of the Si must be avoided. [70]

As Germany was the first country which installed PV in high numbers, it will also be the first which will recycle high numbers. The energy transition is politically desired in Germany, the PV expansion targets of cumulative installed PV power are 215 GWp in 2030 and 400 GWp in 2040, therefore PV recycling must also be considered.

The challenges of PV recycling represent great opportunities for Germany: Currently, Germany is the only country which recycles thin-film CIGS modules (at least at pilot level) and Germany could now take the lead in advanced recycling processes that allow suitable recycling of the different module types and PV technologies as a high level of technology and knowledge as well as high ecological standards in Germany exists.

3.2 Experiences From Collection and Take-Back Coordination

The following sections present the challenges and potential measures for improving the current organization of the take-back and recycling system based on the experiences of the involved stakeholders discussed in the expert workshops conducted in 2021 and 2022.

3.2.1 Challenges

The take-back, collection, and recycling of EOL PV modules is regulated by the implementation of WEEE into national law in Germany in the form of ElektroG, which provides a legal framework for the coordination, treatment, and tracking of EOL PV modules. The involved stakeholders, however, see a considerable need for action in improving the organization and coordination of the take-back and recycling system and in increasing the expansion of the recycling infrastructure suitable for PV modules. The main challenges identified by the stakeholders in the current collection and take-back system are the:

- Low volumes of EOL PV modules collected through the official system and sent to suitable recycling channels
- Low transparency of EOL PV module flows, despite the reporting requirements set out in ElektroG
- High transport costs of the take-back logistics (transport from the collection sites to the treatment facilities)
- Different handling/coordination of the collection of EOL PV modules from commercial (B2B) and residential (B2C) applications
- Comparatively high breakage rates of intact modules, caused by improper dismantling/disassembly of PV modules and by incorrect storage or load securing during transport of the collected EOL PV modules.

Further, due to the high market relevance, both the legislation and the expansion of the initial treatment and recycling infrastructure are strongly focused on EOL modules of Si technologies. So far, the recycling of PV modules from non-Si-based technologies has received less attention in the current system in Germany and has a lower participation rate in the market activities of ElektroG. An exception is CdTe thin-film modules, for which the module manufacturer First Solar operates a collection system and recycling plant adapted to the technology. For copper indium gallium selenide (CIGS) modules, there are ongoing research and development activities in Germany with high technology maturity for the CIGS recycling process.

The following sections further discuss these problems and causes.

Collection Volumes

Different responsibilities in coordinating the take-back and collection of B2B and B2C modules result in various challenges that can affect the collection volumes of EOL PV modules.

Despite the obligations of the registered manufacturers to provide evidence and reporting of discarded PV modules, so far, only small quantities of EOL modules are taken back via the designated recycling system and sent for initial and further treatment. It is roughly estimated that a maximum of 10% of end users order a collection via registered manufacturers and authorized agents [10], such as PV Cycle or take-e-way, and are reported to Stiftung EAR.

With the statistical data that are collected today, it is difficult to track how the remaining EOL PV modules are disposed. It can be assumed that relevant quantities are disposed via alternative routes, that intact used modules are exported via secondary markets, and/or that defective modules are illegally exported as functioning used modules.

For example, private end users of (B2C) PV module waste are only allowed to return typical household quantities at the collection points of the public waste management authorities. According to the LAGA communication M31A [14], typical household quantities range from 20–50 modules. In practice, however, private end users can often only return smaller quantities (10–20 modules) without incurring extra costs. Because the take-back of B2C modules is the shared responsibility of municipalities and module manufacturers, the implementation at the collection points can differ, and additional fees might be incurred. In addition, private end users of PV modules are usually not sufficiently informed about the return options. Private end users expect to return their used PV modules free of charge and might not be willing to pay additional costs. This can lead to alternative ways of disposing EOL modules, such as improper storage, resale, or illegal disposal routes.

For B2B modules, manufacturers have different take-back obligations for modules placed on the market before and after October 24, 2015, as described in Section 2.2. Due to the long lifetimes of PV modules of 20–30 years, currently, and in the coming years, modules that were brought to the market before October 24, 2015, will be sent to the recycling system. With the introduction of the third amendment of ElektroG (ElektroG3), voluntary take-back became mandatory for commercial modules beginning January 1, 2022. This is intended to prevent the problem of alternative or illegal disposal. No experience is available yet on how this change will affect the take-back flows. (Workshops were held in October 2021 and July 2022, so no data from 2022 were available during the preparation of this report.)

Transparency and Tracking of Material Flows in the PV Recycling System

During the expert workshops, the stakeholders noted that small quantities of EOL PV modules are collected through the designated take-back and recycling system. Further, it was mentioned that there are currently few options for tracking the material flows along the treatment chain of the EOL system, hence the need to increase transparency.

Despite the reporting obligation for end users of B2B modules, there is no sufficient supervision or monitoring of the treatment paths of EOL modules. In many cases, the involved actors are not aware of their reporting obligations.

In addition, tracking EOL modules and material flows ends with delivery to the initial treatment facility. Material flows between the initial treatment facilities or recycling facilities are unclear and cannot be traced. Among other things, there is mixing with reuse approaches, which can conflict with the verification requirements of ElektroG.

The incomplete monitoring of the waste management paths and material flows results in a larger number of unreported quantities that are not statistically recorded. This, in turn, has an impact on the quality of the waste statistics for PV modules, such as those submitted to Eurostat.

Transport Costs

In the current disposal system, the transport costs for taking back old PV modules and delivering them to the primary treatment and recycling facilities account for a significant share of the total costs of PV module recycling, which, according to a rough estimate by PV Cycle, can range from 100–250 Euros/ton [10].

On one hand, there are few recycling sites in Germany, so, depending on the location of the collection points, long transport distances must be covered to deliver the modules to be recycled. On the other hand, the collection and coordination of EOL PV modules in the current disposal system result in high logistical efforts.

The insufficient presorting of module types during collection at the collection points leads to permanent diversion of misdirected modules. Direct delivery of EOL modules from collection points to primary treatment facilities or recycling plants currently occurs in mixed batches without other specific requirements.

Although paragraph §21 of ElektroG requires certified primary treatment facilities to carry out a simple presorting of Si-based and non-Si-based technologies before the actual recycling, in practice, mixed batches or misdirected modules end up at the recycling facilities. The lack of treatment companies with a general authorization to accept and treat all PV module types and technologies leads to an increased sorting effort at the primary treatment and recycling facilities and, from a logistical point of view, to a permanent detour of misdirected PV modules. To prevent this, the personnel at the collection points needs to be better trained to ensure correct sorting of the modules.

Another challenge that leads to additional logistical effort with corresponding transport costs is the different regulation and coordination of EOL PV modules from commercial (B2B) and private (B2C) use. In particular, there is still great potential for optimization in the collection and coordination of B2C modules at public collection points. According to current regulations, EOL modules must be collected from the collection points within 48 hours of being reported [10]. This results in many empty runs or transport with low utilization.

In summary, the delivery of EOL PV modules to suitable facilities remains a problem of the current disposal system.

Breakage rates

Improper handling of functional used PV modules often leads to avoidable damage to the modules such that they are no longer suitable for further use and must be recycled.

Even though the dismantling of PV modules must be nondestructive, according to KrWG §3 [19], modules are often damaged during the disassembly and dismantling of plants due to insufficient instruction or qualification of the personnel or due to time pressure, e.g., by breaking modules out of their holders. In addition, modules are damaged by unsuitable storage in temporary boxes at the collection points or by inadequate load securing for further transport. To reduce breakage rates, improved training of personnel is recommended.

3.2.2 Identified Actions and Measures

Based on stakeholder experience of the current practice of the collection, take-back, and initial treatment of PV modules in the recycling system, significant needs for action were identified at all points along the treatment chain. Key measures include:

- Implement consistent registration of PV EOL modules via the official EOL management system and transparent tracking of material streams along the treatment chain.
- Expand recycling infrastructure and treatment methods for non-Si modules.
- Improve coordination of collection and take-back systems and reduce logistics costs.
- Improve information and training of the actors involved in the disposal system.
- Improve the situation at collection points from public waste management authorities.
- Improve initial treatment sites and recycling facilities.

Implement consistent registration of PV EOL modules via the official EOL management system and transparent tracking of material streams along the treatment chain.

To ensure that EOL PV modules are handled via the official recycling system and to avoid illegal exports, it is necessary to consistently register and monitor imported modules when they are launched on the market and to track them after they have been used.

For this purpose, the volume flows must be recorded without gaps, and they must be traceable.

To this end, the stakeholders involved in the take-back and recycling system must be better informed about their obligations. And end users must be better informed about their take-back options and reporting obligations. At the same time, the return options for end users must be made easier. In addition, it must be ensured that user changes are reported and that the relevant information is passed to secondary users.

Especially in the case of legacy EOL PV modules from B2B applications, for which no reserves had to be deposited for recycling, the return options must be improved so that these are not disposed of via alternative routes and that defective modules are not illegally exported via the secondhand market. It is necessary to significantly improve the education of owners and end users about their obligations.

The recent amendments to ElektroG3 have already implemented measures to improve the monitoring, take-back, and information for end users, but due to the short period since these changes have been made, information on the impact of these changes is not yet available. The previously voluntary take-back of B2B modules by manufacturers and at private collection points has been mandatory since January 1, 2022. In addition, ElektroG3 implemented a stronger obligation of the manufacturers and distributors of PV modules to provide information to the owners/users of PV modules. Initial measures were also implemented to better track the modules by tightening the registration obligations of manufacturers and distributors. By removing the restriction on the quantities of modules that can be returned to public collection points free of charge for private end users (B2C), the risk of alternative disposal or inappropriate storing methods for modules can be reduced.

To increase transparency and to track the recovery and disposal routes of EOL PV modules, it is necessary that all quantity flows are recorded without gaps until the recycling or recovery of materials. In particular, the flows between the initial treatment plants and the recycling facilities pose a challenge in this regard. In this context, statistical data must be improved to gain better insight into waste and recycling flows to improve current systems.

Expand the Recycling Infrastructure and Treatment Methods for non-Si Modules.

Although the current quantities of EOL PV modules are lower than expected, it is assumed that the amounts will rapidly increase in the near future (see Figure 2); hence, the expansion of the recycling infrastructure in Germany must also rapidly increase so that the materials are collected and treated via the proper disposal system.

For new and future generations of PV technologies, e.g., tandem modules with more complex material systems, there is a need for suitable treatment processes. Current legislation and treatment processes strongly focus on PV modules of Si technologies due to their market relevance; nevertheless, recycling solutions already exist for CdTe thin-film modules, and Germany is one of the very few locations where recycling for CIGS thin-film modules is already at the pilot scale.

Improve the Coordination of the Collection and Take-Back System and Reduce Logistics Costs.

To reduce the share of EOL logistics in the total cost of PV module recycling, it is important to ensure that unnecessary transport routes are avoided as much as possible and that transport distances to treatment and recycling facilities are shortened.

Collection coordination can be made more efficient by standardizing B2B and B2C module collection and pickup systems—for example, by coordinating the collection and pickup of EOL modules from private use through commercial systems as well. High transport costs are currently caused by the many empty trips and trips with low utilization in collection as well as by the necessary transport for the detour of misdirected modules at the initial treatment facilities or recycling plants.

For better coordination of pickup, it would be beneficial to extend the deadlines for pickup after reporting the module quantities to be picked up. In addition, the collection quantities and module tons need to be clearly communicated. When collecting and distributing EOL PV modules, there must be consistent and reliable presorting of modules by technology and material system. This is the only way to ensure that EOL PV modules are assigned to the correct initial treatment and recycling facilities. Paragraph §21 of ElektroG regulates presorting modules according to Si and non-Si modules, but so far, this has not been satisfactorily implemented. Better training of the personnel both at the collection points and at the initial treatment facilities is necessary. Specific uniform treatment concepts can also make an important contribution to the separation of modules by type.

Transport distances can be achieved by an area-wide expansion of the initial treatment facilities and recycling infrastructure. Due to the strongly increasing volume flows of EOL PV modules in the future, it is necessary to act quickly to accelerate the expansion. Primary treatment facilities with a permit to treat all module types can further reduce transport distances.

In the medium to long term, the development and introduction of mobile primary treatment plants with universal treatment processes can make an important contribution to reducing logistics costs.

Mobile plants could be a valuable complement to today's stationary plants because they allow for the treatment of EOL PV modules directly at PV power plant sites and can direct the recovered materials to the appropriate recovery and disposal routes, greatly reducing transportation needs for collection, pickup, and primary treatment.

Improve Information and Training of the Actors Involved in the Disposal System.

Better education of all end users and actors involved in the disposal system is needed. End users must be regularly informed about their reporting obligations and the return options, and they must be made aware of their roles under ElektroG. This is the only way to ensure that modules are fed into the disposal system.

In addition, specific instructions and training should be given to the personnel at the collection points, initial treatment facilities, and the companies contracted to dismantle the facilities. In addition to the issue of proper presorting, as stated, better training of personnel could help to reduce damage to functioning modules during dismantling, collection, or due to inadequate load securing.

Improve the situation at collection points from public waste management authorities.

In addition to improving the presorting process by trained employees, the standardization of the coordination of public waste management authorities with the commercial collection system of B2B modules could help to clarify the processes of return, collection, and forwarding to the EBAs or recycling facilities.

To allow for better collection and storage of EOL PV modules, the temporary collection boxes should be replaced by standardized collection boxes to simplify handling. LAGA communication 31A recommends "big bags" in combination with pallets or special plastic boxes with covers ("paloxes") for storage and transport. Further, storage should be protected by roofing [14]. The separate collection of PV modules with and without frames can also be useful because these are usually removed in a separate step [14].

Improve initial treatment sites and recycling facilities.

To improve the initial treatment of EOL PV modules, specific competences for WEEE need to be built up at treatment companies, and a mandatory treatment concept for EOL PV modules needs to be adapted and implemented. Currently, initial treatment and recycling plants specialize in one module technology due to it high market share of >95%, mainly Si technologies; however, specific treatment processes for other module types need to be implemented as well.

Further, EOL logistics could be made more efficient by primary treatment plants with an authorization to treat all module types.

4 CONCLUSION

The European WEEE directive delivers an important legal framework to ensure suitable take-back and recycling of PV modules, and has been implemented in German law by ElektroG. Germany was the first country to install large numbers of PV modules, so it will be the first country that will need to handle large numbers of EOL modules, which is expected to happen within the next few years. The question arises, then, whether Germany's current take-back and recycling system is prepared to handle this volume. The main intention of this report is to provide insights into the current framework and conditions of the management of EOL PV modules in Germany and to evaluate practical experiences of stakeholders that are involved in the take-back and recycling system. The results of this report are based on two expert workshops that were held in 2021 and 2022 with approximately 20–25 experts from industry and research along the full treatment chain of EOL PV modules—from production, collection, and take-back coordination to the initial treatment and recycling of recovered materials. The main identified challenges and potential optimization measures are summarized in the following.

Participants of the two expert workshops acknowledged that Germany has taken steps to ensure the proper collection and recycling of PV modules. However, there is a clear need for improvement throughout the treatment chain, especially in anticipation of the growing volume of end-of-life module flows. Germany's experience and lessons learned in managing larger volumes of EOL PV modules will be valuable for other countries preparing for similar challenges. The main areas requiring improvement can be summarized as follows:

Transparency of PV Module Waste Volume

The volume flows of collected and treated PV module waste reported in official statistics are still less than the expected quantities, so it has been assumed by the workshop attendees that even larger quantities are disposed via alternative routes, bypassing the designated recycling system (e.g., via illegal exports). In addition, material flows after initial treatment (e.g., to secondary material recovery facilities) are nontransparent and hard to trace.

Hence, besides the already existing obligatory reporting of PV module streams according to ElektroG, stakeholders suggest that additional measures are required to enable better tracking of EOL modules throughout the complete treatment chain, e.g., provide incentives to ensure that PV module waste is returned to official collection points. Further, it should be ensured that private users can return EOL modules at the collection points without additional fees. Currently, quantities are limited to approximately 20 modules. End users could be better informed about their responsibilities regarding how and where PV module waste must be returned

Take-Back and Collection

Workshop attendees noted that the current collection and take-back system is complex due to the required coordination of PV modules from B2B and B2C use. In terms of take-back logistics, on the one hand, insufficient communication of collection quantities lead to underused transports and on the other hand, inappropriate presorting leads to frequent redirection of modules which were transported to incorrect initial treatment facilities or recycling plants (e.g., non-Si modules sent to recycling facilities that only treat Si modules). Both aspects lead to high transport costs. Further, involved stakeholders in the collection and further treatment of PV module waste are often not fully aware of their obligations.

It was suggested at the workshops that to reduce the high share of transport costs of PV module recycling, a collection deadline of 48 hours after reporting the collection quantities could be extended to increase transport utilization. For avoiding extra transport steps related to the redirection of misplaced modules the following was suggested: Appropriate training of the responsible personnel for sorting and preparing modules for transport at the public collection points, as well as at the initial treatment facilities. Additionally, labeling of the PV module types at the module manufacturer sites could further ease the sorting. A further measure to reduce transport costs is to reduce distances from collection sites to the initial treatment facilities. In this regard, initial treatment facilities that can treat several or all types of modules could lead to significant improvements.

Workshop attendees suggested that the introduction of a uniform, commercial take-back coordination and collection program of PV module waste from B2B and B2C use could reduce the complexity and provide a clearer framework for the stakeholders involved in EOL management.

Module Recycling

Workshop attendees noted that German recycling infrastructure and recycling capacities need to be rapidly expanded, and recycling processes for all module types are required (not only Si-based and CdTe modules but also CIGS and tandem modules). A main challenge of the current industrial scale recycling processes is that glass cullet currently fails the requirements to be recycled for high-quality applications and hence is used for lower-quality applications. In terms of Si-based module recycling, not all valuable material fractions (e.g., Si) can be economically recycled with the current process. Recently, a research project demonstrated the technical feasibility of separating materials and producing passivated emitter and rear contact cells from 100% recycled Si from mechanical treatment. The applied processing, however, is still on a low technology readiness level.

A promising approach, workshop attendees suggest, could be to expand the recycling infrastructure by combining facilities of the established mechanical or mechanical/wet chemical processes with facilities of new process developments using alternative technologies. The main advantages of the established recycling processes (on an industrial scale for Si-based and CdTe modules) are that they are comparably easy to scale and to handle and are independent from PV module dimensions.

Current developments using alternative technologies show interesting approaches to enhance the recycling of valuable materials from different module types. A new recycling process that is using high-energy light pulses to separate material composites shows an advantage in that it is universally applicable. The compact design also allows for mobile operation; thus, the initial treatment of PV module waste could be operated directly at the location of the disassembly of PV power plants, which could reduce transportation efforts because recovered materials could be directly forwarded to suitable recycling plants. If these procedures hold up in practice, they could be a valuable addition to existing procedures.

Taken together, this report provides an in-depth analysis and stakeholder-critique of the current system for end-of-life treatment of PV modules in Germany. It is important to analyze the situation in Germany because it is the first country to support widespread adoption of PV modules, and therefore is expected to be the first to experience larger EOL volumes. While specific to an analysis of the situation in Germany, this report is hoped to offer useful lessons for other countries in advance of their own expected rise in EOL volumes.

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