Status of PV Module Take-Back and Recycling in Germany

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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.