

Advances in Photovoltaic Module Recycling Third Update to Empirical Life Cycle Inventory Data

IEA PVPS Task 12, Report IEA-PVPS T12-32:2026, April 2026

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The Technical Report is available for download from the IEA-PVPS website www.iea-pvps.org.

Executive Summary

Introduction

Global cumulative installed solar photovoltaic (PV) capacity reached approximately 2.8 TW in 2025 [1], and is expected to continue growing. As the installed base expands and matures, an increasing number of PV modules will reach technical or economic end of life (EOL), driven by system aging, damage, and early replacement associated with repowering decisions. Effective EOL management is therefore becoming an increasingly important consideration for PV system owners, operators, policymakers, and other stakeholders. Development and optimization of collection, triage, repair, refurbishment, reuse, and recycling pathways are needed to convert PV materials into assets. These pathways can support circularity and reduce the creation of new waste streams.

PV modules that cannot be restored to safe operation—or whose owners elect not to do so for economic or other reasons—are considered to have reached EOL and are suitable for recycling in most cases. A 2016–2017 IEA PVPS Task 12 study reviewed PV recycling technologies in Europe [2][3]. This included four commercial glass and metal recyclers that processed batches of PV modules periodically, as well as one pilot-scale recycling process customized for PV modules.

Heath et al. showed that recovering high-purity, high-value materials such as silicon (metallurgical-grade with greater than 98% purity or solar-grade with 9-13N purity) and silver is essential to improving the economic viability of recycling [4]. In recent years, new commercial and demonstration-scale recycling options for PV modules have emerged, some of which claim to recover silicon and silver. However, publicly available data on these processes remain limited.

A 2024 EPRI study published by IEA PVPS Task 12 identified advances in PV recycling technology that have the potential to be affordable, technologically feasible, and environmentally responsible [5]. The study included a survey of recyclers, a literature review, and a patent search to identify industry trends and innovations. Additionally, six leading recyclers supplied life cycle inventory (LCI) data for facilities employing advanced recycling treatments to separate PV materials with high quality and yield. A seventh approach combined the recycling processes of Envie and ROSI. This case was modelled using LCI data from a recent IEA-PVPS report on a recycling process developed by the Japanese company Nippon Precision Casting Corp. (NPC) [6].

The acquisition of new or updated LCI data from PV recyclers is the focus of the current study. The United States and European Union were the primary geographic focus for consistency with the prior report and because author contacts predominantly reside in these regions, although outreach also included recyclers in other regions. A recent IEA PVPS Task 12 report provides an overview of PV module recycling in IEA PVPS Task 12 countries, including some of the recyclers that contributed LCI data for this study [7]. The current study builds on the 2024 review of seven PV recycling facilities (six

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surveyed recyclers and one modeled case) [5]. It incorporates new LCI data and interview-based insights from two U.S.-based and one Italian crystalline silicon (c-Si) PV recycler. Additionally, First Solar, a cadmium telluride (CdTe) manufacturer and recycler that participated in the 2024 study, was re-interviewed and provided updated global LCI data to supplement previous findings [5]. The EU Horizon 2020 PHOTORAMA project consortium also contributed LCI data from its demonstration recycling center in Tangermünde, Germany [8]. The facility processes both c-Si and copper indium gallium selenide (CI(G)S) modules.¹ Section 2 presents new or updated data from five contributors. These include First Solar’s re-interview results and data from PHOTORAMA’s pilot line. Section 3 compares the 2025 dataset with LCI data from the 2024 report. Updated life cycle inventory data tables are provided in Section 3, with electronic versions available at IEA PVPS (<http://www.iea-pvps.org>; select Reports under Task 12). Table 1 summarizes LCI data sources for this report.

Table 1: Summary of recycler LCI data presented in this report

Company / Consortium	Facilities Represented in LCI Data	Processing Capacity	Module Type for LCI	New / Updated LCI Data (Section 2)	Data from 2024 Report [5] Used for LCI Comparison (Section 3)
First Solar *	6 facilities: USA (Ohio & Alabama), Germany, Vietnam, Malaysia & India	112 000	CdTe	✓	✓
PHOTORAMA (thin film)	Germany	1 000	CI(G)S	✓	
PHOTORAMA (c-Si)	Germany	1 000	c-Si	✓	
SOLARCYCLE	USA (Texas)	20 000	c-Si	✓	
Solarpanel-recycling.com	3 facilities: USA (North Carolina, Texas, Georgia)	63 000	c-Si	✓	
9-Tech	Italy	33	c-Si	✓	
Reiling **	Germany	50 000	c-Si		✓
LuxChemtech **	Germany	1 000	c-Si		✓
Flaxres **	Germany	1 000	c-Si		✓
ROSI **	France	3 000	c-Si		✓
Envie & ROSI **	France	3 000	c-Si		✓
Tialpi **	Italy	3 000	c-Si		✓

* While First Solar was one of six companies that contributed LCI data in the 2024 publication, only the updated global LCI data provided in the current study are presented in this report.

** LCI data from 2024 publication [5]

¹ The PHOTORAMA (PHOtovoltaic waste management – advanced Technologies for recOvery & recycling of secondary RAW MAterials from end-of-life modules) project was led by CEA (France) and included twelve consortium members. LuxChemtech developed 1 000 t/yr recycling lines (TRL 7) for c-Si and CI(G)S modules. The project term was May 2021 to April 2025 at a total cost of € 10 365 764.

Research Overview

As shown in Table 1, select findings from 2024 were not updated in this current report. The 2024 LCI survey [5] identified 177 PV recyclers and recycling equipment manufacturers globally through press releases, existing networks, past studies, and online searches. It also observed a significant acceleration in research and development (R&D) on PV recycling technologies, alongside growth in related policies and standards. Numerous patents were filed, and announcements of new recycling activities and investments emerged.

In the current study, 13 recyclers employing either best available or emerging PV recycling technologies at commercial or pilot scale were invited to participate in an LCI survey. The same questionnaire used in 2024, with slight revisions, was applied to understand current practices and recycling treatment methods.

Out of the 13 questionnaires sent for this study, four recyclers provided information and LCI data for facilities that treat PV modules. The consortium of the research project PHOTORAMA also contributed information and LCI data, bringing total respondents to five in 2025. The collected LCI data were analyzed across the respondents to compare material recovery rates and energy consumption. To facilitate comparison, a consistent system boundary was applied at the point in each process at which the cell fraction (including metals) is separated from the glass and polymers. Subsequent steps to recover silicon and metals like silver, as well as purification processes, were described in the individual sections where data were available. Not all survey respondents performed these downstream processes. As a result, these data were excluded from the comparative analysis to maintain consistency.

Recycling Survey and LCI Key Findings

Five contributors shared information and LCI data in 2025, including three U.S.-based recyclers, one Italian recycler, and the PHOTORAMA project consortium. Facility capacities ranged from 33 t/yr to 21 000 t/yr. These findings represent a snapshot of operations based on information provided by recyclers. The global industry is rapidly evolving and characterized by diverse approaches and ongoing innovation.

- **Mechanical recycling remains the benchmark for commercial-scale silicon-based modules.** SOLARCYCLE and Solarpanelrecycling.com (SPR) shared results from their mechanical-based c-Si PV recycling plants, which are optimized for cost, capacity, and output, though some outputs are downgraded.
- **Thin-film recycling has substantial commercial experience.** For example, First Solar operates a proprietary recycling system, partly vertically integrated with its thin-film module manufacturing, at six facilities in the United States, Germany, Malaysia, Vietnam, and India. These plants offer a combined capacity of around 112 000 t/yr. The processes vary between plants due to the technology implemented. Since 2005, First Solar has achieved around 90 wt. % material recovery [9], including closed-loop semiconductor recovery for use in new solar modules, with continuous process improvements and updated global average data reported for this report.
- **The PHOTORAMA project combines mechanical, thermal and chemical recycling approaches to achieve high-yield, high-quality outputs.** The first-ever released LCI results were provided from its pilot and demonstration recycling processes implemented in Tangermünde, Germany. These include LCI data (updated from data provided by LuxChemtech for the 2024 report [5]) for junction box and frame removal, high-pressure water jet cleaning of c-Si modules, and Cl(G)S module recycling using diamond wire cutting, flash-light delamination, and silicon, silver, and compound semiconductor material recovery. For c-Si module recycling, silicon is recovered at 5N purity and silver at over 2N purity.



- **9-Tech shared results from its c-Si module pyrometallurgical-based pyrolysis pilot plant near Venice, Italy.** The combination of thermal, mechanical, and chemical treatments enables recovery of 95 wt. % of silicon and 90 wt. % of silver.

Contextual Notes and Limitations:

- **Material recovery comparisons are complex.** Output fractions vary due to differences in module types, process sequences, and glass content (e.g., glass/glass vs. glass/backsheet laminates). For comparison across recyclers, reported outputs were normalized to 100% by expressing each output as a fraction of the total input mass, such that cumulative material fractions correspond to the weight of one module or one metric ton (t) of input. Reported material outputs are not necessarily recovered for subsequent material use; polymer outputs in particular may be directed to energy recovery (e.g., incineration) or landfill disposal. Information on recovered material use and downstream treatment pathways was not explicitly requested in the LCI survey, and consequently, the fate of individual output streams was not consistently specified, although some recyclers voluntarily reported this information.
- **Energy consumption data are limited.** Not all respondents recorded or disclosed detailed energy use.
- **Data gaps remain.** All respondents are scaling up new technologies, and data gaps could not be fully resolved due to limitations in the information provided. Some downstream recovery steps (e.g., purification of silicon and metals) were excluded from comparative analysis to establish as consistent a system boundary as possible.

Despite these limitations, the results offer insights into diverse recycling approaches at different stages of maturity, including associated recovery rates and energy consumption. Trends in this nascent industry are further analyzed through comparison with prior Task 12 LCI reports.

How to Apply Results

The findings of this study offer insights for a range of stakeholders involved in the solar PV value chain:

- **Asset owners, operators, and utility integrated resource planners** can leverage the knowledge and perspectives to inform module EOL management strategies. Integrating recycling considerations into long-term planning—alongside collaboration with authorities, take-back programs, and recycling partners—supports the development of a circular economy for energy materials to address societal critical material challenges.
- **Commercial recyclers and researchers** within the international solar PV community and related disciplines can use the LCI data to enhance recycling quality and economic value and benchmark their performance.
- **Life cycle assessment (LCA) practitioners** can incorporate the LCI data into broader environmental impact assessments of PV systems, enabling more accurate and transparent evaluations of sustainability performance across the product life cycle.
- **PV module manufacturers** can use the identified gaps in treatment technologies and operational experience to guide R&D priorities and facilitate new sustainable module designs.
- **Policymakers** considering R&D or other policies to support the PV recycling industry can benefit from an updated understanding of the state of the practice.