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International Energy Agency
Photovoltaic Power Systems Programme

Task 12 PV Sustainability

PVPS

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

2026

Report IEA-PVPS T12-32:2026

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The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation 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 is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

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What is IEA PVPS Task 12?

Task 12 fosters international cooperation on the sustainable aspects of PV technology, focusing on environmental and social factors. Its work supports the development of circular PV value chains, advances life cycle assessment methods, and addresses environmental, social, and socio-economic challenges to PV market growth.

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COVER PICTURE

Removal of the junction box and frame on a c-Si module (Credit: PHOTORAMA – EU project ©European Union, 2025)

INTERNATIONAL ENERGY AGENCY

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Advances in Photovoltaic Module Recycling

Third Update to Empirical Life Cycle Inventory Data

IEA PVPS
Task 12
PV Sustainability

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
CdTe	Cadmium telluride
CI(G)S	Copper indium (gallium) selenide
c-Si	Crystalline silicon
Demo	demonstration
EOL	End of life
EoW	End of Waste
EU	European Union
EU PVSEC	European Photovoltaic Solar Energy Conference
EVA	Ethyl vinyl acetate
Foil	Polymer part of a module (encapsulant and backsheet)
FE	Ferrous
GPL	Liquified petroleum gas
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCA	Life cycle assessment
LCI	Life cycle inventory
LNG	Liquid natural gas
LPG	Liquefied petroleum gas
NF	Non-ferrous
NLR	National Laboratory of the Rockies
NREL	National Renewable Energy Laboratory
OECD	Organization for Economic Cooperation and Development
PLS	Precipitation and liquid separation
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
R&D	Research & development
SPR	Solarpanelrecycling.com
TCLP	Toxicity Characteristic Leaching Procedure
TRL	Technical readiness level
US	United States
WEEE	Waste from electrical and electronic equipment

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 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 (t/yr)	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	✓	
Envie & ROSI **	France	3 000	c-Si		✓
Flaxres **	Germany	1 000	c-Si		✓
LuxChemtech **	Germany	1 000	c-Si		✓
Reiling **	Germany	50 000	c-Si		✓
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 CI(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.

1 STUDY OVERVIEW

1.1 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.

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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 [5]. The study focused on technologies with the potential to be affordable, technologically feasible, and environmentally responsible. 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. These treatments are designed to separate PV materials with high levels of 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) [5][6][10].

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1.2 Survey of Photovoltaic Module Recyclers

This section presents results of a survey of PV recyclers that process modules at commercial scale. The circular economy for PV materials has grown significantly since previous surveys in 2016–2017 and 2024. As global waste streams increase and recycling policies emerge in some countries, more organizations are entering the recycling sector. A substantial surge in PV waste is expected after 2030 in major PV markets, potentially peaking at 212 million metric tons (t) by 2050 [11]. This underscores the need to scale recycling infrastructure and develop dedicated equipment suppliers. U.S.-based recyclers participating in this study (during the year 2024) expressed confidence in their ability to secure sufficient input volumes to justify facility expansion. Table 2 summarizes participation across multiple IEA PVPS Task 12 LCI PV module recycling studies.

Table 2. Summary of PV module recycler data collection efforts across multiple studies

	2015 [3]	2016 [3]	2023–2024 [5]	2024–2025 (this study)
Contacted recyclers	8 recyclers (1 declined)	16 recyclers (7 declined)	24 (18 did not respond or declined)	13 recyclers (8 did not respond or declined)
Technologies	Crushing/ mechanical separation	Crushing/ mechanical separation Thermal treatment Chemical treatment	Crushing/ mechanical separation, high pressure water jet Thermal treatment (hot knife, infrared heating, light pulse annealing, pyrolysis) Chemical treatment	Crushing/ mechanical separation, high pressure water jet Thermal treatment (hot wire, infrared heating, light pulse annealing) Chemical treatment
Data sets received	2: Anonymous, Germany Exner Trenntechnik, Germany	5: Anonymous, Germany Exner Trenntechnik, Germany #	6:* First Solar Inc., U.S. Flaxres, Germany LuxChemtech, Germany	5 First Solar Inc., U.S.** SOLARCYCLE, Inc., U.S.

[2] 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.

	2015 [3]	2016 [3]	2023–2024 [5]	2024–2025 (this study)
		Maltha, Belgium ## Nike, Italy Sasil (now Tialpi), Italy	Reiling, Germany ROSI SAS, France Tialpi, Italy	SPR, U.S. 9-Tech, Italy PHOTORAMA, EU
# Company sold; activity stopped ## c-Si module recycling stopped; PV glass recycling ongoing * While not a recycler, NPC provided data to Task 12 in a separate study. These data were used along with the 6 recycler-provided datasets.				** Update based on global recycling results

2 RESULTS OF THE 2025 LIFE CYCLE INVENTORY SURVEY AND ASSOCIATED EXPERT INTERVIEWS

This section summarizes information provided by four contributing companies and the PHOTORAMA research consortium, along with brief descriptions of their recycling processes as reported by the respondents. Table 3 presents an overview of the contributing organisations; the PV module types, constructions, and conditions accepted; and the primary treatment methods applied. The term *batch* in this usage means that the process is not automated, whereas *continuous* processes use a feed system to process modules automatically.

Table 3: Overview of contributing organisations, PV modules accepted, and treatment methods applied

Company/consortium	Module type; construction; and condition	Treatment methods
First Solar	CdTe; glass/glass (commonly used in bifacial modules, but not exclusively); intact and broken glass	Batch and continuous; deframing possible; mechanical; chemical
PHOTORAMA (thin film)	CI(G)S; glass/glass and glass/backsheet (generally monofacial); intact glass	*Pilot*: Batch and continuous; deframing; hot wire; light-pulse; mechanical; chemical
PHOTORAMA (c-Si)	c-Si; glass/backsheet and glass/glass; intact glass	*Pilot*: Batch and continuous; deframing; mechanical; chemical; hot wire; high-pressure water jet
SOLARCYCLE	c-Si; glass/backsheet; intact and broken glass	Batch and continuous; deframing; heating; mechanical
SPR	c-Si; glass/glass and glass/backsheet; glass condition not specified	Batch and continuous; deframing; mechanical
9-Tech	c-Si; whether glass/glass or glass/backsheet not specified; intact and broken glass	Batch and continuous; deframing; thermo-mechanical; chemical; ultrasound

The LCI data tables in this section have been standardized for clarity and consistency across respondents, based on the authors' best interpretation of the submitted LCI information. Any misinterpretation is solely the responsibility of the authors and not the recyclers. For transparency, Appendix C presents the original survey responses in their verbatim form, allowing interested readers to review and form their own interpretations. Any published analysis based on the standardized tables should clearly note that these tables reflect the authors' interpretation and not the original submitted LCI data. In addition, given the ongoing evolution of PV recycling technologies, the LCI data presented represent a temporal snapshot and may not reflect subsequent process improvements or operational changes.

2.1 First Solar Inc., Tempe, AZ, U.S.

First Solar (www.firstsolar.com), one of the largest PV producers by global market share, specializes in CdTe thin-film modules. The company operates six recycling plants worldwide for its own EOL products, with a total treatment capacity of about 112 000 t/yr (Table 4). These plants are in the USA, Malaysia, Vietnam, India and Germany and fully meet First Solar's global recycling demand. It is important to note that because First Solar is both a manufacturer and recycler, and its recycling facilities are located within or adjacent to its manufacturing facilities, some of the volumes recycled come from its manufacturing lines, e.g., off-specification modules, broken modules, and mislabeled modules. The annual reported throughput, defined here as the actual mass of material processed each year, does not differentiate between post- and pre-deployment modules recycled.

According to the company's 2024 environmental report, the recycling processes employed, which may differ technically by region and implementation time, achieve an average global mass recovery rate of around 90% [9]. First Solar's proprietary recycling process has been continuously improved over 20 years, reaching a 4th version of the technology deployed in 2022. All four versions are being actively used in facilities around the world.

Table 4. First Solar's CdTe module recycling capacity and throughput

Facility	Total Capacity (t/yr)	2024 Annual Throughput (t/yr) [12]
Cumulative across USA (Ohio & Alabama), Germany, Vietnam, Malaysia, & India	112 000	40 400

As shown in Figure 1, First Solar's V1–4 recycling processes begin by removing the junction box and frame, if present (Step 1). The LCI data are based on frameless modules. The laminate is then shredded (Step 2), and a hammer mill further crushes it to produce fine glass particles (Step 3), which are then separated from the remaining polymers and semiconductor material. The intermediate material is temporarily stored in a buffer (Step 4) prior to further processing. A leaching process using water and chemicals (Step 5) is employed to recover CdTe from the glass, after which the recovered materials are further purified by third parties (Step 7). An evaporator recirculates the water, producing a Na_2SO_4 residue (Step 8). In the final step, First Solar separates the interlayer materials from the glass (Step 6). Depending on the country, the polymer (such as ethyl vinyl acetate, EVA) is either incinerated, landfilled, or used to produce rubber products, while the recovered glass is used in the glass industry. Process flows are shown in Figure 1. An updated process scheme for First Solar's global (V1-V4) recycling process and diagram of recycling process evolution are in Appendix B.1. Specific details regarding process generations and equipment at individual global facilities were not provided.

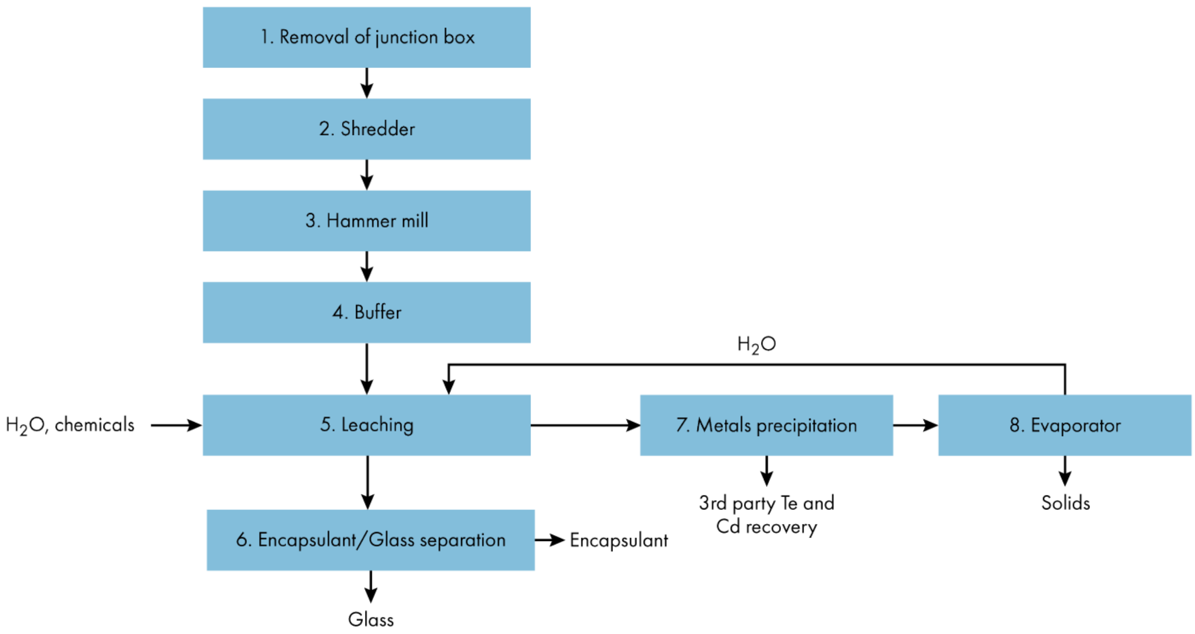


Figure 1. First Solar CdTe module V1–4 recycling process; all steps (1–8) are included in the LCI comparison, including the third-party refining of the semiconductor material

Recycling processes reduce modules to two primary recyclable materials: glass cullet and unrefined semiconductor material (USM). The glass cullet is reused in the glass industry for manufacturing new glass products, while the USM is sent to a third-party facility for processing into semiconductor-grade cadmium telluride, enabling closed-loop recycling for new solar module production. Additionally, copper recovered from connectors and cables is recycled by a third party into secondary copper metal. The encapsulant is either incinerated for energy recovery or repurposed for use in rubber products.

Table 5 presents the LCI results.

Table 5. LCI results for First Solar's recycling processes

Company	First Solar, Inc.
Name	LCI of CdTe module recycling, including semiconductor refining to semiconductor grade CdTe
Time period	2024
Geography	USA, Germany, Vietnam, Malaysia & India
Technology	Mechanical and chemical recycling processes: j-box removal, shredding, hammermill, leaching, and separation and purification (Steps 1–8 below)
Representativeness	Individual real processes in discrete batches (See note on continuous processes in the last table row)
Date	02.08.2024
Collection method	Data based on First Solar Corporate Responsibility Reports for 2024 [9] and 2025 [12]

Plant	Unit	Amount	Comment/Reference
Capacity	t/yr	112 000	Total global recycling plants installed capacity
Scale of plant			Commercial plants
Location			USA (Ohio & Alabama), Germany, Vietnam, Malaysia & India
Module type processed			Cadmium telluride thin-film, glass/glass, frameless solar modules with intact and broken glass
Time period			2024

Process (and Flows)	Unit	Amount	Comment/Reference
Total input	t	1	CdTe PV module for recycling with semiconductor refining to semiconductor grade CdTe
Output			**Source: First Solar Corporate Responsibility Report 2025 [12]**
Metals (frame and junction box, not including semiconductor materials)	wt. % of PV module input mass	0.6	Frameless modules
Semiconductor materials	wt. %	0.5	Unrefined semiconductor material
Glass	wt. %	94	Recycled and sent for use in new glass products
Other materials	wt. %	0.5	Recycled, such as encapsulant for use in rubber products
Encapsulant material	wt. %	0.2	
Dust, glass fines, and encapsulant material	wt. %	1	
Total mass recovered (Steps 1–8)	wt. %	~95	
Components/fuels			
Electricity consumption (Steps 1–8)	kWh/t	265	**Source:** Sinha et al. (2023) [13] **Note:** An older LCI for the recovery stages (covering First Solar's CdTe PV module recycling and third-party processing of USM to

			semiconductor grade CdTe) is used. These data are based on measured V1 batch-process results, which are considered representative of V2–V4. As the latest version of First Solar's recycling technology entails a *continuous process*, the recovered output per unit input is expected to be higher than for a *batch process*, assuming comparable energy consumption.

2.2 PHOTORAMA CI(G)S Recycling Pilot Demonstration Center, LuxChemtech, Tangermünde, Germany

The PHOTORAMA pilot line includes the treatment of CI(G)S EOL modules with a capacity of 1 000 t/yr and has achieved TRL 7. The project team asserts that this recycling line is compatible with CdTe thin-film modules as well.

Figure 2 shows the main steps for the treatment of CI(G)S EOL modules including similar steps as for PHOTORAMA's c-Si process, described in the next section. Disassembly of the frame, junction box, and cables is performed using diamond wire cutting (Step 1). It can also be performed mechanically. The multiple layers of thin-film material are then disconnected from one glass pane through flash-light exposure (high-intensity light pulses to heat light-absorbing material layers and break the adhesive bonds of the encapsulant) (Step 2), followed by further mechanical separation of the encapsulant and metals (Step 3). Subsequently, chemical leaching is performed on the remaining coated glass pane to dissolve metal and semiconductor layers (Step 4). These materials are then extracted by an electrowinning process (Step 5). Most chemicals are recovered through closed-loop processes. The resulting high-quality glass obtained can be either redirected to the flat glass industry (e.g., rolled glass) or directly reused commercially in PV module manufacturing. Metals (In and Ga) are also recovered from the semiconductor layers. The polymers are currently incinerated in waste to energy plants.

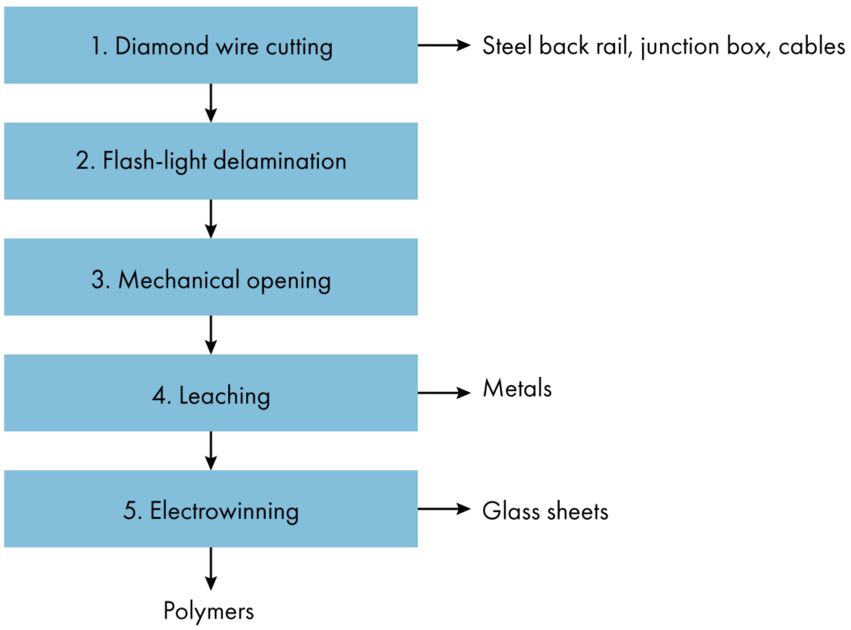


Figure 2. Process flow of PHOTORAMA's CI(G)S recycling, corresponding to the LCI data

Figure 3 a and b show two alternative routes of separation for CI(G)S: diamond wire and flash light separation. Only diamond wire cutting is included in the LCI below. The LCI for the flash light technology may be presented in the future.

a) 

b) 

Figure 3. a) CI(G)S diamond wire frame removal (Credit: LuxChemtech) and b) CI(G)S flash-light separation unit (Credit: PHOTORAMA – EU project ©European Union, 2025)

Batches of modules prepared for recycling can optionally be sorted using X-ray fluorescence (XRF). XRF enables identification of key material characteristics, such as antimony content in glass, cell technology type, and the presence of specific metals including silver, indium, selenium, and gallium. This information allows PHOTORAMA to group modules of the same type, improving control over subsequent separation steps and enhancing process efficiency.

LCI data are provided in Table 6. Steps 1-3 correspond to mechanical processing, while Steps 4 and 5 involve chemical processing.

Table 6. LCI data for CI(G)S recycling at PHOTORAMA demonstration center

Company	PHOTORAMA - EU Project – Demonstration center, LuxChemtech GmbH – Saxony-Anhalt plant, Querstraße 2, 39590 Tangermuende, Germany
Name	LCI of CI(G)S PV module recycling
Time period	2025
Geography	Germany
Technology	Mechanical and chemical recycling processes: disassembly, delamination, and metal recovery using deframing and j-box removal, hot wire, light-pulse, and chemical processes
Representativeness	Individual process technologies within the demonstration line run either continuously or in discrete batches; data are aggregated from runs using both approaches
Date	23.06.2025
Collection method	Data from recycler
Comment	National electricity mix

Plant	**Unit**	**Amount**	**Comment/Reference**
Capacity	t/yr	1 000	
Type of plant			Pilot-scale demonstration plant
Location			Tangermünde, Germany
Module type processed			CI(G)S thin-film framed glass/glass or glass/backsheet modules with intact glass
Time period			2025

Process (and Flows)	Unit	Amount	Comment/Reference
Steps 1–3			**Diamond wire cutting, flash-light delamination, mechanical opening**
Total input	t/yr	1 000	
Components/fuels			
Compressed air	m^3/t	1 075	
Diamond wire	kg/t	15	
Output			
Cables	%	0.7	To cable recycler
Frame	%	14.2	To aluminum smelter or steel recycler, depending on frame material used
Junction boxes	%	1.0	To electronic recycler (150g per panel, inclusive of plugs and cable box)
Mixture of glass cullet, foil* and metals	%	0.8	To electronic recycler
Steps 4–5			**Leaching, cleaning**
Input	t/yr	833	
Components/fuels			
Chemicals	kg/t	11	
Compressed air	m^3/t	186	
Water	kg/t	20	
Output			
Polymers/foils	wt. %	3.6	To waste incineration
Glass cullet	wt. %	79.2	To flat glass production
Mixture of glass cullet, foil, and metals	wt. %	0.4	To electronic recycler

Semiconductors, CI(G)S	wt. %	0.1	To metal recycler
Total mass recovered (Steps 1–5)	wt. %	~96	Excluding mass of materials sent to energy recovery
Electricity consumption (Steps 1–5)		NR	Not reported

* Foil refers to the polymer content within modules (encapsulant and backsheet)

2.3 PHOTORAMA c-Si Recycling Pilot Demonstration Center, LuxChemtech, Tangermünde, Germany

The PHOTORAMA pilot line processes c-Si modules with a capacity of 1 000 t/yr and has achieved TRL 7. It is capable of treating glass/backsheet laminates with intact panes. Batches of modules prepared for recycling are initially sorted using X-ray fluorescence (XRF), which enables identification of key material components. For example, XRF can detect antimony content in the glass or determine the cell technology by identifying elements such as silver, indium, selenium, and gallium. This sorting facilitates the creation of uniform batches of module types and ensures high efficiency in subsequent separation steps.

Figure 4 shows the main steps involved in treating a c-Si waste stream. First, the external components such as the aluminum frame, junction box, and cables are mechanically removed (Step 1). Then, the multi-layer PV laminate is separated using a high-pressure water jet, applied on the polymer backsheet side and moving in x and y directions, to strip away the layers and yield an intact, clean glass sheet (Step 2). This method can only be applied to modules with unbroken glass panes because broken glass cannot be adequately secured for water jet delamination. The removed backsheet/encapsulant layer and the solar cells are fragmented after this treatment, and the cells are isolated from the blasted polymer material (encapsulant and backsheet) through density-based separation (Step 3). Finally, several subsequent chemical steps (Step 4) are applied to dissolve the embedded metals, which are then extracted via an electrowinning process. Most of the water and chemicals used are recirculated through a closed-loop process. The resulting high-quality glass is either redirected to the flat glass industry [14] or directly reused in PV module manufacturing. Within the PHOTORAMA project, recovered glass sheets were successfully integrated into new modules, demonstrating performance comparable to those manufactured with commercial PV glass. Silicon from the solar cells is recovered to 5N purity, while silver is recovered to at least 2N. Other metals, such as indium (in the case of heterojunction technology), are also recovered depending on the composition of the initial waste stream, but process details were not provided.

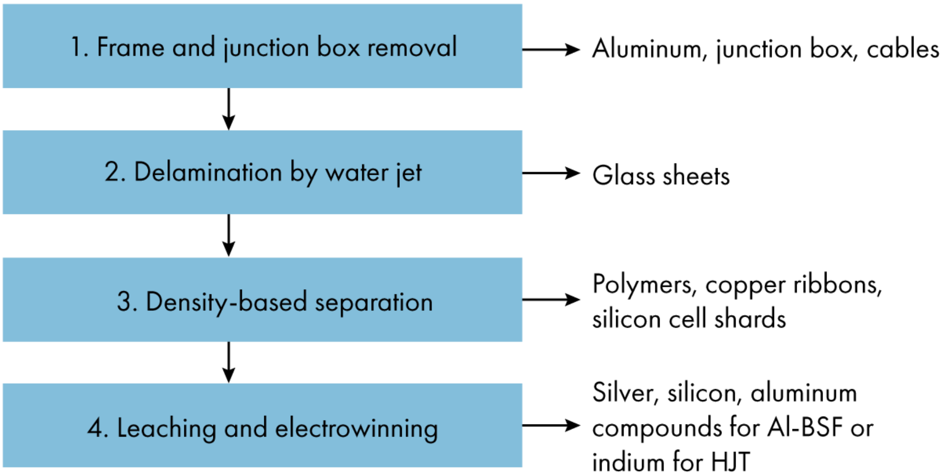


Figure 4. Process flow of PHOTORAMA's c-Si recycling, corresponding to the LCI data

Figure 5. c-Si recycling process steps (from left to right): removal of junction box and frame, water jet cleaning unit, glass after water jet cleaning (Credit: PHOTORAMA – EU project ©European Union, 2025)

LCI data are presented in Table 7. Depending on the module type and design, the process flow is adaptable and may involve different technologies and sequential steps. The technology allows processing of any monofacial c-Si technology with intact glass. The LCI data example presented corresponds to the recycling of a standard, mainstream c-Si PV module (specific type was not provided) and its associated process flow. Steps 1–3 involve mechanical and water jet processing and separation by density, while Step 4 encompasses subsequent chemical processing. In the case of heterojunction technology small amounts of indium may be present that can also be recycled.

Table 7. LCI data for c-Si recycling at PHOTORAMA demonstration center

Company	PHOTORAMA - EU Project – Demonstration center, LuxChemtech GmbH - Saxony-Anhalt plant, Querstraße 2, 39590 Tangermuende, Germany
Name	LCI of c-Si PV module recycling
Time period	2025
Geography	Germany
Technology	Mechanical and chemical recycling processes: removal of j-box and frame, water jet treatment and separation by density, and chemical leaching for silicon metal recovery
Representativeness	Discrete batches
Date	23.06.2025
Collection method	Data from recycler
Comment	National electricity mix

Plant	Unit	Amount	Comment/Reference
Capacity	t/yr	1 000	
Scale of plant			Pilot scale demonstration plant
Location			Germany
Module type processed			Monofacial glass/backsheet c-Si modules with intact glass
Time period			2025

Process (and Flows)	Unit	Amount	Comment/Reference
Steps 1–3			**Frame and junction box removal, water jet delamination and separation of materials**
Total input	t/yr	1 000	
Components/fuels			
Compressed air	m³/t	169	
Water	kg/t	130	
Output			
Cables	wt. %	0.6	To cable recycler
Frame	wt. %	12.4	To aluminium smelter
Junction boxes	wt. %	0.9	To electronic recycler
Polymers/foils	wt. %	8.7	To waste incineration
Glass cullet	wt. %	66.2	To flat glass production
Mixture of glass cullet, foil and metals	wt. %	6.0	To EEE recycler
Copper	wt. %	0.8	To smelter for copper scrap
Non-ferrous (NF) metals and silicon	wt. %	4.3	To Step 4 or 5
Step 4			**Leaching and electrowinning**
Total input	t/yr	43	Non-ferrous metals and silicon
Components/fuels			
Water	kg/t	55	
Chemicals	kg/t	13	
Output			**With reference to Step 1 input**
Non-ferrous metals	wt. %	0.3	To metal recycler

Silicon	wt. %	3.9	To metal recycler
Other	wt. %	0.1	Landfill
Total mass recovered (Steps 1–4)	wt. %	~91.2	Excluding mass of materials sent to landfill and energy recovery
Electricity consumption (Steps 1–4)		NR	Not reported

2.4 SOLARCYCLE, Odessa, TX and Mesa, AZ, U.S.

SOLARCYCLE operates two recycling facilities: one in Odessa, Texas, which is expected to have a capacity of 1 million c-Si modules per year in 2025, and another in Mesa, Arizona that is a pilot facility focused on thin-film CdTe modules. The Odessa facility is certified to meet ISO 9001, 14001, and 45001 standards. Approximately 90% of the modules processed by SOLARCYCLE come from utility-scale PV power plants, while the remaining 10% are from commercial or residential applications.

In addition to recycling, SOLARCYCLE provides EOL management services such as EOL project management support for PV plant owners, transportation of used or EOL PV modules, and testing to determine whether modules can be reused or should be recycled. Certificates of recycling with an estimate of avoided emissions are provided to ensure compliance and transparency.

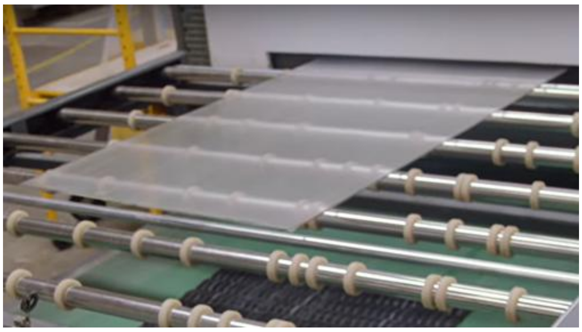
SOLARCYCLE has reused some collected PV modules to build a 500 kW PV system that provides about half of the Odessa facility's power. SOLARCYCLE's process can recover over 92 wt. % of the materials in a typical c-Si module.

Although the specific details of SOLARCYCLE's proprietary recycling process cannot be disclosed, photos of intermediate and final recycling products are available (Figure 6 a - d). A schematic of the process flow is indicated in Figure 7.

a) Laminate after glass removal

b) Shredded laminate

c) Silicon solar cell fragments after separation



d) Glass sheet

Figure 6. SOLARCYCLE's recycling process results a) laminate after glass removal, b) shredded laminate before further processing, c) silicon solar cell fragments after separation, and d) glass sheet after delamination (Credit: SOLARCYCLE)

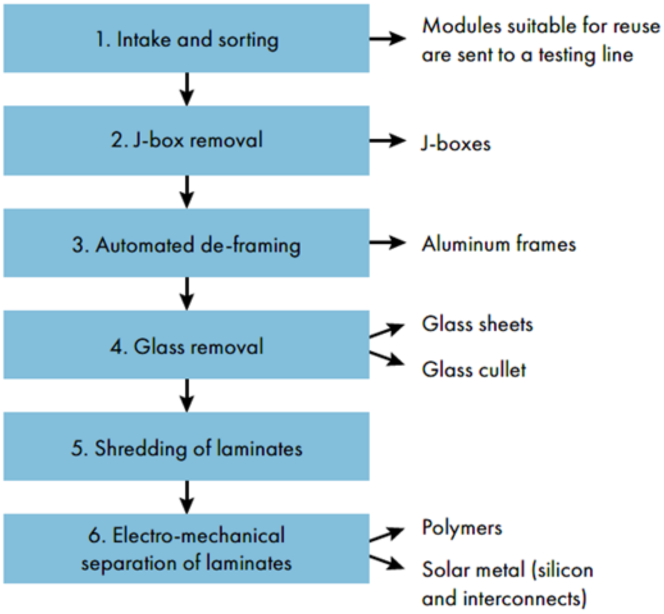


Figure 7. Schematic drawing of SOLARCYCLE's c-Si recycling process, corresponding to the LCI data

The LCI results are presented in Table 8.

Table 8. LCI results for SOLARCYCLE's recycling process

Company	SOLARCYCLE, Inc.; 8000 N. Golder Ave.; Odessa, TX 79764
Name	LCI of PV module recycling
Time period	2022–2023
Geography	USA
Technology	Mechanical recycling processes: automated j-box removal and deframing, shredding, electrostatic separation (Steps 1–6 below)
Representativeness	**Source:** Dias et al. 2022, available here: https://www.sciencedirect.com/science/article/pii/S1364032122007821 The referenced process is considered representative of SOLARCYCLE's c-Si PV module recycling process at its facility in Odessa, TX. One difference implemented here is that virtually 100% of the glass from a solar module is extracted, recovered, and sold, instead of landfilled, as suggested in the paper. This deviation from the published data is noted in the glass cullet output for Step 6.
Date	23.07.2024
Collection method	Data from recycler
Comment	National electricity mix

Plant	Unit	Amount	Comment/Reference
Capacity	t/yr	20 000	Based on TX facility. Capacity in t/yr is based on nameplate capacity of 1M modules, assumed to be 20 kg each.
Scale of plant			Commercial plant
Location			Odessa, TX

Module type processed			C-Si glass/backsheet modules with intact and broken glass
Time period			Since 2022

Process (and Flows)	Unit	Amount	Comment/Reference
Steps 1–3			**Deframing and j-box removal**
Total input	t	1	
Components/fuels			
Diesel/oil consumption	l/t	1.14	Forklift transportation
Output			
Cables and J-box	wt. %	1.00	100% recovery of cables and J-boxes. Sent for recovery of copper wire.
Frame	wt. %	18.00	100% recovery of frame. Sent for aluminum recycling.
Steps 4–5			**Glass removal, shredding**
Total input	t	0.81	Output from Steps 1–3
Output			
Mixture of glass cullet, foil and metals	wt. %	76.14	Entire laminate continues on to Step 6 besides dust.
Dust	wt. %	4.86	Landfill
Step 6			**Separation of materials**
Total input	t	0.7614	Output of Step 5
Output			
Non-ferrous metals	wt. %	2.47	Recovery from initial 761.40 kg input, the non-ferrous fraction contains: 65.96% of input silicon 91.86% of input silver

			72.07% of input aluminum 94.67% of input copper recovered 1.72% of input polymer ends up in this fraction Metals recovered in this fraction are considered ore grade, sent for further refining
Glass cullet	wt. %	69.3	99% of glass recovered as sheet/cullet throughout process. Not represented in published LCA but accurate to operations as of the time period of this LCI table. No significant net change to the total energy consumption of process associated with this change in final outputs.
Mixture of polymer, glass cullet, foil and metals	wt. %	2.09	This fraction contains a majority of the polymer with some glass and metals. This output was previously reported as landfilled in Dias et al. 2022 but is now recovered.
Dust	wt. %	2.28	Landfill
Total mass recovered (Steps 1–6)	wt. %	~92.86	Excluding mass of materials sent to landfill
Electricity consumption (Steps 1–6)		NR	Not reported

2.5 SPR, Solarpanelrecycling.com, Salisbury, NC, U.S.

The parent company of solarpanelrecycling.com (SPR), Powerhouse Recycling, was founded in 2008 and has since become one of the largest e-waste recyclers in the USA. In 2018, they were approached by a utility company to recycle solar modules. After 4–5 years of research, they developed a solution they call “true recycling” with “clean commodity separation,” leading to the establishment of SPR in 2023.

As of late-2024, four PV module recycling lines are in operation in three locations:

- Salisbury, North Carolina (NC) (2 proximate facilities) – original PV recycling location.
- Georgia (GA) – colocated at a third-party facility that uses the recovered solar glass (details not disclosed).
- Texas (TX) – custom-designed line processes bifacial modules, which represents about 80% of the intake at this facility.

Each location has the capacity to process 21 000 t/yr, and across all facilities 14 665 t were processed from January 2023 through October 2024. While the current commercial recycling lines are designed for silicon-based modules, SPR also accepts thin-film modules and is actively pursuing R&D to develop custom recycling solutions.

The SPR team’s role in EOL management often starts in the solar field, following PV installers that are dismantling solar systems to palletize, band, and load PV modules for shipment to one of their recycling facilities. SPR’s transfer-based exclusion permit in applicable states allows them to bypass a hazardous waste determination (i.e., U.S. Environmental Protection Agency Toxicity Characteristic Leaching Procedure, or EPA TCLP, test).

On-site, SPR pre-sorts reusable modules, separating out ones with cracks or other visual defects. Unlike in the EU, where the Waste from Electrical and Electronic Equipment (WEEE) Directive mandates and subsidizes tracking by barcode, SPR typically tracks module quantities in aggregate. In a couple of projects where customers required tracking, SPR scanned each PV module barcode.

Artificial intelligence (AI) and 3D mapping technologies are utilized to scan a representative module in each batch, enabling communication and coordination across the automated recycling line (Step 1). The process begins with a robotic claw removing the junction box, followed by automated frame removal (Step 2). A laser is used to cut the leading edge of the module, and glass is removed via heat and/or mechanical pressure (Step 3). Glass is removed into industrial bulk bags (“super sacks”), with the equipment set to remove glass as close to the Si layer as possible without removing the Si itself. The resulting size-reduced shredded, glassless laminate is then fed into secondary shredders, grinding it to powder form (Step 4). Various in-house technologies are utilized to separate Si/Ag, Cu, and plastic cleanly from the recycling line (Step 5).

Processing time is 30–60 seconds/module (with manual loading) for the PV recycling line, and further development is underway. The third-party glass off-taker needs to do further processing due to the size of the glass pieces produced (both larger and smaller than specification). SPR achieves a constant Si purity within a variation of less than ±0.5 wt.% of the average. A third-party European Union (EU)-based Si purification partner is evaluating use of recovered solar Si in batteries, aimed at making them less volatile and longer lasting.

Process flows and material output streams are shown in Figure 8 . An expanded schematic provided by SPR is located in Appendix B.2. Glass recovery rates are 98 wt. % and 90 wt. % for single-sided (glass/backsheet) and bifacial (glass/glass) modules, respectively. About 98%

of silicon is recovered at approximately 70% purity. The reported recovery rate for copper and other trace metals exceeds 99%, with a purity of about 99%. The polymer recovery rate is also 99%, with a purity of 99%. PV module recycling clients receive a bill of lading when the commodities generated (i.e., glass, metals, silicon) are sent to secondary market companies.

In addition to PV modules, SPR also processes balance of system (BOS) components like trackers, inverters, and racking. While battery recycling is not performed in-house, SPR currently facilitates this service through external partnerships.

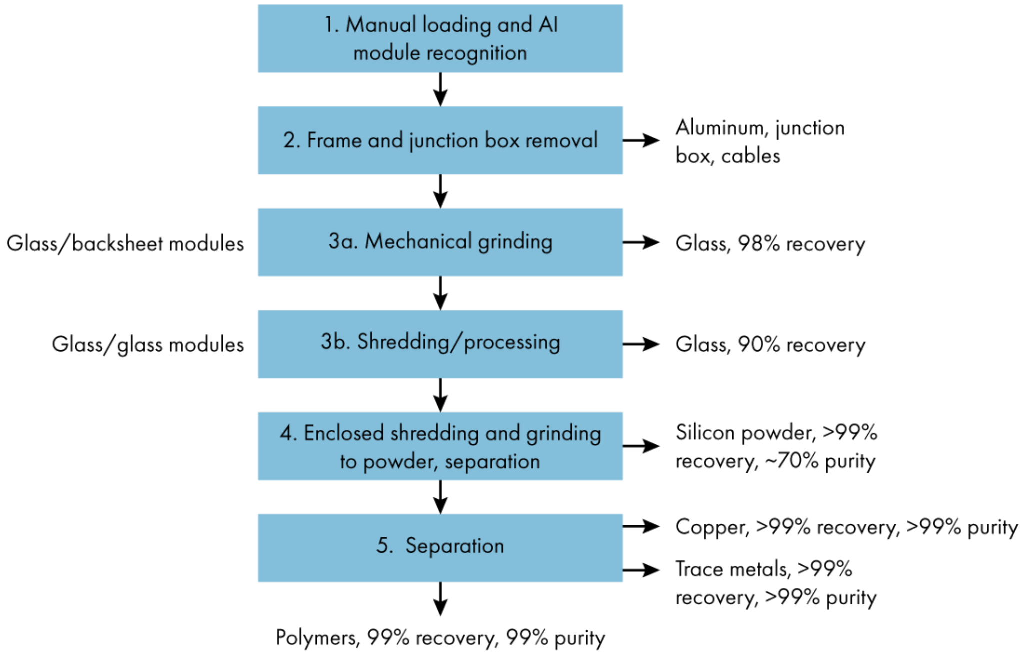


Figure 8. Process flow of SPR's c-Si module recycling facility in NC, corresponding to the LCI data

The corresponding LCI results for the NC facility are reported in Table 9. LCI data are reported in aggregate across all process steps outlined in Figure 8, rather than for individual process steps. Two additional facilities in GA and TX with similar designs are listed in parentheses and included in the reported capacity.

Table 9. LCI results for SPR's recycling process

Company	Solarpanelrecycling.com (SPR), 1325 Litton Drive, Salisbury, NC 28147 USA
Name	LCI of PV module recycling
Time period	2023–2024
Geography	USA
Technology	Mechanical recycling processes: automated deframing and j-box removal, grinding, shredding, and separation processes
Representativeness	Material recovery data based on NC location; batch and continuous processes
Date	10.7.2024
Collection method	Data from recycler

Plant	Unit	Amount	Comment/Reference
Capacity	t/yr	63 000	21 000 t/yr/per plant
Scale of plant			Commercial plants
Location			NC, USA (capacity data include TX and GA facilities)
Module type processed			Crystalline silicon glass/backsheet modules (glass condition not specified)
Time period			January 2023 to October 2024

Process (and Flows)	Unit	Amount	Comment/Reference
Step 1			**Aggregated data for all recycling steps**
Total input	t/yr	14 665	

Output			
Cables	wt. %		In non-ferrous: 100% cable removal & recovery, sent to copper smelter
Frame	wt. %		In non-ferrous: 100% aluminum frame removal & recovery, sent to foundry, aluminum robotic frame removal with AI
Junction boxes	wt. %		In plastics, non-ferrous and ferrous: 100% junction box removal & recovery, sent to SPR's e-waste shredder/separator
Ferrous (FE) metals	wt. %	0.5	100% ferrous removal & recovery, sent to steel mill after in-house shredding
Non-ferrous metals	wt. %	8	100% aluminum frame removal & recovery, sent to foundry
Polymers/foils	wt. %	6	100% polymer removal & recovery, utilizes air flow separation
Glass cullet	wt. %	80	98 wt. % of glass is removed, utilizing mechanical grinding.
Mixture of glass cullet, foil and metals	wt. %	0.25	Represents other 2% of glass/foil mixed
Dust	wt. %	0.25	Captured in dust collection systems and landfilled
Silicon	wt. %	5	98 wt. % silicon captured through separation steps
Total mass recovered (Steps 1–5)	wt. %	~99.75	Excluding mass of materials sent to landfill
Electricity consumption (Steps 1–5)		NR	Not reported

2.6 9-Tech, Venice, Italy

The startup company 9-Tech (www.9tech.it), located in Eraclea, Italy, operates a small pilot plant at technology readiness level (TRL) 6 in Venice, Italy, with an annual processing capacity of 33 t/yr. In 2023, the plant processed 1.1 t.

9-Tech is currently working on a publicly-funded project to build a 4 500 t/year recycling plant for PV modules in Porto Marghera (Venice). Similar to the pilot, the industrial plant will implement three main treatment steps with some advancements (Figure 9):

- **Recognition and dismantling**: Automatic machinery for module type recognition and disassembly of the aluminum frame and junction boxes (Steps 1–2).
- **Thermo-mechanical treatment**: Furnace and mechanical separation system for the recovery of copper strips, glass, and PV cells (Step 3).
- **Chemical and ultrasound treatment**: PV cell treatment system with an ultrasonic system for silver recovery (Step 4).

The pilot system comprises two containers: one for dismounting and storage, and one for thermo-mechanical treatment. External components include a compressor, liquified petroleum gas (GPL) tanks, an aspirator, a heat exchanger, and a scrubber system. Treatment steps and outputs are illustrated in Figure 9. A process flow schematic with images is located in Appendix B.3.

The pilot facility is divided into five areas within two shipping containers:

First container:

- Area A: Storage area for waste awaiting treatment (R13), with an extension of 4.5 square meters, capable of holding 25 stacked PV modules, with a maximum storage capacity of 500 kg.
- Area B: Initial disassembly area for PV modules, performed by manual cutting, covering 2.4 square meters.
- Area C: Storage area for waste produced during the first phase of treatment (aluminum frame and junction boxes), covering 3.0 square meters.
- Area D: Storage area for waste produced by heat treatment and mechanical separation, covering 1.5 square meters.

Second container:

- Area E: Area for performing heat treatment and mechanical separation of components, developed entirely within the machinery compartment.

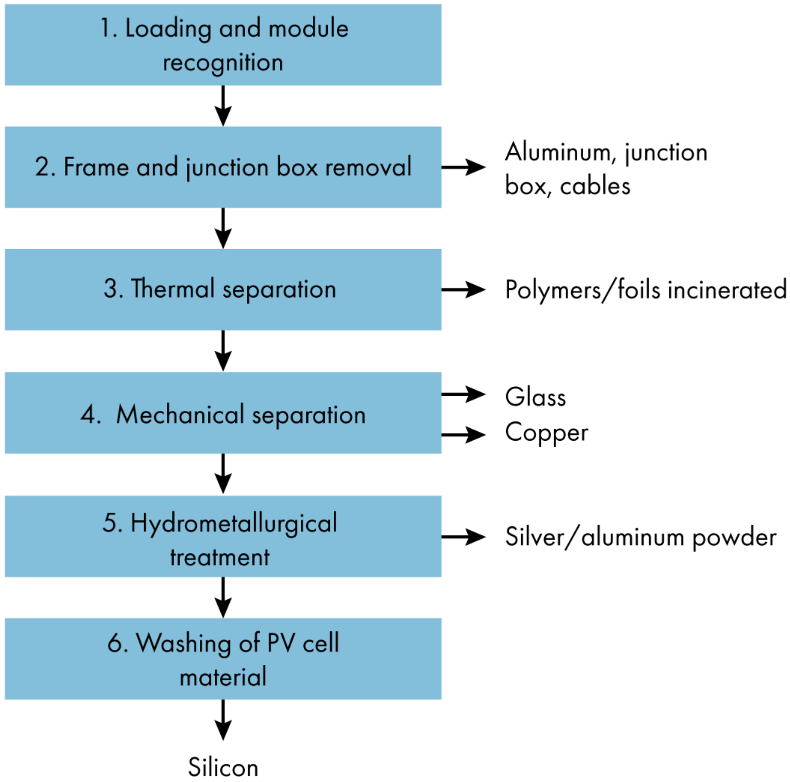


Figure 9. 9-Tech recycling process steps, corresponding to the LCI data

The phases of the continuous process for c-Si modules are as follows. The manual steps are automized in the industrial plant:

Recognition and dismantling (Steps 1–2)

- **Dismantling:** Manual removal of the aluminum frame and the junction box on a suitable worktable. AI recognition and automation will be implemented in Porto Marghera plant.
- **Cutting:** Manual/automized cutting of the module into 33 cm strips (technology not specified). During this phase, the glass, if still intact, generally shatters; otherwise, it is shattered with a hammer to achieve a suitable size for subsequent treatments. The shattered glass remains attached to the EVA encapsulant.

Thermo-mechanical treatment (Steps 3–4)

- **Combustion:** The module is positioned on the conveyor belt (manual operation) and automatically transported inside the furnace where plastic components (EVA and polymeric backsheet, which is typically made of Tedlar) are incinerated using patented combustion technology. The backsheet and the encapsulation layer (EVA) are completely degraded at temperatures exceeding 500°C.
- **Energy recovery:** The energy produced by burning the polymer fraction is recovered and reused via a heat exchanger.
- **Removal of copper strips:** Upon exiting the furnace, the conveyor belt transports the mixed material towards a machine with counter-rotating rollers that remove the copper wirings.
- **Separation of glass from cells:** The mixed material, primarily composed of glass and cells, passes through a series of two vibrating screens. The first separation sieve divides the powder portion (mainly cells and glass) from the coarse fraction. The material is then

directed onto a specially designed sieve in the glass separation system. As the sieve vibrates, the two fractions are collected in separate drawers.

Chemical and ultrasound treatment (Steps 5–6)

- **Chemical and ultrasound treatment:** The recycling process for PV cells involves an ultrasound treatment performed in a specially designed bath. This reactor employs high-power ultrasound without damaging the PV cells. The patented method and equipment combine an aqueous solution of citric acid with ultrasound technology to efficiently remove silver and most of the aluminum paste from PV cells. Unlike conventional leaching processes that use nitric acid, this approach preserves silver in its solid state, avoiding direct chemical interaction for silver leaching. The cavitation effect generated by ultrasound also facilitates the removal of the aluminum paste. The suspension with solids is then separated from the liquid.

Junction boxes, aluminum frames, copper ribbons, glass pieces, silicon, and silver are recovered with high yield and purity: 99 wt. % recovery of aluminum with a purity of 99%, 100 wt. % of junction boxes, 99 wt. % of glass with a purity of 99%, 95 wt. % of copper ribbons with a purity of 95%, 95 wt. % of silicon with a purity of 95%, and 90 wt. % of silver. The silver is recovered along with aluminum in the form of metallic powder. Specifically, the mixed powder derived from the ultrasound process consists of 10% silver and 90% aluminum, with the silver present in this powder having a purity of up to 95%.

Junction boxes are sent to specialised treatment facilities where copper wires can be recovered. Aluminum frames, copper ribbons, and glass are sent directly to respective recyclers. Silicon is sent to aluminum, steel, or iron foundries, or to specialised companies for further purification to be reused in the battery sector. Finally, the silver and aluminum powder is sent to precious metal refiners to extract the silver.

The LCI results are presented in Table 10. A comprehensive life cycle assessment has been published recently [15].

Table 10. LCI results for 9-Tech's recycling process

Company	9-Tech srl, Via Triestina Bassa 74, 30020, Eraclea (VE)
Name	LCI of PV module recycling
Time period	2023–2024
Geography	Italy
Technology	Mechanical, thermal, and chemical recycling processes: deframing and j-box removal, thermo-mechanical treatment, and chemical and ultrasound silver recovery
Representativeness	Continuous batches including box and frame removal, thermal, mechanical, and chemical treatment
Date	10.11.2024
Collection method	Published data provided by 9-Tech
Comment	National electricity mix

Plant	Unit	Amount	Comment/Reference
Capacity	t/yr	33	The pilot plant can treat 100 kg/day (8 hour). Assuming 330 working days per year, the maximum capacity would be 33 t/yr.
Scale of plant			TRL6 pilot plant
Location			Italy
Module type processed			Crystalline silicon modules (whether glass/glass or glass/backsheet not specified) with intact and broken glass
Time period			2023–2024

Process (and Flows)	Unit	Amount	Comment/Reference
Steps 1 and 2			**Module recognition, frame and box removal**
Total input	t/yr	33	c-Si PV waste
Components/fuels			
Electricity consumption	kWh/t	0	In the pilot plant, the disassembly of the aluminum frame and junction box is performed manually; therefore, there is no energy consumption.
Output			
Frame	wt. %	19.1	
Junction boxes	wt. %	1.8	
Other	wt. %	79.1	PV sandwich sent to furnace
Step 3			**Thermal separation**
Total input	t/yr	26.1	Input from Step 2
Components/fuels			
Electricity consumption	kWh/t	98	Electricity consumption for extractor fan and compressor
Liquefied petroleum gas (LPG)	kWh/t	250	The pilot plant uses LPG to maintain the correct temperature inside the combustion chamber.
Filters	t/t	0.1	
Active carbon	t/t	0.001	
Output			
Polymers/foils	wt. %	10.3	Inside the furnace the polymers of the panel are burned; therefore, material is lost
Other	wt. %	68.8	Mixed inorganic materials

Step 4			**Mechanical separation**
Total input	t/yr	22.7	Input from Step 3
Components/fuels			
Electricity consumption	kWh/t	6	2.8 kWh/t are consumed to separate the copper ribbons, 1.4 kWh/t are used to separate the fine fraction, and 1.8 kWh/t are consumed to separate the glass from the PV cells
Output			
Non-ferrous metals	wt. %	1	Copper ribbons
Glass cullet	wt. %	63	
Dust	wt. %	1.7	
Other	wt. %	3.1	PV cells (made of Si, Ag, and Al) to Step 5
Step 5			**Hydrometallurgical treatment**
Total input	t/yr	1	Input from Step 4
Components/fuels			
Electricity consumption	kWh/t	6	Electricity consumed by the ultrasound bath
Citric acid	t/t	0.005	
Water	t/t	0.09	
Output			
Non-ferrous metals	wt. %	2.8	Silicon wafer fragments to Step 6
Other	wt. %	0.3	Al/Ag powder
Step 6			**Washing of PV cells**
Total input	t/yr	0.9	Silicon wafer fragments without Al/Ag

Components/fuels			
Electricity consumption	kWh/t	2	
Water	t/t	0.04	
Output			
Non-ferrous metals	%	2.8	Silicon
Total mass recovered (Steps 1–6)	wt. %	~88	Excluding mass of materials sent to landfill or combusted
Electricity consumption (Steps 1–6)	kWh/t	112	

3 DISCUSSION OF LCI RESULTS

3.1 Data Quality and Limitations

This report includes data from five new PV module recycling facilities, based on information provided and approved by the contributing organisations. These include two new commercial operations (SOLARCYCLE and SPR) and first-ever released LCI data from three pilot recycling facilities (9-Tech, PHOTORAMA CI(G)S and c-Si). Aggregated data from First Solar's global CdTe recycling operations are also included.

New data were not obtained from recyclers that participated in the 2024 study, except for First Solar. Advancements achieved by these recyclers since data collection for the 2024 publication are not included. A summary of LCI data reviewed in this section is summarized in Table 11.

Table 11: Summary of recycler LCI data presented in this report

Company/ Consortium	Facilities Represented in LCI Data	Processing Capacity (t/yr)	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	✓	
Envie & ROSI **	France	3 000	c-Si		✓
Flaxres **	Germany	1 000	c-Si		✓

LuxChemtech **	Germany	1 000	c-Si		✓
Reiling **	Germany	50 000	c-Si		✓
ROSI **	France	3 000	c-Si		✓
Tialpi **	Italy	3 000	c-Si		✓

* See Table 12 for a comparison of LCI data in the 2024 publication and the current study.

** LCI data from 2024 publication [5]

The LCI survey results presented in this study, along with those from the 2024 study [5], are a mix of measurements from pilot-scale systems and more mature, commercial-scale operations, as shared by the contributing organizations. Many data gaps could not be fully resolved due to limitations in the data provided or constraints in the information obtained through expert interviews. In some cases, LCI data do not cover the entire recycling process. For example, Tialpi's data from the 2024 study include only glass removal and backsheet separation (even though they have investigated the full process sequence, including silver recovery via electrolysis from chemical treatment of the solar cells).

The data presented provide a snapshot of the participating recyclers' operations during 2023–2024, and in some cases from 2025 (e.g., PHOTORAMA). All recyclers are continuously improving their processes, expanding capacity, and introducing advanced or new technologies. Despite these variations, the results offer insights into diverse recycling approaches at different stages of maturity, along with associated recovery rates and energy consumption.

Direct comparison of LCI data across the two studies is challenging due to several nuances and inconsistencies. These differences apply to all nine respondents and the modeled Envie & ROSI combined process, as described below.

Process Scale and Throughput: The capacity of the processes varies significantly, from pilot-scale batch testing of 7.5 t/yr (e.g., Flaxres) to commercial-scale plants with capacities up to 50 000 t/yr (e.g., Reiling). Some data reflect projections for facilities or process steps still under construction or in ramp-up phases (PHOTORAMA, 9-Tech), whereas all others are based on actual data from established facilities. One LCI case from the 2024 study was modeled using Envie's application of the commercial NPC hot blade cutting process, combined with preliminary data from ROSI.

System Boundary: Table 13 summarizes all LCI data for c-Si modules. To facilitate comparison of data within the graphical representations (Figure 10 and Figure 11), the LCI data are applied only at the point in each process where a 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, are excluded from the summary figures because these LCI data are not available for all recycling facilities. Recycling steps that are omitted from the figures are footnoted in each figure caption. One reason that First Solar's LCI is not included in Table 13 and instead in Table 12 is that its LCI data for CdTe module recycling encompass the entire recycling process, including CdTe recovery and third-party refining of the USM to semiconductor-grade CdTe, reflecting an extended system boundary. This makes a direct comparison challenging.

Variations in Module Type: Differences in the reported percentages of cables, frames, junction boxes, and non-ferrous metals in the lower portion of Table 13 are largely attributable to variations in module types and the specific output fractions in which materials were collected during the reporting period. For example, SPR mechanically grinds single-sided (glass/backsheet) modules and shreds bifacial (glass/glass) modules. Both cullet streams are then shredded and ground into powder, with materials separated by their physical properties.

The different types of modules processed at each facility require distinct recycling methods, resulting in variations in the metrics and values reported. While eight of the nine facilities process c-Si modules, c-Si module composition varies across manufacturers, models, and vintages. LCI data reported by each recycler are based on one or more specific module compositions that they have processed. First Solar's CdTe modules are glass/glass construction, resulting in a higher percentage of glass output (94%) compared with glass/backsheet modules (66.2–69.3%), where glass represents a smaller share of total module mass. Similarly, PHOTORAMA's CI(G)S pilot processes glass/glass CI(G)S modules with 79.2% glass output (see Section 2.2).

Reported wt. % glass recovery varies across processes, but these values are not directly comparable. Tialpi, Reiling, and Flaxres report similar wt. % glass outputs per metric ton of module input, while LuxChemtech and ROSI, with and without Envie, report slightly higher values. However, differences in reported yields may reflect variations in input module glass thickness and impurity levels in the recovered glass rather than inherent process performance. Thermal and advanced separation approaches, such as flash lamp separation and water jet cleaning, can achieve high glass yield and purity but may require more energy or intact modules as feedstock (e.g., flash lamp, water jet, infrared light, and blade delamination technologies).

Unspecified Output Stream Fates: 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.

3.2 Comparison of LCI Data

The data collected are summarized in Table 12 and Table 13. Electronic versions of the LCI data tables are available at IEA PVPS (http://www.iea-pvps.org; select Reports under Task 12).

Table 12. Comparison of First Solar LCI Data between 2021 (2024 IEA PVPS publication [5]) and 2024 update (this report)

		First Solar 2021 (2024 IEA PVPS publication [5])	First Solar 2024 Update (this report)
	Unit	**Amount**	**Amount**
Capacity	t/yr	50 000	112 000
Scale of plant		4 commercial recycling plants	6 commercial recycling plants
Location		USA, Malaysia, Vietnam, Germany	USA, Malaysia, Vietnam, Germany, India,

Module type		CdTe	CdTe
Time period		2021	2024

Process (and Flows)	Unit	Amount	Amount
Annual Throughput			
Total input	t/yr	41 921	40 400
Process steps included		Mechanical, chemical	Mechanical, chemical
Components/Fuel			
Electricity	kWh/t	265	265 *
Output			
Metals (frame and junction box, not including semiconductor materials)	wt. %	1.5	0.6
Semiconductor materials	wt. %	0.4	0.5
Glass	wt. %	87	94
Other materials	wt. %	0.3	0.5
Encapsulant material	wt. %	Not provided	0.2
Dust, glass fines, and encapsulant material	wt. %	Not provided	1
Total mass recovered	wt. %	Not provided	~95

* The reason the electricity consumption is the same is that no new data were provided; an older data source was cited instead.

Table 13. LCI data for c-Si recycling facilities (current study and 2024 study)

Notes: Blank fields indicate information is not available. Materials not recovered or incinerated may be present in polymer, pyrolyzed, mixed, and other fractions (see Figure 10).

		LCI Data Contributors for this Report				LCI Data Contributors for 2024 IEA PVPS publication [5]					
	Unit	PHOTORAMA (c-Si)	SOLARCYCLE, Inc.	SPR	9-Tech	Reiling	ROSI	Envie & ROSI	Tialpi	LuxChemtech	Flaxres
Capacity	t/yr	1 000	20 000 *	63 000 **	33	Year 2022–2023: 10 000 Year 2024: 50 000	3 000	3 000	3 000	1 000	1 000
Scale of plant		Manual/automated pilot	Automated commercial	Automated commercial	Manual/ automated pilot	Automated commercial	Automated pilot	Modelled combination: Envie commercial, ROSI pilot	Automated pilot	Manual/partially-automated pilot	Automated pilot
Process type(s)		Mechanical, chemical, optical	Mechanical, thermal	Mechanical	Mechanical, thermal (furnace), chemical, ultrasound	Mechanical	Mechanical, thermal (pyrolysis), chemical	Mechanical, thermal (hot blade, pyrolysis), chemical	Mechanical, thermal, chemical	Mechanical, chemical	Mechanical, optical (light pulse)
Location		Tangermünde, Germany	Texas, USA	North Carolina, USA (Texas & Georgia)	Venice, Italy	Marienfeld, Münster, other, Germany	La Mure, France	Saint-Loubès & La Mure, France	Mottalciata (Biella), Italy	Tangermünde, Germany	Dresden, Germany
Module type processed		c-Si, glass/ backsheet, intact glass	c-Si, glass/backsheet, intact and broken glass	c-Si, glass/ backsheet and glass/glass (glass condition not specified)	c-Si (whether glass/glass or glass/ backsheet not specified), intact and broken glass	c-Si and silicon-based thin film (whether glass/glass or glass/ backsheet not specified), intact and broken glass	c-Si, glass/ backsheet and glass/ glass, intact and broken glass	c-Si, glass/ backsheet, intact glass	c-Si, glass/ backsheet, intact and broken glass	c-Si, glass/ backsheet, intact glass	c-Si (whether glass/glass or glass/ backsheet not specified; glass condition not specified)
Time period		2025	2022–2023	2023–2024	2023–2024	2022	2022–2023	2022–2023	2022	2021–2022	2022

		LCI Data Contributors for this Report				LCI Data Contributors for 2024 IEA PVPS publication [5]					
	Unit	**PHOTORAMA (c-Si)**	**SOLARCYCLE, Inc.**	**SPR**	**9-Tech**	**Reiling**	**ROSI**	**Envie & ROSI**	**Tialpi**	**LuxChemtech**	**Flaxres**
Total input	t/yr	1 000	12 733 §	14 665	33	4200	3 000	2 850	1 000	1 000	7
Process steps included		Automated deframing and j-box removal + water jet + mechanical separation + chemical leaching and electrowinning (Steps 1–4, Figure 4)	Automated deframing and j-box removal + glass removal (process not disclosed) + shredding + electro-mechanical separation (Steps 1-6, Figure 7)	Automated Al-assisted recognition, deframing, and j-box removal + laser cutting + grinding and shredding + separation (Steps 1–5, Figure 8)	Manual deframing and j-box removal + thermal separation + mechanical separation + hydrometal-lurgical treatment + washing (Steps 1–6, Figure 9)	Crushing and shredding + automated frame extraction (j-box removal process unknown) + manual sorting + mechanical separation (Steps 1-12, Figure 5, see [5])	Deframing and j-box removal (unknown automation) + pyrolysis + mechanical separation + leaching (Steps 1–6, Figure 11, see [5])	Automated deframing and j-box removal + hot blade cutting + pyrolysis + mechanical separation (Steps 1–4 Envie + Steps 3–6 ROSI, Figure 12, see [5])	Deframing and j-box removal (unknown automation) + infrared heating, blade, and mechanical separation + leaching (Steps 1–5, Figure 13, see [5])	Deframing and j-box removal (automation unknown) + water jet + mechanical separation + leaching (1–6, Figure 7, see [5])	Deframing and j-box removal (automation unknown) + light pulse + mechanical separation (Steps 1–6, Figure 9, see [5])
Components/fuels											
Electricity	kWh/t				112	60		52	136	130	50
CNG/LNG	kWh/t				250	0.36			None	None	
Compressed air	m^3/t	169									
Water	kg/t	130									
Diesel/oil consumption	l/t				None	2.5		15	0	None	
Output* **											
Cables	wt. %	0.6	1	#		0.65	0.85	0.85	1	0.42	1
Frames	wt. %	12.4	18	#	19.1	11.5	7.79	7.79	15	11.07	17

		LCI Data Contributors for this Report				LCI Data Contributors for 2024 IEA PVPS publication [5]					
	Unit	PHOTORAMA (c-Si)	SOLARCYCLE, Inc.	SPR	9-Tech	Reiling	ROSI	Envie & ROSI	Tialpi	LuxChemtech	Flaxres
Junction boxes	wt. %	0.9	Included with cables	#	1.8	0.35	4.3	4.3	1	0.39	1
Ferrous metals	wt. %			0.5	0	0.2	0	0	0	0	
Non-ferrous metals	wt. %	1.1	2.47	8	3.8	1.2	0.87	0.85	0	4.05	3
Polymers/ foils	wt. %			6	0		0	0	14	11.13	12
Glass cullet	wt. %	66.2	69.3	80	63	64	71.42	72.06	65	72.5	66
Mixture of glass cullet, foil, and metals	wt. %	6	2.09	0.25		6.6	3.4	0	3	0	
Dust	wt. %		7.14	0.25	1.7	1.5			0		
Other	wt. %	4.1		5	0.3		4.87†	3.18‡	1		
Pyrolised or combusted material	wt. %	8.7			10.3	14	6.5	10.97		0.44	
Total	wt. %	100	100	100	100	100	100	100	100	100	100

* Capacity in t/yr is based on nameplate capacity of 1M modules, assumed to be 20 kg each.
** Total capacity across 3 locations; process data is based on NC location; other facility locations are shown in parentheses
*** Output materials are not necessarily recovered for subsequent material use and may instead be directed to energy recovery (e.g., incineration) or landfill disposal. See the information reported for each recycler in Section 2 regarding the fate of each output stream, with additional context provided in Figure 10 and the accompanying discussion.
† 2.87% from silicon/silver, 2% other, unspecified
‡Silicon and silver
§ Calculated from reported data ("Diverted 28,071,002 pounds of waste from landfills") https://www.solarcycle.us/press-releases/solarcycle-2024-annual-impact-data, accessed 2025-10-28
# SPR included this in non-ferrous fraction

Materials reported in the Output section of Table 13 are not necessarily recovered for subsequent material use and may instead be directed to energy recovery (e.g., incineration) or landfill disposal. Section 2 presents the information reported by each recycler regarding the fate of individual output streams, with additional context provided in Figure 10 and the accompanying discussion.

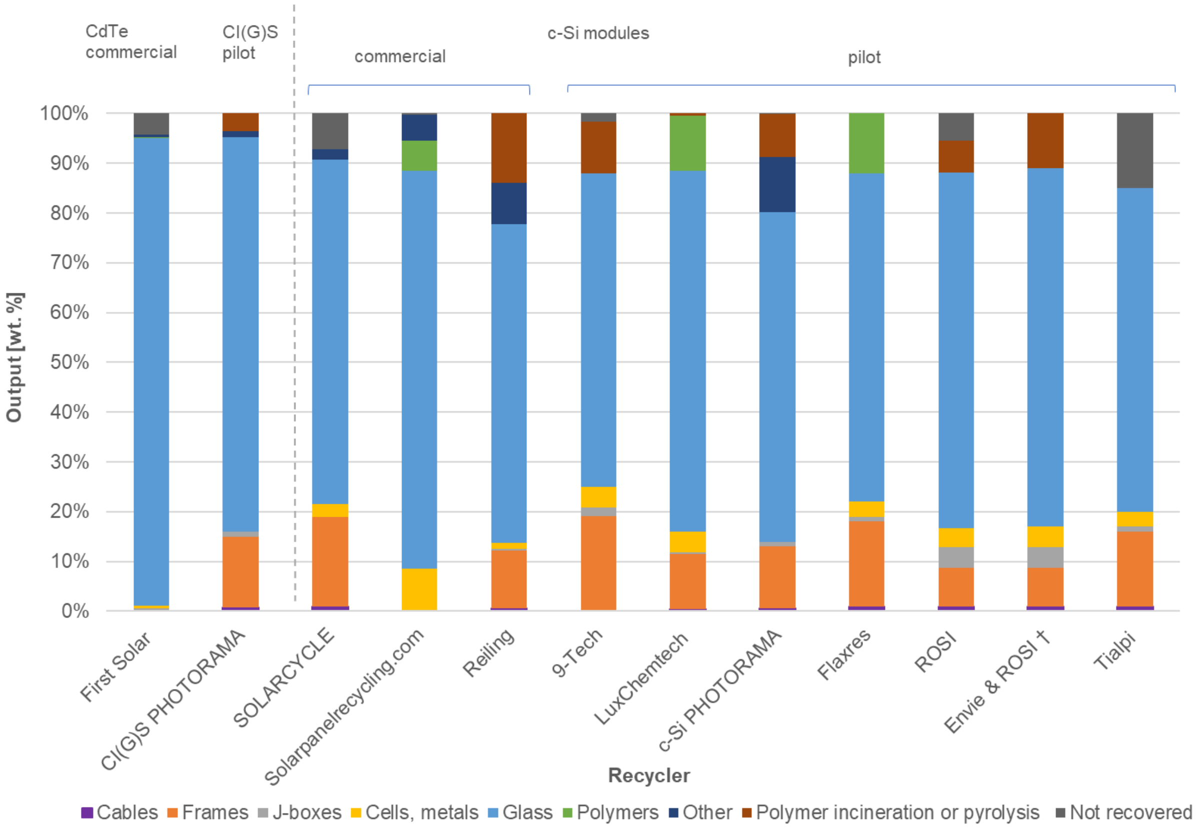
As noted previously, each recycling process assumes a significantly different input mix, primarily based on the type of module. Output fractions vary due to differences in module type and design, process sequence, and glass content (e.g., glass/glass vs. glass/backsheet laminates). To enable comparison across recyclers, the reported outputs shown in Figure 10 are normalized to 100 wt. % 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 of input. All respondents recover the frames (if present), cables, and junction boxes (j-boxes), though the proportions vary based on the module type. Foil and polymer (whether it is recycled, recovered, incinerated, or landfilled) is relatively consistent across processes (~0–15 wt. %), depending on the total polymer content of the input modules and the composition of the polymer output fraction which might contain glass, metal, or solar cell residues. The "other" materials fraction (~0–12 wt. %, shown in dark blue in Figure 10) varies significantly between respondents and may contain mixtures of cullet, foil, metals, or dust.

In addition to the data quality and limitations outlined in Section 3.1, process-specific notes include:

- Frame recovery ranges from 0% (frameless modules) to about 20 wt. %, depending on module design.
- ROSI's process fully pyrolyzes the foil fraction, which includes pyrolyzed polymer residues and dust from mechanical sortation that are not recovered.
- 9-Tech, PHOTORAMA (c-Si and CI(G)S), and Reiling completely incinerate polymers, and LuxChemtech incinerates trace amounts of dust.
- Pure mechanical processes (e.g., shredding and grinding) do not fully separate glass from polymers, resulting in mixed fractions and residual dust, usually incinerated or landfilled.

To enable comparison in Figure 10, limited interpretations were applied to group outputs listed in Table 13 into the "Cells, metals," "Other," and "Not recovered" categories. Polymers were classified as "Polymer incineration or pyrolysis" only when this treatment pathway was explicitly specified by the recycler. Similarly, materials categorized as "Not recovered" include only those identified by the recycler as waste or residual fractions not reported as recovered. Appendix D provides a tabulated dataset containing the underlying values used in Figure 10.

Also of note, lead (Pb) is frequently present in small concentrations in the solder alloy covering the Cu interconnectors. Consequently, some Pb is collected in the Cu fraction and treated during Cu refining. Trace amounts may also be present as PbO glass frit on the solar cells. In some recycling processes, Pb may be precipitated from chemical or wastewater treatment streams for disposal, although this was not reported by the recyclers in this study [16].



† Envie uses NPC's commercial process, but the combined Envie & ROSI process is considered a pilot.

Figure 10. Relative output composition (normalized wt. %) for 12 recycling processes by 10 recyclers using significantly different input mixes (module type). For c-Si recyclers, the system boundary is defined as the point in the process at which the cell fraction (including metals) is separated from the glass and polymers.[3] The system boundary for PHOTORAMA's CI(G)S LCI data is up to and including recovery of the unrefined semiconductor material (Cu, In, Ga, Se) (Steps 1–5). First Solar's LCI data are up to and including recovery of the unrefined CdTe semiconductor and third-party refining of the USM to semiconductor-grade CdTe for use in new solar modules (Steps 1–6). SPR's LCI data are based on framed modules, but the recovered Al frame material is captured in the NF metals output.

Note: Data for Reiling, LuxChemtech, Flaxres, and Tialpi are sourced from the 2024 LCI report [5]. LuxChemtech data from the 2024 report do not reflect the maturity level, equipment, or facilities associated with PHOTORAMA. First Solar's LCI data are for frameless modules. LCI data for PHOTORAMA CI(G)S is based on modules with back rails; this material is included in the frames output.

Table 14 summarizes available information on metal and semiconductor recovery across respondents. In addition to recovery rates, the quality of recovered materials influences the economics of PV module recycling. Higher-purity outputs can be sold into higher-value

[3] 9-Tech data do not include ultrasound and chemical cleaning (Steps 5–6); LuxChemtech data do not include electricity consumption for chemical and mechanical separation and purification treatments after water jet treatment (Steps 3–6); c-Si PHOTORAMA data do not include leaching and electrowinning (Step 4); Flaxres data do not include third party processing to recover silver and silicon; and Tialpi data do not include silver electrolysis (Step 6), because it is an experimental process.

markets, potentially offsetting recycling costs. While the survey focused on LCI data, some recyclers shared material quality information, and Table 14 also includes available information on material purity.

Table 14. Recovered semiconductor materials and other metals within the laminate and reported purity, as available

LCI Data Contributors	Metal and Semi-conductors	Description
LCI Data Contributors for this Report		
First Solar	CdTe	0.5 wt. % of PV module input mass of CdTe recovered and refined by third-party for reuse in new modules, with semiconductor material recovery of >90 wt. % [9].
CI(G)S PHOTORAMA	CI(G)S	0.1 wt. % semiconductor metals recovered as compounds (dissolved and precipitated) and sent to metal recycler
SPR	Si, Cu	5 wt. % Si includes 98% of input Si recovered at approximately 70% purity; 99% of input Cu is recovered at >99% purity; 99% of other trace metals (unnamed) are recovered at >99% purity (destinations were not reported)
SOLARCYCLE	Si, Ag, Al, Cu	2.47 wt. % NF metals recovered includes 65.96% of input Si, 91.86% of input Ag, 72.07% of input Al, and 94.67% of input Cu; recovered metals are considered ore grade and sent to a refinery
c-Si PHOTORAMA	Si, In, Ag	3.9 wt. % Si recovered at 5N purity and sent to metal recycler; 0.3 wt. % NF metal recovery, including Ag recovered at ≥2N purity and other metals, such as In (in the case of heterojunction technology, though purity capabilities were not specified), depending on module composition and sent to metal recycler
9-Tech	Si, Ag, Cu, Al	1 wt. % NF metal recovery includes 95 wt. % of input Cu (Cu ribbons) recovered at purity of 95%; 2.8 wt. % of Si represents 95% recovery of input Si at purity of 95%; and 0.3 wt. % Al/Ag metallic powder recovery includes 90 wt. % Ag recovered at purity of up to 95% and 90% Al recovery at unspecified purity
LCI Data Contributors for 2024 IEA PVPS publication [5] *		
ROSI	Si, Ag, Cu	2.78 wt. % Si at 5-6N purity and 0.07 wt. % Ag recovered (destinations were not reported), and 0.87 wt. % NF metal (Cu ribbon) sent to refinery if needed
Envie & ROSI	Si, Ag, Cu	3.11 wt. % Si at 5-6N purity and 0.07 wt. % Ag recovered (destinations were not reported), and 0.85 wt. % NF metal (Cu ribbon) sent to refinery if needed

Tialpi	Si	55 wt. % NF metals, includes Si wafer and EVA, which is sent to an Al furnace; Si, Cu, and Ag recovery processes are under development
LuxChemtech	Si, In, Sn, Ag, Cu	Approximately 3.3 wt. % metal recovery includes: 0.027 wt.% NF metals (Ag, In, and Sn) sent to metal recyclers; 0.45% Cu interconnectors for metallurgy; 2.826% Si for battery anodes, sputter targets, and metallurgy; and trace semiconductors (In, Ga, Se, Te, and Cd) depending on module type sent to metal recyclers; Nearly 100 wt. % recovery of all listed materials
Flaxres	Si, Ag	3 wt. % NF metals, includes Si wafer with Ag, which can be processed by third parties to recover Si and Ag. Flaxres is actively developing this capability.

* Information is based on 2024 IEA PVPS publication [5] and may not reflect current capabilities.

Some recyclers in the current study provided information about the quality and subsequent use of the output glass:

- **First Solar** recovers glass cullet suitable for reuse in the glass industry for manufacturing new glass products
- **LuxChemtech,** including updated PHOTORAMA results, reported that its water jet process produces high-purity glass, often as intact sheets, that can be reused in the flat glass industry or directly reused in PV module manufacturing.
- **SPR** reported that one facility is collocated with a third-party facility that receives the recovered solar glass and further processes it to achieve a specified size of glass pieces.
- **9-Tech** sends recovered glass cullet to a glass recycler.

Contributors to the 2024 IEA PVPS publication also shared insights on glass quality and applications [5]:

- **Flaxres** reported in the 2024 study that its light pulse delamination process produces very clean glass (sheets or cullet), suitable for recycling into flat glass.
- **ROSI** reported recovery of high-quality clean glass cullet after pyrolysis but did not specify subsequent uses. In the **Envie & ROSI combined process**, the output glass removed by hot blade is sent to glass recyclers for further treatment.

3.3 Material Outputs

All participating recyclers have established outlets for their recovered material fractions, supplying mainly to other industries, with some materials reused in closed-loop recycling for new PV modules; some fractions may be incinerated or landfilled. Based on insights from the 2024 report where Reiling reported a 50 000 t/yr facility commissioned in 2023 [5] and the current study, where companies like SPR and SOLARCYCLE are rapidly expanding their commercial operations, new technologies and equipment are being introduced with the aim of improving material quality and yield. 9-Tech is also progressing toward commercialization of its new process in Italy. PHOTORAMA has successfully demonstrated reintegration of secondary raw materials such as glass into new modules.

Different recycling processes achieve output materials with different levels of quality. For example, some recycling processes achieve high purity outputs that can be reused in new PV modules, while others are downcycled to be used in other industries. Currently, few PV recyclers publish detailed data on the quality and purity of recovered materials. Reiling noted in the 2024 study that past batch processing of mixed module compositions sometimes led to cross-contamination and lower-purity output fractions, resulting in material downcycling. Their newly commissioned dedicated PV recycling line is expected to improve output quality. While wt. % purities are occasionally reported by recyclers, the chemical composition of impurities––which can significantly affect material properties and performance—is often omitted. As the PV recycling industry matures, output stream quality may become a key differentiator in determining profitability. In the meantime, there is clear R&D value in collecting measurable quality data, an area that future studies could address.

3.4 Electricity Consumption

Figure 11 presents a comparison of electricity consumption for c-Si module recycling, comparing the 9-Tech process (new in this report) with data from the 2024 study (Reiling, LuxChemtech, Flaxres, and Tialpi). (None of the other recyclers in the current survey disclosed electricity consumption data, nor did ROSI or the Envie & ROSI combined process.) The recycling processes shown vary in terms of the number of steps, use of chemical treatments, and fossil fuel consumption, so direct comparison should take these differences into account.

Among the respondents, Reiling and Flaxres report the lowest electricity consumption. Tialpi's electricity consumption is comparable to LuxChemtech's when considering only Steps 1–4 (recovery of Al and glass, and separation of Si), which had been achieved in its pilot process as of the 2024 study. However, if Steps 5–6—which include polymer decomposition, recovery of copper, silicon, and silver, and silver winning by electrolysis—were included, Tialpi would likely exhibit the highest overall electricity consumption.

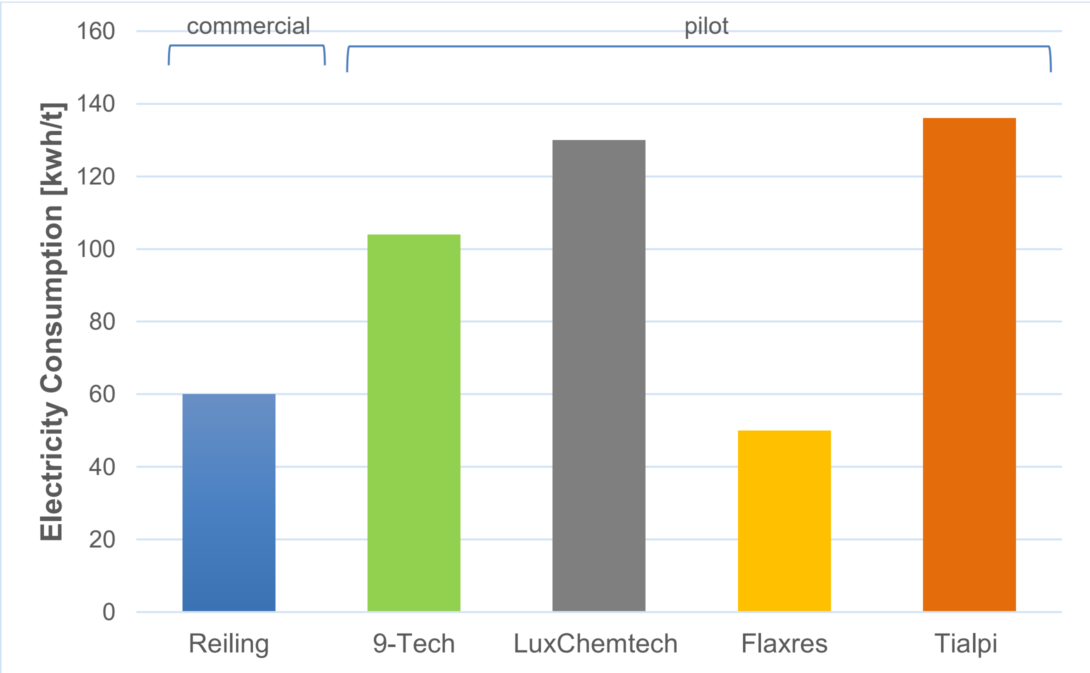


Figure 11. Disclosed electricity consumption across c-Si module recycling processes, excluding SOLARCYCLE, SPR, ROSI, Envie & ROSI, and PHOTORAMA due to lack of data. The system boundary is defined as the point in the process at which the cell

fraction (including metals) is separated from the glass and polymers.[4] Refer to Table 13 for the process types included in the LCI comparison.

Note: Data for Reiling, LuxChemtech, Flaxres, and Tialpi are sourced from the 2024 LCI report [5]. LuxChemtech data from the 2024 report do not reflect the maturity level, equipment, or facilities associated with PHOTORAMA.

[4] 9-Tech data do not include ultrasound and chemical cleaning (Steps 5–6); LuxChemtech data do not include electricity consumption for chemical and mechanical separation and purification treatments after water jet treatment (Steps 3–6); Flaxres data do not include third party processing to recover silver and silicon; and Tialpi data do not include silver electrolysis (Step 6), because it is an experimental process.

4 CONCLUSIONS

This report builds upon the previous IEA PVPS Task 12 PV recycling LCI study [5] by incorporating updated and expanded data from the following sources:

- Two U.S.-based commercial c-Si module recyclers: SOLARCYCLE and SPR
- One Italian pilot-scale c-Si module recycler: 9-Tech
- The PHOTORAMA project, including pilot-scale c-Si and CI(G)S processes at LuxChemtech
- First Solar provided updated global LCI data for CdTe modules to supplement previous findings

Global PV module recycling capacity is increasing rapidly in response to the growing volume of EOL PV modules. This trend reflects both the solar industry's maturation and the urgent need for sustainable EOL management solutions.

In parallel, numerous international R&D activities are advancing innovative recycling technologies with demonstrated improvements in material recovery rates, process yields, and output purity [7].[Error! Bookmark not defined.] Novel delamination methods—such as water jet separation (PHOTORAMA), light pulse delamination (Flaxres, as reported in the 2024 study), and thermal processes including pyrolysis (ROSI, as reported in the 2024 study) and furnace treatment (9-Tech)—are now being applied. These approaches are intended to minimize material loss during laminate separation and enable recovery of clean glass and semiconductor fractions. Chemical methods, including leaching (First Solar), leaching combined with electrowinning (PHOTORAMA), and ultrasound-assisted citric acid treatment (9-Tech), enable efficient recovery of metals bound within the laminate. These developments collectively support circular economy objectives.

Recovery rates for high-value materials have improved significantly compared to the 2024 study, in which the pure-mechanical benchmark recycling technology did not recover Si or Ag [5]. In the current study, SPR reports recovery of 98 wt. % of input Si using a pure-mechanical process at commercial scale, while 9-Tech achieves 95 wt. % Si recovery in a pilot-scale system that employs mechanical, thermal, and chemical recycling processes. Commercial recyclers further report the ability to recover non-ferrous metals, including Ag, Al, and Cu, representing a new capability for mechanical processes at scale. SOLARCYCLE reports recovery of nearly 92 wt. % for Ag and approximately 95 wt.% for Cu, while SPR reports 99 wt. % Cu recovery. In its pilot-scale system, 9-Tech achieves recovery rates of 95 wt. % for Cu, 90 wt. % for Ag, and 90 wt. % for Al. First Solar reports recovery of more than 90 wt. % for the semiconductor material and more than 90 wt. % of metals beyond the semiconductor materials [9].

Glass recovery has likewise progressed relative to the 2024 mechanical recycling benchmark of recovered glass cullet suitable for foam glass and glass fiber [5]. Advanced mechanical, thermal, and other separation approaches, such as flash lamp separation and water jet cleaning, can achieve high glass yield and purity but may require more energy than pure-mechanical processes or intact modules as feedstock (e.g., flash lamp, water jet, infrared light, and blade delamination technologies). PHOTORAMA and Flaxres (as reported in the 2024 study) produce intact, high-purity glass sheets, and Tialpi reported generating glass cullet that meets End-of-Waste (EoW) criteria under the EU Framework Directive (2008/98/EC) in the 2024 study [5].

Advancements in output purity further enhance the value of recovered materials. In the 2024 study, the pure-mechanical benchmark technology reported material downcycling due to inconsistent output fractions, and ROSI was the only recycler to quantify recovered material quality, reporting Si purity of 5–6N [5]. In the current study, PHOTORAMA achieves 5N purity for Si and greater than 2N purity for Ag. SPR reports 99% purity for recovered Cu and other trace metals (unnamed) through mechanical processing, while 9-Tech achieves up to 95% purity for Cu and Ag in recovered metallic powders.

Applications for reuse of recovered materials are expanding. CdTe recovery by First Solar and refinement by third parties for reuse in new modules exemplifies closed-loop recycling for thin-film technologies. Recovered Si is being used for battery anodes, sputter targets, and metallurgical grade applications, while other NF metals such as Al, Cu, and Ag are sent to metal recyclers, smelters, and refineries, reducing reliance on virgin resources. Glass streams from PHOTORAMA and Flaxres (reported in the 2024 study) can be reused in flat glass production, further decreasing demand for virgin silica. Additional information on downstream use and treatment pathways would strengthen future efforts to quantify material recovery, energy recovery, and landfill disposal and improve assessment of reuse pathways in future updates.

As the PV industry continues its rapid global expansion, the importance of transparent, high-quality recycling data is growing. The results of this study demonstrate meaningful advancements in both commercial and pilot-scale technologies, but they also highlight persistent gaps in material quality reporting, system boundary harmonization, and energy-use characterization. Continued collaboration among recyclers, researchers, policymakers, and standard-setting bodies will be essential to improve data consistency, guide R&D priorities, and support the development of circular, high-value pathways for PV materials. By updating empirical LCI data and documenting emerging practices, this report provides a foundation for future analysis of the environmental performance and material circularity of PV systems worldwide. A forthcoming Task 12 study will develop LCA-based analyses to assess life-cycle implications across different PV recycling pathways.

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APPENDIX A: EXAMPLE PV MODULE RECYCLING VIDEOS

PV Module Recycling Process Videos

SOLARCYCLE: https://www.solarcycle.us/

Solarpanelrecycling.com: https://solarpanelrecycling.com/about-us/

PV CYCLE: https://www.youtube.com/watch?v=81-MEpcA-Rc

Reiling: https://www.reiling.de/recycling-produkte#progress--anchor--157, or https://www.youtube.com/watch?v=ylE3h9gX2U0

ROSI: https://www.youtube.com/watch?v=_TaH0tabYRQ

PHOTORAMA: https://audiovisual.ec.europa.eu/en/reportage/P-066680

LuxChemtech, Loser: https://www.youtube.com/watch?v=392uBSgPoNo

La Mia Energia s.c.ar.l.: https://www.youtube.com/watch?v=L7UDkRX-6Qw

Eggersmann: https://www.youtube.com/watch?v=filrKYLQeU0

NPC: https://www.youtube.com/watch?v=uR9ASY9afkY

Flaxres: https://www.youtube.com/watch?v=L5iMLBMkXUE

Buhck Group on reuse: https://www.youtube.com/watch?v=iqMqOGRJTm0

Henan Renewable Energy Technology Co. Ltd.: https://www.youtube.com/watch?v=wpkk6ihlB6s

Henan Honest Heavy Machinery Co., Ltd: https://www.youtube.com/watch?v=Z1t2ylEpPwA

Review Movies

https://www.youtube.com/watch?v=Sm0MlNsQKio

https://www.youtube.com/watch?v=fU8C5t2Jl48

https://www.youtube.com/watch?v=SsZCjy84o1g

Santa Monica, CA, partnered with the California Product Stewardship Council, CalRecycle, the California Conservation Corps, and Cal Micro to pilot the first-in-state solar panel recycling program: https://www.youtube.com/watch?v=uodHTg_vi1s

APPENDIX B: PROCESS FLOW DIAGRAMS PROVIDED BY PARTICIPATING PV RECYCLERS

B.1 First Solar Inc.

First Solar contributed an updated process scheme (Figure B.1) illustrating its high-value recycling process (V1-V4). Following junction box and frame pre-treatment, EOL CdTe PV modules undergo a series of recycling steps: shredding and milling, thin-film layer removal, leaching, solid-liquid separation, laminate encapsulant/glass separation and removal of chemicals by water rinsing, and precipitation and filtration. First Solar's fourth-generation recycling technology achieves higher leaching efficiency with reduced chemical consumption compared to prior versions.

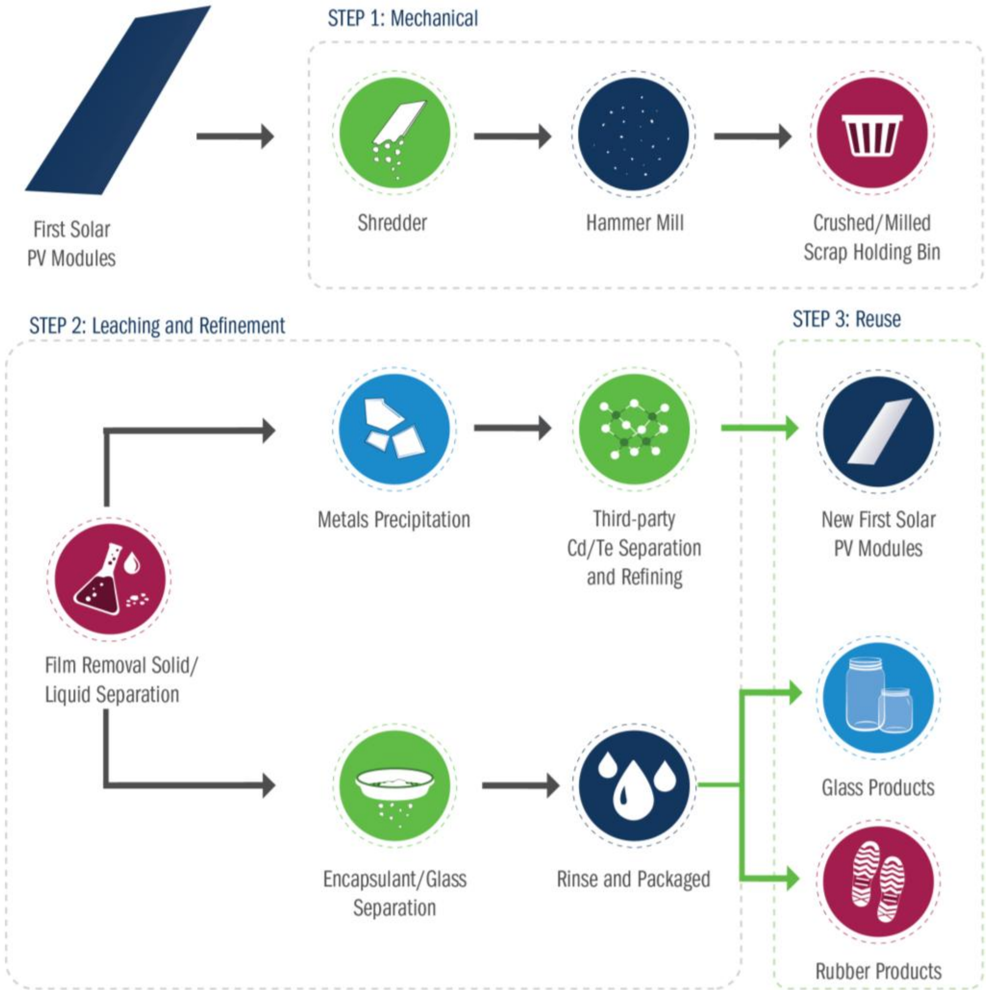

Figure B.1. Schematic of First Solar's High-Value (V1-V4)recycling process and reuse applications (Credit: First Solar Inc.)

Figure B.2 illustrates the evolution of First Solar's recycling process, which transitioned from batch processing of PV modules (V1 and V2) to continuous processing (V3 and V4).

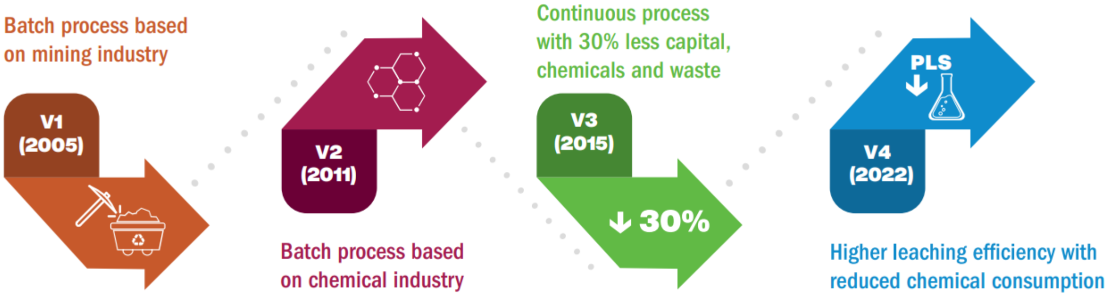

Figure B.2. Evolution of First Solar's recycling process (Credit: First Solar Inc.)

B.2 Solarpanelrecycling.com

A schematic of SPR's recycling process is depicted in Figure B.3.

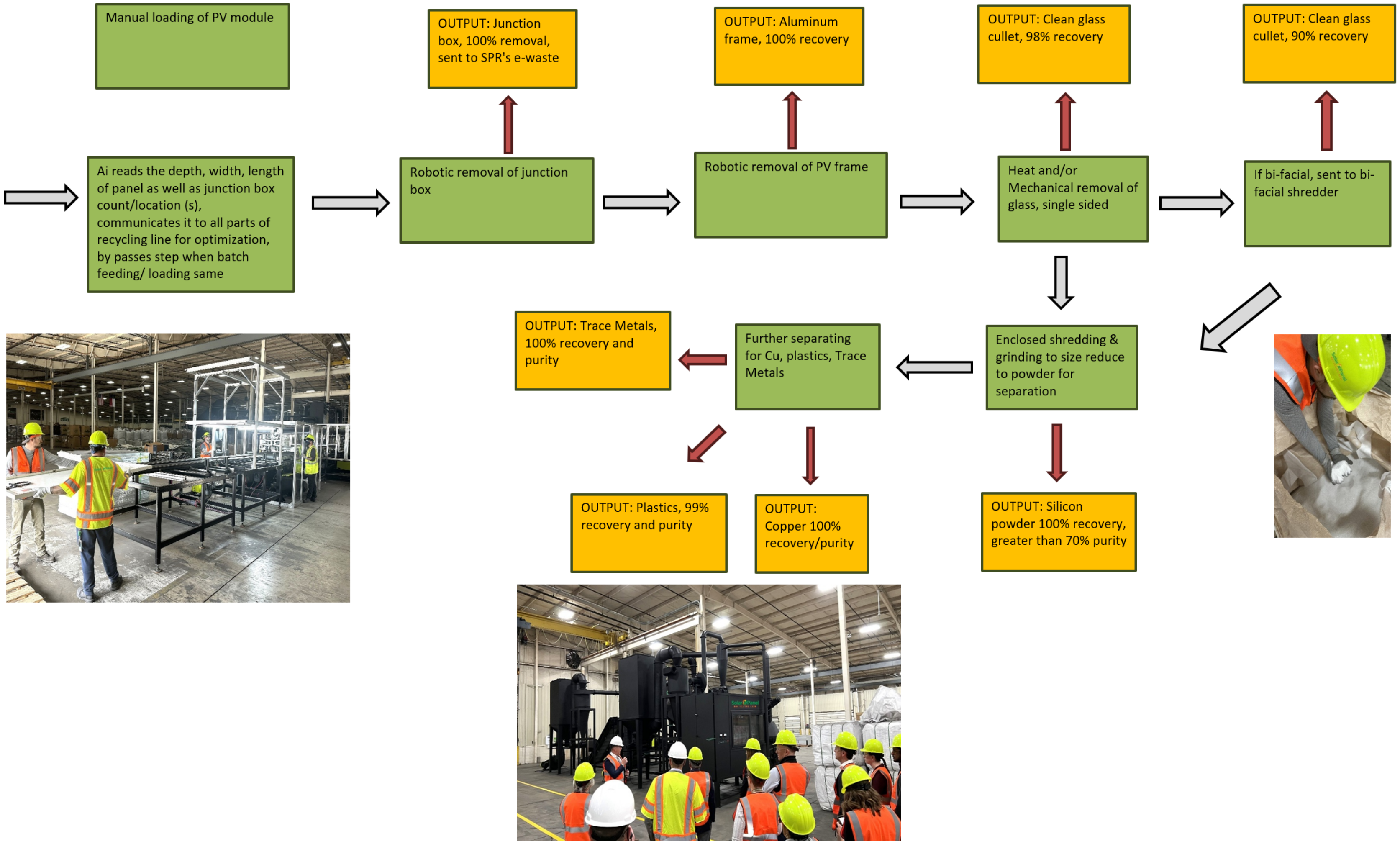

Figure B.3. SPR recycling process (Credit: Solarpanelrecycling.com)

B.3 9-Tech, Venice, Italy

Treatment steps and outputs are illustrated in Figure B.4.

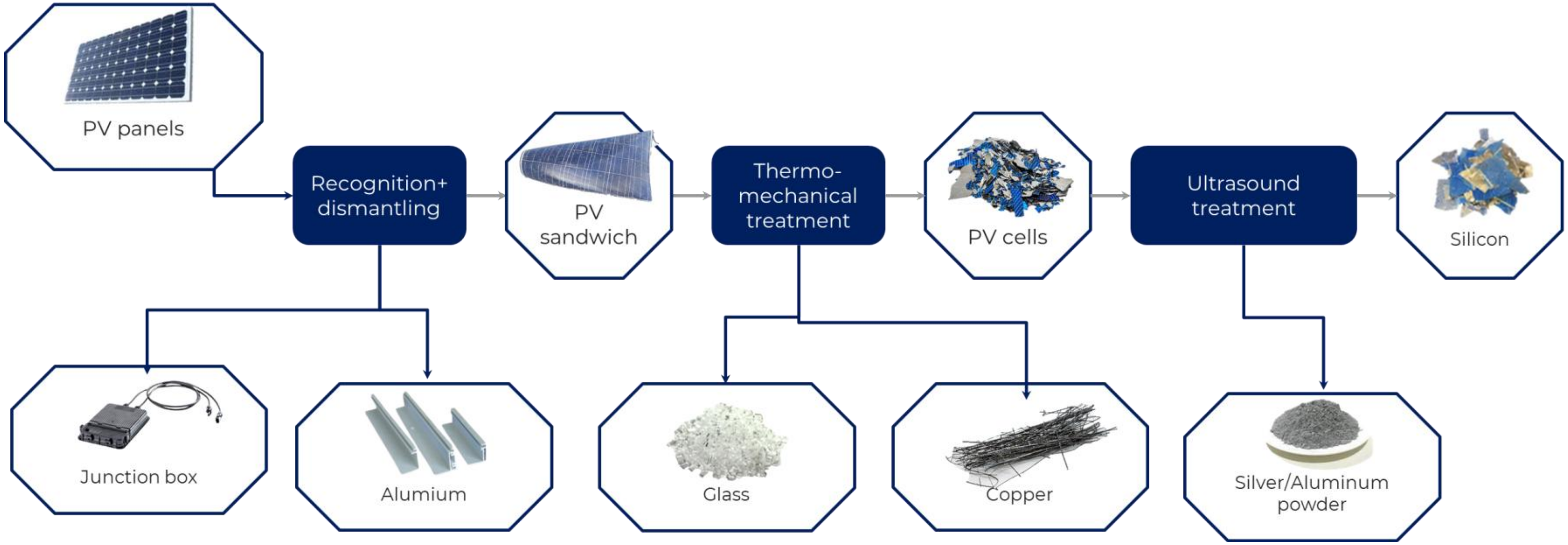

Figure B.4. Process steps of current pilot-scale (TRL 6) 9-Tech recycling plant in Venice, Italy (Credit: 9-Tech)

APPENDIX C: ORIGINAL LCI DATA TABLES FROM PARTICIPATING PV RECYCLERS

While the LCI data tables in Section 2 have been edited for clarity and consistency across respondents, this appendix provides the original survey responses verbatim.

Table C-1. LCI results for First Solar's recycling processes based on their environmental report 2023–2024

Company		First Solar, Inc.	
Name		LCI of CdTe module recycling, including semiconductor refining to semiconductor grade CdTe.	
Time period		2024	
Geography		USA, Germany, Vietnam, Malaysia & India	
Technology		Cadmium telluride solar modules	
Representativeness		Individual real processes in discrete batches	
Date		02.08.2024	
Collection method		Data from recycler	
Comment		National Electricity mix	
Plant	Unit	amount	comment/reference
capacity	t/yr	112,000	Total global recycling plants installed capacity
Type of plant	Recycling	Thin film PV High Value Recycling Plant	High value recycling plant (mechanical & chemical treatment)

Location	Country/State	USA (Ohio & Alabama), Germany, Vietnam, Malaysia & India	
module type processed	Thin film	CdTe modules	Cadmium telluride solar modules
time period		2024	
Treatment			
total input	tons	1	CdTe PV module for recycling with semiconductor refining to semiconductor grade CdTe.
Components/fuels			
electricity consumption	kWh/t	265	**Source:** Sinha et al. (2023). **Note:** Due to unavailability of data, an older LCI for recovery stage is used which is a batch process. As the latest First Solar recycling entails a *continuous process*, the recovered output is expected to be higher for the same input as compared to a *batch process*.
Output			**Source:** First Solar Corporate Responsibility Report 2025
Metals (frame and junction box, not including semiconductor materials)	%	0.6	
Semiconductor materials	%	0.5	
Glass	%	94	
Other materials	%	0.5	

Sent to a thermal energy recovery facility	%	0.2	
Sent to a thermal or landfill facility for disposal	%	1	
Total	%	~95	

Table C-2. LCI data for CI(G)S recycling at PHOTORAMA demo center

Company		PHOTORAMA - EU project - DEMO site LuxChemtech GmbH - Saxony-Anhalt plant Querstraße 2, 39590 Tangermuende, Germany	
Name		LCI of PV module recycling	
Time period		2025	
Geography		Germany	
Technology		Disassembling/ delamination / metal recovery	
Representativeness		Individual real processes in continuous or discrete batches	
Date		23.06.2025	
Collection method		Data from recycler	
Comment		National Electricity mix (please modify if needed)	
Plant	Unit	amount	comment/reference
capacity	t/yr	1,000	
Type of plant		pilot scale	

Location		Tangermünde	
module type processed		CIGS	
time period		2025	
Step 1			Diamond wire cutting, flash light delamination, mechanical opening
total input	t/yr	1,000	
Components/fuels			
electricity consumption	kWh/t		
CNG/LNG	kWh/t	-	
Diesel/oil consumption	l/t	-	
Compressed air	m^3/t	1075	
Diamond wire	kg/t	15	
Output			specify and indicate utilisation, subsequent treatment
cables	%	0.7	to cable recycler
frame	%	14.2	to aluminium smelter
junction boxes	%	1.0	to electronic recycler
ferrous metals	%	-	Backrails 2.6 kg per panel
non-ferrous metals	%	-	
polymers/foils	%	-	Approx. 100g
glass cullet	%	-	
glass clean	%	-	
mixture of glass cullet, foil and metals	%	0.8	to EEE recycler
semiconductors	%	-	
dust	%	-	
other	%	-	

Step2			Leaching, cleaning
total input	t/yr		
Components/fuels			
electricity consumption	kWh/t	not disclosed	
CNG/LNG	kWh/t	-	
Diesel/oil consumption	l/t	-	
Chemicals	kg/t	11	
Compressed air	m^3/t	186	
Water	kg/t	20	
Output			specify and indicate utilisation, subsequent treatment
cables	%	-	
frame	%	-	
junction boxes	%	-	
ferrous metals	%	-	
non-ferrous metals	%	-	
polymers/foils	%	3.6	in waste incineration
glass cullet	%	79.2	in flat glass production
mixture of glass cullet, foil and metals	%	0.4	to EEE recycler
semiconductors	%	0.1	to metal recycler
dust	%	-	
other	%	-	

Table C-3. LCI data for c-Si recycling at PHOTORAMA demo center

Company		PHOTORAMA - EU project - DEMO site LuxChemtech GmbH - Saxony-Anhalt plant Querstraße 2, 39590 Tangermuende, Germany	
Name		LCI of PV module recycling	
Time period		2025	
Geography		Germany	
Technology		Disassembling/ delamination / metal recovery	
Representativeness		discrete batches	
Date		23.06.2025	
Collection method		Data from recycler	
Comment		National Electricity mix (please modify if needed)	
Plant	Unit	amount	comment/reference
capacity	t/yr	1,000	
Type of plant		pilot scale	
Location		Tangermünde	
module type processed		c-Si	
time period		2025	2025
<u>Step 1</u>			Frame and junction box removal, delamination and separation
total input	t/yr	1,000	
<u>Components/fuels</u>			
electricity consumption	kWh/t	not discolsed	use of solar PV electricity
CNG/LNG	kWh/t	-	
Diesel/oil consumption	l/t	-	

Compressed air	m^3/t	169	
Water	kg/t	130	
Output			specify and indicate utilisation, subsequent treatment
cables	%	0.6	to cable recycler
frame	%	12.5	to aluminium smelter
junction boxes	%	0.9	to electronic recycler
ferrous metals	%	-	
non-ferrous metals	%	-	
polymers/foils	%	8.7	in waste incineration
glass cullet	%	66.2	in flat glass production
mixture of glass cullet, foil and metals	%	6.0	redirected to EEE recycler
copper	%	0.8	in smelter for copper scrap
dust	%	-	
other	%	-	
Step2			Leaching and electrowinning
total input	t/yr		
Components/fuels			
electricity consumption	kWh/t	not discolsed	
CNG/LNG	kWh/t	-	
Diesel/oil consumption	l/t	-	
Water	kg/t	55	
Chemicals	kg/t	13	
Output			specify and indicate utilisation, subsequent treatment
cables	%	-	

frame	%	-	
junction boxes	%	-	
ferrous metals	%	-	
non-ferrous metals	%	0.3	to metal recycler
polymers/foils	%	-	
glass cullet	%	-	
mixture of glass cullet, foil and metals	%	-	
copper	%	-	
Silicon	%	3.9	to metal recycler
dust	%	-	
other	%	0.1	landfill

Table C-4. LCI results for SOLARCYCLE's recycling process

Company		**SOLARCYCLE, Inc.; 8000 N. Golder Ave.; Odessa, TX 79764**
Name		LCI of PV module recycling
Time period		2021-2023
Geography		USA
Technology		Automated deframing, shredding, electrostatic process (Steps 1-3 below)
Representativeness		Some individual processes and some aggregated processes in continuous industrial line. The LCI data herein is sourced from that published in Dias et al. 2022, and for the purposes of this activity is considered representative of SOLARCYCLE's crystalline-silicon PV module recycling process at its facility in Odessa, TX. The difference is that since its inception, SOLARCYCLE can extract and recover virtually 100% of the glass from a solar module and sell it instead of having to landfill it as suggested in the paper. Dias et al. 2022, available here: https://www.sciencedirect.com/science/article/pii/S1364032122007821
Date		23.07.2024

Collection method		Data from recycler
Comment		National Electricity mix (please modify if needed)

Plant	**Unit**	**amount**	**comment/reference**
capacity	t/yr	20,000	In TX facility. Nameplate capacity, 1M (modules assumed to 20kg each)
Type of plant		Recycling	
Location		Odessa, TX	
module type processed		crystalline silicon	
time period		Since 2022	
Step 1			
total input	tons	1	Functional unit
Components/fuels			
electricity consumption	kWh/t	0.94	Electricity consumption of automatic deframer
CNG/LNG	kWh/t		
Diesel/oil consumption	l/t	1.14	Forklift transportation of Modules
Output		**% by weight**	**specify and indicate utilisation, subsequent treatment**
cables	%	1.00	100% recovery of cables. Cables + jbox is considered 1% of module wt. Sent for recovery of copper wire
frame	%	18.00	100% recovery of frame. Sent for aluminum recycling
junction boxes	%	-	100% recovery of jboxes. Cables + jbox is considered 1% of module wt. Sent for recovery of copper

ferrous metals	%		
non-ferrous metals	%		
polymers/foils	%		
glass cullet	%		
mixture of glass cullet, foil and metals	%		
dust	%		
other	%	81.00	Laminate
Step2		**See paper**	
total input	tons	0.81	Continuous process, # of modules processed in Step 1 will be processed in Step 2. If frame + jbox/cable = 19 wt% of module (Latanussa 2016), this value will be 81% of Step 1
Components/fuels			
electricity consumption	kWh/t	45.00	Electricity consumption of shredder
CNG/LNG	kWh/t	nil	
Diesel/oil consumption	l/t	nil	
Output			
cables	%		
frame	%		
junction boxes	%		
ferrous metals	%		
non-ferrous metals	%		
polymers/foils	%		
glass cullet	%		

mixture of glass cullet, foil and metals	%	76.14	Entire laminate continues onto Step 3 besides dust.
dust	%	4.86	
other	%		
Step 3		See paper	
total input	kg	0.7614	
Components/fuels			
electricity consumption	kWh/t	6	Electricity consumption of electrostatic process
Output			
non-ferrous metals	%	2.47	Recovery from initial 761.40 kg input: 65.96% of input silicon 91.86% of input silver 72.07% of input aluminum 94.67% of input copper recovered 1.72% of input polymer ends up in this fraction Metals recovered in this fraction are considered ore grade, sent for further refining
glass cullet	%	69.3	99% of glass recovered as sheet/cullet throughout process. Not represented in published LCA but accurate to operations as of the time period of this LCI table. No significant net change to the total energy consumption of process associated with this change in final outputs.
mixture of polymer, glass cullet, foil and metals	%	2.09	Majority polymer with some glass in this fraction, landfilled in LCA paper published.
dust	%	2.28	

Table C-5. LCI results for Solarpanelrecycling.com's recycling process

Company		Solarpanelrecycling.com (SPR)	
Name		1325 Litton Drive, Salisbury, NC 28147 USA	
Time period		2023/24 (please enter right period	
Geography		USA	
Technology			
Representativeness			
Date		10.7.2024	
Collection method		Data from recycler	
Comment			
Plant	Unit	amount	comment/reference
capacity	t/yr	21,000 t/yr/per plant	
Type of plant		Recycling Plant	
Location		NC, USA (TX & GA)	
module type processed		cryst. Silicon, thin film type	
time period		2023/2024 YTD	
Step 1			
total input	t/yr	14,665 tons (23/24 YTD)	419,000 panels for all three plants
Components/fuels			
electricity consumption	kWh/t	low	
CNG/LNG	kWh/t		
Diesel/oil consumption	l/t		

Output	%		
cables	%	in non-ferrous	100% cable removal & recovery, sent to copper smelter
frame	%	in non-ferrous	100% ALUM frame removal & recovery, sent to foundry, we utilize dedicated solar recycling line, aluminum robotic frame removal with AI
junction boxes	%	in plastics,non-ferrous and ferrous	100% junction removal & recovery, sent to our e-waste shredder/separator utilizing shredders, screening, cross magnets, eddy current, optical sorters
ferrous metals	%	0.5	100% ferrous removal & recovery, sent to steel mill, first shredded and prepared in our shredding system
non-ferrous metals	%	8	100% ALUM frame removal & recovery, sent to foundry
polymers/foils	%	6	100% polymer removal & recovery, utilizes air flow separation
glass cullet	%	80	98% clean glass removal, utilizes mechanical grinding
mixture of glass cullet, foil and metals	%	0.25	represents other 2% of glass/foil mixed
dust		0.25	captured in dust collection systems
silicon	%	5	98% silicon captured through air flow separation

Table C-6. LCI results for 9-Tech's recycling process

Company		9-Tech srl, Via Triestina Bassa 74, 30020, Eraclea (VE)
Name		LCI of PV module recycling
Time period		2023/24
Geography		Italy
Technology		Thermo-mechanical treatment + ultrasound silver recovery

Representativeness		Continuous batches
Date		10.11.2024
Collection method		Data from recycler
Comment		National Electricity mix

Plant	Unit	amount	comment/reference
capacity	t/yr	33	The pilot plant can treat 100kg/day (8 hour). Assuming 330 working days per year, the maximum capacity would be 33 ton/year.
Type of plant		TRL6 pilot plant	
Location		via della Geologia 31, 30176, Venezia	
module type processed		Crystalline silicon	The plant can treat only crystalline silicon PV modules
time period		2023/24	
Step 1			**Manual disassembly**
total input	t/yr	33	PV waste
Components/fuels			
electricity consumption	kWh/t	0	In the pilot plant the disassembly of the aluminum frame and junction box is performed manually, therefore there is no energy consumption.
Output			
frame	%	19.1	
junction boxes	%	1.8	

other	%	79.1	PV sandwich send to furnace
Step2			**Thermal delamination**
total input	t/yr	26.1	PV sandwich send to furnace
Components/fuels			
electricity consumption	kWh/t	98	Electricity consumption for extractor fan and compressor
LPG	kWh/t	250	The pilot plant uses LPG to maintain the correct temperature inside the combustion chamber.
filters	t/t	0.1	
active carbons	t/t	0.001	
Output			
polymers/foils	%	10.3	Inside the furnace the polymers of the panel are burned, so we have a loss of 10.3%.
other	%	68.8	mixed inorganic materials
Step 3			**Mechanical Separation**
total input	t/yr	22.7	mixed inorganic materials
Components/fuels			

electricity consumption	kWh/t	6	2.8 kWh/t are consumed to separate the copper ribbons, 1.4 kWh/t are used to separate the fine fraction and 1.8 kWh/t are consumed to separate the glass from the PV cells
Output			
non-ferrous metals	%	1	Copper ribbons
glass cullet	%	63	
dust	%	1.7	
other	%	3.1	Photovoltaic cells (made of silicon, Ag, and Al)
Step 4			Hydrometallurgical treatment
total input	t/yr	1	PV cells
Components/fuels			
electricity consumption	kWh/t	6	Electricity consumed by the ultrasound bath
citric acid	t/t	0.005	
water	t/t	0.09	
Output			
non-ferrous metals	%	2.8	silicon chips
other	%	0.3	Al/Ag powder
Step 5			**Washing of PV cells**
total input	t/yr	0.9	PV cells without Al/Ag
Components/fuels			

electricity consumption	kWh/t	2	
water	t/t	0.04	
Output			
non-ferrous metals	%	2.8	Silicon

APPENDIX D: RELATIVE OUTPUT COMPOSITION

Data in Table D-1 were used to generate Figure 10. To enable comparison, limited interpretations were applied to group outputs into the “Cells, metals,” “Other,” and “Not recovered” categories. Polymers were classified as “polymer incineration or pyrolysis” only when this treatment pathway was explicitly specified by the recycler.

Table D-1. Relative output composition for 12 recycling processes by 10 recyclers

Notes: Blank fields indicate information is not available. Groupings of the material outputs presented in Table 13 and the Section 2 LCI tables are described in the table notes.

Module type		CdTe	CI(G)S	c-Si modules									
Scale of plant		Commercial	Pilot	Commercial			Pilot						
	Unit	First Solar*	PHOTORAMA CI(G)S*	SOLARCYCLE, Inc.*	SPR*	Reiling**	9-Tech*	LuxChemtech**	PHOTORAMA c-Si*	Flaxres**	ROSI**	Envie & ROSI**	Tialpi**
Cables	wt. %		0.7	1	[a]	0.65		0.42	0.6	1	0.85	0.85	1
Frames	wt. %		14.2	18	[a]	11.5	19.1	11.07	12.4	17	7.79	7.79	15
J-boxes	wt. %	0.6	1	[b]	[a]	0.35	1.8	0.39	0.9	1	4.3	4.3	1
Cells, metals	wt. %	0.5[c]	0.1[d]	2.47	8.5[e]	1.2[f]	4.1[g]	4.05[f]		3[f]	3.74[h]	4.03[i]	3[j]
Glass	wt. %	94	79.2	69.3	80	64	63	72.5	66.2	66	71.42	72.06	65
Polymers	wt. %	0.2			6		0	11.13		12	0	0	
Other	wt. %	0.5	1.2[j]	2.09[j]	5.25[k]	8.3[l]			11.1[m]				
Polymer incineration or pyrolysis	wt. %		3.6			14	10.3	0.44[n]	8.7		6.5	10.97	
Not recovered		4.2		7.14[n]	0.25[n]		1.7[n]		0.1[o]		5.4[p]		15
Total	wt. %	100	100	100	100	100	100	100	100	100	100	100	100

* LCI data contributor for this report

Module type		CdTe	CI(G)S	c-Si modules									
Scale of plant		Commercial	Pilot	Commercial			Pilot						
	Unit	First Solar*	PHOTORAMA CI(G)S*	SOLARCYCLE, Inc.*	SPR*	Reiling**	9-Tech*	LuxChemtech**	PHOTORAMA c-Si*	Flaxres**	ROSI**	Envie & ROSI**	Tialpi**

** LCI data contributor for 2024 IEA PVPS publication [5]
[a] Included in non-ferrous fraction (NF), categorized as “Cells, metals”
[b] Included with cables
[c] Semiconductor materials
[d] Semiconductors, CI(G)S
[e] Ferrous (FE) (0.5) + NF (8)
[f] NF
[g] NF (3.8) + 0.3 (Other)
[h] Si/Ag (2.87) + NF (0.87)
[i] Other (3.18) + NF (0.85)
[j] Mixture of glass cullet, foil, and metals
[k] Mixture of glass cullet, foil, and metals (0.25) + Other (5)
[l] Mixture of glass cullet, foil, and metals (6.6) + Dust (1.5) + FE (0.2)
[m] NF (1.1) + mixture of glass cullet, foil, and metals (6) + Other (4)
[n] Dust
[o] Other
[p] Other/unspecified (2) + Mixture of glass cullet, foil, and metals (3.4)

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