

Advances in Photovoltaic Module Recycling

Third Update to Empirical Life Cycle Inventory Data



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EU PVSEC

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Overview of PV Recycling

Current commercial recycling

- Predominantly **mechanical processing** (e.g., shredding, milling)
 - CdTe recycling additionally involves chemical processing
- Commercial-scale capacity, typically **20,000–50,000 t/yr**
- Conventional mechanical c-Si processes may produce **lower purity, lower-value outputs** (e.g., silicon fractions of 40–80% purity)

Emerging advanced recycling

- **Hybrid mechanical** processes combined with moderate heating, light-based approaches, electrodynamic fragmentation
- **High-temperature thermal and chemical treatments** (e.g., pyrolysis)
- Generally demonstrated at pilot-scale: **<10,000 t/yr**
- Potentially **higher recovery and purity** (e.g., silicon purity up to 5N)



Credit: LuxChemtech



Credit: Okon

Recovered Silicon

Advanced processes may increase output quality and value if they can be successfully scaled

Project Overview

■ Study Objective

- Provide updated, comparative life cycle inventory (LCI) data for PV module recycling technologies to support environmental assessment, technology benchmarking, and end-of-life decision-making

■ Scope & Approach

- Survey and interview recyclers using commercial and emerging technologies *
- Compile process inputs, outputs, recovery rates, and energy consumption
- Compare results with prior Task 12 studies to identify advances, trends, and data gaps

■ LCI Data Contributors

- First Solar
- PHOTORAMA: c-Si and CI(G)S
- SPR
- SOLARCYCLE
- 9-Tech



Task 12 PV Sustainability Activities

PVPS

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Third Update to Empirical Life Cycle Inventory Data

2026

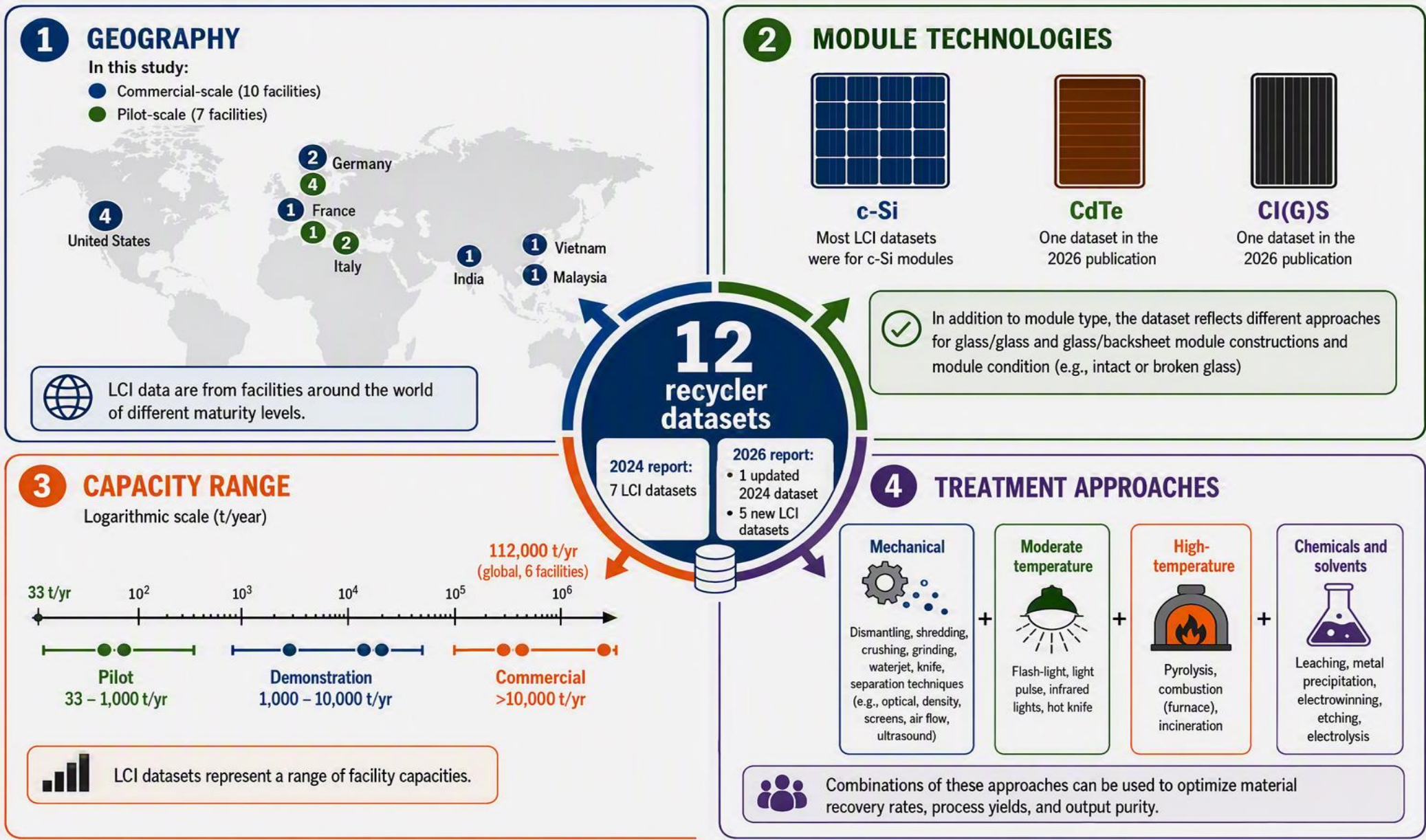
Report IEA-PVPS T12-32:2026

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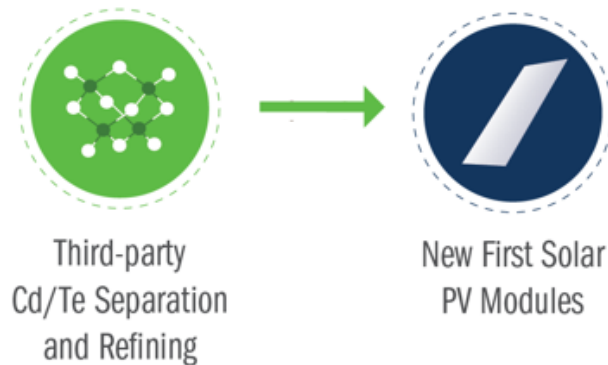
* Data were self-reported and shared from 2024 through mid-2025

LCI Data Span PV Technologies, Scales, and Geographies



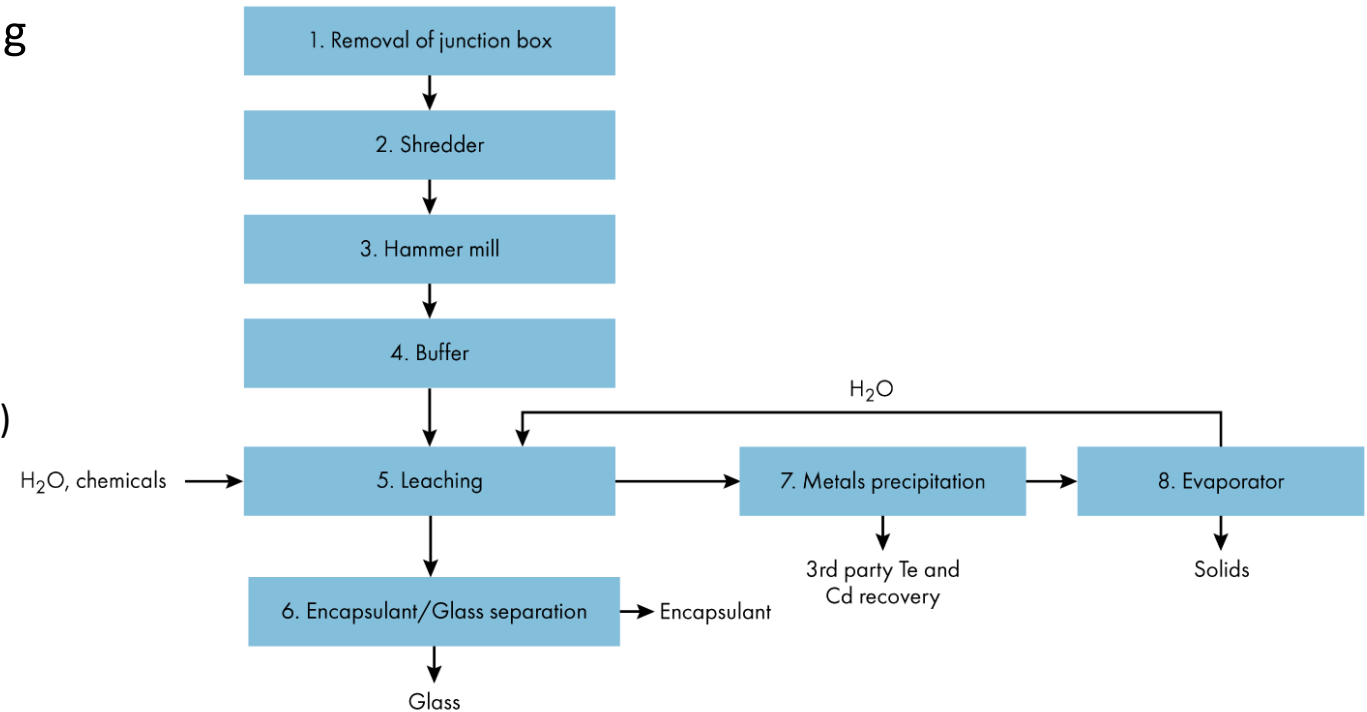
First Solar Inc., USA

- Operates six commercial thin-film CdTe recycling facilities with over 20 years of commercial experience
- Capacity: ~112,000 t/yr worldwide
- Throughput (2024): 40,400 t processed
- Distinctive process features
 - > 90% material recovery (global average across facilities)
 - Closed-loop recycling of CdTe



Closed-loop recycling of CdTe

Credit: First Solar, Inc.



Mechanical and chemical treatment of CdTe modules recovers glass cullet and unrefined semiconductor material

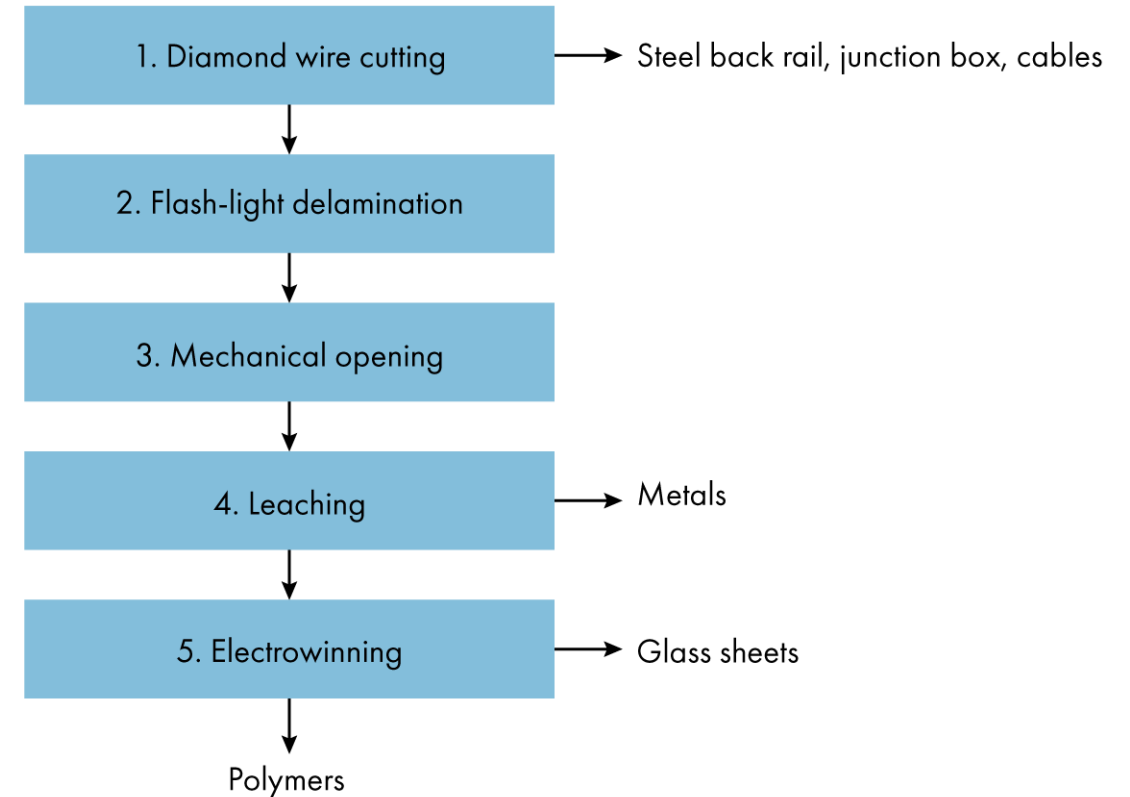
EU Project PHOTORAMA CI(G)S, Germany

- Pilot-scale demo center at LuxChemtech in Tangermünde
- Capacity and throughput: 1000 t/yr
- Distinctive process features
 - Mechanical dismantling of frame and junction box using diamond wire cutting
 - Optical delamination by flash light
 - Metal extraction through chemical leaching and electrowinning



CI(G)S diamond wire frame

Credit: PHOTORAMA - EU project, European Union, 2025



Mechanical and chemical treatment of CI(G)S modules recovers high-quality glass, In, and Ga

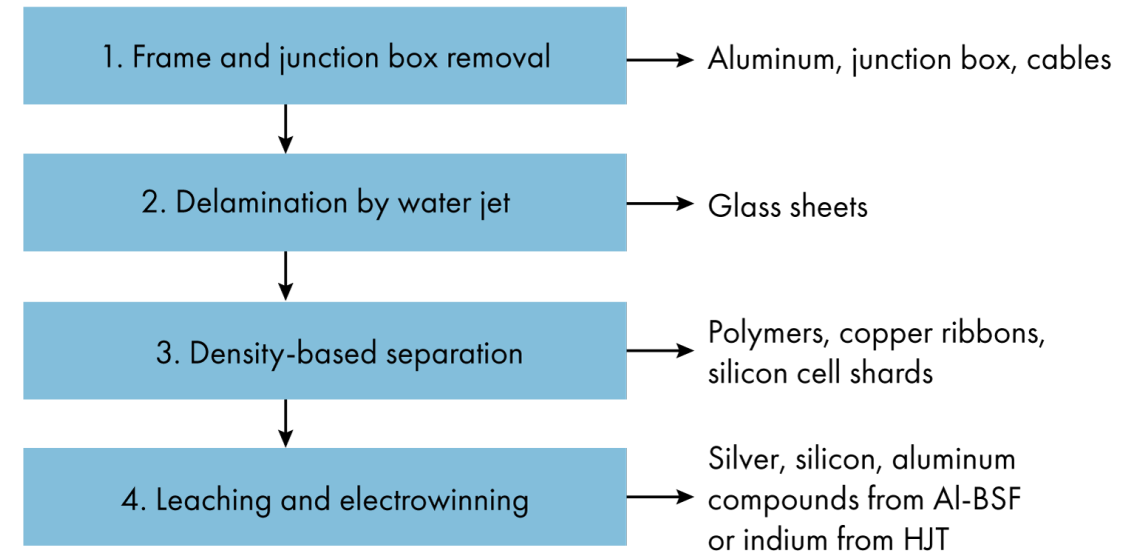
EU Project PHOTORAMA c-Si, Germany

- Pilot-scale demo center at LuxChemtech in Tangermünde
- Capacity and throughput: separate 1000 t/yr lines to process CI(G)S and c-Si modules
- Distinctive process features
 - X-ray fluorescence (XRF) to identify materials
 - Delamination by water jet (glass/backsheet modules)
 - Metal extraction via leaching and electrowinning



Credit: PHOTORAMA - EU project, European Union, 2025

Glass after water jet cleaning



Mechanical and chemical treatment of c-Si modules recovers high-quality glass, Si, Ag, Al compounds from Al-BSF or In from HJT

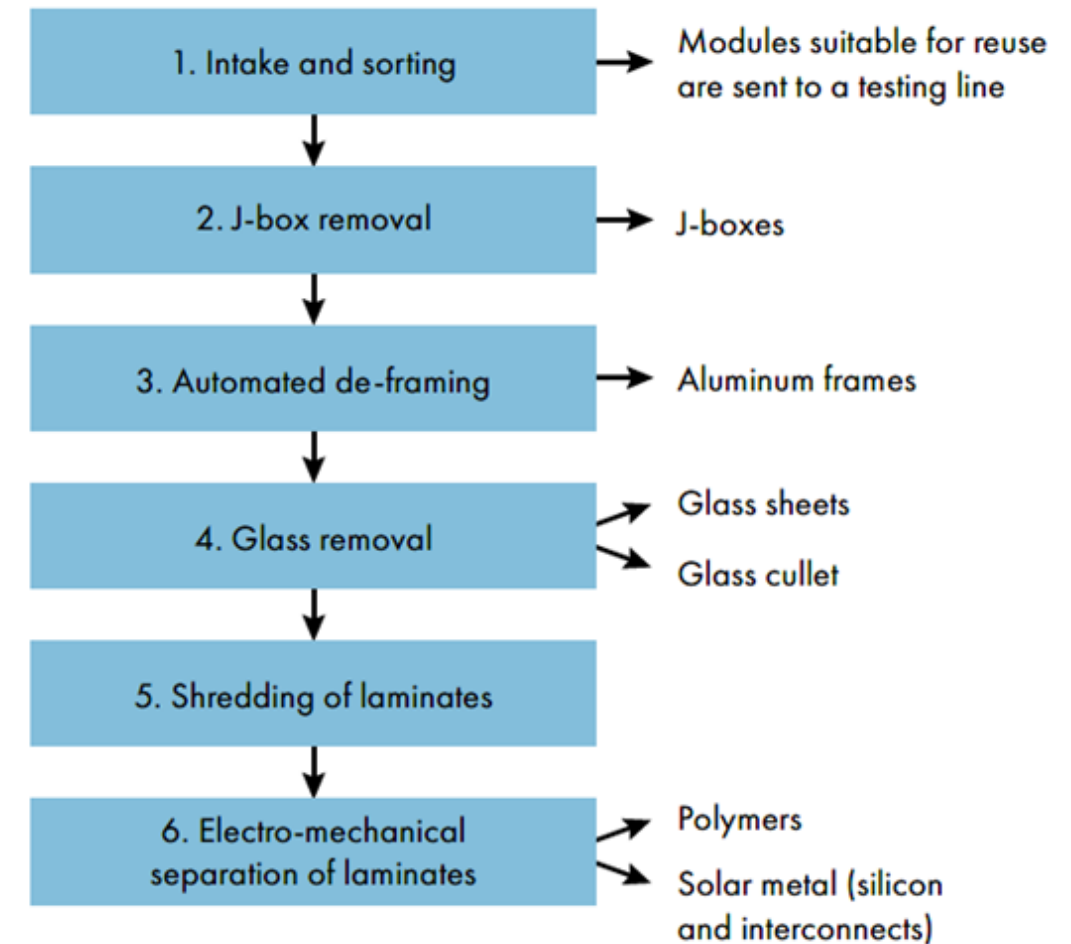
SOLARCYCLE, US

- Commercial c-Si module recycler since 2022
- Capacity: 20,000 t/yr (1 million modules assumed to be 20 kg each)
- Throughput: 1 t/yr (assumed functional unit)
- Distinctive process features
 - Recover nearly 92 wt.% for Ag and approximately 95 wt.% for Cu
 - 99% of glass is recovered and sold



Credit: SOLARCYCLE

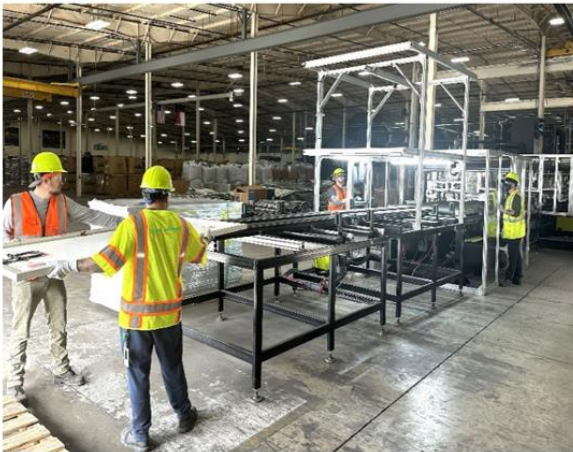
Laminate after glass removal



Mechanical treatment of c-Si modules recovers glass sheet or cullet and a cell and metal fraction for further refining

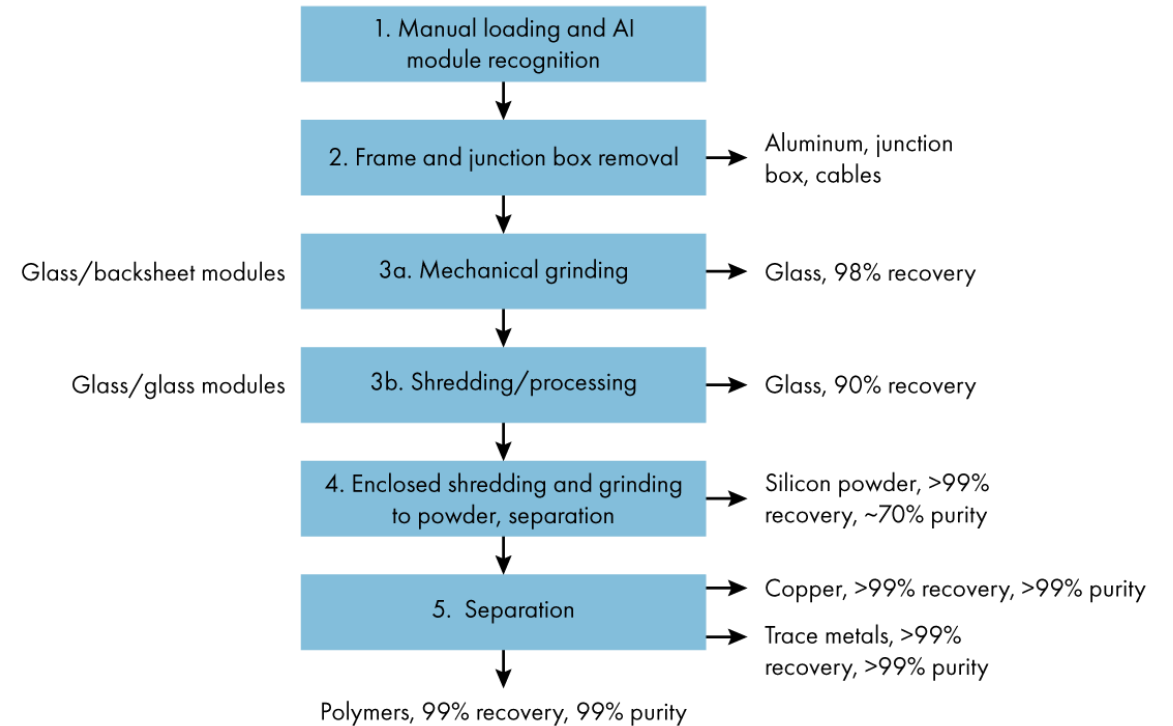
SPR (Solarpanelrecycling.com), US

- Commercial c-Si module recycler since 2023, with ~15 years of e-waste experience
- Capacity: 63,000 tons (3 locations)
- Throughput: 14,665 t (2023-Oct. 2024)
- Distinctive process features
 - AI and 3D mapping technologies for module recognition
 - Metal recovery rates >99% with >99% purity for Cu



Credit: SPR

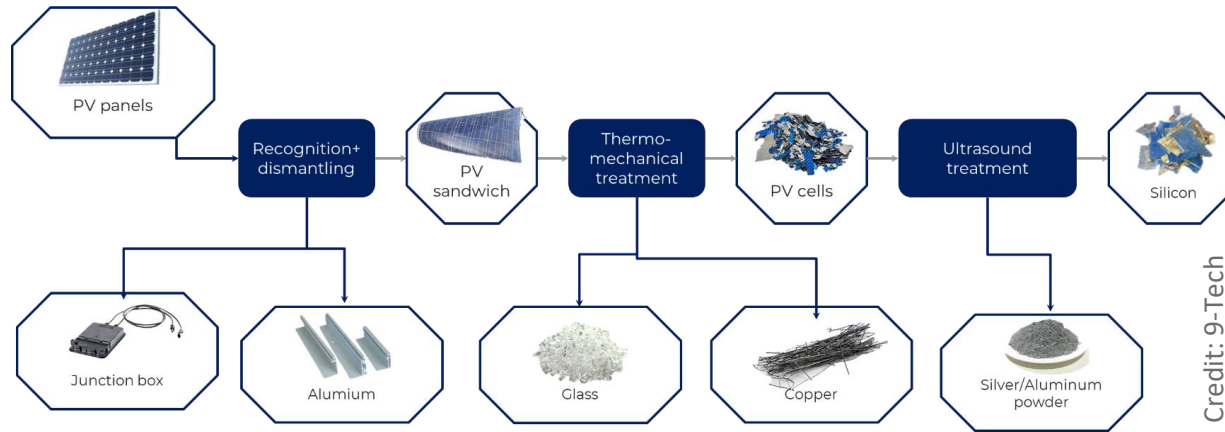
Loading modules on conveyor



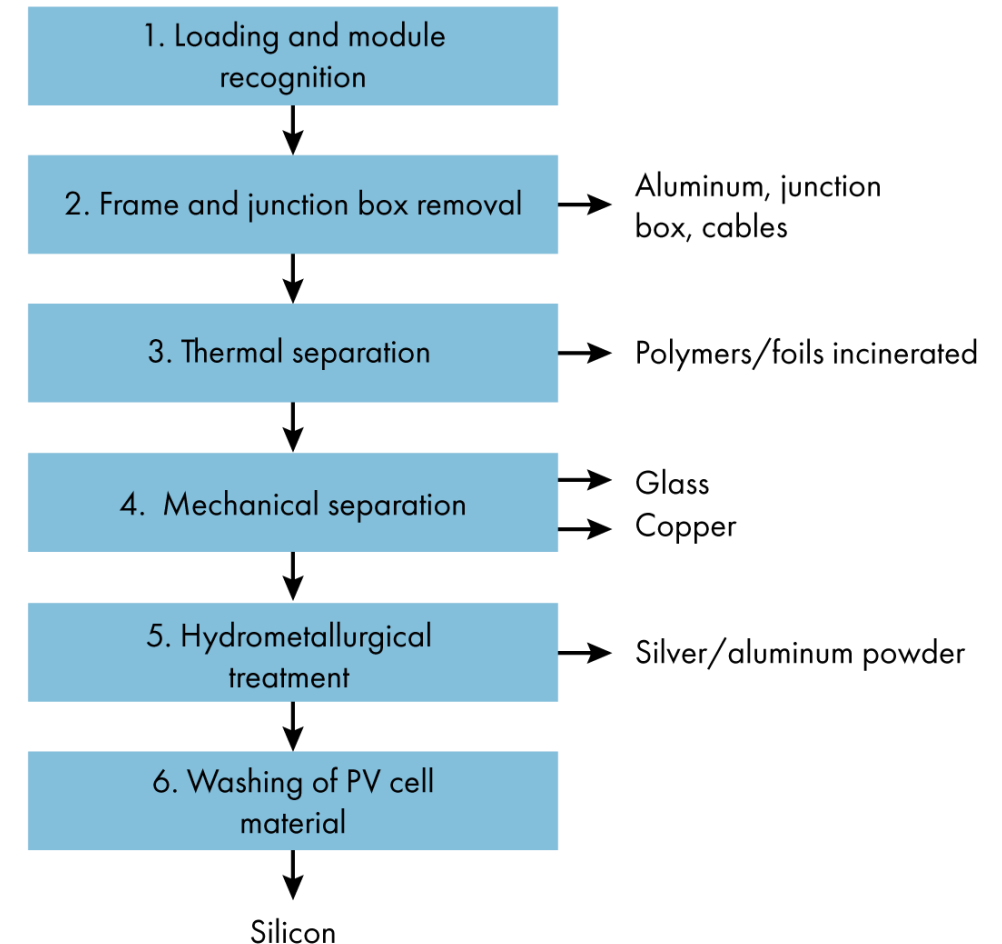
Mechanical treatment of c-Si modules recovers glass cullet, Si, Cu, and other metals

9-Tech, Italy

- 9-Tech is a startup company founded in 2020 with a pilot line
- Capacity: 33 t/yr
- Throughput: 1.1 tons/yr (2023)
- Distinctive process features
 - Incineration of encapsulation and backsheet at $>500^{\circ}\text{C}$
 - High-power ultrasound removes Ag and Al paste from cells in an aqueous solution of citric acid



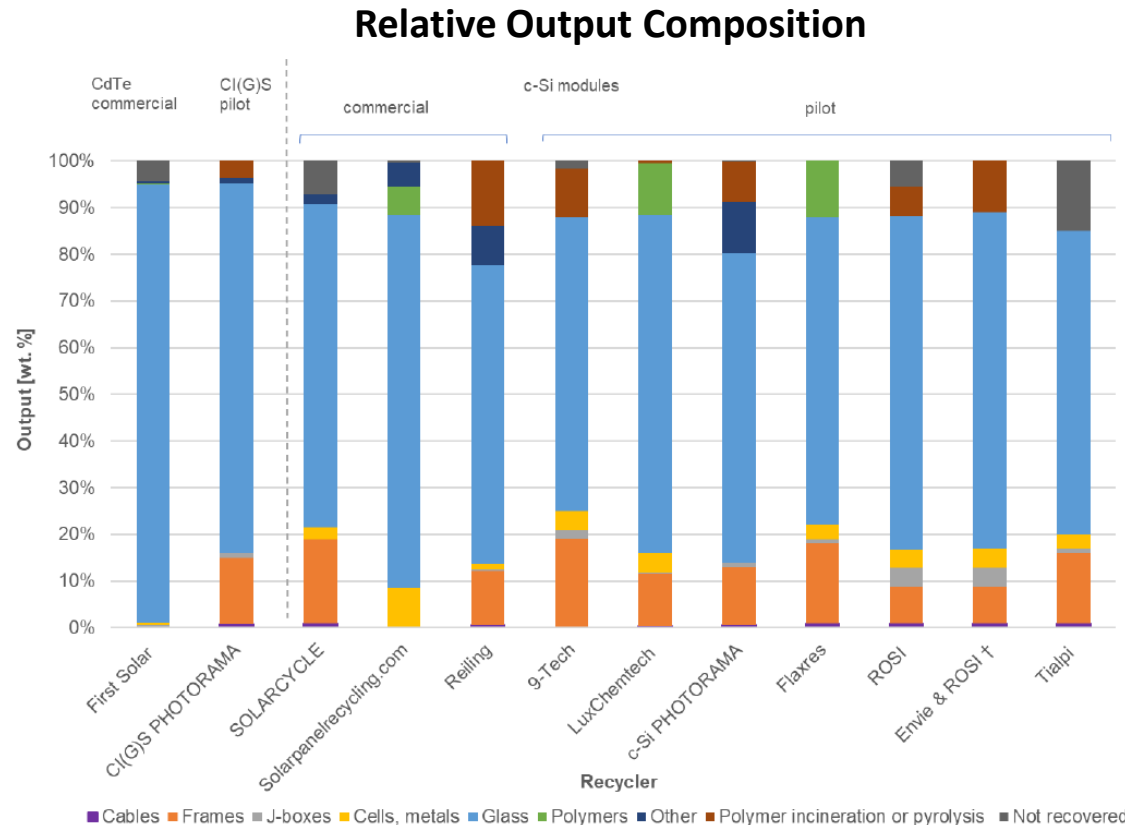
Process steps and output streams



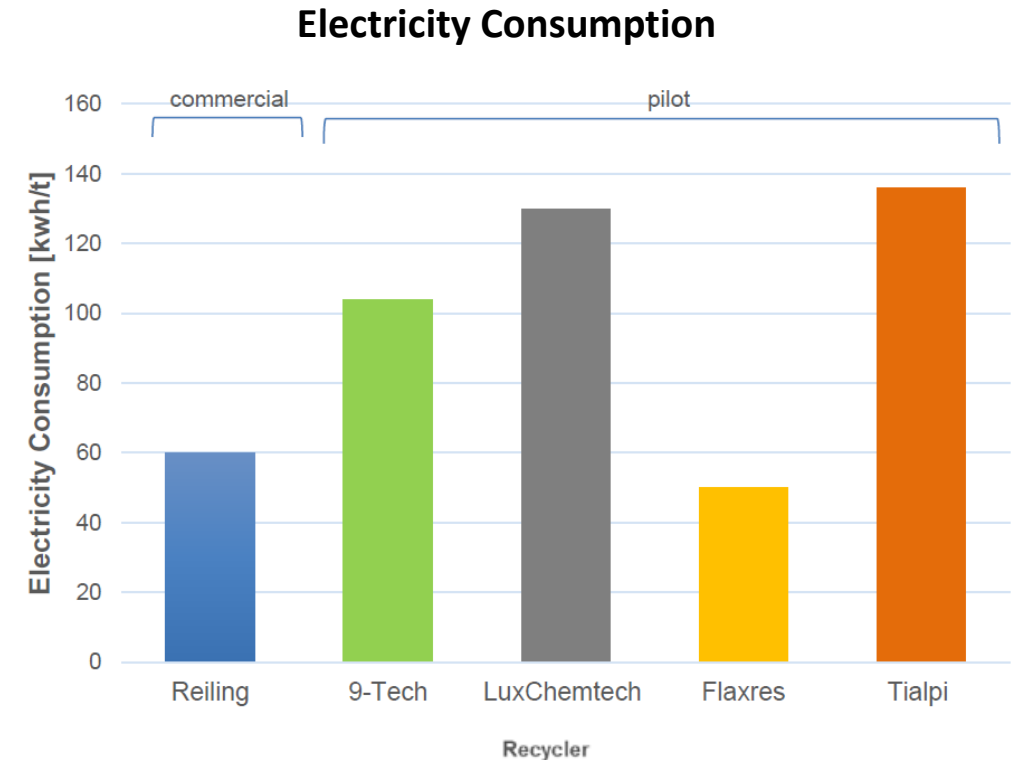
Thermomechanical and chemical treatment of c-Si modules recovers glass, Si, Cu, Ag, and Al

LCI Results Reflect Process and System Boundary Differences

The charts illustrate process variation, not a ranking of recycler performance



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



- **Inputs differ:** Module type and construction affects the initial proportions of glass, metals, frames, and polymers
- **Recovery endpoints differ:** Some processes stop at mixed fractions; other recover specific metals or semiconductor materials
- **Energy boundaries differ:** Electricity data are incomplete and do not represent total process energy or environmental performance

Key Takeaways

- **Recovery is advancing beyond bulk materials.** New and updated processes report improved recovery, yields, or purity for silicon, silver, copper, and semiconductor materials.
- **Process design shapes scale, recovery, and output quality.** Mechanical pathways support commercial-scale throughput, while thermal chemical, waterjet, and light-based treatments can improve separation and recovery of higher-value materials.
- **Addressing data gaps is a priority for comparative assessment.** More consistent material recovery reporting, system boundary harmonization, and energy-use data would strengthen technology evaluation and end-of-life decision-making.

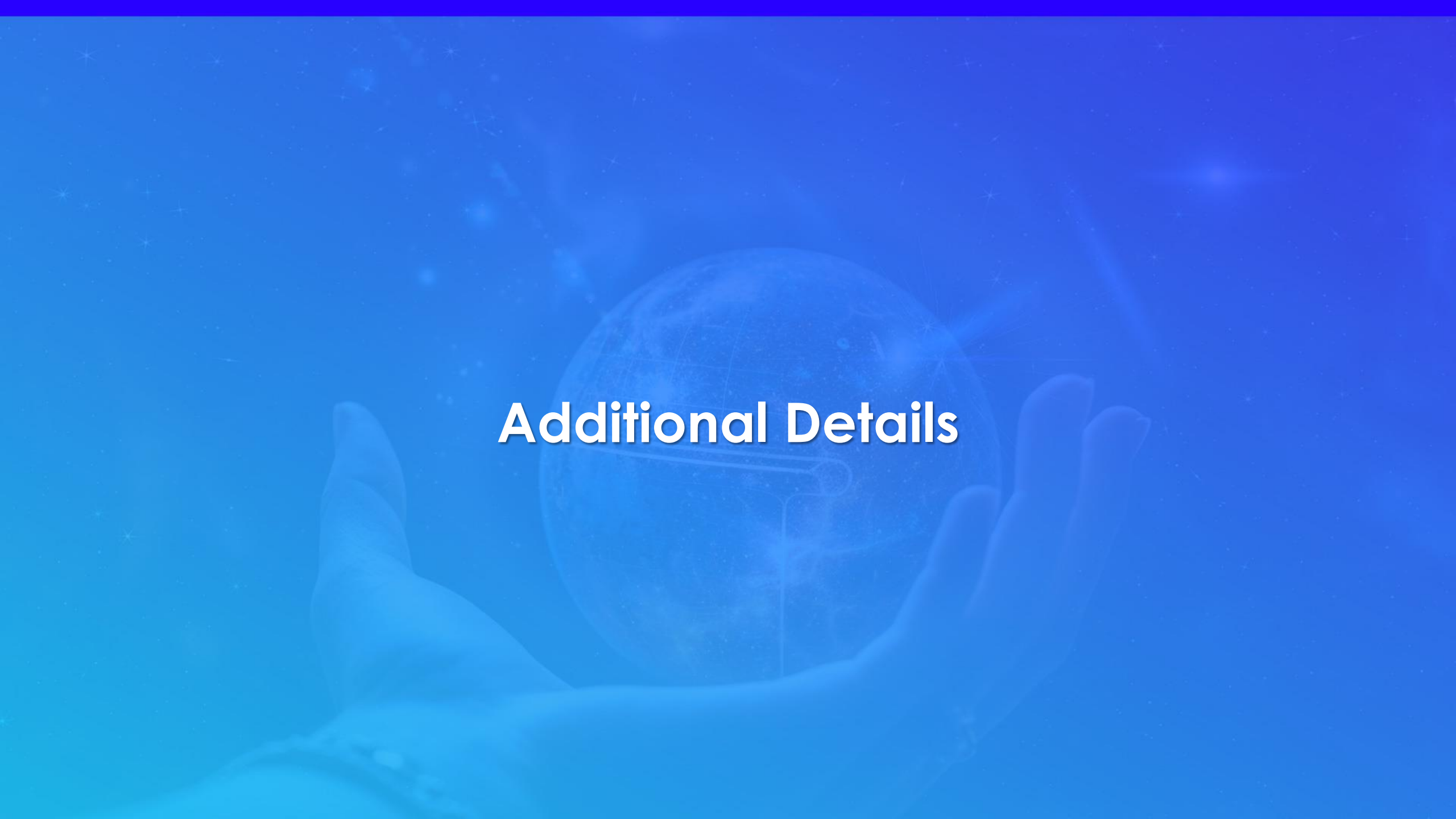


Different recycling objectives favor different process pathways.



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Additional Details

12 recyclers supplied life cycle inventory (LCI) data

LCI Data Contributors for this Report	Facility	Module Type	Processing Capacity (t/yr)	Dismantling of Frames, Junction Boxes, and Cables	Delamination	Material Separation
	First Solar *	CdTe	112,000	Removed before delamination; process details not provided	Shredder, hammer mill	Leaching, metal precipitation
	CI(G)S PHOTORAMA	CI(G)S	1,000	Mechanical or diamond wire cutting	Flash-light, mechanical opening	MSA leaching, electrowinning, incineration (polymers)
	c-Si PHOTORAMA	c-Si	1,000	Mechanical	High-pressure water jet	Density, leaching, electrowinning, incineration (polymers), smelter (Cu)
	SOLARCYCLE	c-Si	20,000	Automatic deframing	Shredder	Electrostatic
	Solarpanel-recycling.com	c-Si	63,000	Automatic deframing, robotic j-box removal	Heat and/or mechanical pressure, shredder, grinder	Air flow (polymers/foils)
	9-Tech	c-Si	33	Currently manual; new plant includes automatic module recognition, deframing, and j-box removal	Cutting, hammer, combustion (furnace)	Chemical, ultrasonic (Ag, Al), counter-rotating rollers (Cu),vibrating screens
	Reiling **	c-Si	50,000	Frame removal post-crush/shred; 10% with impurities	Crush, shredder	Manual sort, screening, optical
	LuxChemtech **	c-Si	1,000	Process details not provided	High-pressure water jet	Leaching, electrowinning, incineration (polymers)
	Flaxres **	c-Si	1,000	Process details not provided	Light pulse	Process details not provided
	ROSI **	c-Si	3,000	Removed before pyrolysis	Pyrolysis (requires after burner and wet scrubber)	Screening, density, chemical etching
	Envie & ROSI **	c-Si	3,000	Electricity consumption data provided; process details not provided	Hot knife, pyrolysis (requires after burner and wet scrubber)	Screening, density, chemical etching
	Tialpi **	c-Si	3,000	Removed before delamination; process details not provided	Infrared lights, room-temperature knife, crush	Liquid nitrogen, sieve, electrostatic, leaching, electrolysis
LCI Data from 2024 IEA PVPS publication						

* 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

Source: Wambach & Libby (2026); Wambach, Libby, and Shaw (2024)

LCI Data: First Solar

	Unit	First Solar 2021 (2024 IEA PVPS publication)	First Solar 2024 update (this report)
Capacity	t/yr	50,000	112,000
Type of plant		4 commercial recycling plants	6 commercial recycling plants
Location		USA, Malaysia, Vietnam, Germany	USA, Malaysia, Vietnam, Germany, India
Module		CdTe	CdTe
Time period		2021	2024
Process	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/JB, not incl. semiconductor)	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, encapsulant	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.

LCI Data: c-Si Recyclers (Facility Overview)

LCI Data Contributors for this Report						LCI Data from 2024 IEA PVPS publication					
	Unit	PHOTORAMA (c-Si)	SOLARCYCLE	SPR	9-Tech	Reiling	ROSI	Envie & ROSI	Tialpi	LuxChemtech	Flaxres
Capacity	t/yr	1,000	20,000 *	63,000 **	33	10,000- 50,000	3,000	3,000	3,000	1,000	1,000
Scale of plant		Manual/ auto. pilot	Auto. commercial	Auto. commercial	Manual/ auto. pilot	Auto. commercial	Auto. pilot	Modelled combination	Auto. pilot	Manual/ partial auto.	Auto. pilot
Process type(s)		Mech., chem., optical	Mech., thermal	Mechanical	Mech., thermal, chem., ultrasound	Mechanical	Mech., thermal (pyrolysis), chem.	Mech., thermal, chem.	Mech., thermal, chem.	Mech., chem.	Mech., optical (light pulse)
Location		Tangermunde , DE	Texas, USA	NC, USA (TX & GA)	Venice, IT	Germany	La Mure, FR	FR	Biella, IT	Tangermunde, DE	Dresden, DE
Module type		c-Si, glass/BS	c-Si, glass/BS	c-Si, glass/BS & glass/glass	c-Si	c-Si & Si thin film	c-Si, glass/BS & glass/glass	c-Si, glass/BS	c-Si, glass/BS	c-Si, glass/BS	c-Si
Time period		2025	2022- 2023	2023- 2024	2023- 2024	2022	2022- 2023	2022- 2023	2022	2021- 2022	2022

* 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.

LCI Data: c-Si Recyclers (Process Inputs and Outputs)

LCI Data Contributors for this Report					LCI Data from 2024 IEA PVPS publication						
	Unit	PHOTORAMA (c-Si)	SOLARCYCLE	SPR	9-Tech	Reiling	ROSI	Envie & ROSI	Tialpi	LuxChemtech	Flaxres
Total input	t/yr	1,000	12,733	14,665	33	4,200	3,000	2,850	1,000	1,000	7
Electricity	kWh/t				112	60		52	136	130	50
CNG/LNG	kWh/t				250	0.36			None	None	
Comp. air	m3/t	169									
Water	kg/t	130									
Diesel/oil	l/t				None	2.5		15	0	None	
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
Junction boxes	wt. %	0.9	Incl.	#	1.8	0.35	4.3	4.3	1	0.39	1
Ferrous metals	wt. %			0.5	0	0.2	0	0	0	0	
NF 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
Mix glass/foil	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		
Pyrolyzed/comb.	wt. %	8.7			10.3	14	6.5	10.97		0.44	
Total	wt. %	100	100	100	100	100	100	100	100	100	100

SPR included in non-ferrous fraction. Output materials are not necessarily recovered for subsequent material use.

Recovery of Semiconductor Materials & Metals within Laminate

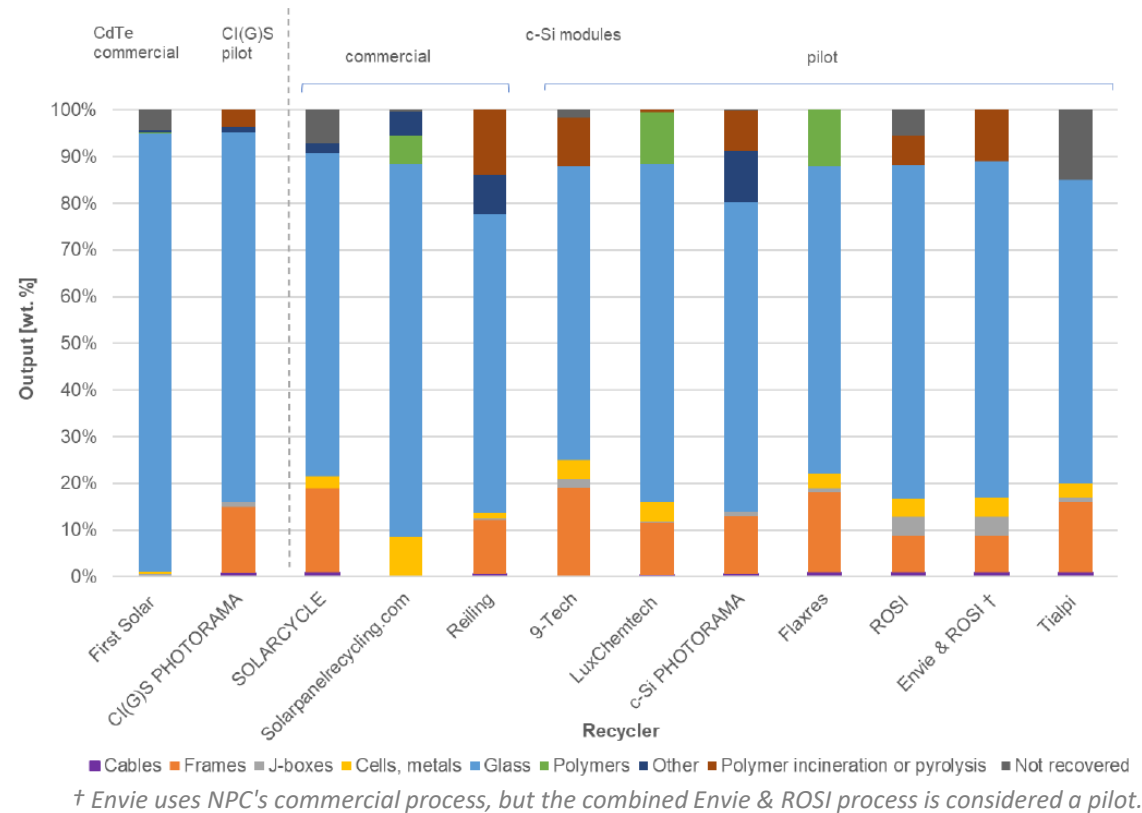
LCI Data Contributors	Metal and Semiconductors	Description
LCI Data Contributors for this Report		
First Solar	CdTe	0.5 wt. % of PV module input mass of CdTe recovered and refined by third-party for reuse in new modules, with semiconductor material recovery of >90 wt. % *
CI(G)S PHOTORAMA	CI(G)S	0.1 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 ~70% purity; 99% of input Cu recovered at >99% purity; 99% of other trace metals recovered at >99% purity
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; ore grade sent to refinery
c-Si PHOTORAMA	Si, In, Ag	3.9 wt. % Si recovered at 5N purity; 0.3 wt. % NF metal recovery including Ag at 2N+ purity and other metals (e.g. In for HJT)
9-Tech	Si, Ag	1 wt. % NF metal recovery; 95% Cu recovery at 95% purity; 2.8 wt. % Si at 95% recovery/purity; 0.3 wt. % Al/Ag metallic powder recovery
LCI Data from 2024 IEA PVPS publication **		
ROSI	Si, Ag, Cu	2.78 wt. % Si at 5-6N purity and 0.07 wt. % Ag; 0.87 wt. % NF metal (Cu ribbon) sent to refinery
Envie & ROSI	Si, Ag, Cu	3.11 wt. % Si at 5-6N purity and 0.07 wt. % Ag; 0.85 wt. % NF metal (Cu ribbon) sent to refinery
Tialpi	Si	55 wt. % NF metals, includes Si wafer and EVA sent to Al furnace; Si, Cu, Ag recovery under development
LuxChemtech	Si, In, Sn, Ag, Cu	~3.3 wt. % metal recovery; 0.027 wt.% NF metals (Ag, In, Sn); 0.45% Cu; 2.826% Si for battery anodes/targets
Flaxres	Si, Ag	3 wt. % NF metals, includes Si wafer with Ag; can be processed by third parties

* First Solar Corporate Responsibility Report 2024. ** Information is based on 2024 IEA PVPS publication and may not reflect current capabilities.

LCI Results Reflect Process and System Boundary Differences

The charts illustrate process variation, not a ranking of recycler performance

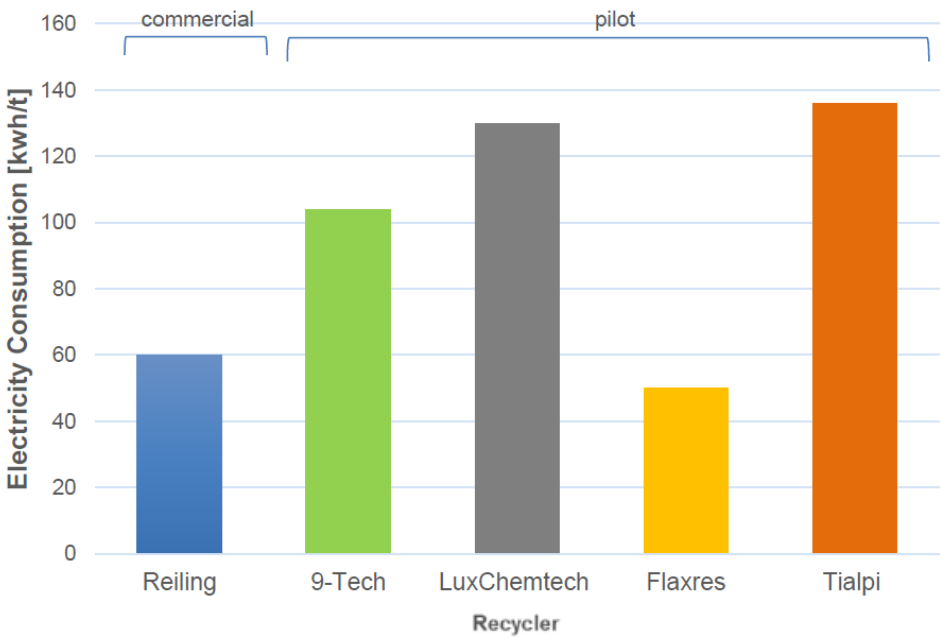
Relative Output Composition



Notes on system boundaries

- c-Si: up to separation of the cell fraction (incl. metals) from glass and polymers
- PHOTORAMA CI(G)S: up to and including recovery of unrefined semiconductor material (Cu, In, Ga, Se)
- First Solar: up to and including unrefined CdTe recovery and third-party refining to semiconductor-grade CdTe.

Electricity Consumption



Notes on LCI data interpretation

- Sources: Reiling, LuxChemtech, Flaxres, and Tialpi are from the 2024 Task 12 LCI report; LuxChemtech data do not reflect PHOTORAMA's current facilities or maturity
- Module assumptions: Input modules include frames except for First Solar; PHOTORAMA CI(G)S modules include back rails (counted as frames); SPR aluminum frames are reported within metals
- Limitations: Electricity consumption was not reported by most recyclers; Direct comparison is constrained by differences in scale, module composition, projected vs. measured values, and full vs. partial treatment pathways