PV End-of-Life management and circularity

an overview

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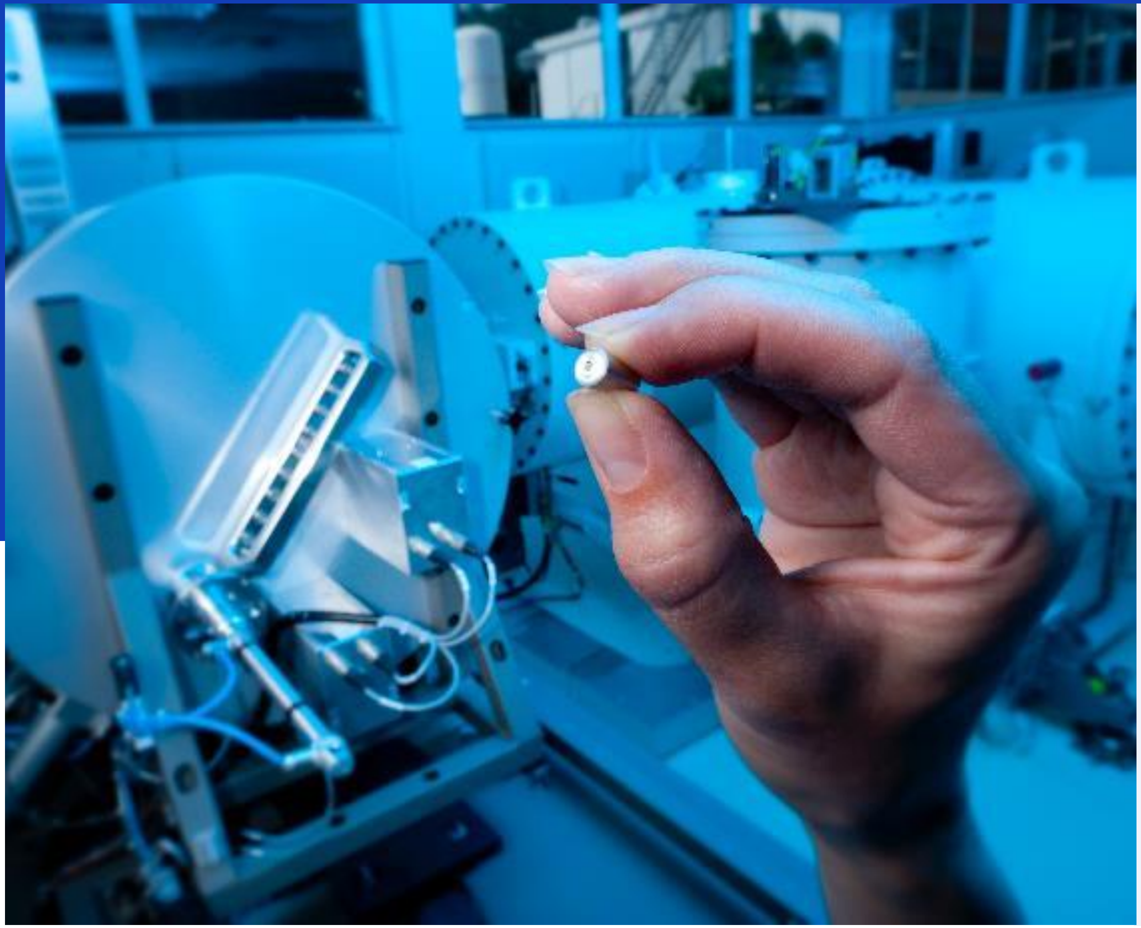
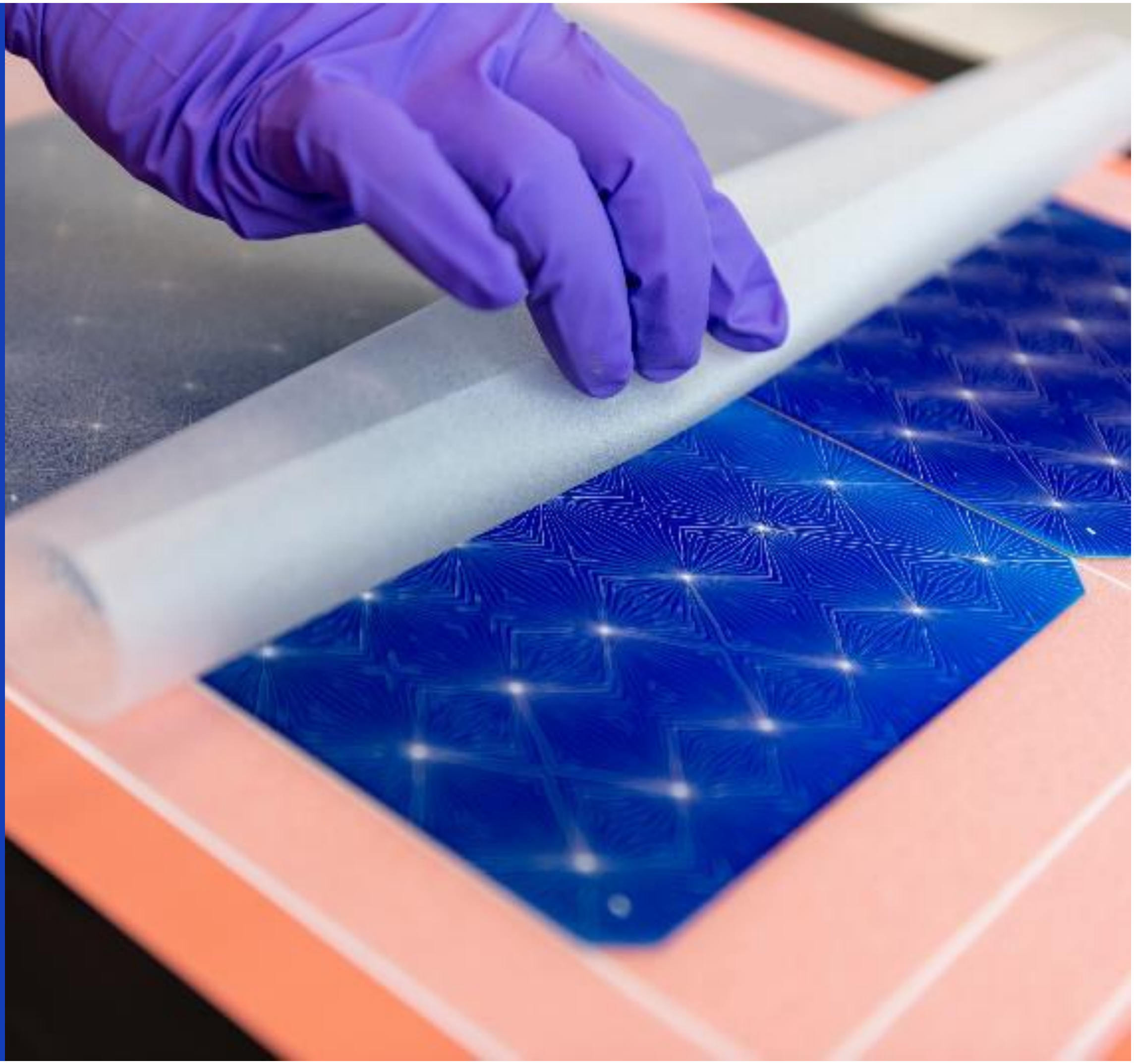
Content



1. EoL management of solar panels (past, present and future)
2. Existing LCA's
3. Circularity indicators vs. circularity of panels

EoL management of solar panels (past, present and future)



PV technologies in EU

Table: Market share of PV panels by technology groups (2014-2030) Technology. [1]

Technology		2014	2020	2030
Silicon-based (c-Si)	Monocrystalline	92%	73.3%	44.8%
	Poly- or multicrystalline			
	Ribbon			
	a-Si (amorph/micromorph)			
Thin-film based	Copper indium gallium (di)selenide (CIGS)	2%	5.2%	6.4%
	Cadmium telluride (CdTe)	5%	5.2%	4.7%
Other	Concentrating solar PV (CPV)	1%	1.2%	0.6%
	Organic PV/dye-sensitised cells (OPV)		5.8%	8.7%
	Crystalline silicon (advanced c-Si)		8.7%	25.6%
	CIGS alternatives, heavy metals (e.g. perovskite), advanced III-V		0.6%	9.3%

[1] End-Of-Life Management: Solar Photovoltaic Panels, 2016. , IRENA and IEA-PVPS. IRENA 2016 AND IEA-PVPS 2016.
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Past and present

Recycling pathways – current situation (c-Si)

- Past up to present

In first-generation recycling processes, c-Si PV modules are treated in recycling plants designed for laminated glass, metals or electric and electronic waste [2]

  - Only junction box and aluminium frame recovered*
  - glass cullet feedstock
  - -> foam or fiberglass production [3]
  - -> mostly landfilled or incinerated

CdTe panels market share in EU small
CIGS panels haven't reached EoL yet

Table: Summary of Recyclers that Participated in the Study of PVPS task 12 [3]

Company	Country	Process	Type of Recycler	PV Volume (t/yr)
Anonymous	Germany	Mechanical	Glass	1,200
Exner Trenntechnik GmbH	Germany	Mechanical	Metal	100-250
Maltha	Belgium	Mechanical	Glass	1,000
Nike	Italy	Mechanical	Glass	600
Sasil S.r.l.	Italy	Combination of mechanical, thermal, and chemical	Prototype PV recycling system	(1t/hr tests)

[2] Stolz, P., Frischknecht, R., Wambach, K., Sinha, P., Heath, G., 2018. Life Cycle Assessment of Current Photovoltaic Module Recycling. https://iea-pvps.org/wp-content/uploads/2020/01/Life_Cycle_Assesment_of_Current_Photovoltaic_Module_Recycling_by_Task_12.pdf
[3] Heath, G., Wade, A., Wambach, K., Libby, C., 2017. Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe.
[6] Balancing Costs And Revenues For Recycling End-of-life Pv Panels In The Netherlands TNO 2022 R10860 https://circulairekennis.nl/wp-content/uploads/2022/12/O027-Kosten-en-opbrengsten-bij-recycling-PV-panelen.pdf

Recycling pathways – current situation (c-Si)

- Past up to present

In first-generation recycling processes, c-Si PV modules are treated in reycling plants designed for laminated glass, metals or electric and electronic waste [2]

  - Only junction box and aluminium frame recovered
  - Volume not enough to enable better PV dedicated recycling
  - processes were not available
  - PV recycling was/is not profitable

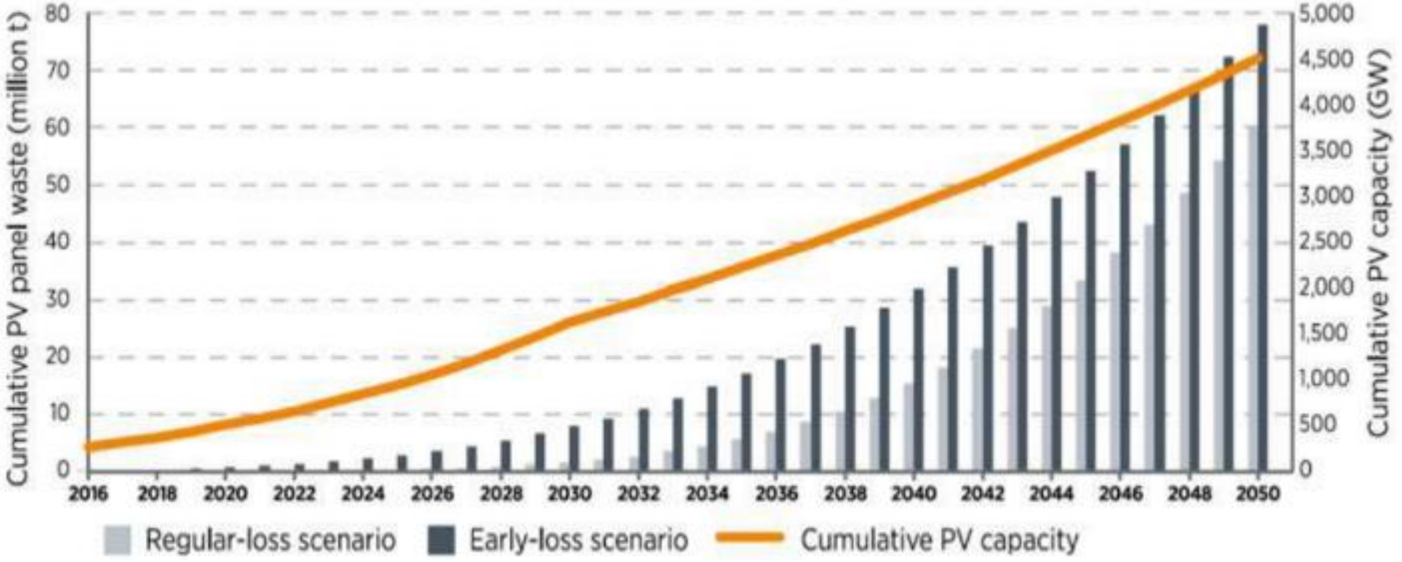

Figure: Estimated cumulative global waste volumes of end-of-life PV modules, by IRENA/Task12 [4]

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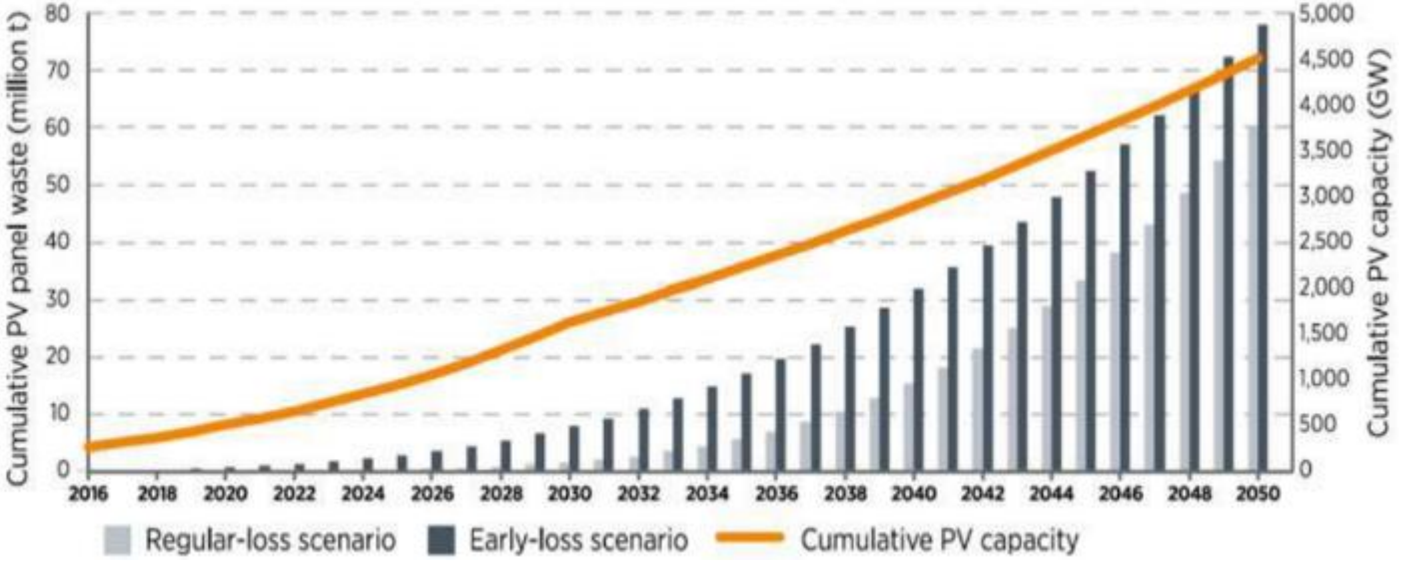
Recycling pathways – current situation (c-Si)

Solar World had to stop their in-house developed pyrolysis based PV panel recycling. This process proved to be non-economically viable with the available waste volumes at that time and the decreasing cell thickness, which prevents the reuse of wafers [5]

It was acquired by SunPower in 2018, when it filed for insolvency in Germany in 2017. SunPower, the company that acquired SolarWorld, offers end-of-life management services for their own PV modules, which includes recycling and recovery of valuable materials.



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[5] Peeters, J.R., Altamirano, D., Dewulf, W., Duflou, J.R., 2017. Forecasting the composition of emerging waste streams with sensitivity analysis: A case study for photovoltaic (PV) panels in Flanders. Resour. Conserv. Recycl. 120, 14–26. https://doi.org/10.1016/J.RESCONREC.2017.01.001

Recycling pathways - (c-Si)

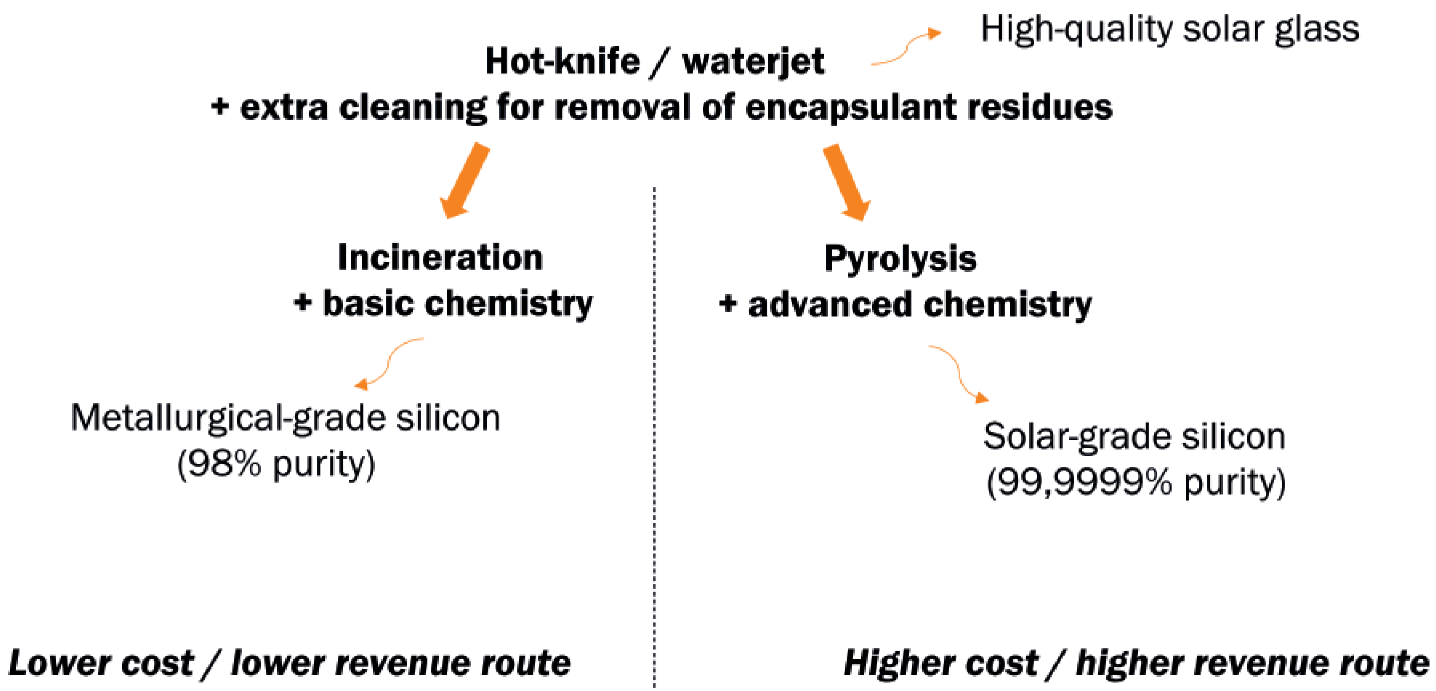

Figure: Recycling routes incineration and pyrolysis Higher [6]

[6] BALANCING COSTS AND REVENUES FOR RECYCLING END-OF-LIFE PV PANELS IN THE NETHERLANDS TNO 2022 R10860 https://circulairekennis.nl/wp-content/uploads/2022/12/O027-Kosten-en-opbrengsten-bij-recycling-PV-panelen.pdf

Recycling pathways – (c-Si) [6]

- Next step / near future
  - Dismantling
    - Junction box, aluminium frame
  - Delamintaion
    - solar glass recovered
  - Volume rapidly increasing but not enough to enable recycling of cells (not profitable)

High-quality solar glass

Hot-knife / waterjet
+ extra cleaning for removal of encapsulant residues

Incineration
+ basic chemistry

Metallurgical-grade silicon
(98% purity)

Lower cost / lower revenue route

Figure: Recycling routes incineration and pyrolysis Higher [6]

- Aluminium from the frame (for refinement to secondary aluminium);
- Copper from wires and tabs (for refinement to secondary copper);
- Glass (for refinement to secondary glass);
- Silicon from the solar cells (metallurgical grade);
- Silver from the solar cells (for refinement to secondary silver).

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Recycling pathways - (c-Si) [6]

- Future
  - Dismantling, delamination,

  +
  - chemical step to remove:
    - anti- reflection coating,
    - thin, highly doped silicon layers at the front and back side of the cells
  - Large volume of c-Si PV panels at EoL = more routes that are economically viable

- Aluminium from the frame (for refinement to secondary aluminium);
- Copper from wires and tabs (for refinement to secondary copper);
- Glass (for refinement to secondary glass);
- **Silicon from the solar cells (solar grade);**
- Silver from the solar cells (for refinement to secondary silver).

Hot-knife / waterjet
+ extra cleaning for removal of encapsulant residues

High-quality solar glass

Pyrolysis
+ advanced chemistry

Solar-grade silicon (99,9999% purity)

Higher cost / higher revenue route

Figure: Recycling routes incineration and pyrolysis Higher [6]

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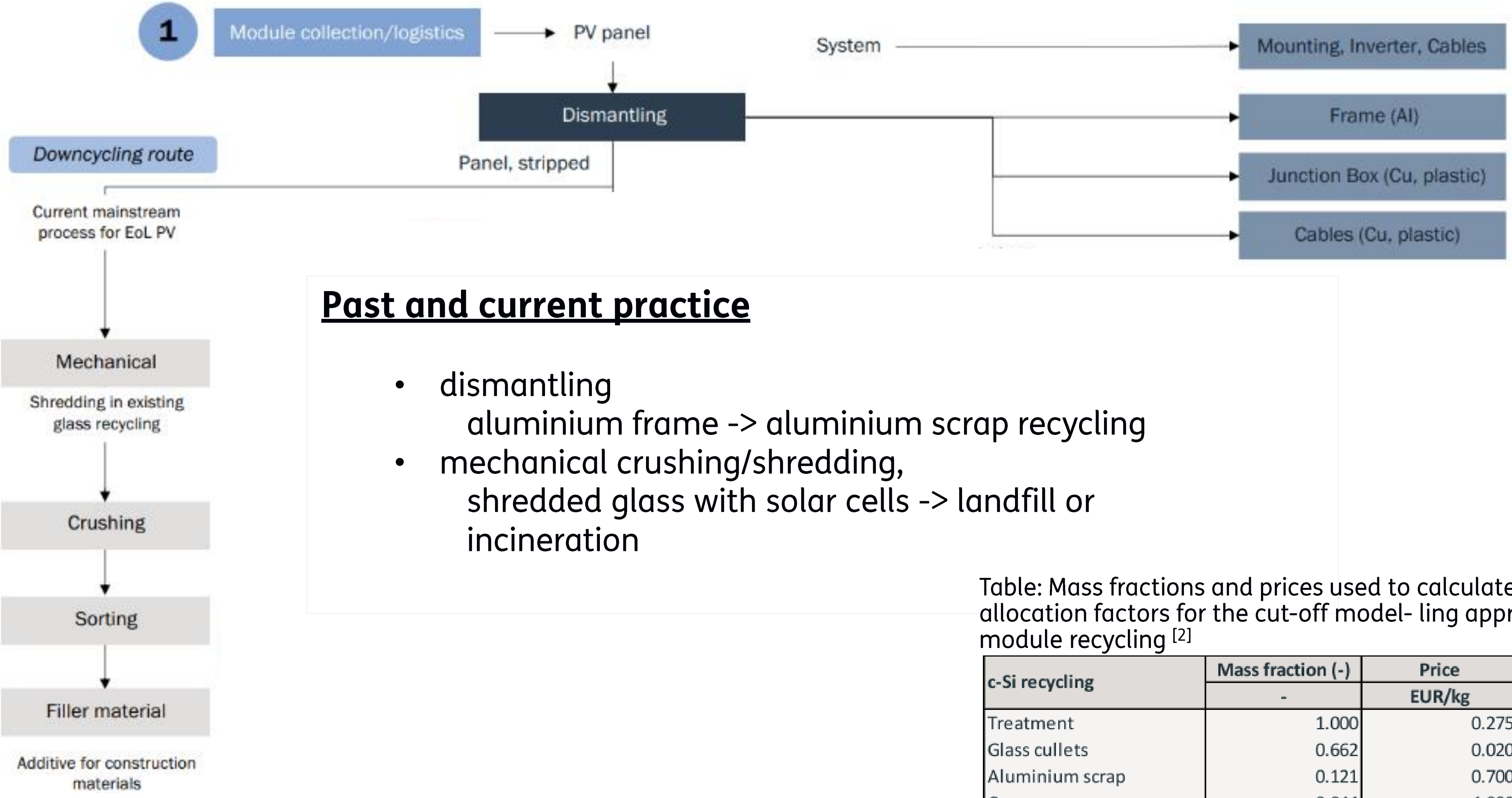
Recycling pathways (c-Si) – processing steps [6]



Past and current practice

- dismantling
  aluminium frame -> aluminium scrap recycling
- mechanical crushing/shredding,
  shredded glass with solar cells -> landfill or incineration

Table: Mass fractions and prices used to calculate economic allocation factors for the cut-off model- ling approach of c-Si PV module recycling [2]

c-Si recycling	Mass fraction (-)	Price	Allocation factor
	-	EUR/kg	-
Treatment	1.000	0.275	**0.500**
Glass cullets	0.662	0.020	**0.024**
Aluminium scrap	0.121	0.700	**0.154**
Copper scrap	0.044	4.000	**0.322**

[2] Stolz, P., Frischknecht, R., Wambach, K., Sinha, P., Heath, G., 2018. Life Cycle Assessment of Current Photovoltaic Module Recycling. https://iea-pvps.org/wp-content/uploads/2020/01/Life_Cycle_Assesment_of_Current_Photovoltaic_Module_Recycling_by_Task_12.pdf
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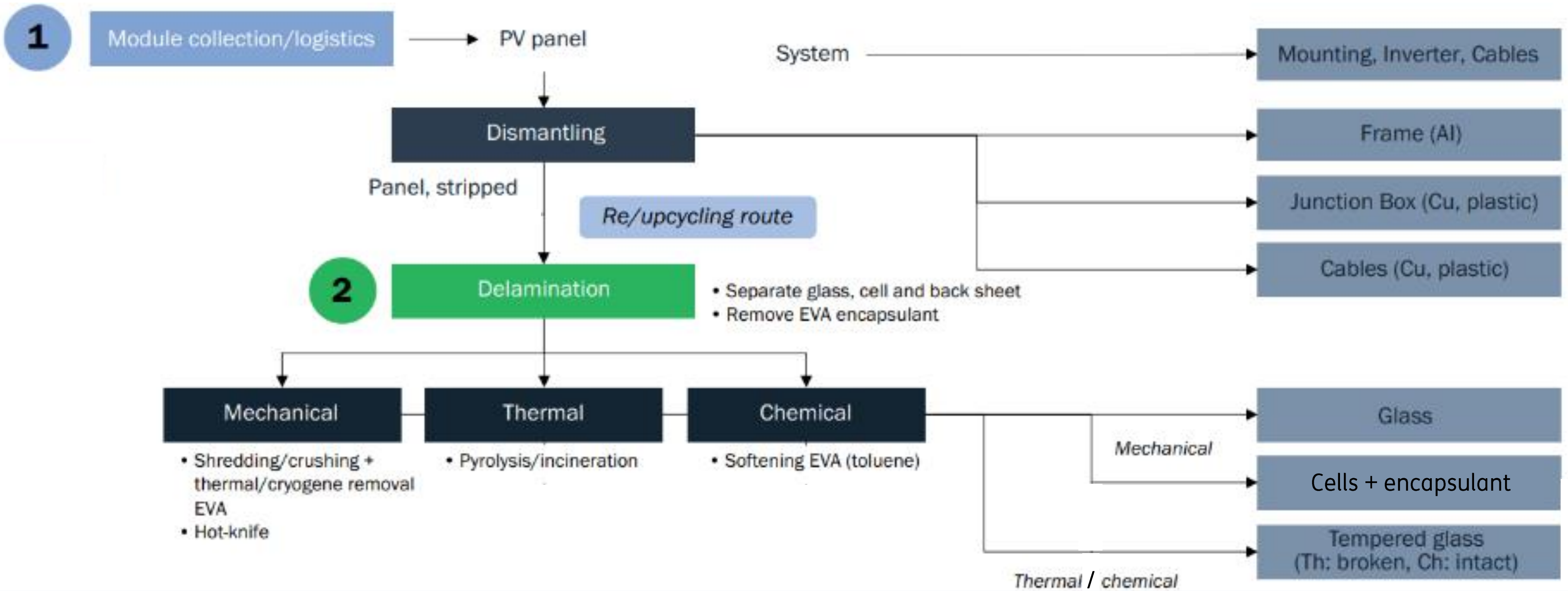

Next step / near future

- Dismantling: aluminium frame -> aluminium scrap recycling
- Delamination Waterjet, hot knife, pyrolysis or chemical separation
  glass and back sheet -> recycling
  cells -> acid leaching + electrolysis (Metallurgical grade silicon)

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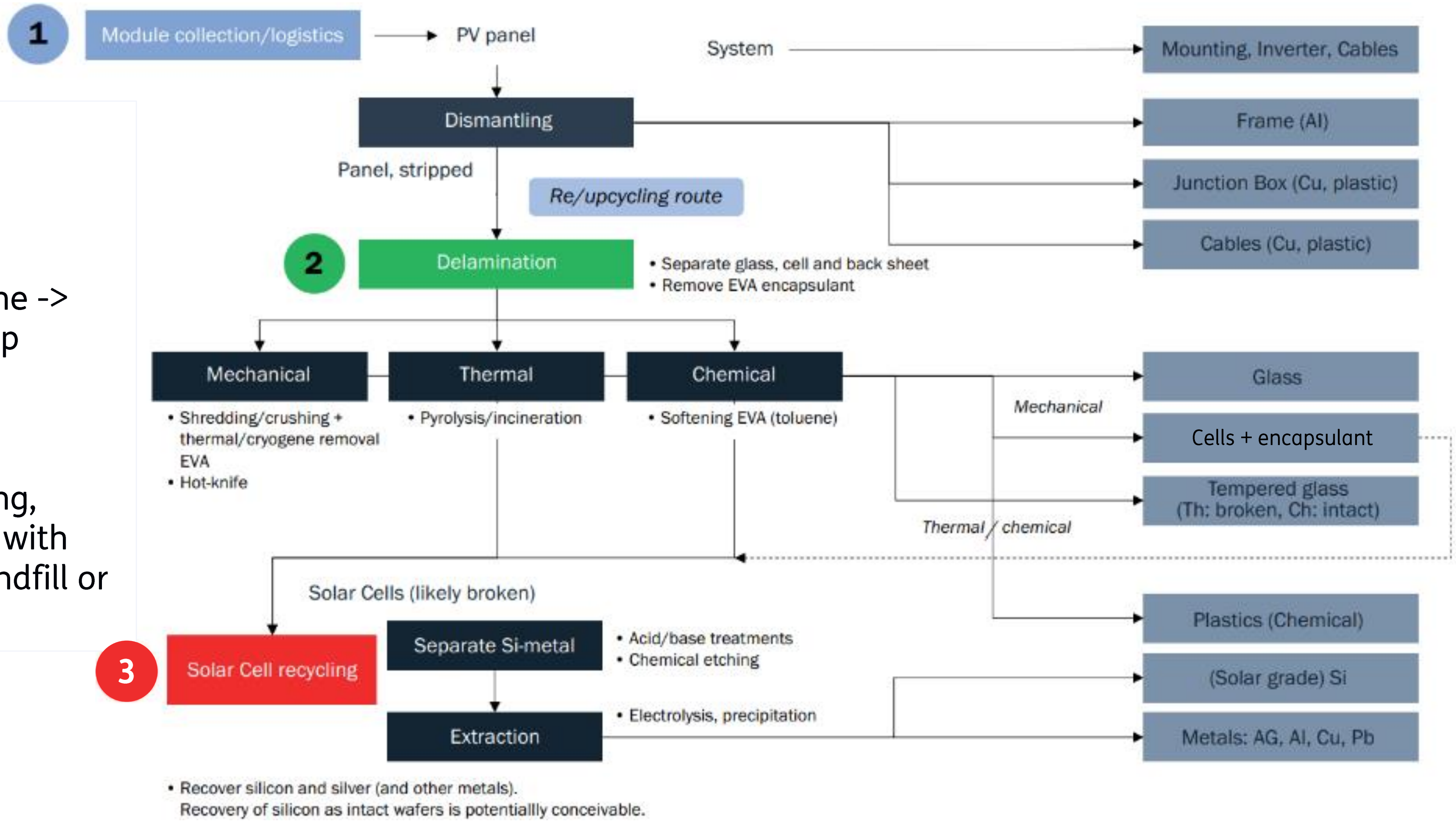

TNO innovation for life

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Recycling pathways – current situation (CdTe)

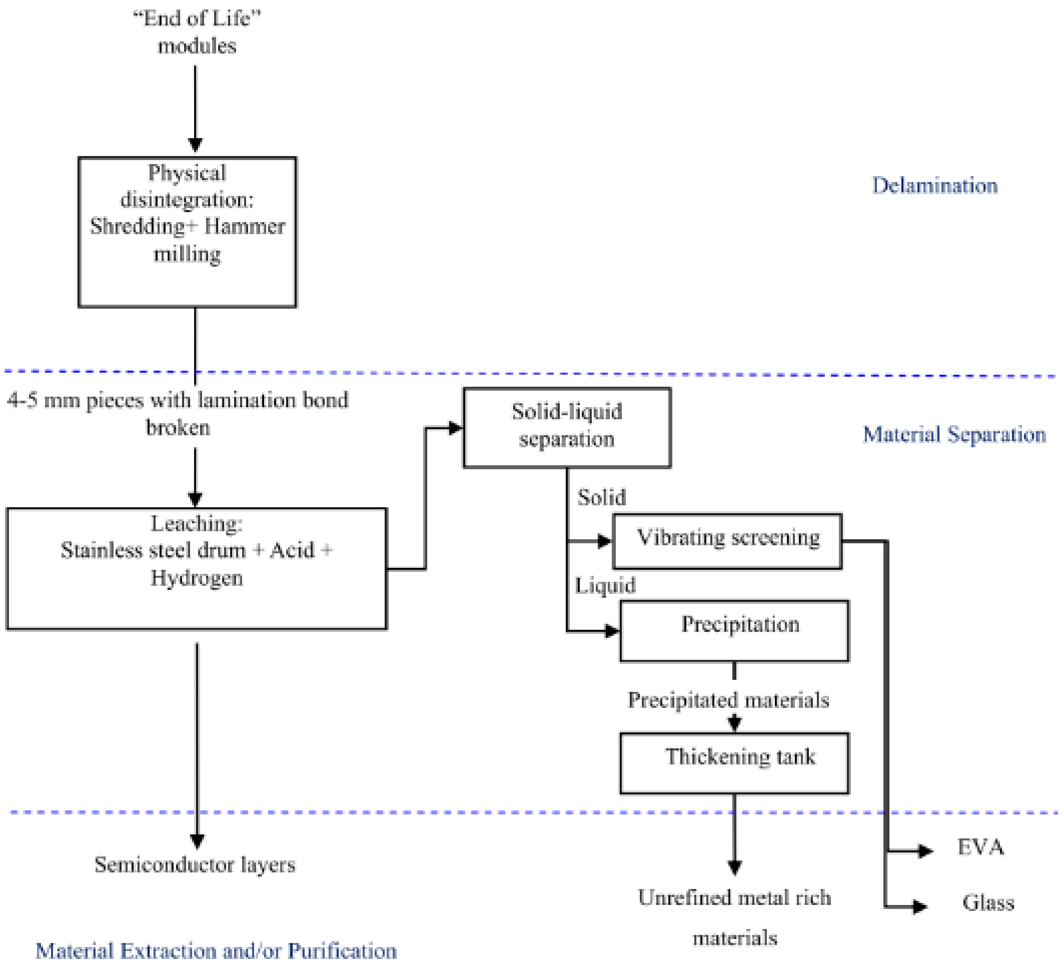


Figure: PV module recycling processes of FirstSolar [7]

FirstSolar process[7]
FirstSolar is a manufacturer of thin-film PV located in Frankfurt an der Oder, Germany.

Process:
1. Dismantling: aluminium frame -> aluminium scrap recycling
2. Shredding and hammer milling modules to break lamination bonds
3. Leaching in a rotating drum to remove semiconductor films
4. Classification to separate solids (glass and laminate materials)
5. Vibrating screen separates the glass from the laminate
6. Cleaning of the glass to remove residual semiconductor
7. Precipitation of the metals in three stages + concentration

Recovery:
- Glass for refining (90% recovery)
- metal-rich material is refined by third party (CdTe) (95%)
- 80% Tellurium recovered at a purity level of (99.7% Te)

[7] Tao, J., Yu, S., 2015. Review on feasible recycling pathways and technologies of solar photovoltaic modules. Sol. Energy Mater. Sol. Cells 141, 108–124. https://doi.org/10.1016/j.solmat.2015.05.005

Near and mid-term Future

Recycling pathways – c-Si (Veolia - FR)

Veolia uses a "thermal-mechanical treatment"

Processing:

1. Pre-treatment: thermal delamination. Separation of cells from panels and removal of the aluminum contacts.

2. Pyrolysis: cells heated up to 800°C in a furnace to break down the materials into their constituent parts. Materials are vaporized and then condensed to produce a mixture of metals and other materials.

3. Separation: Magnetic, eddy current and other mechanical methods. The resulting materials are sent to recyclers of valuable metals such as silver, copper, and silicon.

4. They claim that their process can recover up to 95% of the mass of solar panels.

Source: weee-solar-panels-recycling | Veolia

Recovery:

- Copper shot (cables and connectors)
- Crystalline silicon (precious metal sectors)
- Glass, 2/3 recovered as clean cullet is used in the glass-making sector,
- Aluminium scrap
- Energy (plastics burned in cement works)

Source: A factory recycles photovoltaic panels | UpToUs (veolia.com)

- No inventory available

Recycling pathways - Future

- Future
  - Dismantling, delamination (thermal, mechanical or optical),

  +
  - chemical step to remove:
    - anti-reflection coating,
    - thin, highly doped silicon layers at the front and back side of the cells (c-Si)
    - Other high value semi-con materials (thin-film)

Closed loop recovery: (>90%)

- Aluminium from frame;
- Copper from wires and tabs;
- Glass (solar grade);
- Silicon from solar cells (solar grade);
- Indium, Galium, Telluride etc. (high purity);
- Silver (high purity)

Recycling pathways – near/mid-term future (CIGS) [4]

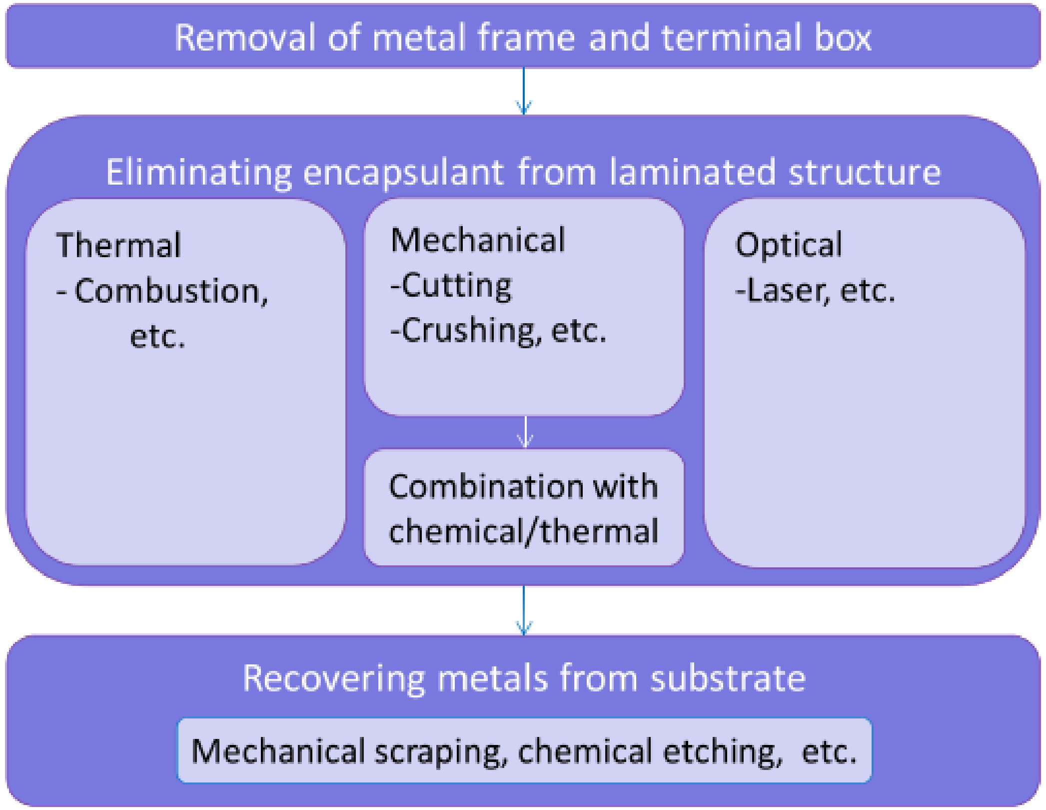


Figure: Recent R&D for compound PV module recycling [4]

Most approaches suitable for c-Si are also suitable for treating thin-film

- Pyrolysis for delamination + leaching
  remove encapsulant and allow recovery of cover and substrate glass

  Or

- Grinding / crushing + leaching
  chemically removal of semi-con layer and stepwise precipitation

Crushing is more suitable for non Si based PV as those metals can be recovered at a high purity through leaching even if the whole panel is ground.

[4] Komoto, K., Lee, J.-S., Zhang, J., Ravikumar, D., Sinha, P., Wade, A., Heath, G.A., 2018. End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies. Golden, CO (United States). https://doi.org/10.2172/1561523

Recycling pathways – Perovskite solar cells (PSC)

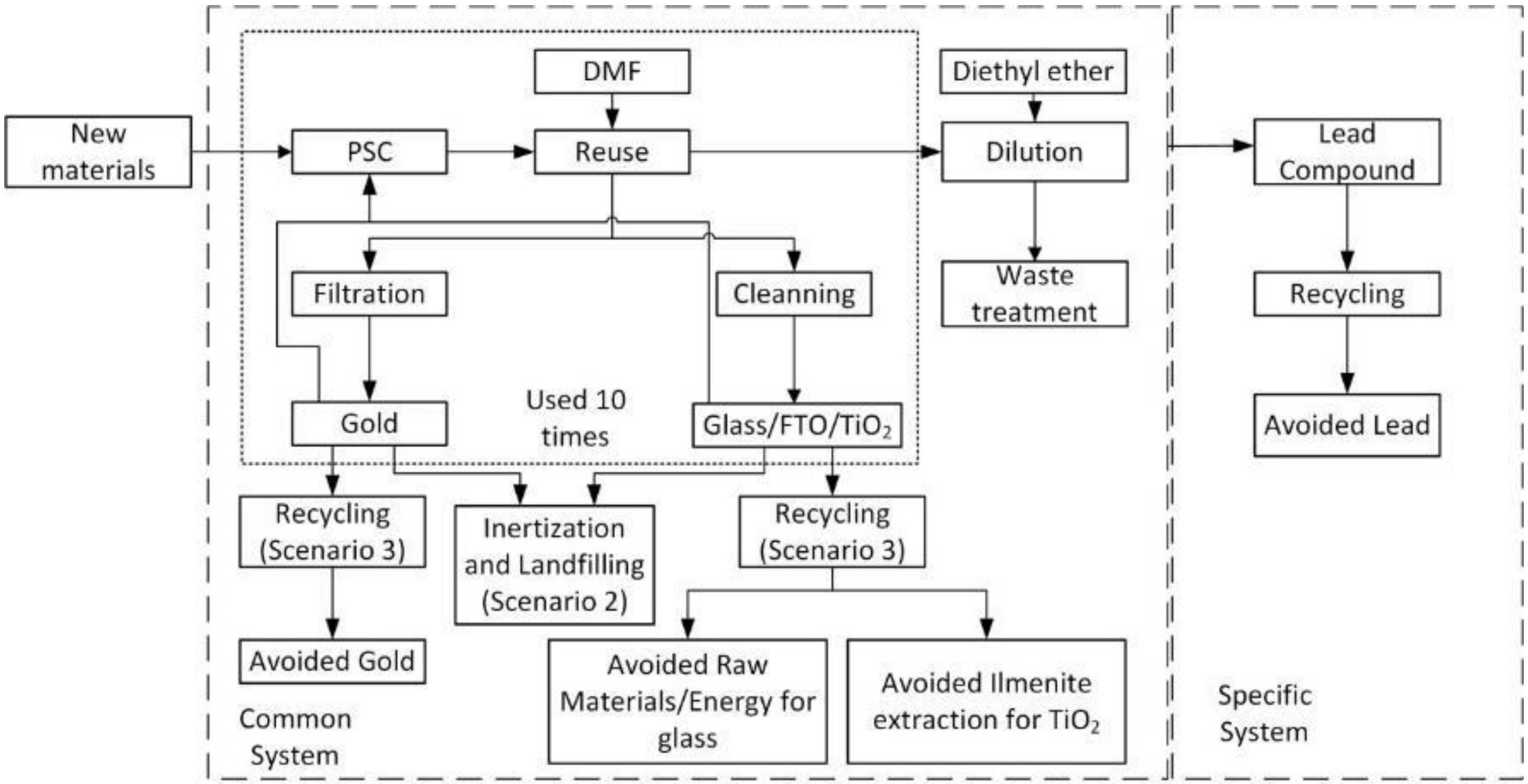


Figure: Scheme of the recycling process for scenario s3. [8]

[8] Alberola-Borràs, Jaume-Adrià, et al. "Relative impacts of methylammonium lead triiodide perovskite solar cells based on life cycle assessment." Solar Energy Materials and Solar Cells 179 (2018): 169-177.
https://doi.org/10.1016/j.solmat.2017.11.008

Recycling pathways – Perovskite solar cells (PSC)

TABLE 3

Present recycle and recovery technologies of PSCs.

Components or Materials	Architectures	Key Methods	Recycled/Recovered Materials
TCO and ETL			
	glass/FTO/$CH_3NH_3Pb_{3-x}Cl_x$/spiro-MeOTAD/Ag	Dissolution by DMF	glass/FTO
	glass/FTO/c-TiO_2 or (c-TiO2 /m-TiO_2)/spiro-MeOTAD/Ag	Dissolution by DMF	glass/FTO/TiO_2
	glass/ITO/PEDOT:PSS/$MAPbI_3$/PC60BM/Ca/Al	Dissolution by KOH	glass/ITO
	glass/FTO/TiO_2/$CsPbIBr_2$/carbon	Dissolution by DMF	glass/FTO/TiO_2
Perovskite Film and HTL			
	glass/FTO/TiO_2/$MAPbI_3$/spiro-OMeTAD/Au	Dissolution by chlorobenzene, reuse of undegraded perovskite films	$MAPbI_3$
	glass/FTO/TiO_2/$MAPbI_3$	Recovery from PbI_2 using MAI	$MAPbI_3$
	glass/FTO/c-TiO_2/m-TiO_2/$MAPbI_3$/spiro-OMeTAD/Ag	Dissolution by chlorobenzene, thermal decomposition	$MAPbI_3$
Pb			
	glass/FTO/TiO_2/$MAPbI_3$, $FAPbI_3$, or $MAPb_{3-x}I_x$	Dissolution by eutectic solvent, electrodeposition	Pb
	glass/FTO/TiO_2/$MAPbI_3$/spiro-OMeTAD/Au	Etraction by water, dissolution by DMF, reuse of PbI2	PbI_2
	glass/FTO/c-TiO_2/m-TiO_2/$MAPbI_3$/carbon	NH3·H2O treatment, HI treatment	PbI_2
All Major Components			
	glass/FTO/c-TiO_2/m-TiO_2/$MAPbI_3$ or $(FAPbI_3)_{0.85}(MAPbBr_3)_{0.15}$/spiro-OMeTAD/Au	Dissolution by DMF, extraction by ether, ion-exchange by hydroxyapatite	glass/FTO/TiO_2, Pb, Au
	glass/FTO/c-TiO_2/m-TiO_2/$MAPbI_3$/spiro-OMeTAD/Au	Dissolution by chlorobenzene, ethanol treatment, dissolution by DMF	glass/FTO/TiO_2, Pb, Au
	glass/FTO/c-TiO_2/m-TiO_2/$MAPbI_3$/mp-Al_2O_3/np-Au:NiO_x	Special design for reusing most components but perovskite layer.	glass/FTO/c-TiO_2/m-TiO_2/mp-Al_2O_3/np-Au:NiO_x

- Toxicity of Pb contained in perovskite layer is key issue for waste management of PSC
- Most common approach is dissolution “layer by layer” to recover different components of PSC
- Current recycling processes are carried out at lab scale, research and investment efforts are needed to upscale this technology

[9] Liu, Fan-Wei, et al. "Recycling and recovery of perovskite solar cells." Materials Today 43 (2021): 185-197.

Recycling process – c-Si (ROSI - FR)

ROSI Solar (Return Of Silicon)

- from Grenoble – FR,
- EIT RawMaterials partner
- Capacity: 3,000 tonnes of solar panels per year.
- among the first companies in Europe to offer an industrial solution to economically recover high-purity silicon, silver, and copper from end-of-life PV modules.

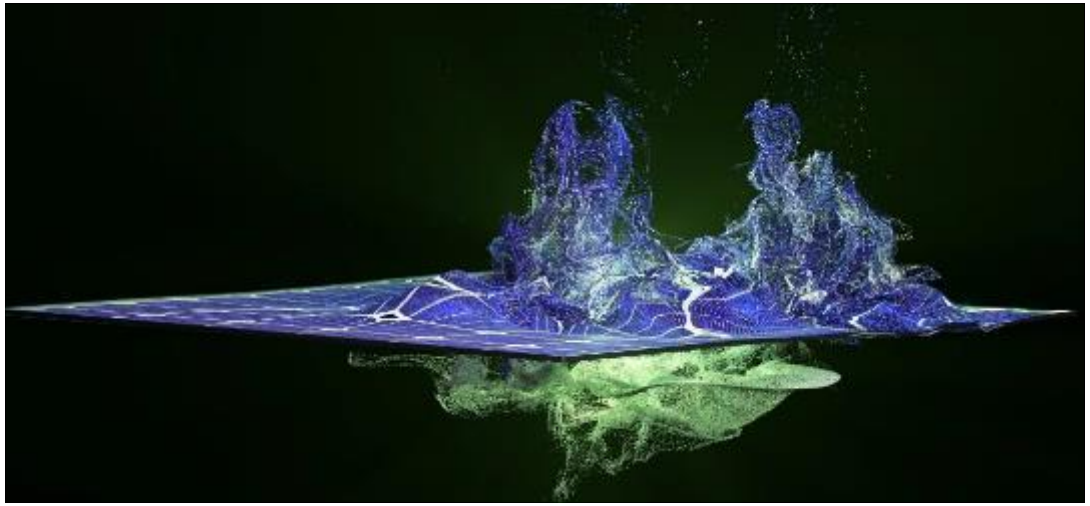
Process:

1. Delamination -> Pyrolysis
2. mechanical sorting process -> PV cells recovered (Si + Ag)
3. chemical process -> detaches the silver wires from cells
4. Chemical process -> fragments of silicon cells recovered as very high purity silicon

No inventory available

Photovoltaic modules recycling | ROSI (rosi-solar.com)
EIT RawMaterials start-up ROSI selected by Soren to recycle photovoltaic modules in France - EIT RawMaterials

Delamination – thin film and c-Si (FLAXRES – DE)



Process: [6]

- high-intensity and low-energy light pulses
- millisecond flash pulse of a certain wavelength interacts with the polymer layer
- glass plate separated and other components are separated layer by layer

Application:

- Developed for thin film PV (CdTe / CIGS)
- recently used for c-Si panels

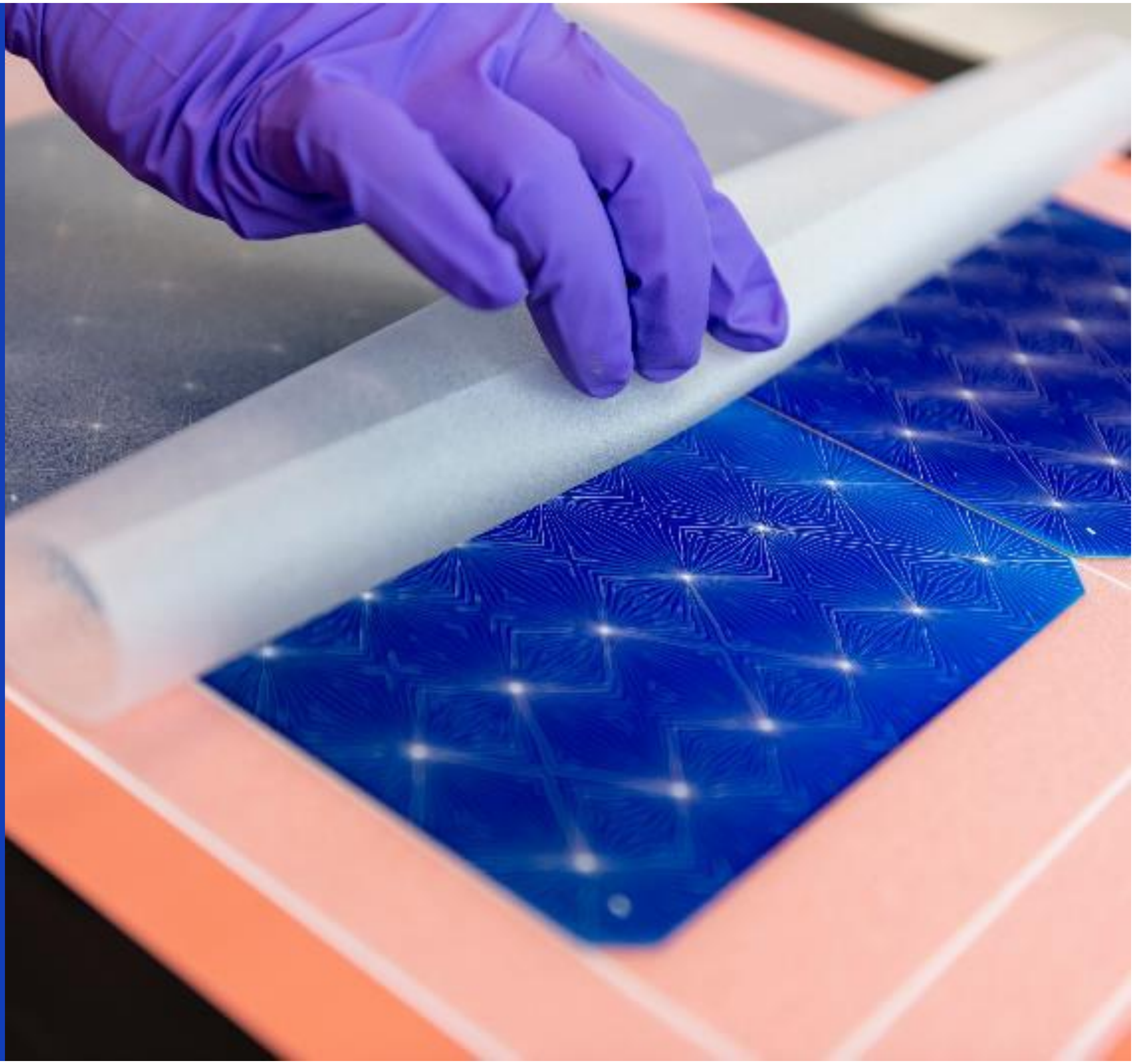
Status:

- construction of a pilot line

No inventory available

Technologie – FLAXRES
[6] Balancing Costs And Revenues For Recycling End-of-life Pv Panels In The Netherlands TNO 2022 R10860 https://circulairekennis.nl/wp-content/uploads/2022/12/O027-Kosten-en-opbrengsten-bij-recycling-PV-panelen.pdf

PV End-of-Life LCA studies and inventories



Past and present

Recycling Inventories – c-Si (average)

Table: Life cycle inventory of the treatment of used c-Si PV modules in a first generation recycling process and of the recovered materials according to the cut-off approach. Data were obtained from four recycling plants in Europe (3 laminated glass recyclers, 1 metal recycler). [2]

	Name	Location	InfrastructureProcess	Unit	treatment, c-Si PV module	glass cullets, recovered from c-Si PV module treatment	aluminium scrap, recovered from c-Si PV module treatment	copper scrap, recovered from c-Si PV module treatment	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	treatment, c-Si PV module	RER	0	kg	1	0	0	0			
	glass cullets, recovered from c-Si PV module treatment	RER	0	kg	0	1	0	0			
	aluminium scrap, recovered from c-Si PV module treatment	RER	0	kg	0	0	1	0			
	copper scrap, recovered from c-Si PV module treatment	RER	0	kg	0	0	0	1			
technosphere	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	5.56E-2	4.05E-3	1.42E-1	8.09E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers; Economic allocation;
	diesel, burned in building machine	GLO	0	MJ	3.24E-2	2.36E-3	8.25E-2	4.71E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers; Economic allocation;
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	7.34E-2	5.34E-3	1.87E-1	1.07E+0	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers; Economic allocation;
	disposal, plastics, mixture, 15.3% water, to sanitary landfill	CH	0	kg	1.28E-2	9.33E-4	3.26E-2	1.87E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers; Economic allocation;
	transport, lorry 3.5-7.5t, EURO5	RER	0	tkm	5.00E-2	3.64E-3	1.27E-1	7.27E-1	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to collection point: 100 km; Economic allocation; Latunussa et al. 2016
	transport, lorry >16t, fleet average	RER	0	tkm	2.00E-1	1.45E-2	5.09E-1	2.91E+0	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to recycling site: 400 km; Economic allocation; Latunussa et al. 2016

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[2] Stolz, P., Frischknecht, R., Wambach, K., Sinha, P., Heath, G., 2018. Life Cycle Assessment of Current Photovoltaic Module Recycling. https://iea-pvps.org/wp-content/uploads/2020/01/Life_Cycle_Assesment_of_Current_Photovoltaic_Module_Recycling_by_Task_12.pdf

Recycling Inventories – c-Si (average)

Table: Life cycle inventory of the avoided burdens due to materials recovered from used c-Si PV modules in a first-generation recycling process according to the end-of-life approach. Data were obtained from four recycling plants in Europe (3 laminated glass recyclers, 1 metal recycler). [2]

	Name	Location	InfrastructureProcess	Unit	avoided burden from recycling, c-Si PV module	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	avoided burden from recycling, c-Si PV module	RER	0	kg	1			
technosphere	natural gas, burned in industrial furnace >100kW	RER	0	MJ	-8.15E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	-5.28E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	silica sand, at plant	DE	0	kg	-3.44E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	soda, powder, at plant	RER	0	kg	-1.36E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	limestone, milled, packed, at plant	CH	0	kg	-2.38E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	copper, at regional storage	RER	0	kg	-2.48E-2	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary copper production materials from junction box and cables; Recycling content of copper is 44 % according to KBOB-list; Weighted average of data from recyclers; KBOB LCI data DQRv2:2016
	copper, secondary, at refinery	RER	0	kg	2.48E-2	1	1.14	(2,4,1,1,3,BU:1.05); Efforts for making secondary copper from scrap;
	aluminium, primary, at plant	RER	0	kg	-5.34E-2	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary aluminium production materials from frame; Recycling content of AlMg3 alloy is 77 % according to KBOB-list; Weighted average of data from recyclers; KBOB LCI data DQRv2:2016
	aluminium, secondary, from old scrap, at plant	RER	0	kg	5.34E-2	1	1.14	(2,4,1,1,3,BU:1.05); Efforts for making secondary aluminium from scrap;
emission air, unspecified	Carbon dioxide, fossil	-	-	kg	-1.24E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016

[1] Stolz, P., Frischknecht, R., Wambach, K., Sinha, P., Heath, G., 2018. Life Cycle Assessment of Current Photovoltaic Module Recycling. https://iea-pvps.org/wp-content/uploads/2020/01/Life_Cycle_Assesment_of_Current_Photovoltaic_Module_Recycling_by_Task_12.pdf

Recycling Inventories – CdTe (FirstSolar)

Table: Life cycle inventory of the **treatment** of used **CdTe** PV modules in a first generation recycling process and of the recovered materials according to the **cut-off approach**. Data are representative for the First Solar recycling facility in Germany. [2]

	Name	Location	InfrastructureProcess	Unit	treatment, CdTe PV module	glass cullets, recovered from CdTe PV module treatment	copper scrap, recovered from CdTe PV module treatment	cadmium sludge, recovered from CdTe PV module treatment	copper telluride cement, recovered from CdTe PV module treatment	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				DE	DE	DE	DE	DE			
	InfrastructureProcess				0	0	0	0	0			
	Unit				kg	kg	kg	kg	kg			
product	treatment, CdTe PV module	DE	0	kg	1	0	0	0	0			
	glass cullets, recovered from CdTe PV module treatment	DE	0	kg	0	1	0	0	0			
	copper scrap, recovered from CdTe PV module treatment	DE	0	kg	0	0	1	0	0			
	cadmium sludge, recovered from CdTe PV module treatment	DE	0	kg	0	0	0	1	0			
	copper telluride cement, recovered from CdTe PV module treatment	DE	0	kg	0	0	0	0	1			
technosphere	electricity, medium voltage, at grid	DE	0	kWh	2.24E-1	1.51E-2	3.02E+0	6.95E-2	5.89E+0	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha et al. 2012
	water, deionised, at plant	CH	0	kg	2.78E-1	1.87E-2	3.74E+0	8.60E-2	7.29E+0	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha et al. 2012
	sulphuric acid, liquid, at plant	RER	0	kg	4.28E-3	2.87E-4	5.75E-2	1.32E-3	1.12E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha et al. 2012
	hydrogen peroxide, 50% in H2O, at plant	RER	0	kg	2.93E-2	1.97E-3	3.94E-1	9.07E-3	7.68E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha et al. 2012
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	5.34E-3	3.59E-4	7.18E-2	1.65E-3	1.40E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha et al. 2012
	transport, lorry 3.5-7.5t, EURO6	RER	0	tkm	8.47E-2	5.69E-3	1.14E+0	2.62E-2	2.22E+0	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to collection point: km; Sinha et al. 2012; Latanussa et al. 2016
	transport, lorry >16t, fleet average	RER	0	tkm	4.90E-1	3.29E-2	6.59E+0	1.52E-1	1.29E+1	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to recycling site: km; Sinha et al. 2012; Latanussa et al. 2016
	treatment, PV cell production effluent, to wastewater treatment, class 3	CH	0	m3	2.46E-4	1.65E-5	3.30E-3	7.61E-5	6.45E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha et al. 2012
	disposal, plastics, mixture, 15.3% water, to sanitary landfill	CH	0	kg	3.16E-2	2.12E-3	4.25E-1	9.78E-3	8.29E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha et al. 2012
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	6.59E-3	4.43E-4	8.86E-2	2.04E-3	1.73E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha et al. 2012
emission air, unspecified	Cadmium	-	-	kg	3.02E-10	2.03E-11	4.06E-9	9.35E-11	7.93E-9	1	5.02	(2,4,1,1,1,3,BU:5); ; Sinha et al. 2012
emission water, unspecified	Cadmium, ion	-	-	kg	4.58E-9	3.08E-10	6.15E-8	1.42E-9	1.20E-7	1	3.02	(2,4,1,1,1,3,BU:3); ; Sinha et al. 2012

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[2] Stolz, P., Frischknecht, R., Wambach, K., Sinha, P., Heath, G., 2018. Life Cycle Assessment of Current Photovoltaic Module Recycling. https://iea-pvps.org/wp-content/uploads/2020/01/Life_Cycle_Assesment_of_Current_Photovoltaic_Module_Recycling_by_Task_12.pdf

Recycling Inventories – CdTe (FirstSolar)

Table: Life cycle inventory of the **avoided burdens** due to materials recovered from used **CdTe** PV modules in a first generation recycling process according to the **end-of-life approach**. Data are representative for the First Solar recycling facility in Germany [2]

	Name	Location	InfrastructureProcess	Unit	avoided burden from recycling, CdTe PV module	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				DE			
	InfrastructureProcess				0			
	Unit				kg			
product	avoided burden from recycling, CdTe PV module	DE	0	kg	1			
technosphere	natural gas, burned in industrial furnace >100kW	RER	0	MJ	-1.19E+0	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	-7.67E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	silica sand, at plant	DE	0	kg	-5.01E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	soda, powder, at plant	RER	0	kg	-1.98E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	limestone, milled, packed, at plant	CH	0	kg	-3.47E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	copper, at regional storage	RER	0	kg	-2.68E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary copper production materials from junction box; Recycling content of copper is 44 % according to KBOB-list; Personal communication Parikhit Sinha, 06.10.2014; KBOB LCI data DQRv2:2016
	copper, secondary, at refinery	RER	0	kg	2.68E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); Efforts for making secondary copper from scrap; Personal communication Parikhit Sinha, 06.10.2014
	cadmium sludge, from zinc electrolysis, at plant	GLO	0	kg	-1.72E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided unrefined semiconductor materials; Sinha et al. 2012
	copper telluride cement, from copper production	GLO	0	kg	-1.95E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided unrefined semiconductor materials; Sinha et al. 2012
emission air, unspecified	Carbon dioxide, fossil	-	-	kg	-1.80E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016

[2] Stolz, P., Frischknecht, R., Wambach, K., Sinha, P., Heath, G., 2018. Life Cycle Assessment of Current Photovoltaic Module Recycling. https://iea-pvps.org/wp-content/uploads/2020/01/Life_Cycle_Assesment_of_Current_Photovoltaic_Module_Recycling_by_Task_12.pdf

Discussion

- Inventories based on data from 2012 – 2016*, average of 4 recyclers
  - But amount of solar panels at EoL remained low
  - New recycling processes not operational at industrial scale yet
  - Recycling processes are still similar to the ones described in [2]
  - Suitable for modelling EoL of first generation panels, not suitable for new panels being installed now

*Updated in the last report 2020 [10]

- Updates needed for EoL modelling:
  - Panel thickness and material amounts according to year of production, data not readily available
  - c-Si efficiency increased in the past years -> thinner panels = less materials
  - Somewhat different composition (back contact)

- Avoided burdens:
  - Will vary according to country situation
  - In NL avoided burden = recovered aluminium, the rest is mostly landfilled or stockpiled to recycle in the future

Discussion

- Under the EU WEEE Directive, recycling of end-of-life PV modules is mandatory in the European Union
  - More refined recycling processes become more viable and necessary for compliance

Current (under implementation)

Recycling pathways – c-Si (Sasil IT - FRELP)

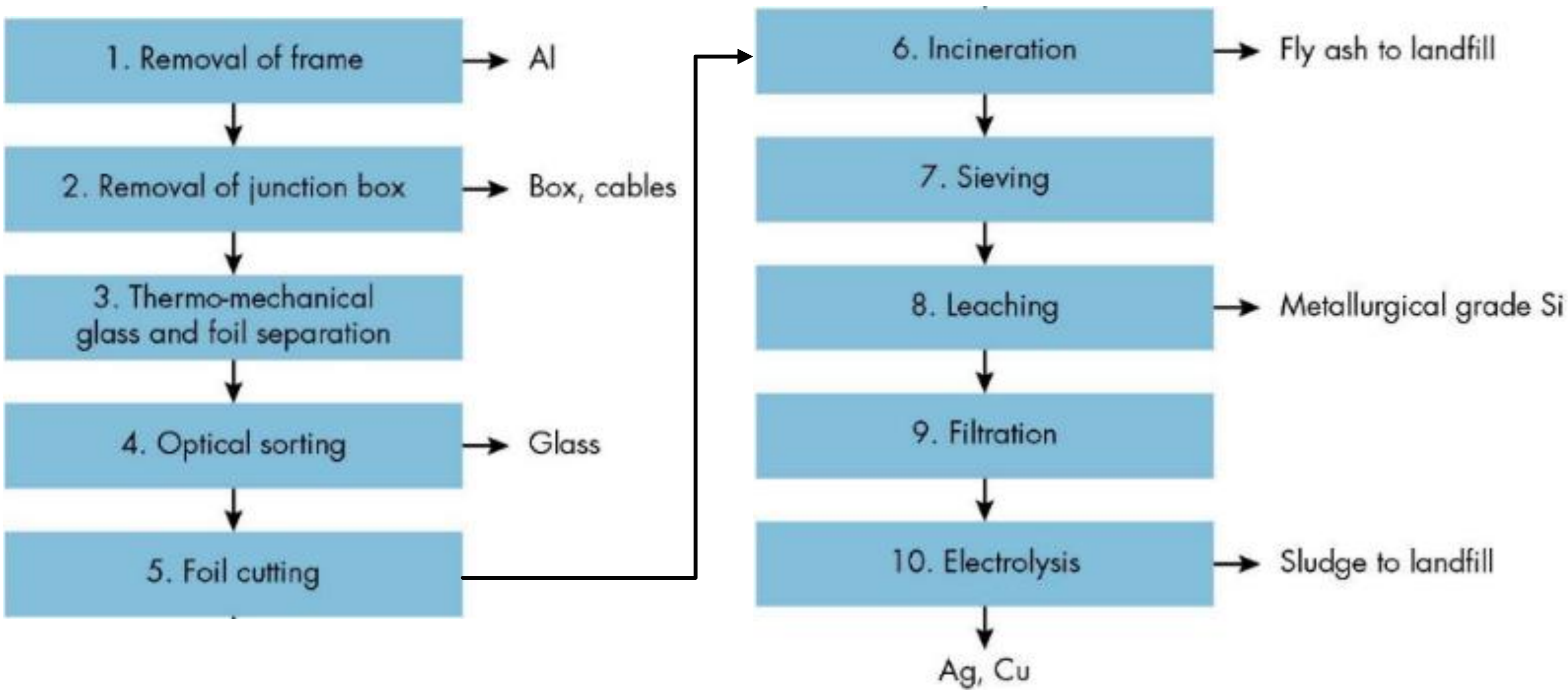


Figure: Schematic process flow of company Sasil that uses the FRELP process [3]

FRELP Project financed by European call LIFE12 ENV/IT/000904

Process[3]:

1. Removal of the frame
2. Removal of junction box, and cables
3. Module glass is broken and heated to soften EVA + separate from cells (e.g., using a vibrating knife)
4. optical-sorting of glass
5. Polymer fraction is cut to pieces
6. Polymers incinerated
7. Grinding and sieving metals and solar cells
8. Leaching (metals completely dissolved)
9. Metal solution is separated from the silicon by filtration
10. Electrolyzing of metal solution
11. Residual sludge -> landfilled.

Recovery[3]:

- high-quality extra-clear glass
- metallurgical-grade silicon (ferro-silicon production)
- Silver and copper (purified by electrolysis)

[3] Heath, G., Wade, A., Wambach, K., Libby, C., 2017. Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe.

Recycling pathways – c-Si (Sasil IT - FRELP)

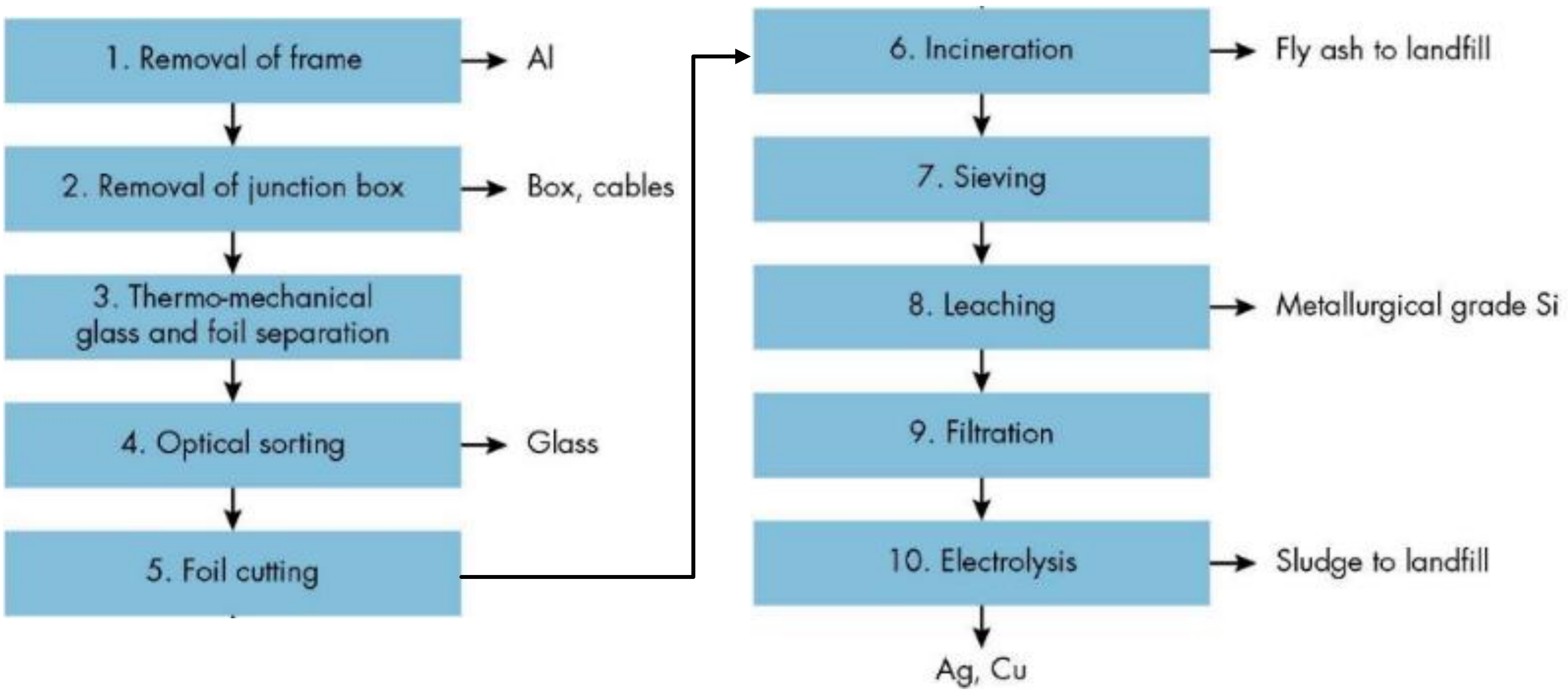


Figure: Schematic process flow of company Sasil that uses the FRELP process [3]

Recovery[3]:

- high-quality extra-clear glass
- metallurgical-grade silicon (ferro-silicon production)
- Silver and copper (purified by electrolysis)

- 88% of the input material
- up to 95% of the glass

FRELP
Project financed by European call
LIFE12 ENV/IT/000904

Life

[3] Heath, G., Wade, A., Wambach, K., Libby, C., 2017. Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe.

Recycling pathways – c-Si (Sasil IT - FRELP)

Table: Summary of input and outputs of the 'FRELP' process for the recycling of 1000 kg of silicon PV waste panels. [11]

Input/output	Quantity	Unit
Input		
PV waste panels	1000	kg
Electricity	113.55	kW h
Diesel fuel	1.14	l
Water	309.71	kg
HNO_3	7.08	kg
$Ca(OH)_2$	36.5	kg
Output, recovered materials		
Aluminium scrap	182.65	kg
Glass scrap	686	kg
Copper scrap	4.38	kg
Silicon metal (Metallurgical Grade)	34.68	kg
Silver	0.5	kg
Output, energy recovery		
Electricity	248.84	MJ
Thermal Energy	502.84	MJ
Output, waste to landfill		
Contaminated glass	14	kg
Fly ash (hazardous waste)	2	kg
Liquid waste	306.13	kg
Sludge (hazardous waste)	50.25	kg
Output, emission to air		
NO_x	2	kg

Recovery[3]:

- high-quality extra-clear glass
- metallurgical-grade silicon (ferro-silicon production)
- Silver and copper (purified by electrolysis)

- 88% of the input material
- up to 95% of the glass

[11] Latunussa, C.E.L., Ardente, F., Blengini, G.A., Mancini, L., 2016. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Sol. Energy Mater. Sol. Cells 156, 101. https://linkinghub.elsevier.com/retrieve/pii/S0927024816001227
[3] Heath, G., Wade, A., Wambach, K., Libby, C., 2017. Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe.

Future (under development)

Recycling Inventories – Perovskite solar cells (PSC)

Process	Input	Amount	Comments
Dissolution of perovskite layer with DMF	DMF	10^{-4} kg/cm^2	Recovered materials were reused 10 times before recycling. DMF was then used 10 times
Filtration	Gold	1.16 10^{-7} kg/cm^2	Gold recovered after filtration of DMF. Reused 9 times and then recycled (benefit: avoided product “Gold, primary, at refinery” with a recycling rate of 0.6895
Cleaning	Glass	3.4 10^{-3} kg/cm^2	Glass FTO and TiO_2 recovered after cleaning. Reused 9 times and then recycled. (Benefit credited avoided raw materials and energy reduction for glass.
Cleaning	FTO	1.57 10^{-6} kg/cm^2	
Cleaning	TiO_2	6.75 10^{-7} kg/cm^2	Recovered with glass after cleaning. Reused 9 times and then recycled. (Benefit credited “ilmenite, 54% titanium dioxide, at plant”)
Lead precipitation	Diethyl-ether	10^{-3} kg/cm^2	To precipitate lead compounds
Lead recycling	Lead		Benefits of recycling were modeled as avoided “lead, from combined metal production, at beneficiation
Incineration			Incineration of remaining components of perovskite and dilution products

[8] Alberola-Borràs, Jaume-Adrià, et al. "Relative impacts of methylammonium lead triiodide perovskite solar cells based on life cycle assessment." Solar Energy Materials and Solar Cells 179 (2018): 169-177.

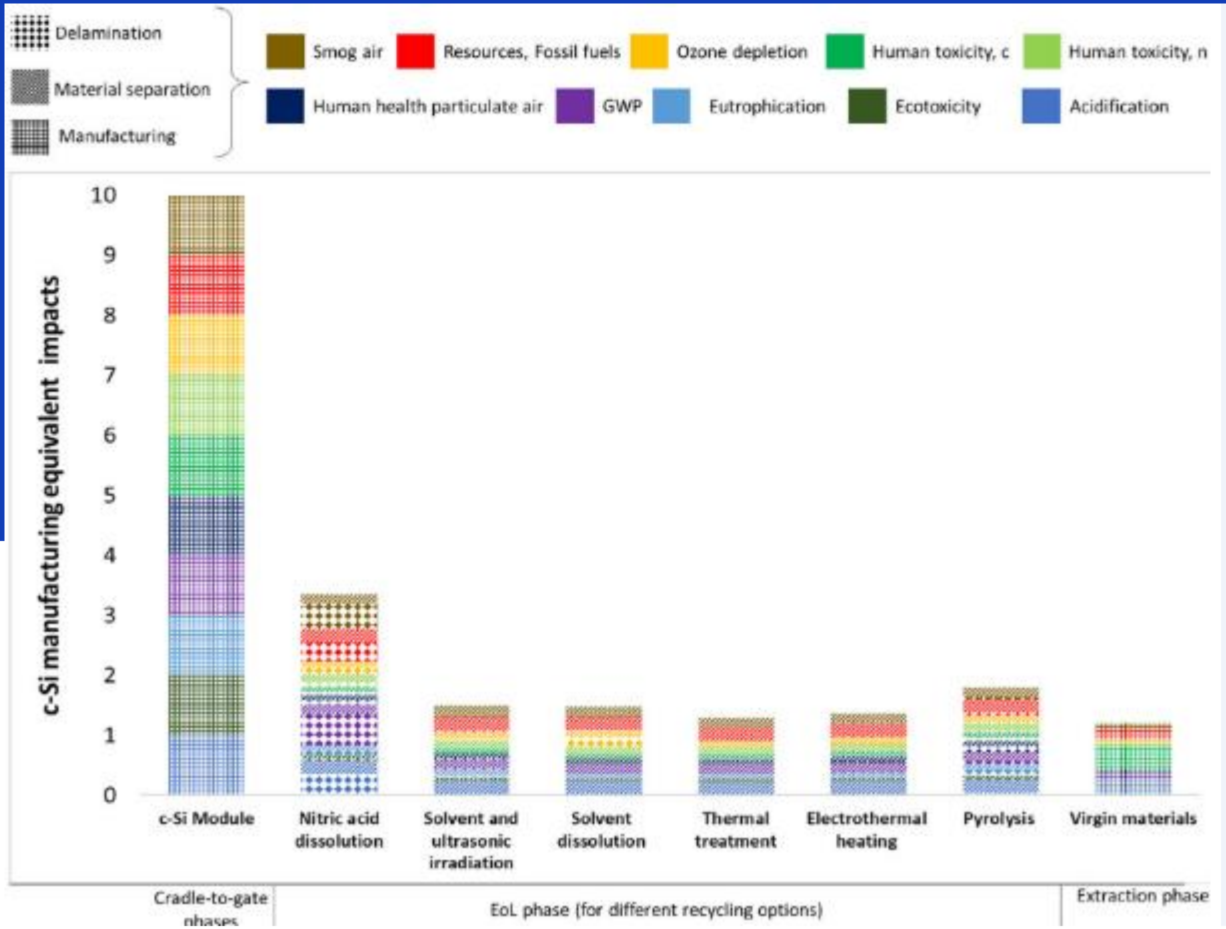
Discussion

- Current inventories don’t consider change in c-Si panel composition
  - As shown in [5] the thickness and material amounts of PV panels are changing
  - c-Si technology evolution -> efficiency gains

- Kerf recycling
  - 40% of Si is lost as a slurry material during waffer production
  - Advanced recycling processes aiming to recover the wafer intact -> production line waste

- Thermal approaches such as pyrolysis -> consume a lot of energy
- Chemical approaches -> produce hazardous effluents and demand reagents
- Mechanical approaches -> not enough to recover materials up to the quality needed to reintroduce them into the PV production chain

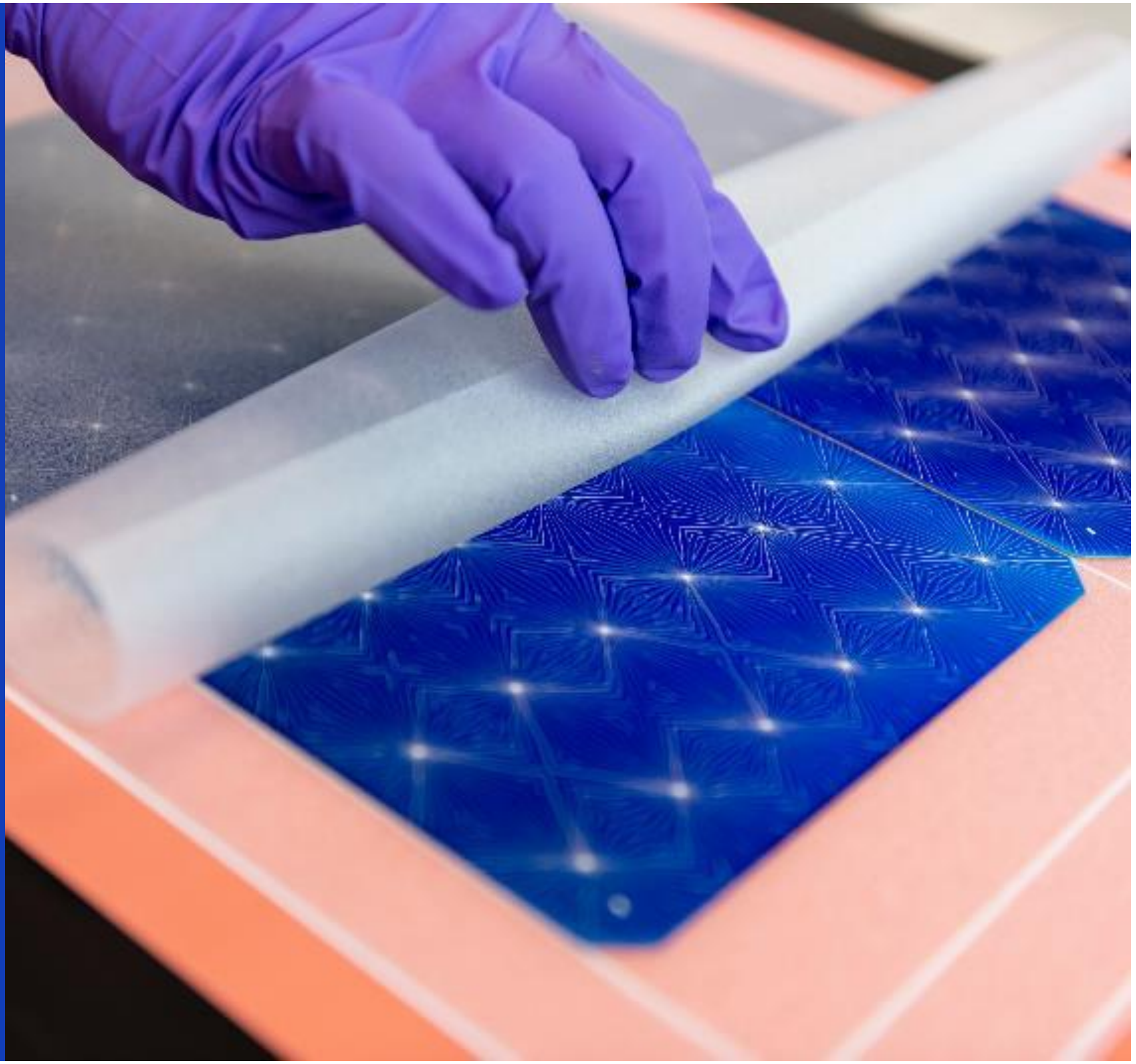
- Extended producer responsibility and the European urge to reduce supply risk of critical raw materials + rapidly increasing inflow of PV panels at EoL are leading to new technology development and implementation at commercial scale



- Figure: Comparison of impact results for c-Si delaminationwith material separation (chemical etching) incorporated into each method and normalized to c-Si manufacturing.
- Within each impact category, the impact (per m2 of panel recycled) from each process was divided by the impact from c-Si manufacturing.
- For c-Si the bar height is unity for each impact category. For ten impact categories, the total impact for c-Si is given as ten units. [12]

[12] Maani, T., Celik, I., Heben, M.J., Ellingson, R.J., Apul, D., 2020. Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels. Sci. Total Environ. 735, 138827.
https://doi.org/10.1016/j.scitotenv.2020.138827

Circularity indicators and what they say about circularity of PV panels



Circularity

How to evaluate circularity of solar panels?

- Recycling rates (RR) -> only considers mass of materials recycled
- MCI -> does not consider energy spent in material recovery and quality of recovered materials
- Cumulative Energy Demand -> only considers energy

- Other, less popular indicators are available but have similar shortcomings

- Exergy (CExD) -> materials and energy although energy is weighted heavier
  - Baseline process or reference scenario needed for comparison
  - Mass and energy balances needed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Thank you
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References

- End-of-life management:

[1] End-Of-Life Management: Solar Photovoltaic Panels, 2016. , IRENA and IEA-PVPS. IRENA 2016 AND IEA-PVPS 2016. https://iea-pvps.org/wp-content/uploads/2020/01/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf

[2] Stolz, P., Frischknecht, R., Wambach, K., Sinha, P., Heath, G., 2018. Life Cycle Assessment of Current Photovoltaic Module Recycling. https://iea-pvps.org/wp-content/uploads/2020/01/Life_Cycle_Assesment_of_Current_Photovoltaic_Module_Recycling_by_Task_12.pdf

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[4] Komoto, K., Lee, J.-S., Zhang, J., Ravikumar, D., Sinha, P., Wade, A., Heath, G.A., 2018. End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies. Golden, CO (United States). https://doi.org/10.2172/1561523

[5] Peeters, J.R., Altamirano, D., Dewulf, W., Duflou, J.R., 2017. Forecasting the composition of emerging waste streams with sensitivity analysis: A case study for photovoltaic (PV) panels in Flanders. Resour. Conserv. Recycl. 120, 14–26. https://doi.org/10.1016/J.RESCONREC.2017.01.001

[6] Balancing Costs And Revenues For Recycling End-of-life Pv Panels In The Netherlands TNO 2022 R10860 https://circulairekennis.nl/wp-content/uploads/2022/12/O027-Kosten-en-opbrengsten-bij-recycling-PV-panelen.pdf

[7] Tao, J., Yu, S., 2015. Review on feasible recycling pathways and technologies of solar photovoltaic modules. Sol. Energy Mater. Sol. Cells 141, 108–124. https://doi.org/10.1016/j.solmat.2015.05.005

[8] Alberola-Borràs, Jaume-Adrià, et al. "Relative impacts of methylammonium lead triiodide perovskite solar cells based on life cycle assessment." Solar Energy Materials and Solar Cells 179 (2018): 169-177.

[9] Liu, Fan-Wei, et al. "Recycling and recovery of perovskite solar cells." Materials Today 43 (2021): 185-197

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- End-of-life management:

[10] Frischknecht, R., Stolz, P., Krebs, L., Wild-Scholten, M. de, Sinha, P., 2020. Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems. https://iea-pvps.org/wp-content/uploads/2020/12/IEA-PVPS-LCI-report-2020.pdf

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- Inventories:

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