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Strategy Consulting in Solar PV

Solar PV recycling: overview and outlook

Agenda

1 | Solar PV waste - sources, volumes and management strategies

2 | Solar PV material recovery technologies

3 | Challenges and opportunities

4 | Solar PV waste recycling in islands

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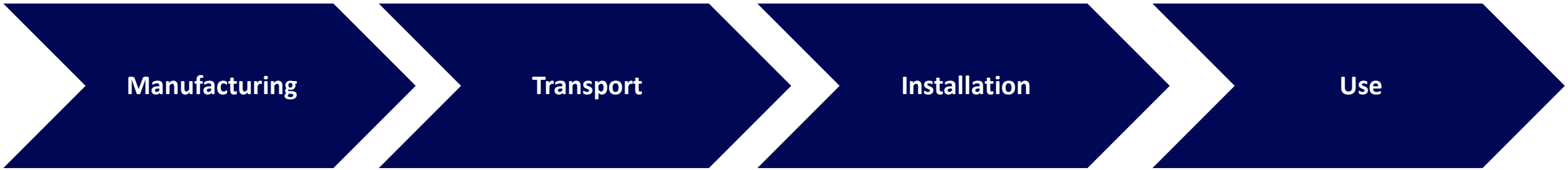
PV module can enter the waste stream at different steps of the value chain



- PV modules with premature failures resulting from production defects

- PV modules with premature failures resulting from damages from transport

- PV modules with premature failures resulting from damages from installation

- PV modules damaged by severe weather
- PV modules reaching the end of their useful lifetime

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Overview of global PV panel waste projections

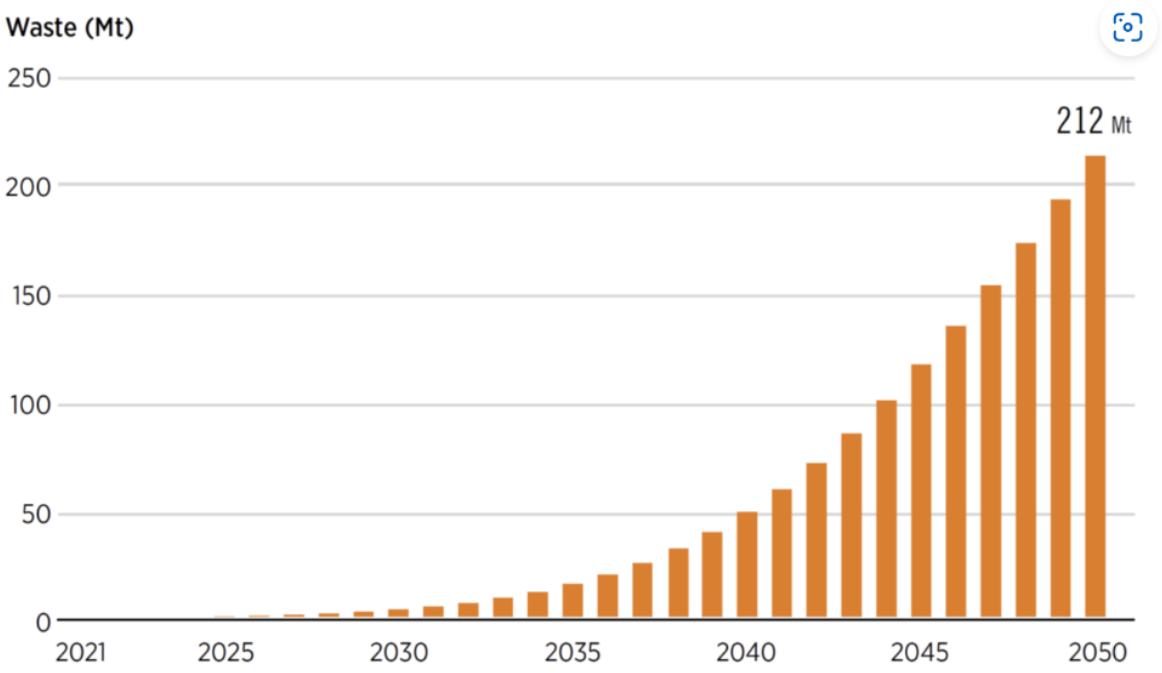

Figure: Projected cumulative waste from solar PV projects under IRENA's 1.5°C Scenario to 2050

- IRENA estimates that waste from cumulative solar PV projects globally was **200 000 tonnes in 2021.**
- IRENA's projections indicate that this volume could increase to
  - 4 000 000 tonnes in 2030,
  - almost 50 000 000 tonnes in 2040
  - and more than **200 000 000 tonnes by 2050.**
- The **largest historical solar PV markets** are dominantly contributing to the waste in the short-medium term. But PV waste volumes are also becoming a pressing issue in countries with more recent PV market development (e.g., Brazil or India).

IRENA, Circular economy
https://isolaralliance.org/uploads/docs/a18d926b951d4b566cf1780ea0baf8.pdf
https://www.pv-magazine.com/2021/08/26/increasing-volumes-for-pv-module-recycling-in-brazil/

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General waste management strategies entail five main options for the managing and disposing of waste (from preferred to least preferred)

- Raw material consumption reduction
- Lifetime extension
- Breakage rates reduction during manufacturing, transport, installation, …

- Second-life after visual inspections, testing and repairing

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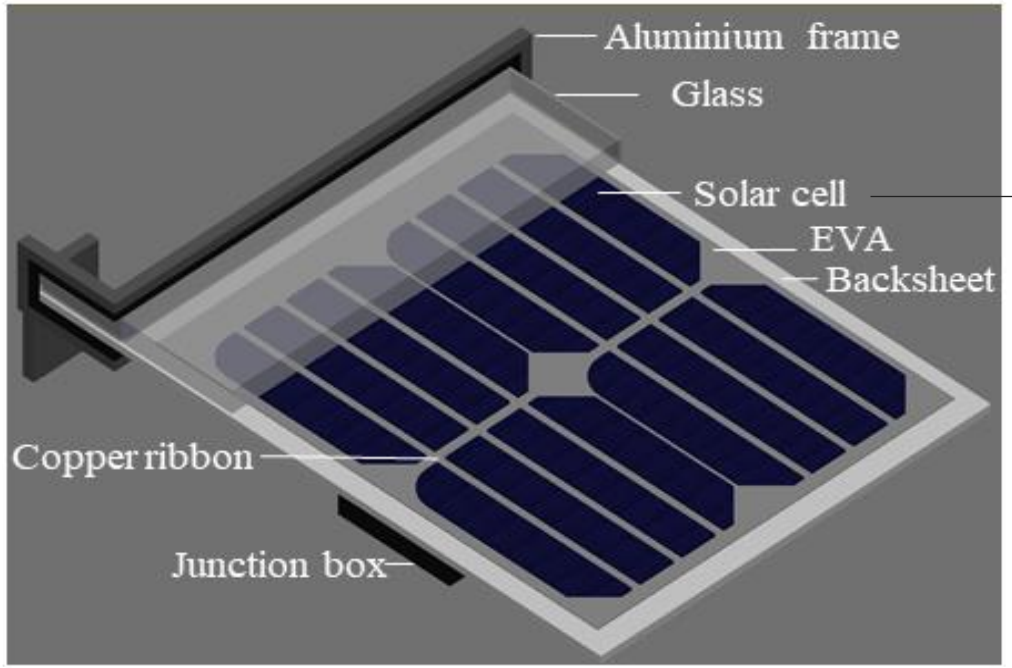
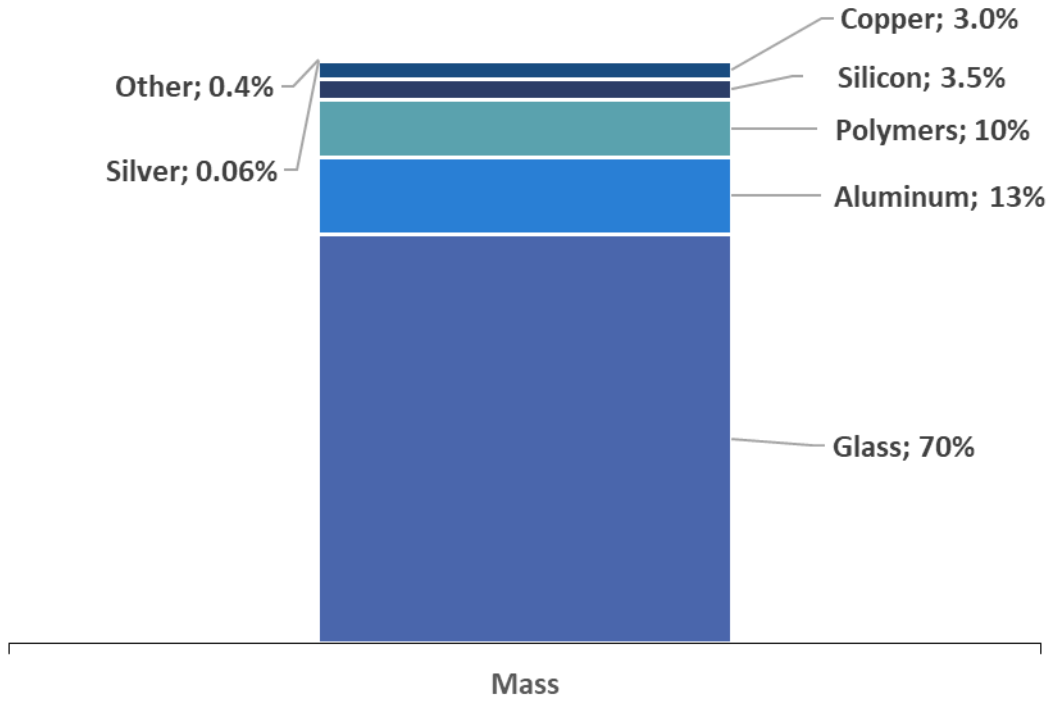
A few components/materials only make up the majority of a PV module's weight



Silicon
Silver
Aluminum



Source: IEA's Special Report on Solar PV Global Supply Chains

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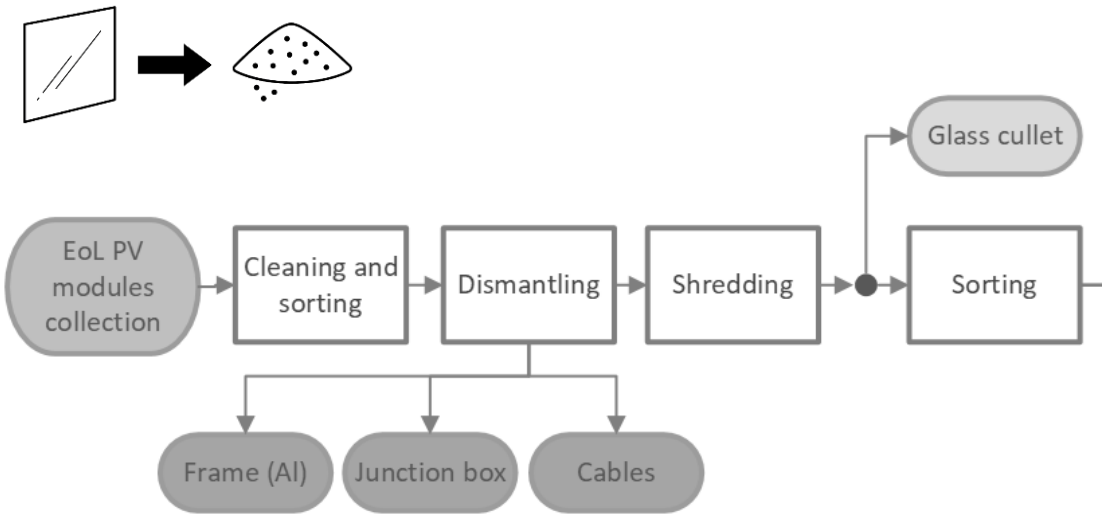
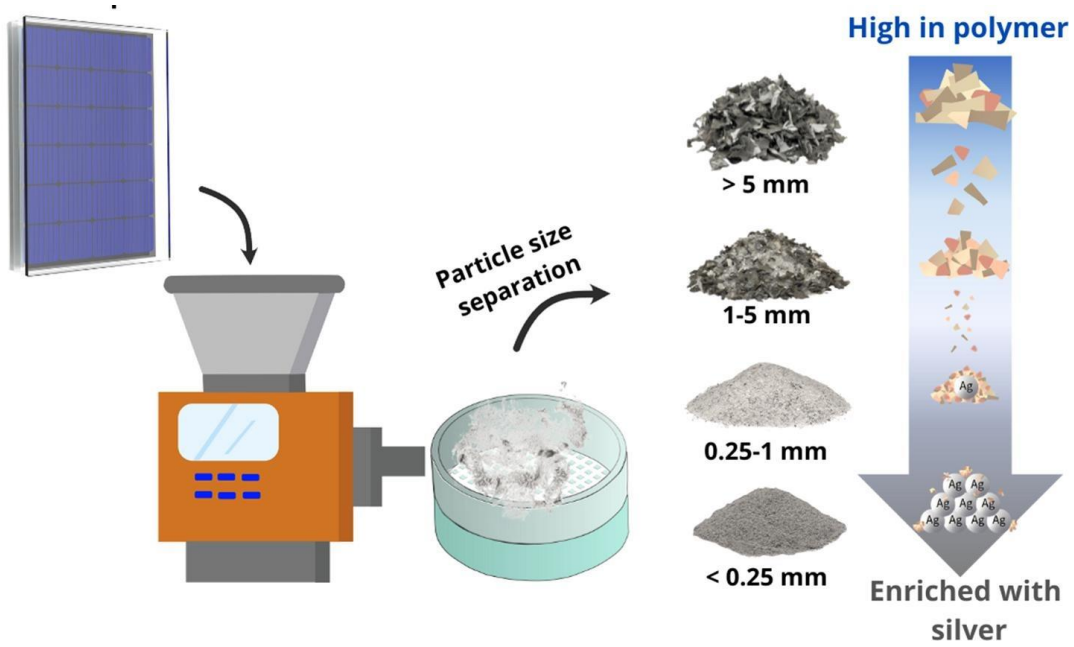
Mechanical shredding + sorting is a mature process with attractive throughput, recovery rate and cost.

But purity levels are low, and the recovery of the highest value material (silver) is not addressed.





Example of shredding and sorting process based on sieving (Sim et al, 2022)

\+ **High throughput 1-1.5 min/module**

\+ **Recovery rate can be 75% up to nearly 95%**

\+ **Low net cost 100-200 USD/ton**

\- **Recovered materials are at low purity level** (e.g. 75% for silicon)

\- **Silver is not recovered separately**

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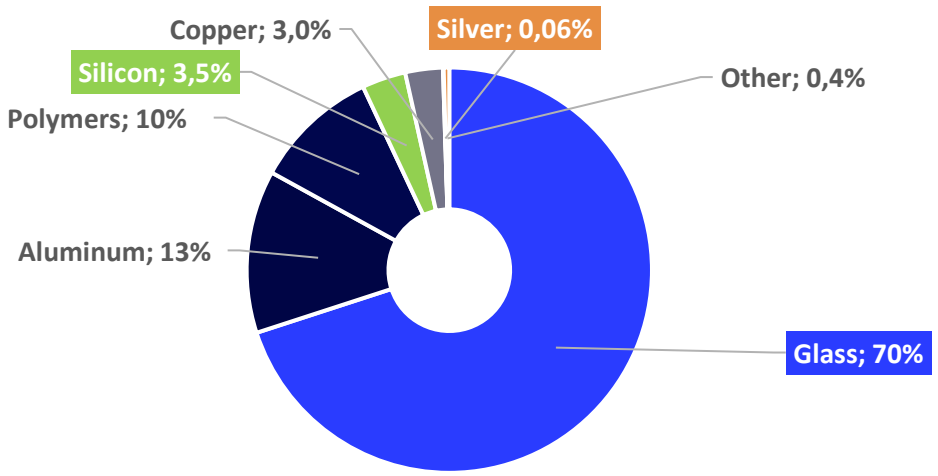
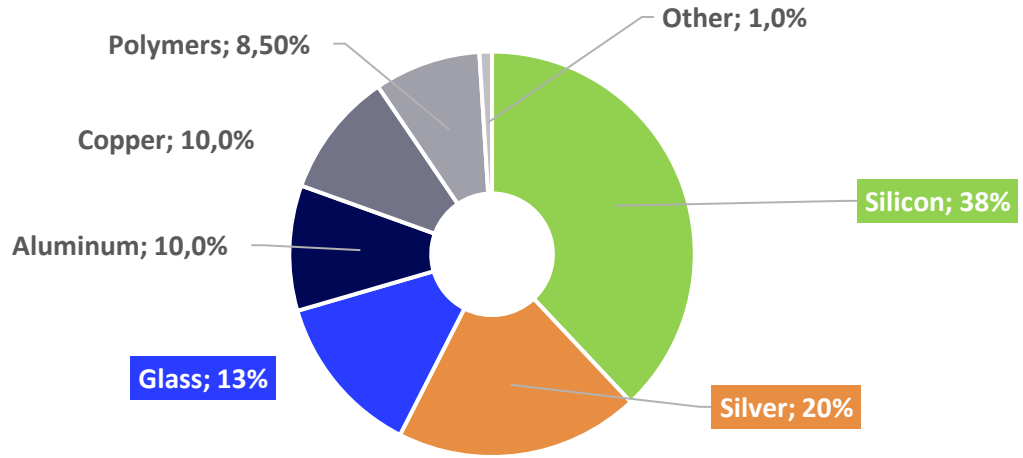
Silicon and silver which make around 4% of a PV module's mass represent close to 60% of its value

Glass which represents 70% of a PV module's mass only represent 13% of its value.

Mass-breakdown



Value-breakdown



IEA's Special Report on Solar PV Global Supply Chains

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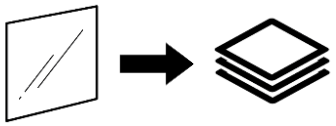
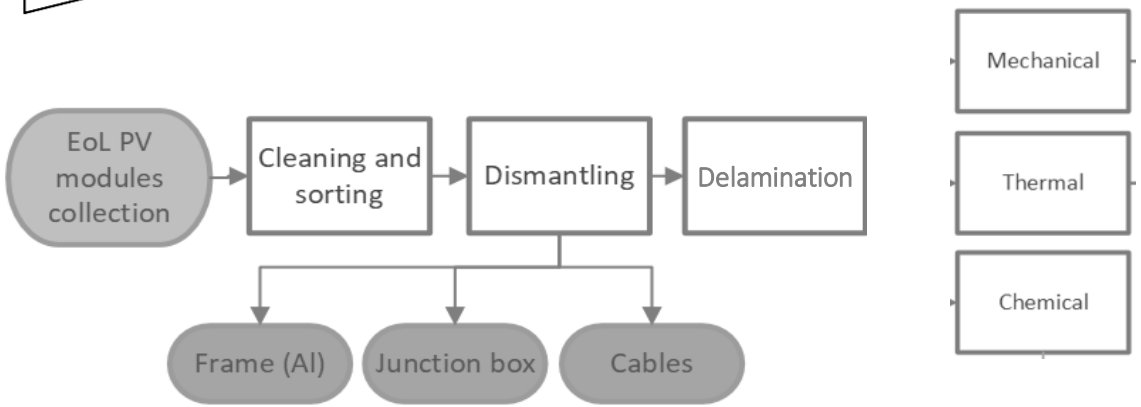
Thermal or mechanical delamination recycling processes are more costly and operating at a lower throughput.
But the glass pane can be recovered in one piece, and these processes pave the way to the recovery of the highest value material (silver) by allowing to reach the solar cells.





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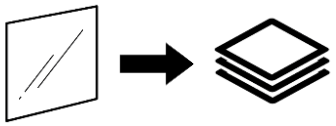

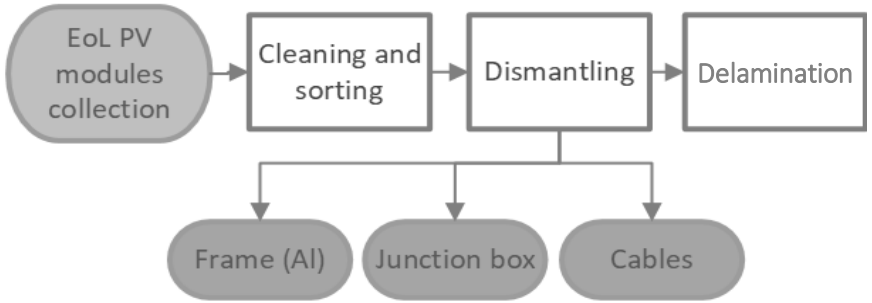

Mechanical delamination: **hot-blade, diamond wire sawing, waterjet cutting**

Glass separated from PV module by hot-knife technique (NPC)

\+ **Glass can be recovered in one piece**

\+ **Paves the way to the recovery of silver**

\+ **Some methods are commercially available and implemented**

\- **PV panels cannot have broken glass** (handling of dismantling and transport to recycling site)

\- **More costly, lower throughput, some methods are at very low TRL**

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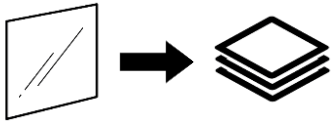

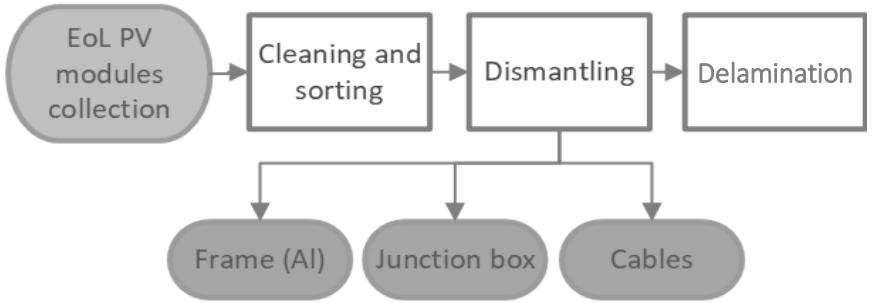

Chemical delamination: solvent-based dissolution

Delaminated components of a PV module employing supercritical CO2 (Lovato et al, 2021)

\+ **Paves the way to the recovery of silver**

\- **Glass needs to be removed before**
\- **More costly**
\- **Lower throughput, low TRL**
\- **Large amount of hazardous chemicals required, and large amount of waste generated** (although green solvent and waste reduction can be implemented)

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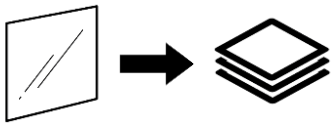

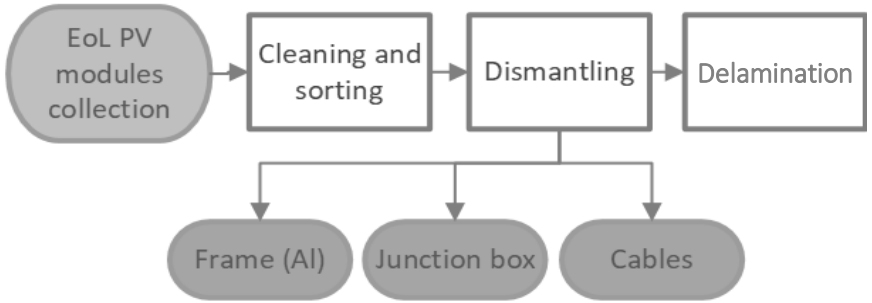

Thermal delamination: pyrolysis (medium T°/without O_2), incineration (high T°)

+ **Glass can be recovered in one piece**
+ **Paves the way to the recovery of silver**
+ **Burning of polymers gives access to the cells**
+ **Silicon can be recovered with purity >90%**

- **More costly and energy-intensive** (energy cost, although energy recovery is possible)

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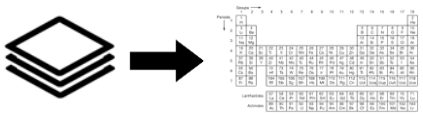
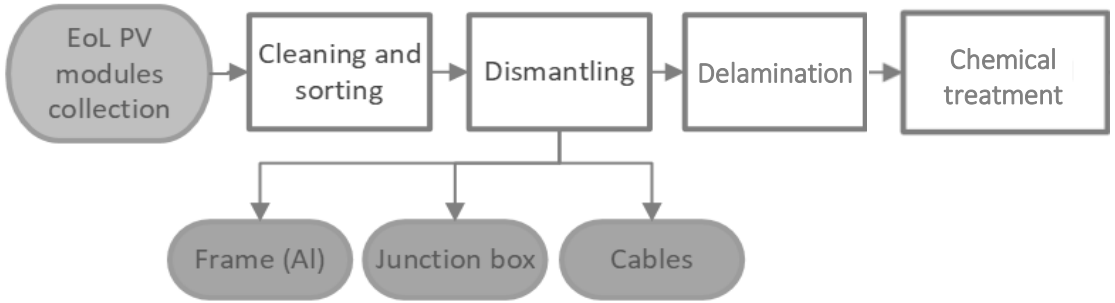
Chemical processes allow to recover silver and silicon from the solar cell (full solar cells, fragments or ash).





Chemical processes: hydro-metallurgy (leaching and etching), electro-metallurgy, pyro-metallurgy

\+ **Silver can be recovered**

\+ **Silicon can be recovered (>99% purity)**

\- **Lower throughput, low TRL**

\- **Large amount of hazardous chemicals (etching agents) required, and large amount of waste generated** (although environmentally friendly etching agents can be implemented)

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Technical challenges and opportunities

- The recycling benchmark process can already offer very high recovery rates at reasonable cost (a few euros per module)

- The different existing recycling processes can combined into hybrid recycling processes (recovery of the glass before thermal delamination (reduced heating time, higher capacity per oven, …))

- **Technical challenges are limited** as there are many technical solutions available to reach even the highest value materials of a PV module, some of which are already commercially available. On can mention:
  - Glass can typically be taken as input by glass companies although **antimony content** (above a certain threshold) and impurities (variety in the input) can be technical challenges.
  - The most common routes for polymers are thermal treatment (mostly incineration) in waste-to-energy plants, but the presence of **fluoropolymers in the backsheet** of old modules imposes special measures (filters).

    => Perspective to **improve trackability** of the materials used in each PV module through labels

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Advanced recycling processes typically come at a higher cost despite higher revenues.

Regulatory push and economies of scale can contribute to reduce their net cost.

- The main economic challenge is that typically the **more advanced recycling processes, despite higher revenues, come at a higher net cost.**

- This should be exacerbated by the important technology improvements under the form of **raw material usage reduction** which have taken place for silicon and silver.

  => Silver consumption shrunk from 51.8–65.1 mg/W in 2010 to around 15 mg/W in 2024 (TOPCon).

  => Silicon consumption reduced from 16 g/W in 2004 to just around 2 g/W in 2024 (TOPCon).

- There are several opportunities:
  - **Increase revenues through regulatory environment**:
    - On 23 May 2024, the EU's Critical Raw Materials Act (CRMA) entered into force following its adoption by the Council of the EU and European Parliament. Although non-bidding, the Act calls for a significant increase in recycling efforts, totaling up to 25 % of annual consumption in the EU.

  - **Decrease costs through economies of scale**: with growing waste volumes there is the possibility to reach at least >50 000 tons/year to go in the direction of the order of magnitude observed in other waste sectors (500 tons/day).

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Solar PV waste recycling in islands

- In other Islands such as Hawaii, Guadeloupe or La Réunion, current solar PV waste volumes are not important enough to develop local recycling capacities.
- Solar PV waste collection schemes are in place and the gathered solar PV waste is shipped to mainland (US or France).
- In island conditions, it can be relevant where possible to remove the aluminum frame, the junction box (or even the glass) prior to shipping in order to reduce the weight and increase compactness.

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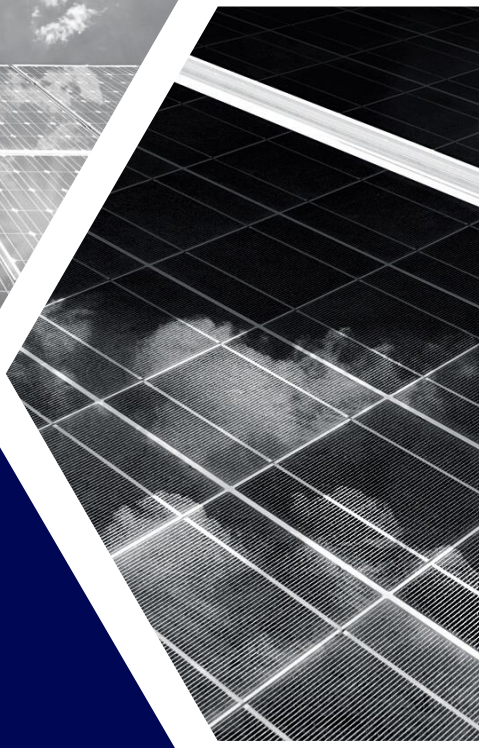

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