PV Recycling: status and perspectives

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edited by Wilfried van Sark, Pierre Verlinden, Angele Reinders, Bram Hoex and Nicholas J. Ekins-Daukes

Introduction – some facts about PV

- Globally installed PV capacity passed the milestone of **1 TWp** in 2022
- The equivalent electricity production was **~ 1300 TWh**
- This corresponds to **~4,5% of global electricity consumption** (28,000 TWh)

- **Urgency of sustainable PV waste treatment**
- Avoid waste problem (and related damages to the image of PV)
- Ensure sustainability of PV across the entire value chain, i.e. including the End-of-Life phase (EoL)

Evolution of global PV waste in the coming decades

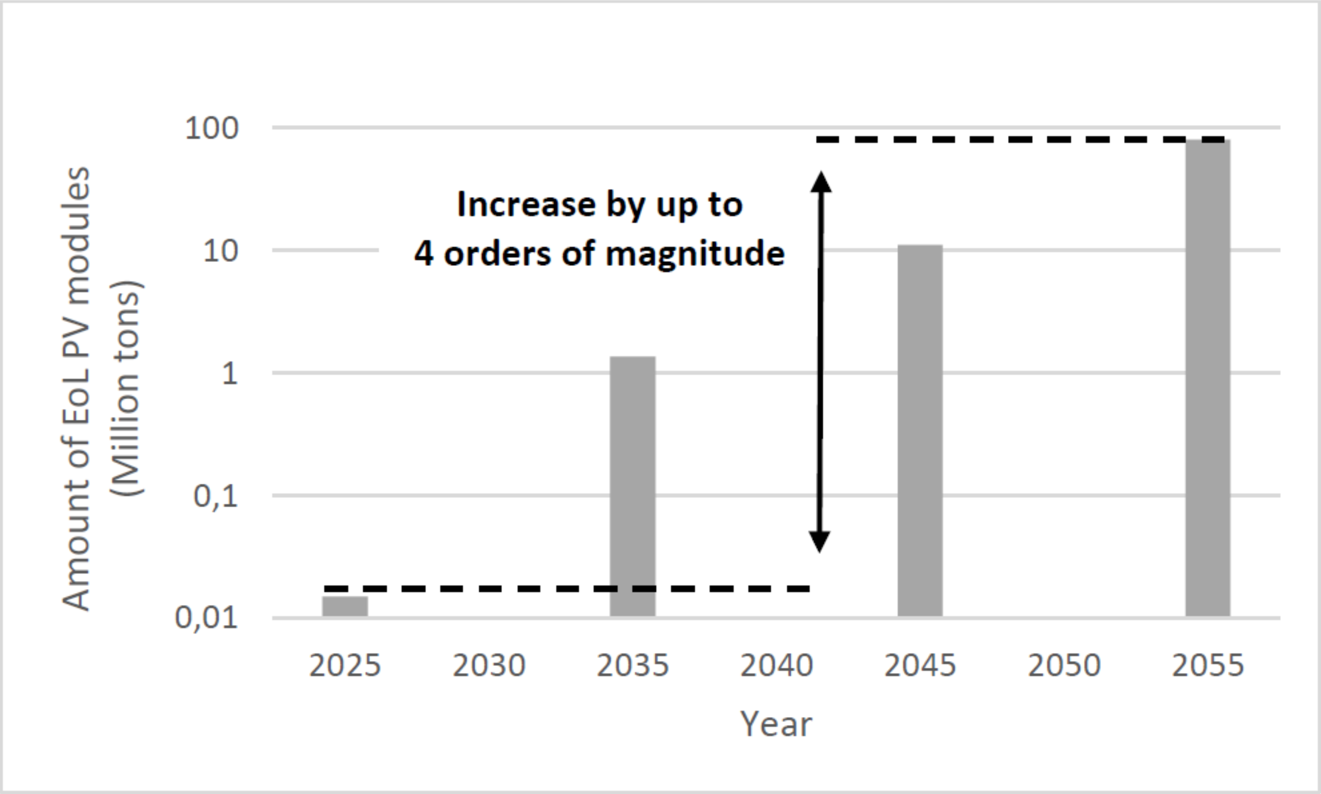

Figure 1: Expected increase of global PV waste in the coming decades

Compositional characteristics of EoL PV panels

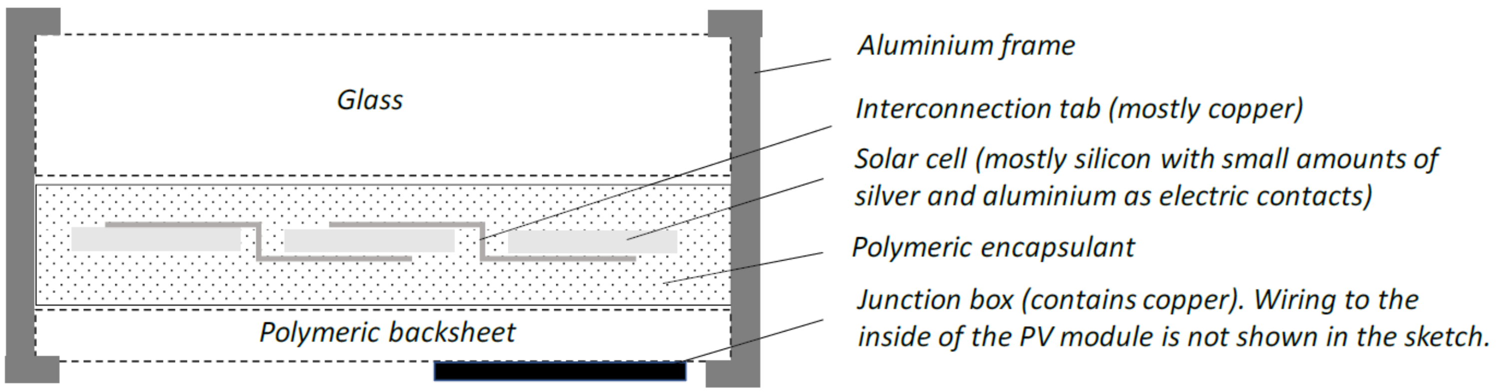

Figure 2: Structure of a PV module and its key components

Material	Mass (kg)
Glass (front pane)	14
Aluminium (frame)	3,6
Polymers (encapsulant and backsheet)	1,3
Silicon (solar cell wafers)	0,7
Copper (internal and external wiring)	0,2
Silver (internal electric contacts)	0,01

Table 1: List of key materials and their mass in an average EoL PV module

Materials breakdown by mass

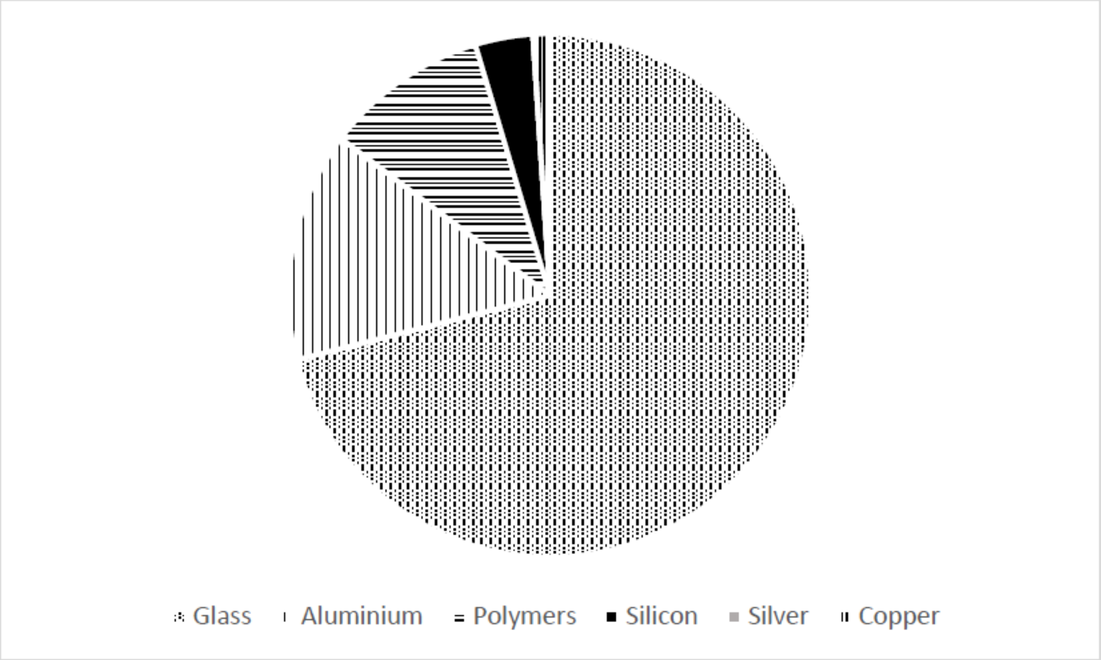

Figure 3: Materials breakdown by mass of an average EoL PV module (total is around 20 kg)

The **mass is dominated primarily by glass**, followed by:
- aluminium (frame), and
- polymers (encapsulants and backsheet)

Silicon (~ 3,5 wt%) and silver (~ 0,05 wt%) are only minor or negligible components in the mass breakdown

Materials breakdown by embodied energy

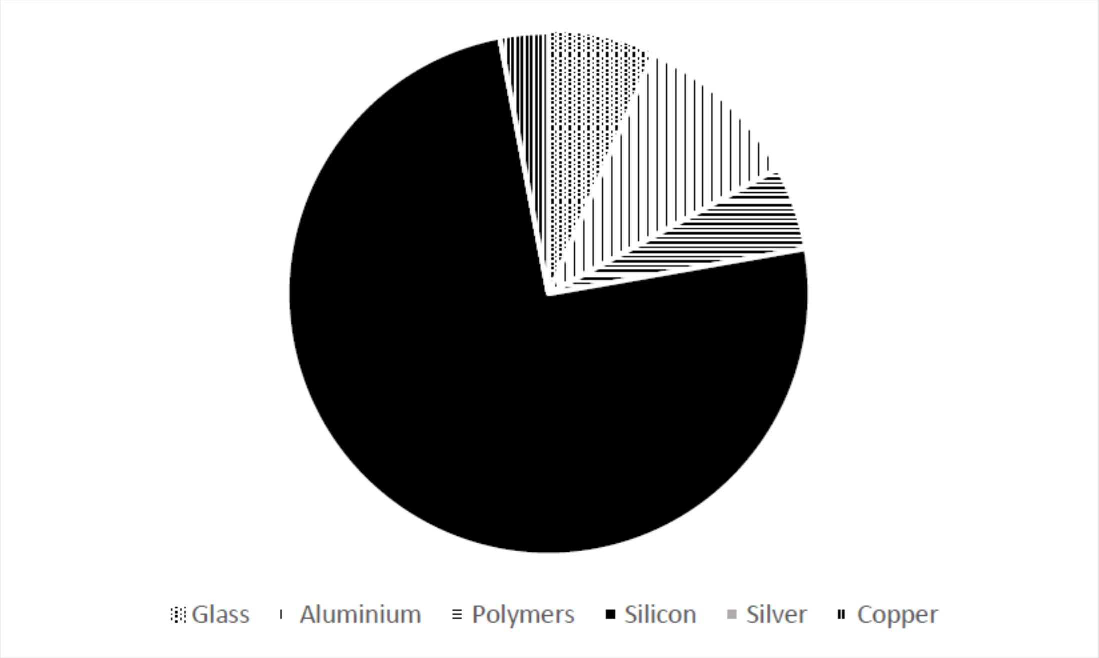

Figure 4: Materials breakdown by embodied energy of an average EoL PV module (total is around 2000 MJ)

The **embodied energy is dominated by silicon** despite its ow mass fraction.
Reason for that is the energy intensive process steps in the chain of wafer production. In particular, the refinementof metallurgical to solar grade silicon as well as ingot growth.

Materials breakdown by economic value

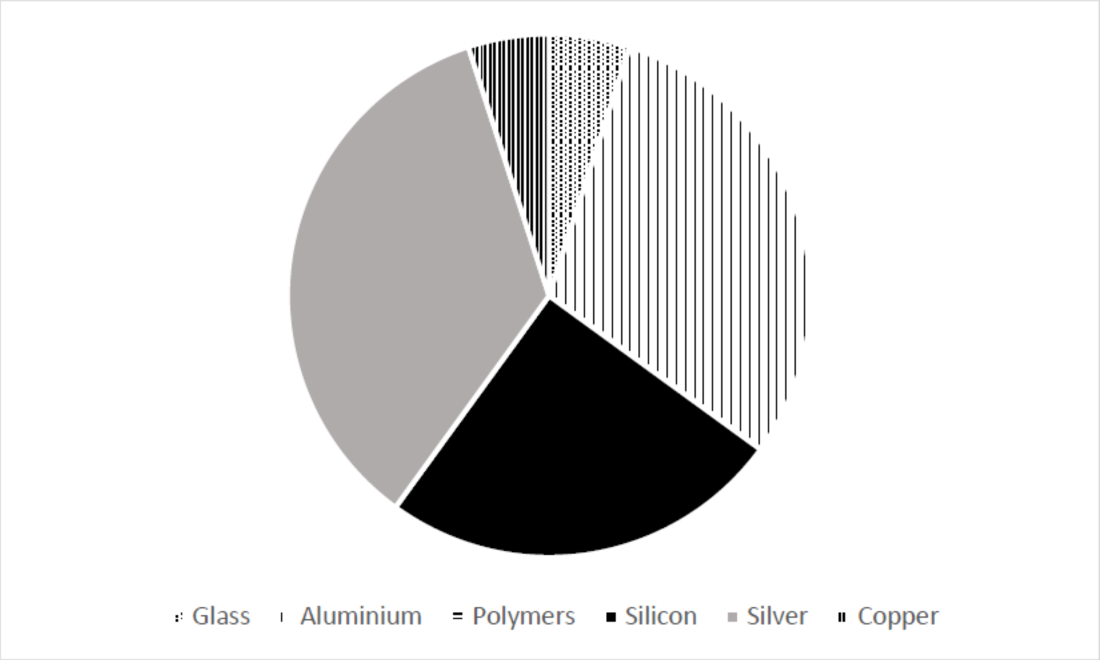

Figure 5: Materials breakdown by economic value of an average EoL PV module (total is around 10 €)

The **economic value** is mostly due to three components. Next to the high mass fraction component (**aluminium**), these are the two low mass fraction components:

- **silicon**, and
- **silver**

Challenges versus need of PV recycling

Challenges

- **(Very) low PV waste volume** thus far > operation of economically viable recycling plants impossible
- **Unfavorable value to weight ratio** of EoL PV panels , only ~ 400 – 700 €/t
- Electronic waste has almost twice the value (~ 1000 €/t)
- Technologically, it is relatively **difficult to extract and recycle silicon and silver** from EoL PV modules

Need

- **Sustainability of PV!**
- High potential to significantly reduce embodied energy of PV panels when using recycled (rather than virgin) Si
- This is important because of enormously increasing electricity demand of PV production
- Recycling of silver is important to help avoiding future Ag supply constraints
- Environmental pollution risks from landfilling or incinerating of PV panels should be avoided (Pb, F-polymers)

Contemporary downcycling approach

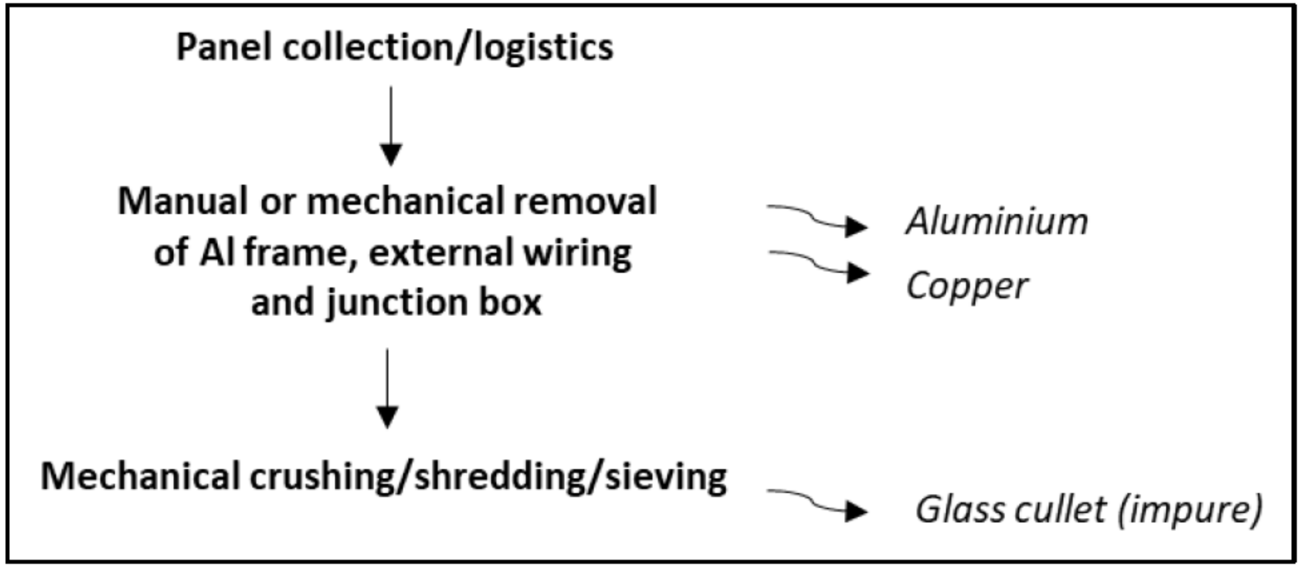

Figure 6: Scheme showing process steps and recovered materials for contemporary downcycling technology

Low cost, low value
Takes place in existing recycling facilities for recycling of other waste streams (e.g. laminated glass, metal, electronics).
80% recovery by weight. But this is misleading > low economic recovery value; critical materials not recovered (Si, Ag, Pb, F-polymers).

Future re-/upcycling approach

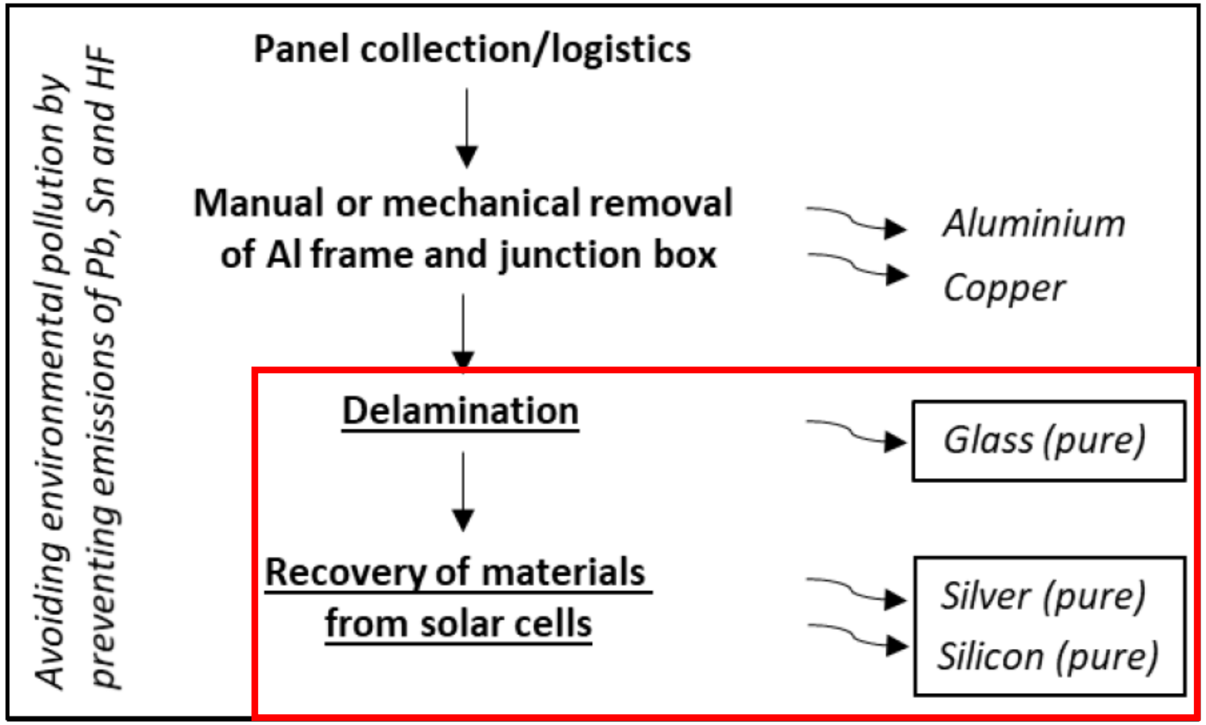

Figure 7: Scheme showing process steps and recovered materials of future high-value recycling

High(er) cost, high(er) value

Dedicated PV recycling plants needed (under development).

Two main process steps required:

1. Delamination (mechanical, thermal, chemical)
2. Recovery of materials from solar cells (chemical)

> Critical materials (Si, Ag) are recovered

First industrial initiatives for high value PV recycling

Examples

1. Rosi Solar (France)
   Delamination by pyrolysis
   Recovery of materials from solar cells by chemical processing
   Output a.o.: high purity glass, silicon, silver
   Scale ~ 3000t/y

2. Reiling (Germany)
   Delamination by mechanical processing and sorting
   Recovery of materials from solar cells by chemical processing
   Output a.o.: solar grade silicon (!)
   PERC solar cells processed from recycled silicon with efficiency of 19,7% (vs. 22,2 from virgin solar grade silicon)

Conclusions

- In view of increasing EoL volumes improved PV recycling is becoming more and more urgent and important
- Contemporary downcycling approach is not sufficient (no recovery of critical materials, i.e., Si, Ag)
- Future, advanced re-/upcycling approaches under development (allowing recovery of critical materials)
- Advanced PV recycling not yet economically viable
- Policy stimulation needed to get if off the ground!

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