

Recycling of End-of-Life Photovoltaic Modules: Annoying Obligation or Profitable Business?

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Fraunhofer IWKS + Fraunhofer CSP: joint activities for PV-recycling

IWKS: Focus on recycling processes and circular economy, manufacturing of new materials.

Hanau and Alzenau



CSP: Focus on photovoltaic processes (crystallization, wafering etc.), recycling of PV-modules



Legal Situation in Germany

Recycling is mandatory

In Germany, EoL PV modules are electronic waste:

Landfill or export are **not allowed**

A recycling rate of >80% is mandatory

B2C: free of charge for the user, costs are covered by the foundation *ear*

B2B: not clearly defined, at the end of the day, the PV park operator is responsible



stiftung
elektro-altgeräte register® **ear**



Elektrogesetz



Installed PV Capacity (end of year 2024)

Accumulated Material Consumption of Totally Installed Modules (Order of Magnitude)

	Inst. Capacity	Modules / t	Silicon / t	Organic / t	Aluminum / t	Glass / t
Germany	≈100 GW	≈8,000,000	≈250,000	≈800,000	≈1.000,000	≈5,500,000
World	>2,000 GW	≈160,000,000	≈5,000,000	≈16,000,000	≈20,000,000	≈110,000,000

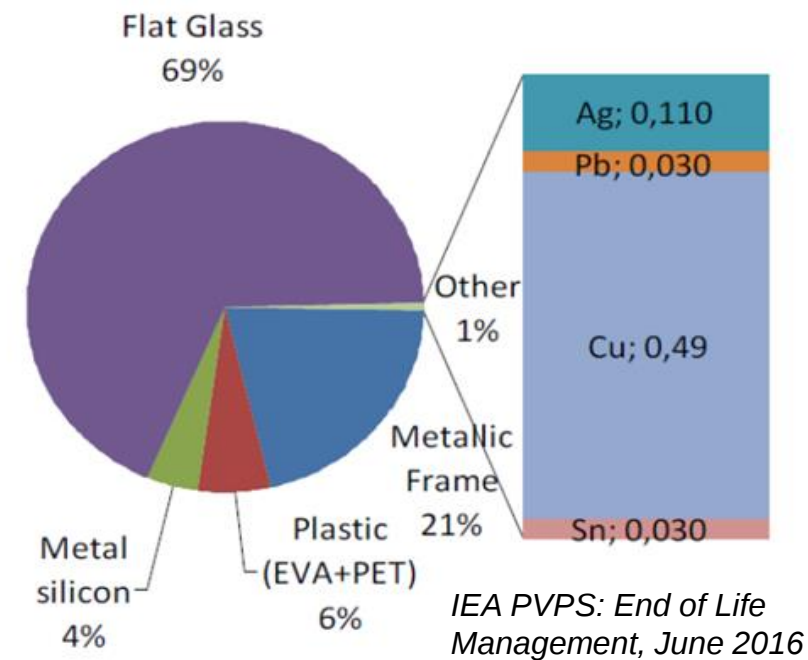


- Older modules: more weight per kW_p
- Wafer thickness: changed only slightly over the last 15 years
- Data varies strongly, depending on the module type and manufacturer
- Typical life-time of older modules: 20 years

Material Composition of PV Modules

Average Values

1 t EoL-Modules	
125 - 200 kg	Aluminum
600 - 725 kg	Glass
25 - 35 kg	Silicon
0.2 – 0.7 kg	Silver
60 - 110 kg	Plastics
50 - 80 kg	Cable
40 - 90 kg	Junction Boxes



Material Composition of PV Modules

Material Value

The material value of **one module** is approx. 15-20 €, if all the materials are recovered:

Aluminum:	4 € (≈ 1.5 €/kg)
Silver:	11.2 € (≈ 1.220 €/kg *) <i>*(12.8.2025)</i>
Silicon:	1 – 3 € (≈ 1.5 – 4 €/kg mg-Si)
Glass:	1 – 1.4 € ($\approx 0,10$ €/kg)

Roughly: 50 modules are 1 ton => 1 ton has a material value of 750 to 1,000 €; recycling costs include:

Transport and logistics

CAPEX

OPEX

Waste disposal

For a good business case, enough input material is mandatory!

(Enough means something like 10,000 t/y.)

Silver should be addressed, in particular for older modules,

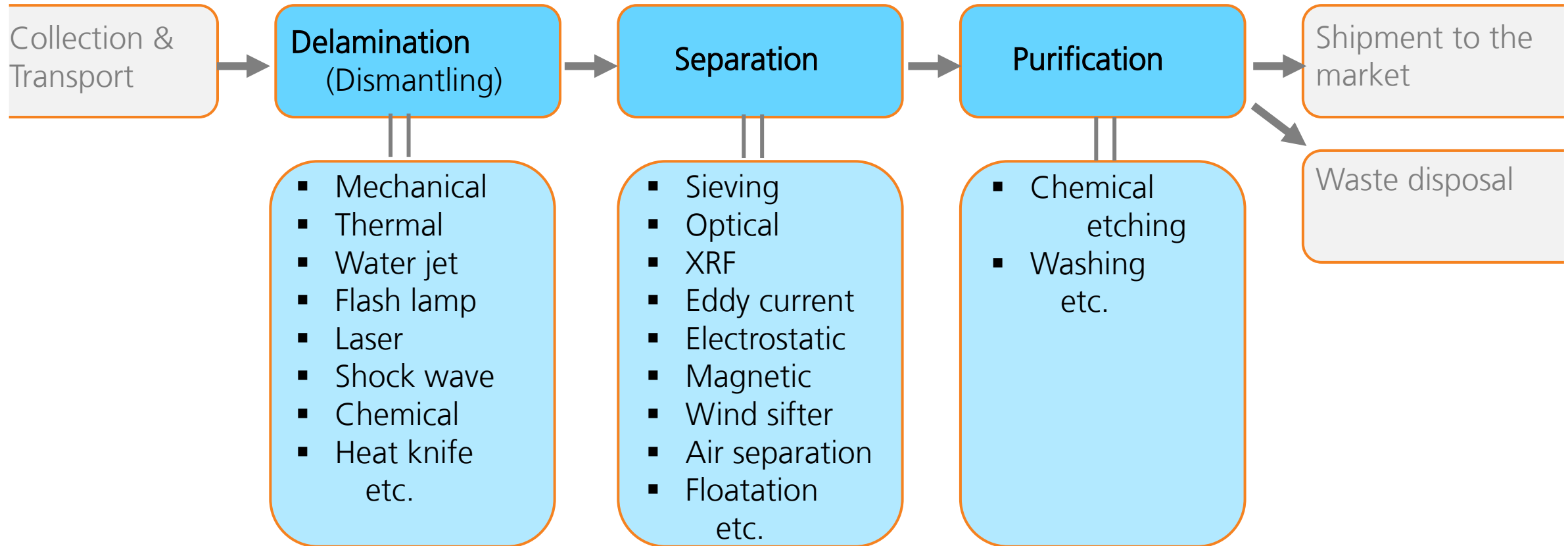
Labor cost have to be minimized.

Waste disposal (etching acids!) has to be minimized (->regeneration!)

**(12.8.2025)*

PV Module Recycling: It is a 3-step Process

(Like most recycling processes)

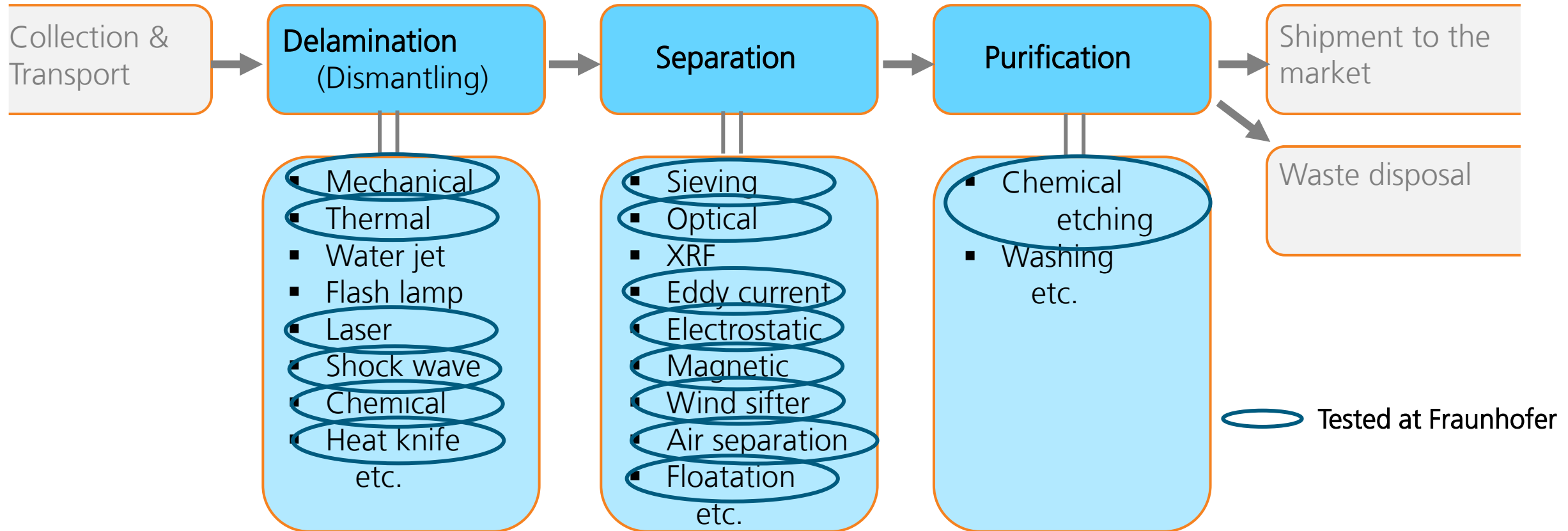


Most methods are working well – the core question is: how can you reach high throughput at low cost?

How to combine? How to optimize?

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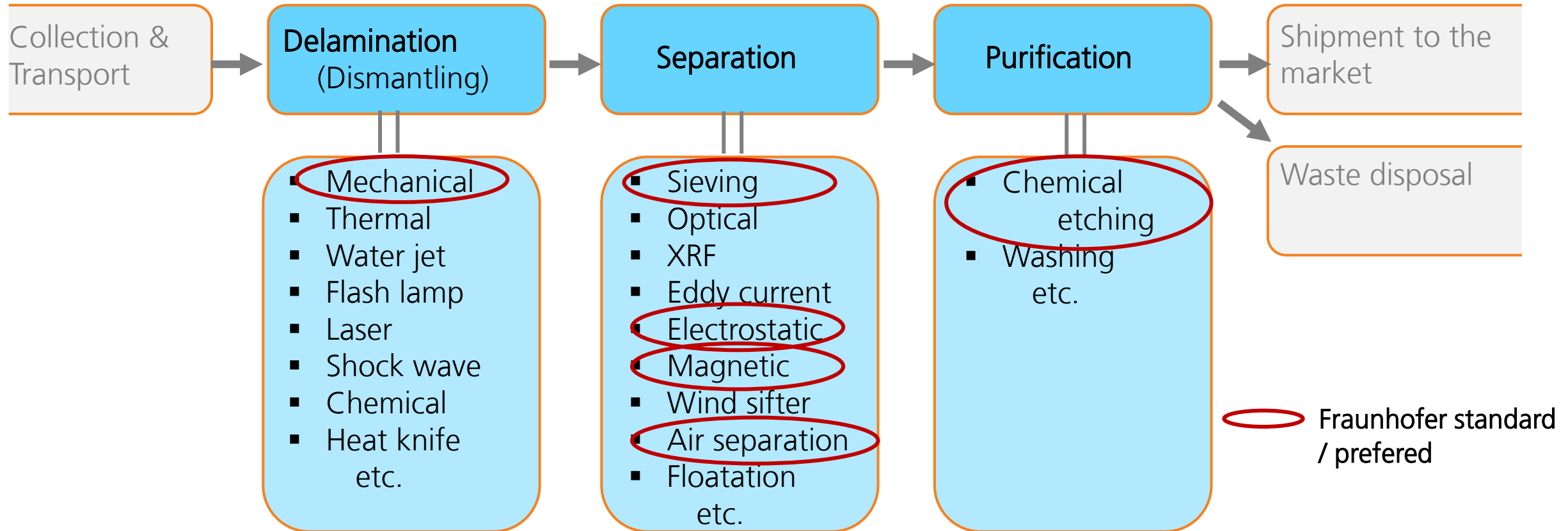


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PV Module Recycling: It is a 3-step Process

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How to combine? How to optimize?

Four shaft shredder RS50 – Untha (Horn) Impact crusher – BHS Grinder – BHS Sonthofen

Specifications

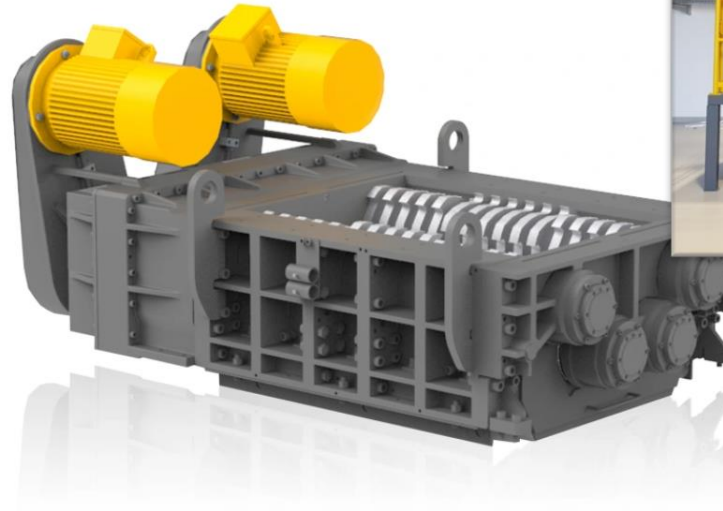
Rated capacity: 44 kW

Feed opening: 960 x 700 mm

Fraction sizes (based on the screen): 15 - 40 mm

Rotational speed main shaft: 21 - 29 U/min

Throughput (depending on material): ca. 100 kg/h



Specifications

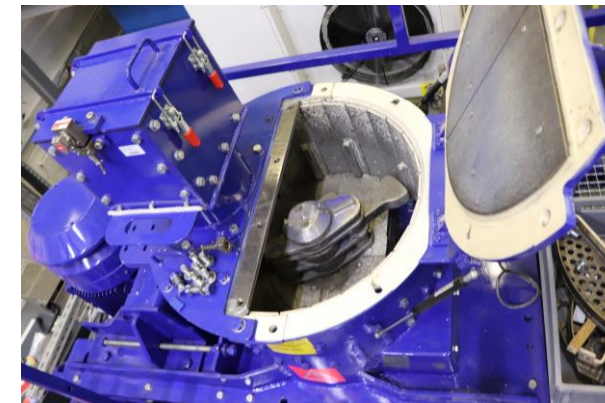
Crushing by impact and shearing effects

Adjustable crushing degree by integrated sieve

Diameter of rotor: 780 mm

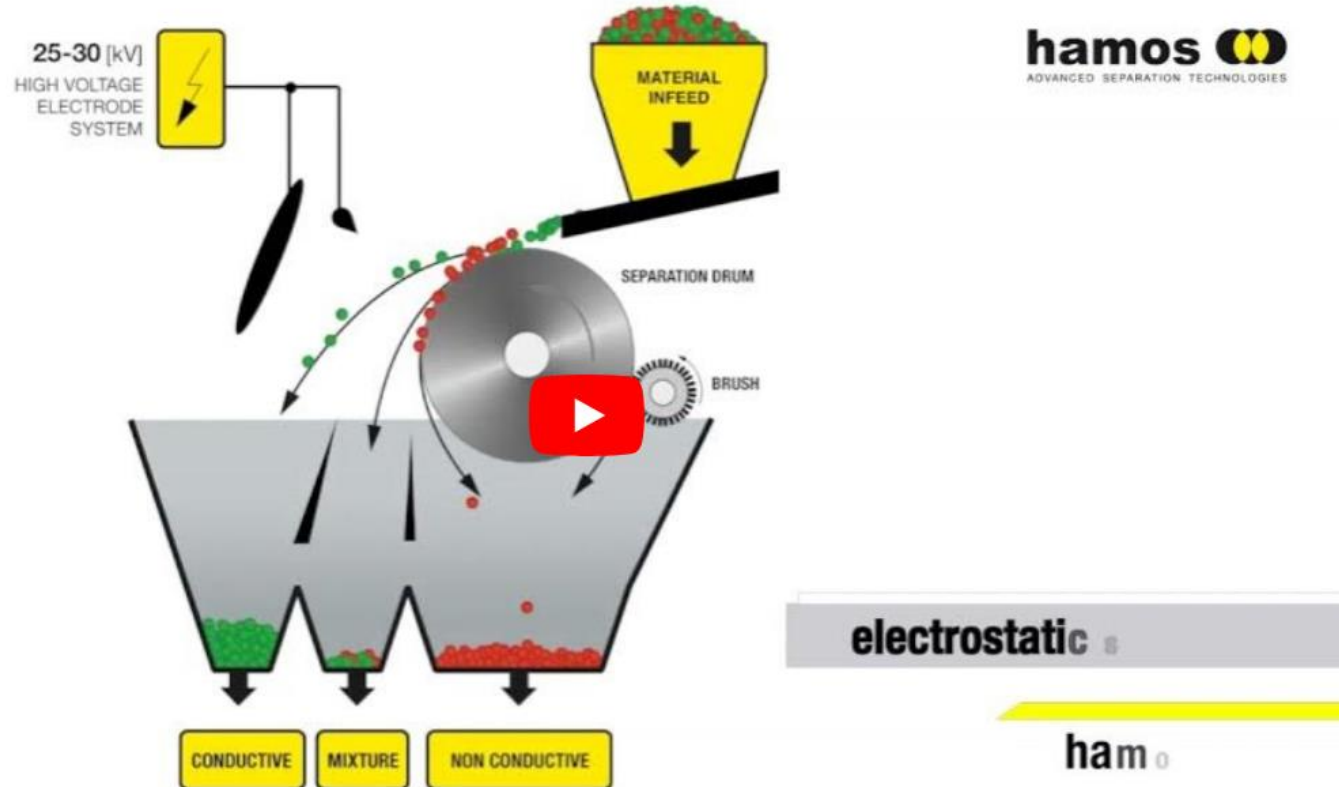
Motor drive power: 1 x 45 kW

Motor voltage: 400 V



Recycling of Photovoltaic Modules

Electrostatic separator



Non-conducting particles (glass, plastics) are sticking to the drum and fall into the right hand container, conducting particles are going to the left hand side.

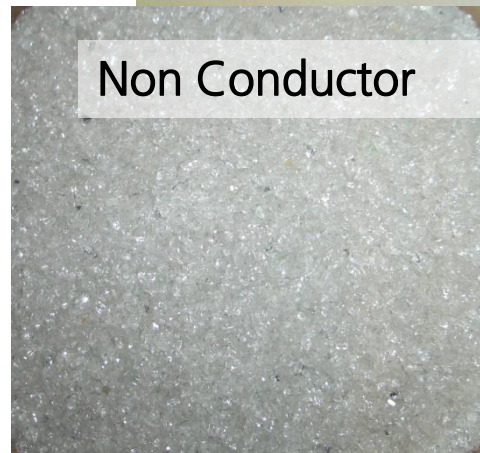
[Elektrostatischer Separator für Metallabtrennung aus PV Modulen - hamos KWS](#)

Innovative Recycling Concepts

Electrostatic Separation



6 tons of cell
Fragments /
conductor material
has been recovered,
which corresponds
to 10.000 PV-
modules.



Innovative Recycling Concepts

Electrostatic Separation



Recycling Concepts @Fraunhofer IWKS and Fraunhofer CSP

Chemical etching

Barrel – Lab.
(static)



Tubes (semi-cont.)

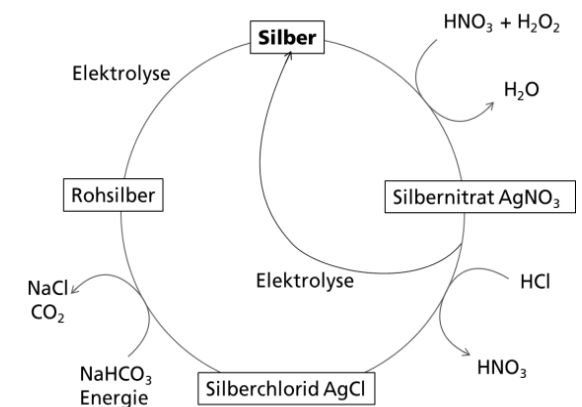
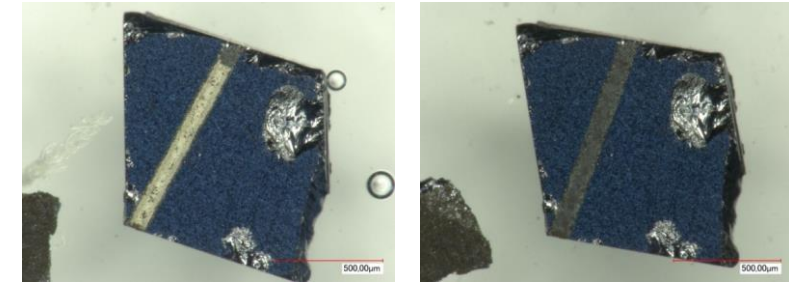


100 kg (left) – 2x25 kg (right)

Drum (dynamic)



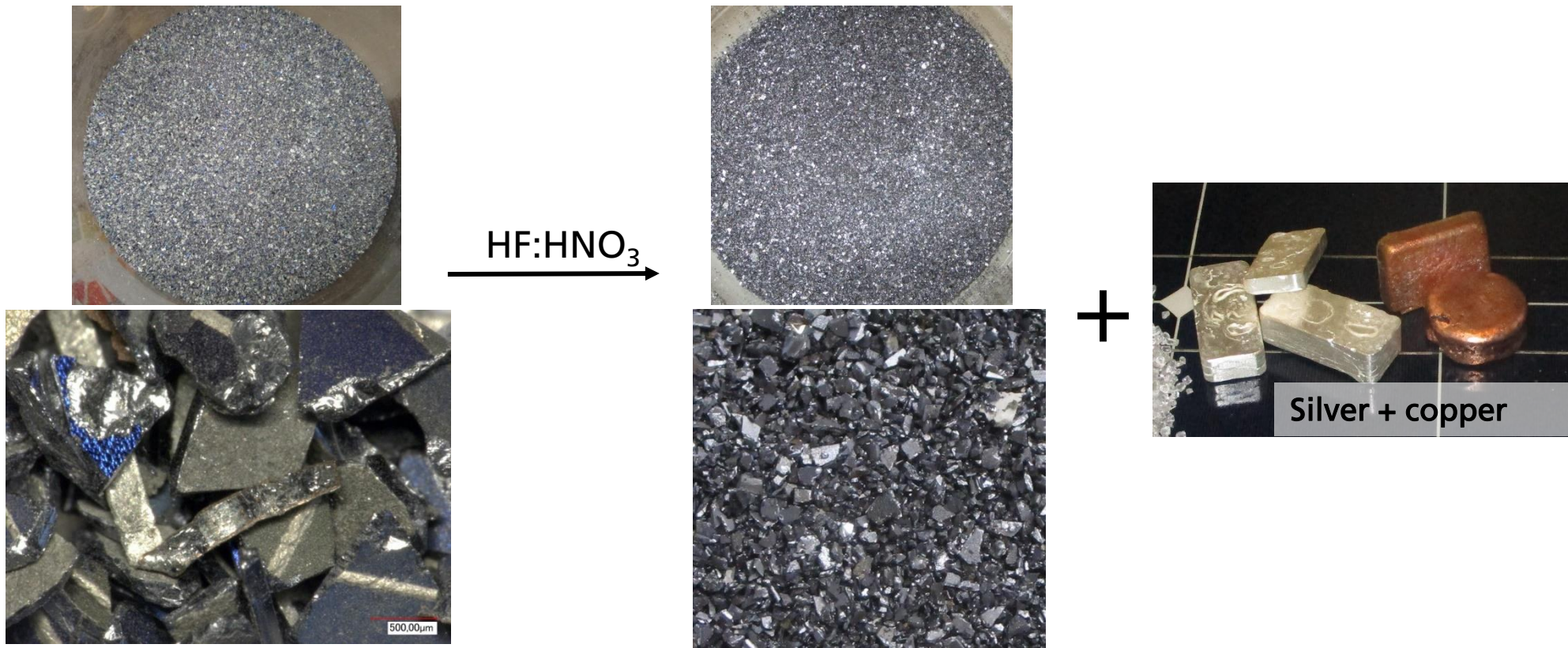
300 liter / 60 kg



Recycling Concepts @Fraunhofer IWKS and Fraunhofer CSP

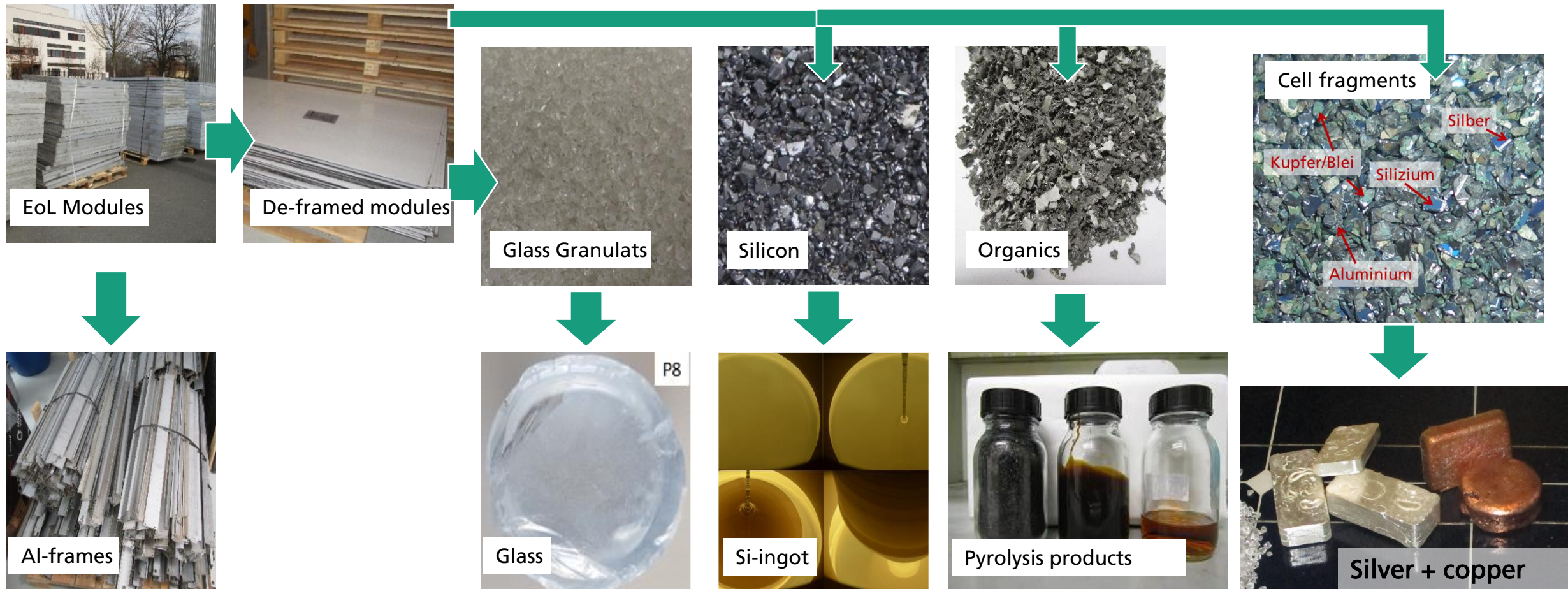
Chemical etching

Removal of the back-contact, the AR-coating and the emitter.



Innovative Recycling Concepts

2011-2025: Recycling von PV-Modulen @Fraunhofer



Innovative Recycling Concepts

Fraunhofer IWKS & Fraunhofer CSP

Requirements for a suitable recycling process:
Separation and purification of glass, foils, cells etc.
and recovery of the metals.



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