RECYCLING OF PV MODULES – WHICH IS THE MOST PROMISING APPROACH?

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Halle/Saale
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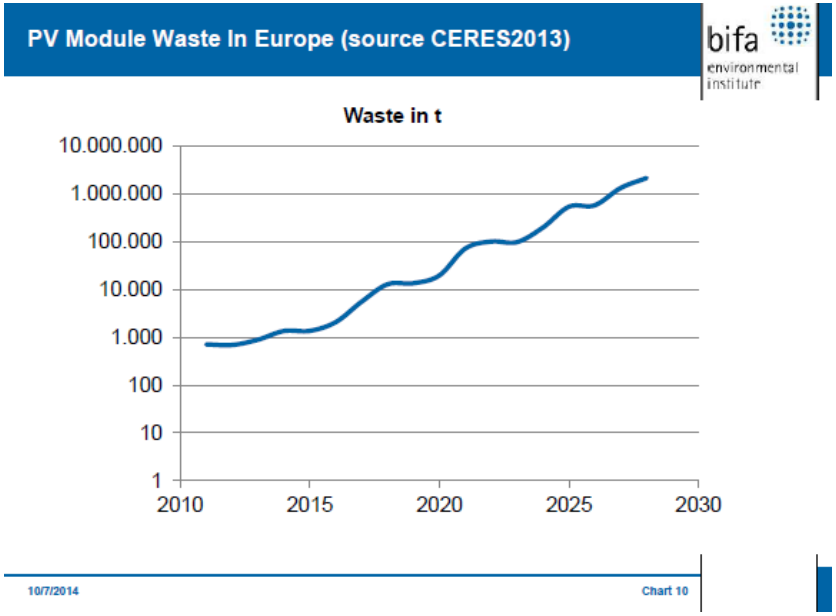
Current situation
Installation of PV Modules in Germany 2016

- Total power installed: ≈ 40 GWp[1]
- Market share of crystalline Si-modules 2013: 90 % [2]
- Power per module: ≈ 200 - 250 Wp
- Weight per module: ≈ 20 - 25 kg

=> 4 million tons of PV modules are installed in Germany and will come back within the next years. PV modules are electronic waste and have to be recycled!



Forecast for the return of EoL-modules in Europe[3]

[1] H.Wirth, Aktuelle Fakten zur Photovoltaik in Deutschland, ISE, 2017
[2] Renewables 2014, Global Status Report, ISBN 978-3-9815934-2-6 [3] K. Wambach, bifa Umweltinstitut GmbH

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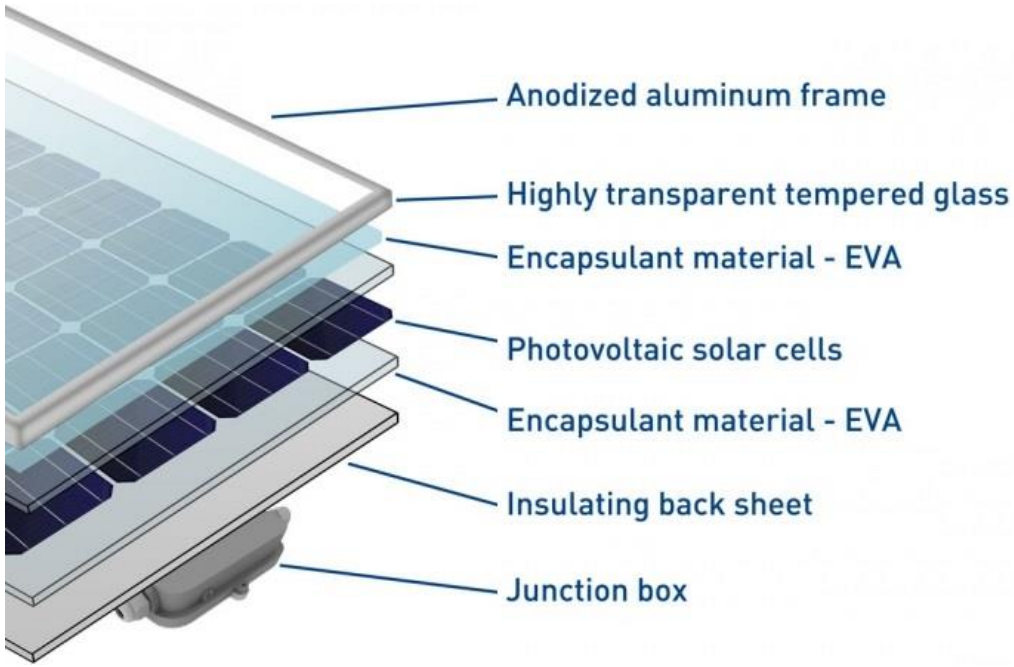
Current situation
Composition of PV-Modules



- ~ 60 cells per module
- Cells encapsulated in EVA
- EVA undergoes crosslinking during lamination
- Backsheet: fluorine containing, though, chemically inert

→ **Complex compound material Great challenges for the decomposition process!**

http://www.pvcompare.net/images/structure_of_photovoltaic_module.jpg

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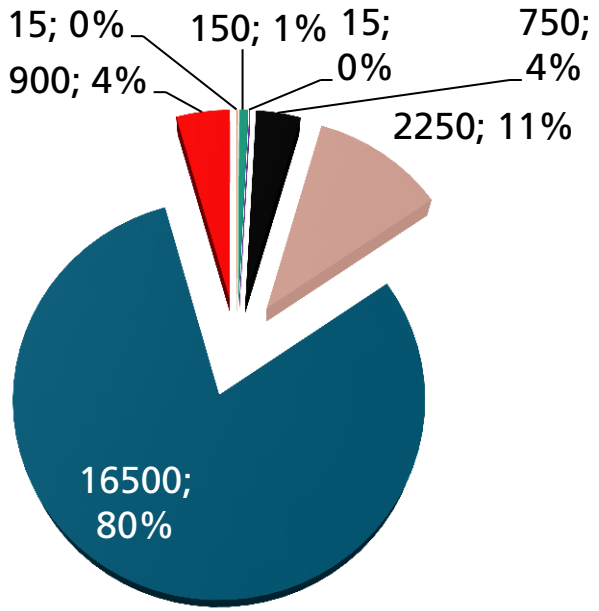
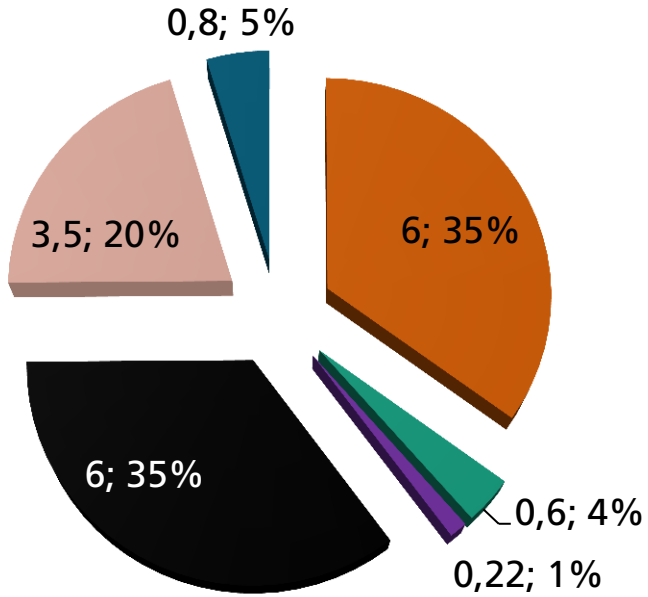
Current situation

Material Distribution in Crystalline Silicon PV-Modules



Mass composition of a crystalline silicon PV-module [g] (average, rounded)



Value of the components of a single PV-module [€]* (averages, rounded)

The mass composition is not the same as the value distribution in an EoL-PV-module!

The value potential for EoL-module recycling is about 2 - 6 bil. € in Germany alone!

* Material Prices of 2017

** Depending on achieved Purity!

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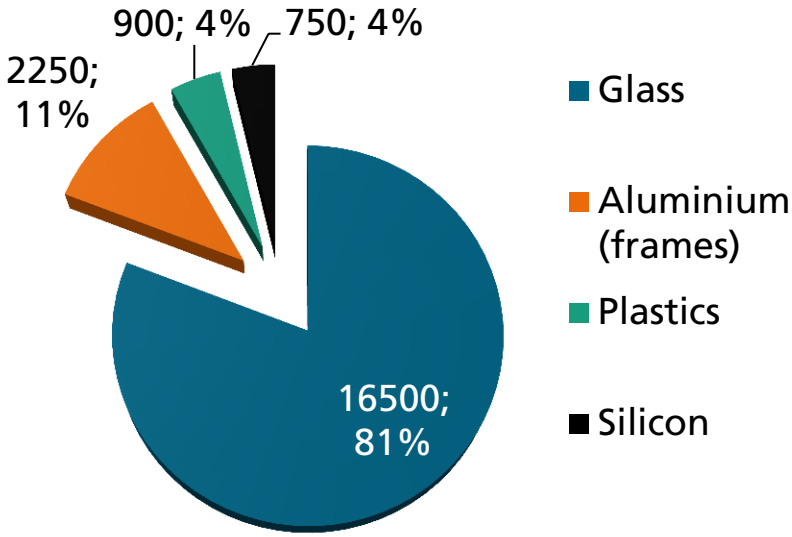
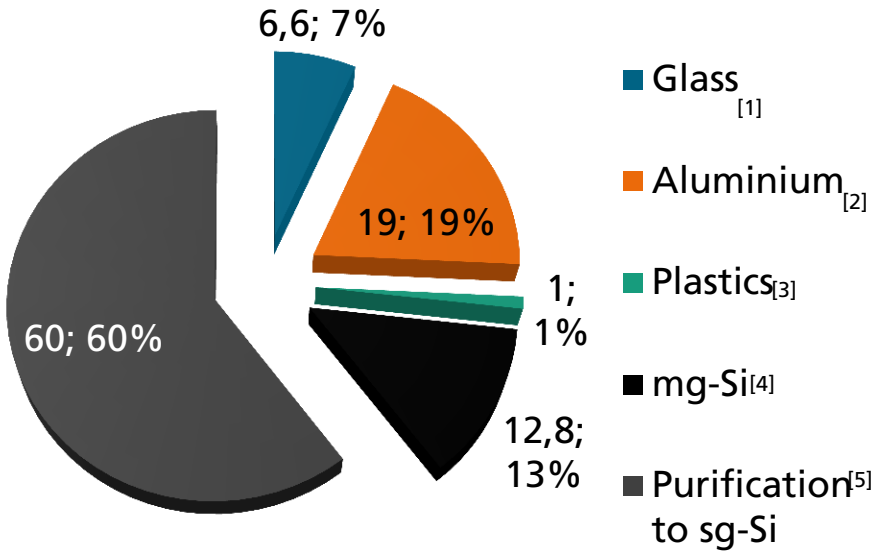
Current situation
Carbon Footprint



Mass composition of a crystalline silicon PV-module [g] (averages, rounded)



CO2-Emission per component of a crystalline silicon PV-module [kg] (averages, rounded)

The purification of silicon contributes significantly to the CO_2 emission!

[1] B. H. W. S. de Jong, R. G. C. Beerkens, P. A. Nijnatten, E. le Bourhis, *Glass, 2. Production*, Wiley-VCH Verlag GmbH & Co. KGaA, In: Ullmann's Encyclopedia of Industrial Chemistry, 7. Aufl., 2010, p. 9.
[2] W. B. Frank et al., *Aluminium*, Wiley-VCH Verlag GmbH & Co. KGaA, In: Ullmann's Encyclopedia of Industrial Chemistry, 7. Aufl., 2010, p. 503.
[3] Estimated based on general plastic production.
[4] B. Andresen, *Operational Aspects of the Metallurgical Silicon Process*, In: Silicon for the Chemical and Solar Industry XIII, Kristiansand, June 13 – 16, 2016, p. 64.
[5] L. Fabry, K. Hesse, *Crystalline Silicon Feedstock Preparation and Analysis*, In: Semiconductors and Semimetals Vol. 87, 2012, p. 226.

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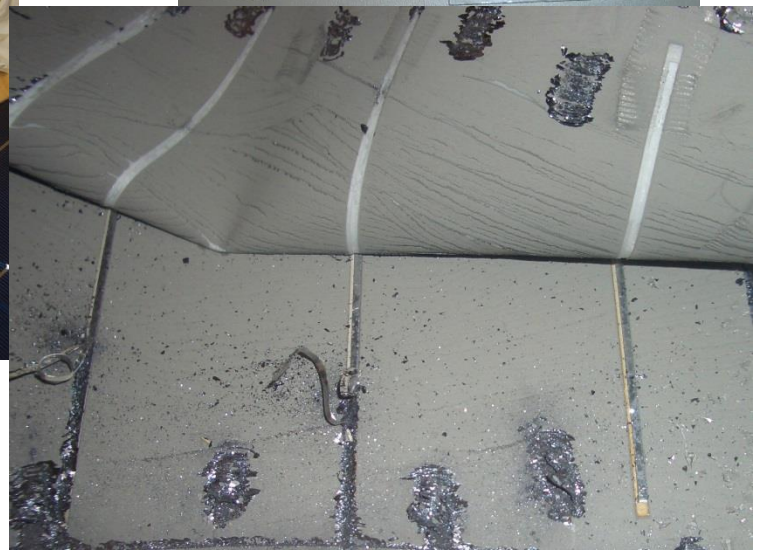
Recycling Concepts
Manual Delamination of PV-Modules



- Step-by-step delamination of the modules is possible but time-consuming. Economically difficult to do / to scale-up.

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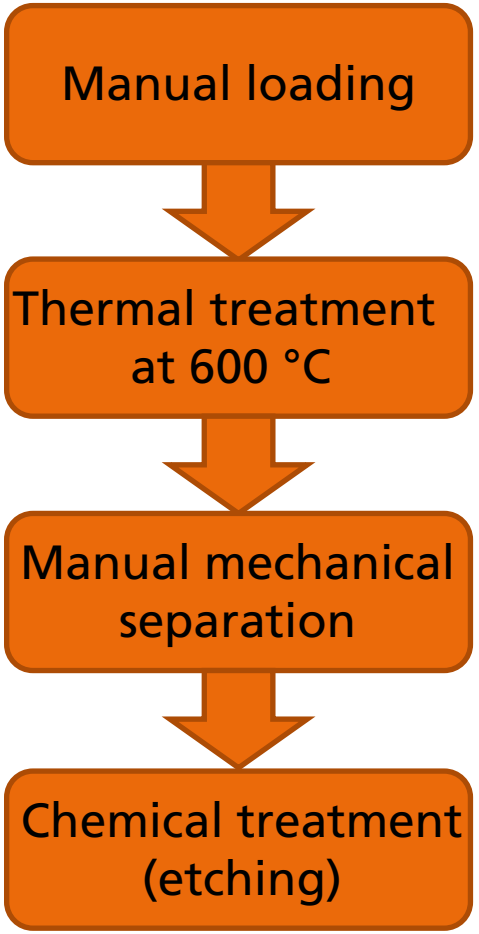
Recycling Concepts
Pyrolysis (Solarworld)

- Pilot line in Freiberg
- Focused on recovery of complete PV-cells
  (long time ago silicon was highly priced)
- Many manual steps
- Silicon contamination during pyrolysis
- Off-Gas recovery (fluorine!)

Recycling activities abandoned in 2014!



R.Fiedler Recycling von PV-Modulen, Solarworld AG, 06.09.2016.

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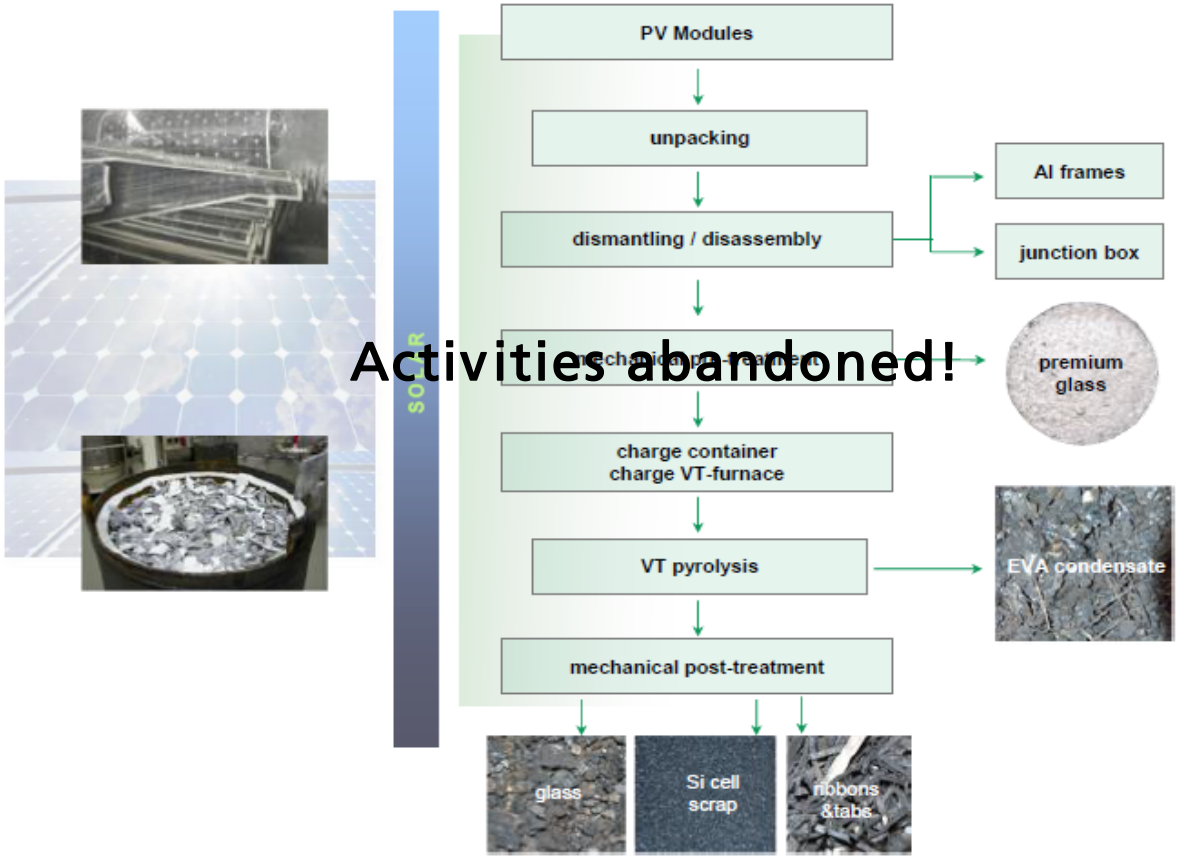
Recycling Concepts

Pyrolysis (ACCUREC)

ACCUREC´s crystalline Si based process



Activities abandoned!

R.Weyhe, Accurec Recycling, EU PVSEC Workshop, Amsterdam, 2014.

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Recycling Concepts

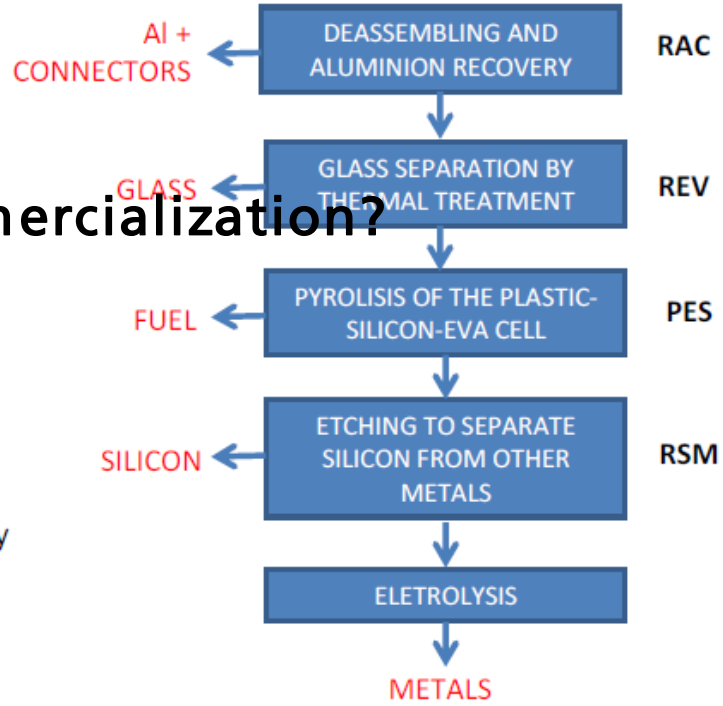
Pyrolysis (FRELP)

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

FRELP PROCESS

- recovery of aluminum profiles and connectors;
- separation of glass from the rest of the panel through thermal effect, softening and cutting the EVA (ethylene vinyl acetate) adhesive;
- pyrolysis of the plastic silicon-EVA-cell structure conductor-back-sheet sandwich, recovering ashes and energy by obtaining fuel oil;
- treatment of ashes with acid etching to separate silicon from the other metals;
- selective recovery of the eluate, formed by the silicon and the other metals, through micro and nano filtering and selective electrolysis of the acid solution.

Commercialization?



23/09/2014 - Ramon Lodovico - Amsterdam - EU PVSEC Workshop "PV Life Cycle Management & Recycling" *14*

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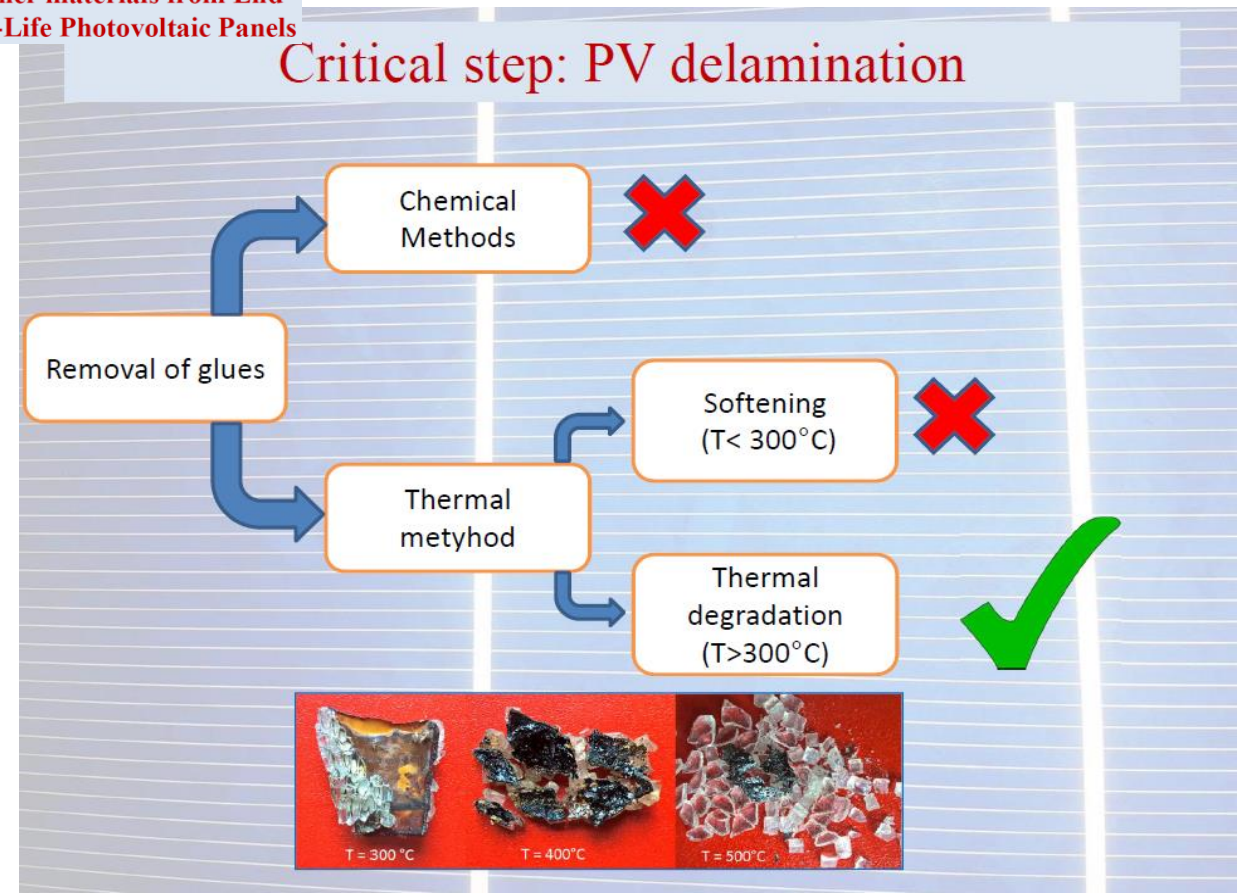
Recycling Concepts
Pyrolysis (ReSIELP)

ReSIELP:
Recovery of Silicon and other materials from End-of-Life Photovoltaic Panels



KIC EIT RAW MATERIALS - Project Number 16327

Project duration: 2017-2020

www.rinnovabili.it/wp-content/uploads/2017/05/Dabala_UniPadova.pdf

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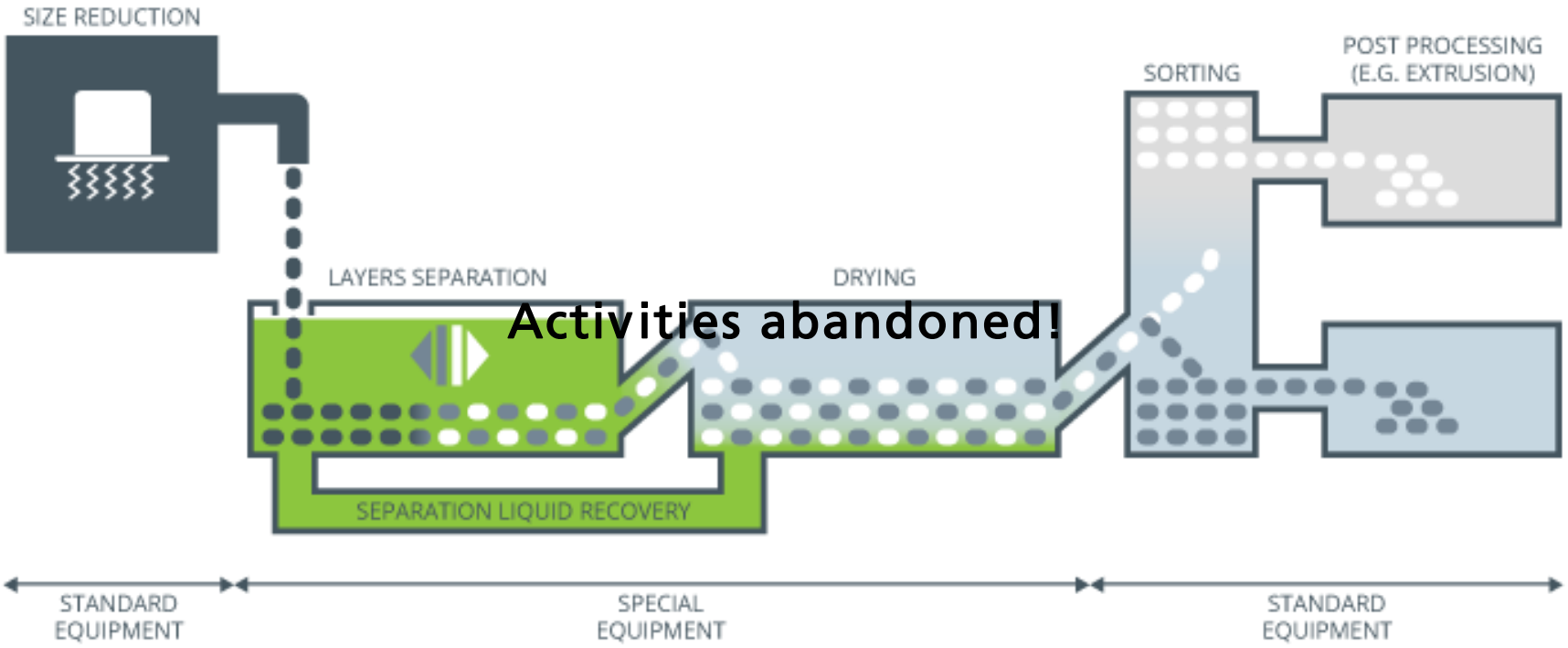
Recycling Concepts
Chemical Delamination (Saperatec)



- Process duration?
- Tenside recovery?

www.plastigram.eu/#technology www.saperatec.de/technology

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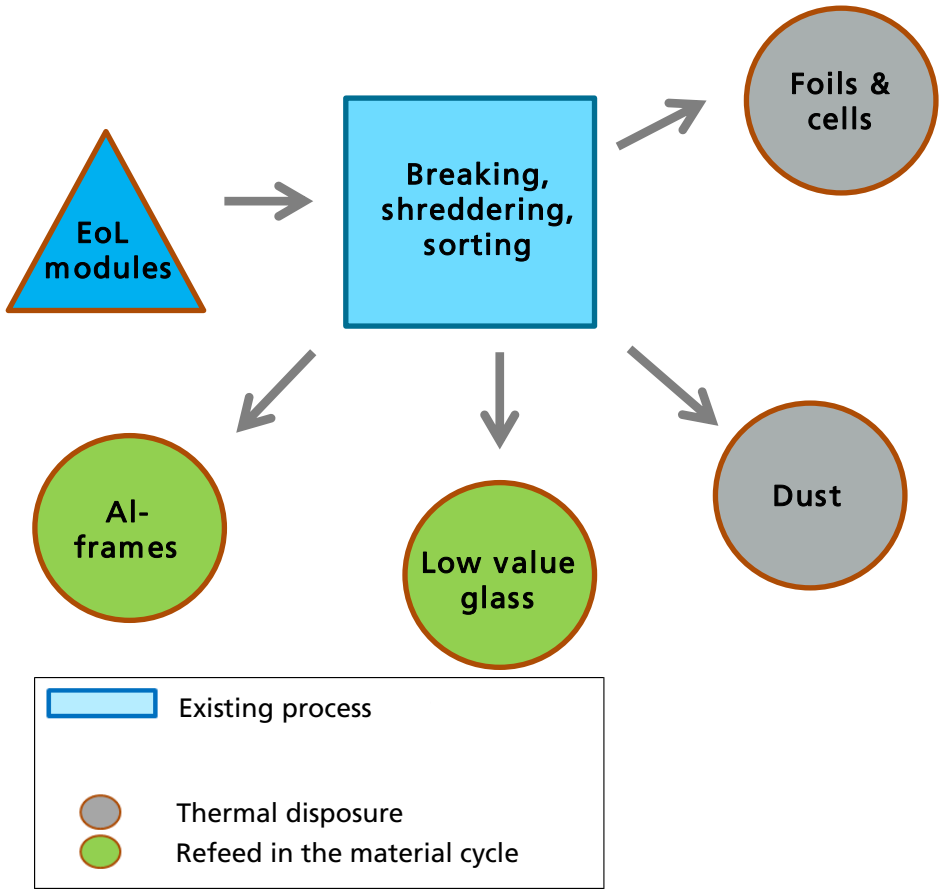
Recycling concepts
Mechanical Dismanteling

Shredder (Reiling, Exner etc.)



Shredder, Reiling GmbH

- High through-put, scalable
- Product purity not sufficient (downcycling)

Reiling Unternehmensgruppe

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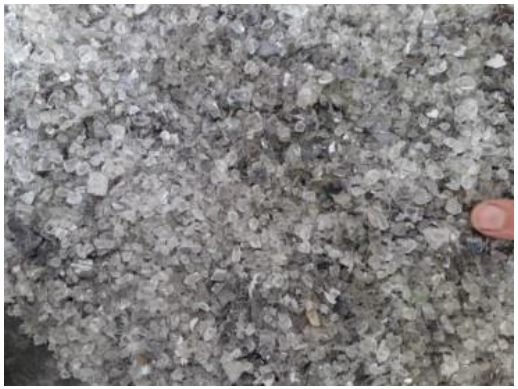
Actual Recycling Strategy
Mechanical Approach / Shredder

Dismantled Al-frames

EoL-modules, containing glass, PV-cells and foils

PV-cell and foil fraction for thermal disposure („Sorte 2")



Glass used as insulation or building material („Sorte 1")

Reiling Unternehmensgruppe

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Actual Recycling Strategy
Mechanical Approach / Shredder

- Large scale processing (tons)
- High throughput sorting

Reiling Unternehmensgruppe

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Project EoL-Cycle
Reusing Valuable Materials from EoL PV Systems

- Development of an economically viable process to recycle end-of-life PV modules
- Recovery of silver, copper and tin from PV modules
- Extraction and reprocessing of solar silicon
- Recovery of glass and return as special low-iron glass to glassworks

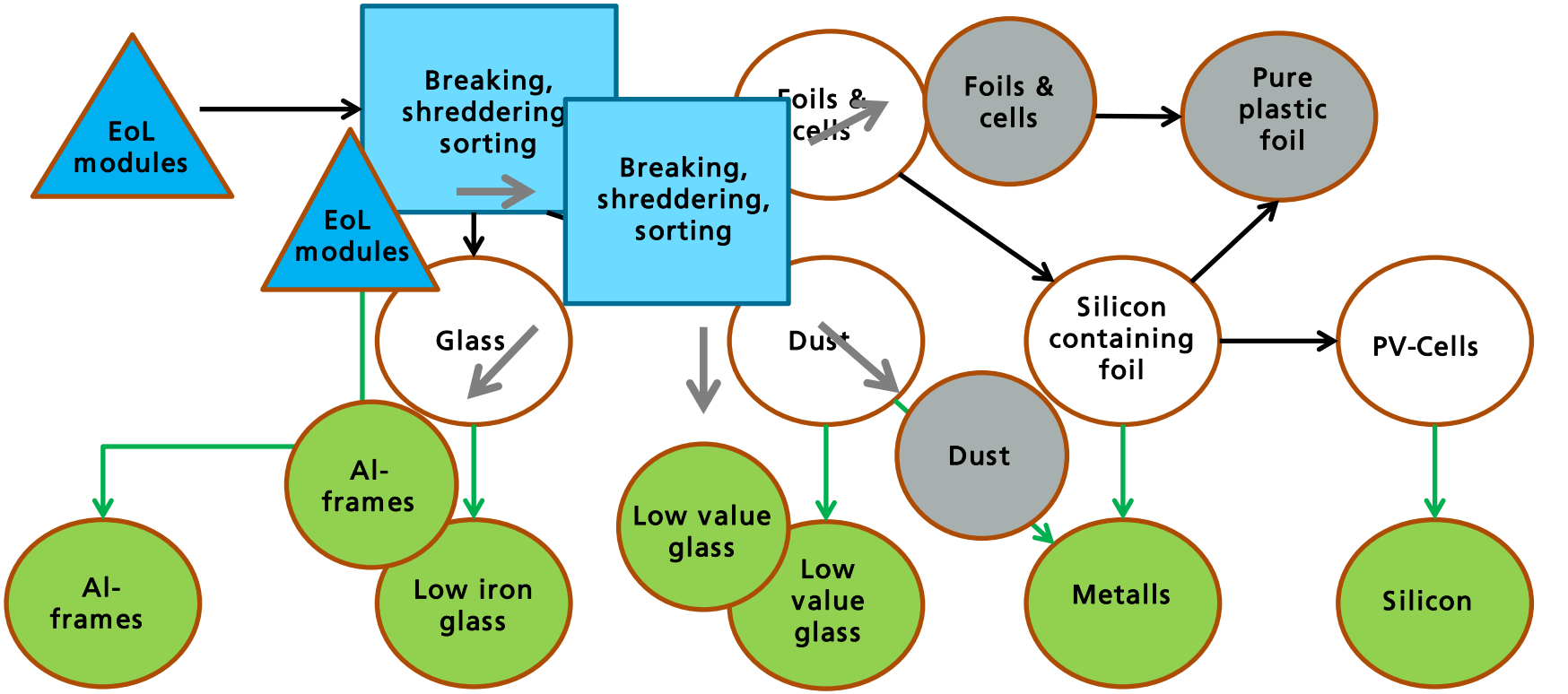
Project EoL-Cycle
Optimized Separation Process

- Use of existing technology – combination and development of industrial scale methods
- Mechanical, physical and chemical separation operations under observance of the technical requirements of an industrial Process
- Ensuring the robustness of the process!

  Recycling of all crystalline silicon solar panel types must be possible.
- Objective: profitable recycling process → EoL modules should no longer be regarded as a waste but rather as a raw material source!

Project EoL-Cycle - Concept

Combination of Mechanical and Chemical Treatment



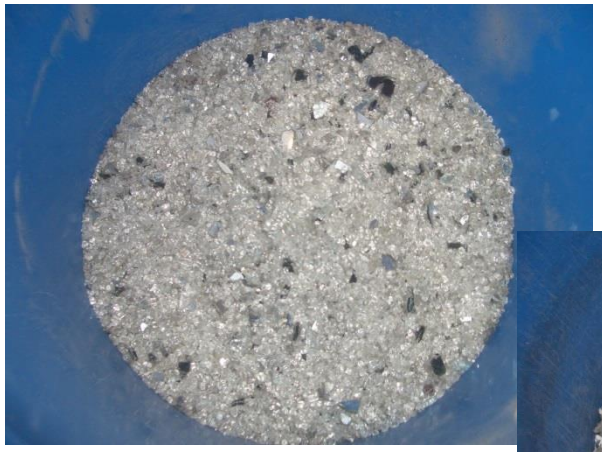
- Full use of the value potential of the EoL-modules
- Prevention of flat glass downcycling

Reiling Unternehmensgruppe tesoma Fraunhofer CSP

Project EoL-Cycle

Mechanical Separation and Sieving

Large particles (glass)



900 kg

Batch Test (1,2 t)
“Sorte 1”

Volatile fraction / plastics

95 kg

Fines <1 mm

255 kg

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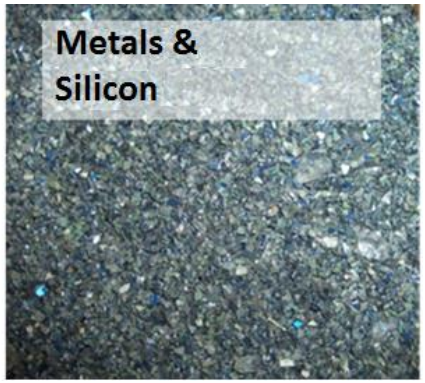
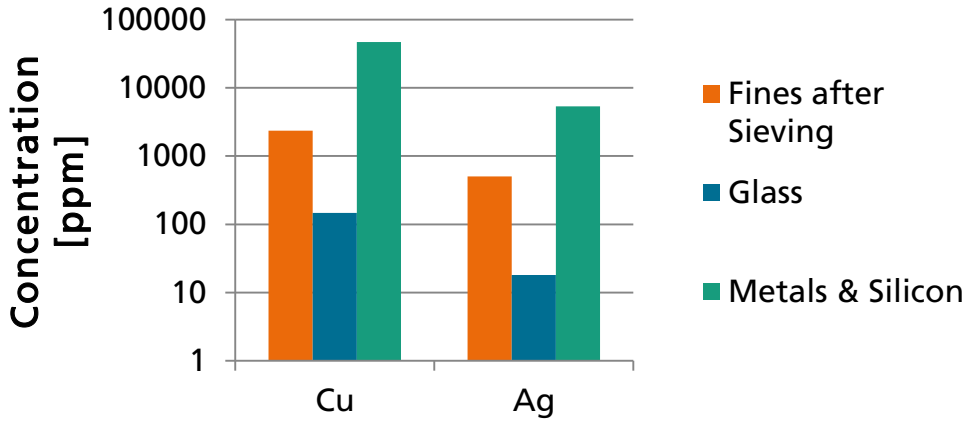
Project EoL-Cycle
Recycling of Fines (< 1 mm)



	Cu [ppm]	Ag [ppm]
Fines after Sieving	2368	502
Glass	147	18
Metals & Silicon	46930	5340



Determination of content done by RFA

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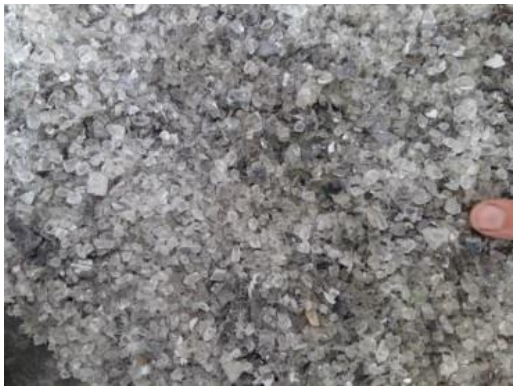
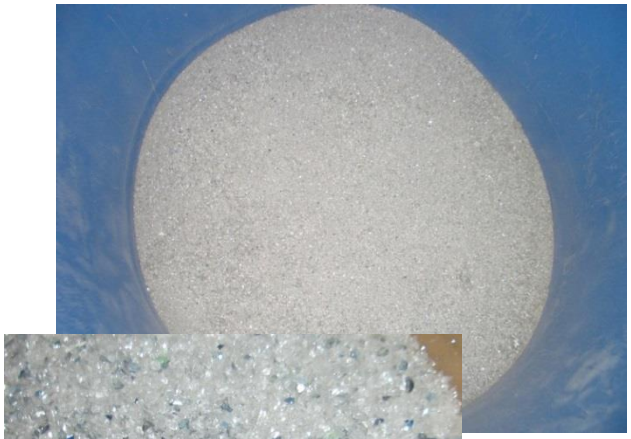
Project EoL-Cycle
Accumulation of Silver



Starting material (Sorte1):
100 ppm Ag

Metals and silicon are accumulated in the fine fraction!



Fines after sieving:
500 ppm Ag

Fines after separation:
5.000 ppm Ag

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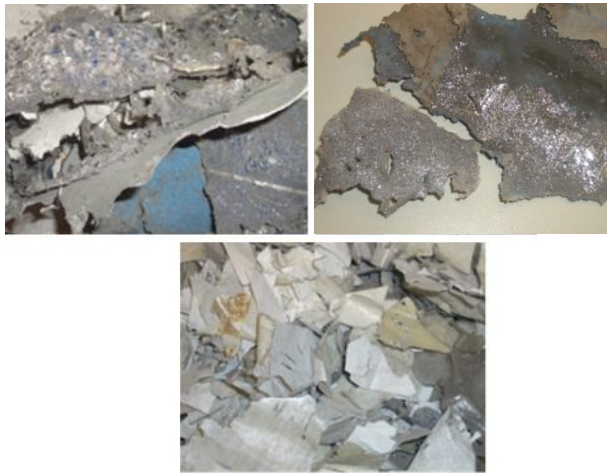
New Recycling Strategy
Recovery of Silicon

Starting material cell and foil fraction („Sorte 2“)



Sorting in glass containing, glass free and pure plastic components

Recovered silicon

- Mechanical and chemical separation of plastics and silicon.
- Proof of concept was successful, but process still under development (economics, automation).

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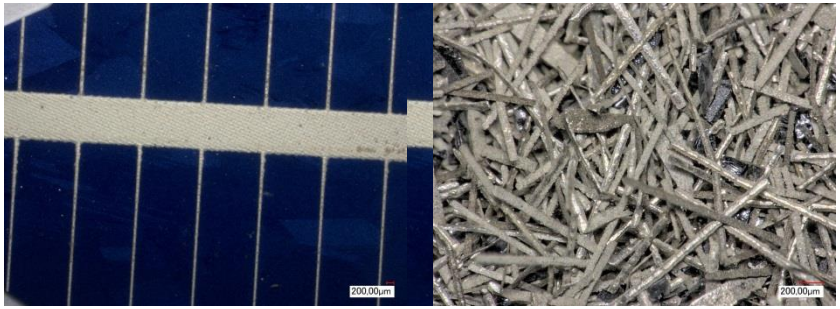
Project EoL-Cycle
Chemically Recycling of Copper

Busbars after tin removal

Remolten copper

- Removal of tin from busbars
- Removal of back contacts
- Separation of the metals from silicon
- Recovery of silver



Separation of silver (front contacts)

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Si-PV
The Value Cycle

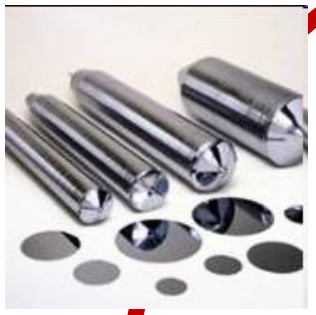
wafering

cell

module manufacturing

system installation

recycling



crystallization

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Conclusion

- The strong increase in the amount of EoL modules in the next few years, forces the development of a resource-saving recycling process

- In the EoL-Cycle project, the following improvements to the existing recycling process have been achieved in the laboratory scale:

  - Increase of the glass quality by additional cleaning steps
  - Concentration of metals and production of silver and copper
  - Recovery of pure silicon

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