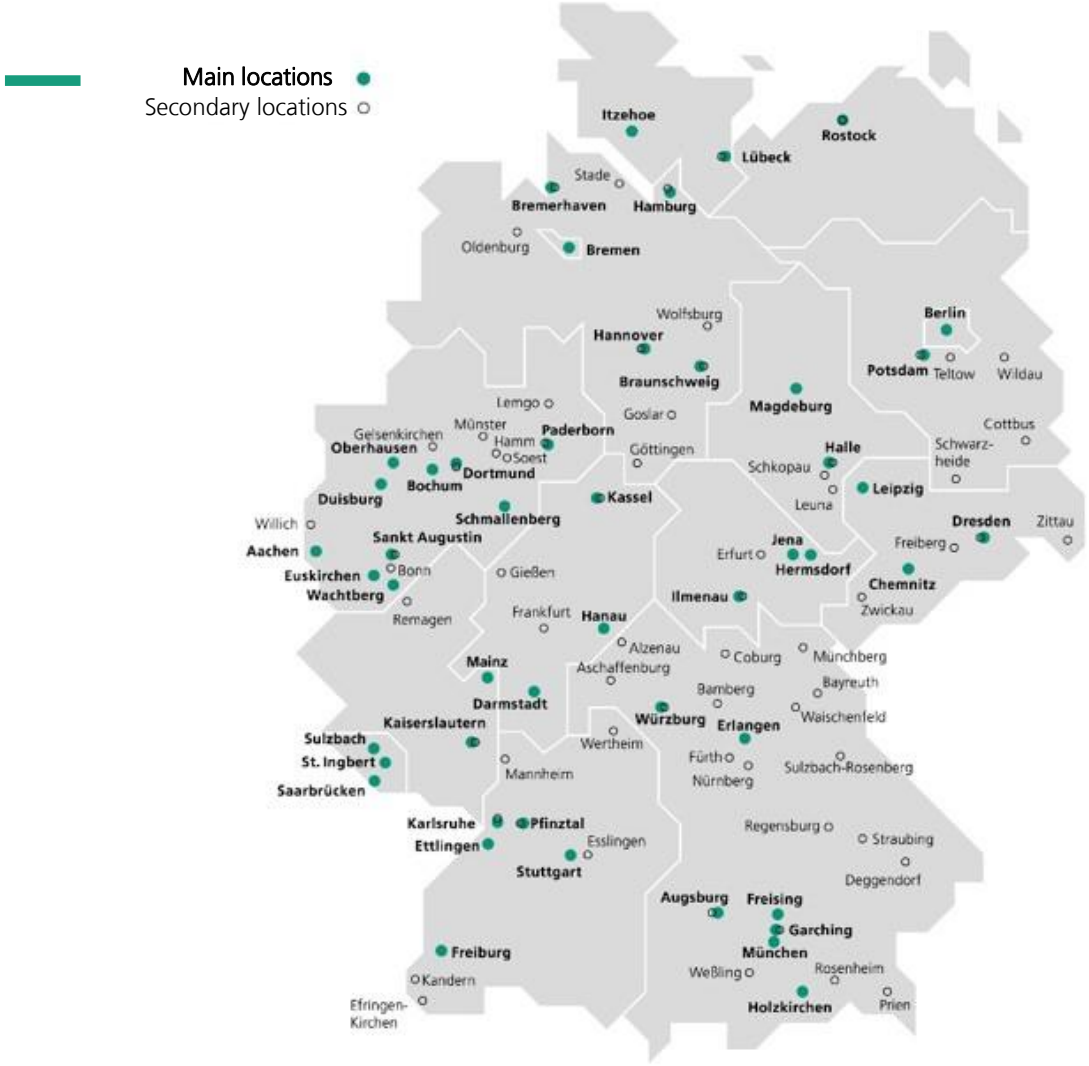
Von Altmodulen zu neuen Rohstoffen – Ein Überblick zu Photovoltaik-Recycling-Technologien und Verfahren

Peter Dold, Fraunhofer IWKS

Fraunhofer-Gesellschaft in Germany



Founded in 1949, the organization currently operates 74 institutes and research facilities in Germany.

Fraunhofer IWKS

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

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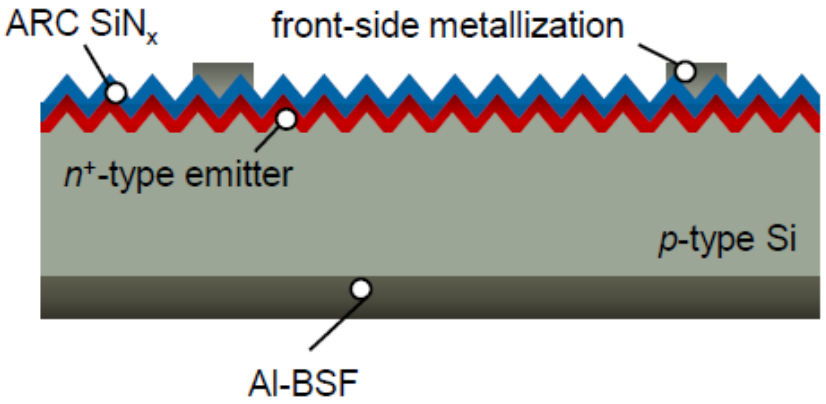
Solar Cells

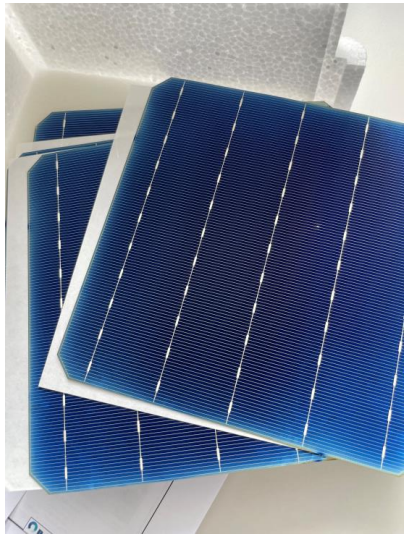
Technical Details: Cross-Section and Design

- Solar cell: 2D, planar diode with one pn-junction
  Radiation (sun-light) "mobilizes" electrical carriers and due to the pn-junction, they are separated and collected at the front / at the back.



Solar cells: Materials

Si	Ag	Cu
Pb	Sn	Al
Bi	Zn	



Thickness: 140-200 µm
Weight: approx. 10 g
Geometry: 156x156 mm
Power: ≥5 Watt

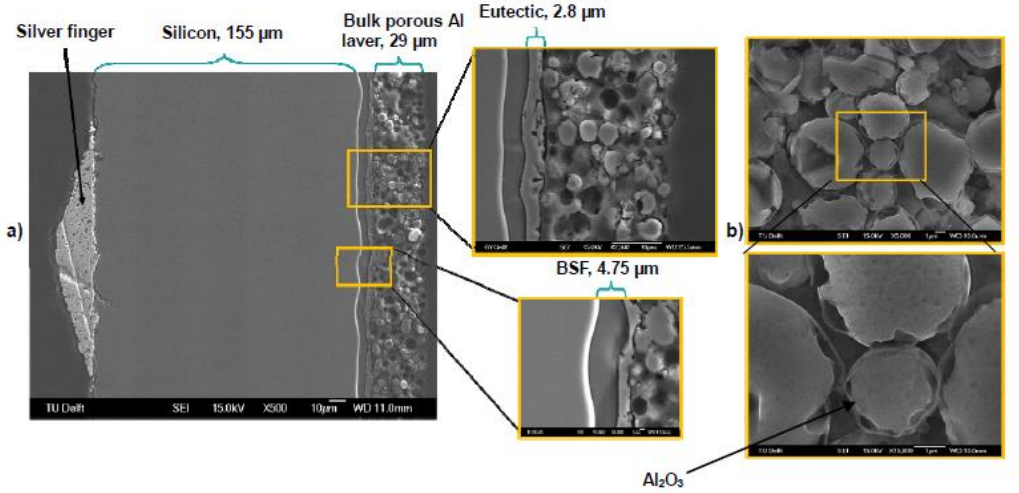
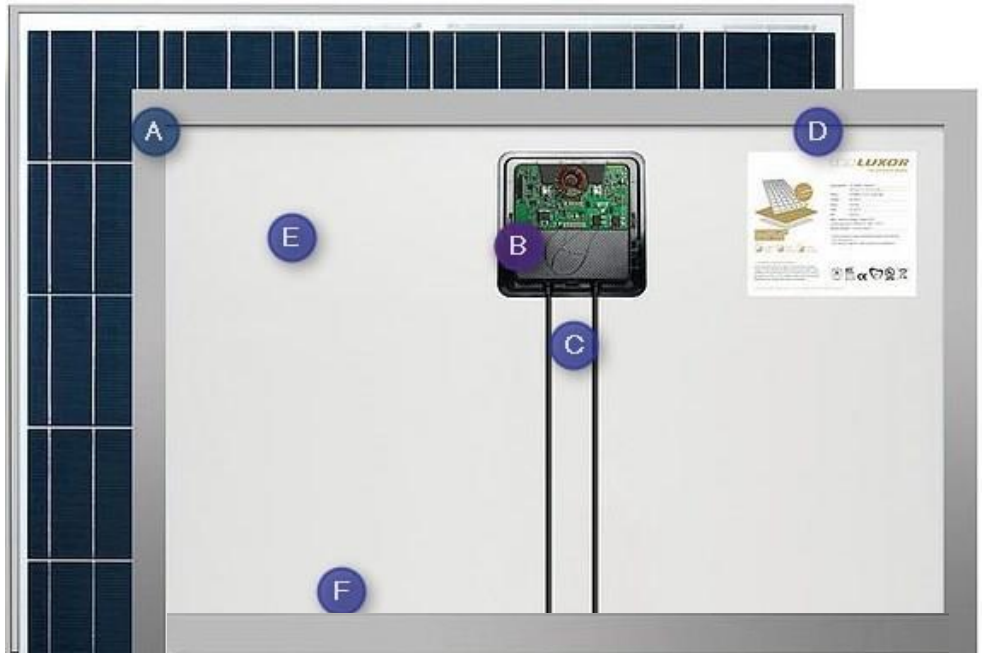
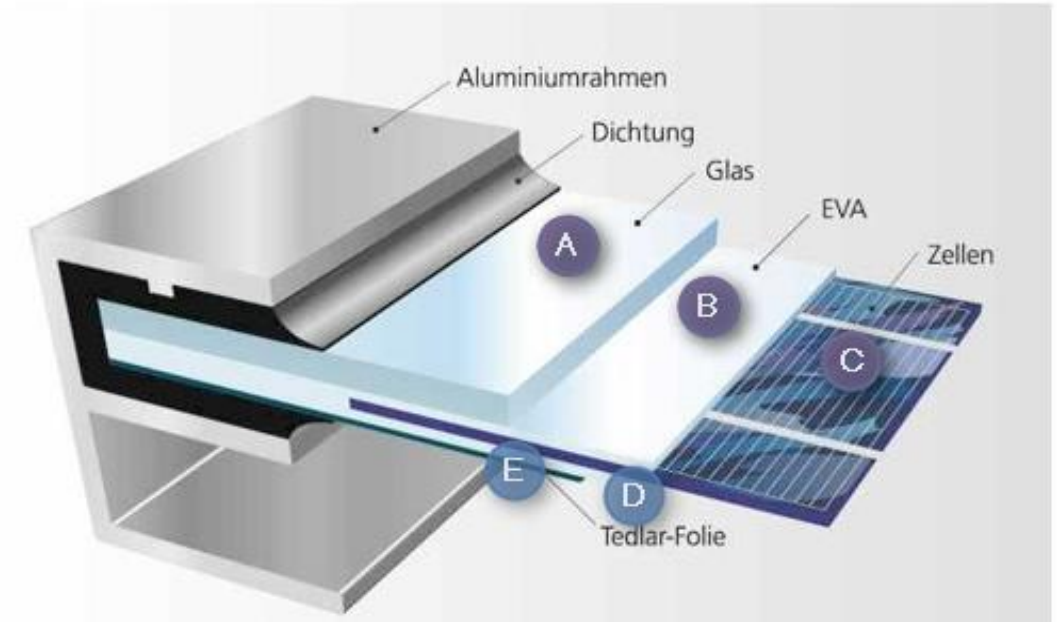


Figure 2. (a) SEM micrograph of a cross section of a conventional silicon solar cell (155 × 155 mm^2, 200 µm), comprising 5 distinct layers; (b) Microstructure of porous Al layer with Al-Si spherical particles, surrounded by a thin film of alumina (Al_2O_3).

Design of c-Si Modules



http://www.luxor-solar.de/root/img/pool/download/pressemitteilungen/lx_pr_eco_smart_line_box_web.jpg



http://www.renewable-energy-concepts.com/german/sonnenenergie/solaranlage-solartechnik/solarmodule-aufbau.html

Components

A) Frame
B) Junction Box
C) Cable
D) Manufacturer Lable
E) Laminate
F) Backrail

Laminate

A) Front glass
B) EVA-Foil
C) Solar cell
D) EVA-Foil
E) Tedlar Foil / rear-side glass

Materials:

Glass (≈70%)
Plastics (≈12%)
Alu (≈15%)
Solar cells (≈3%)

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Material Composition of PV Modules

Material Value

The material value of **one module** is approx. 10-15 €, if all the materials are recovered:

Aluminum:	4 € (≈1.5 €/kg)
Silver:	8.4 € (≈840 €/kg)
Silicon:	1 – 3 € (≈1.5 – 4 €/kg mg-Si)
Glass:	0.5 – 0.7 € (≈0,04 €/kg)

Roughly: 50 modules are 1 ton => 1 ton has a material value of 500 to 750 €; 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.

Legal Situation
Germany

Elektrogesetz

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

Installed PV Capacity over Time

Germany

Germany: 20 year feed-in-tariff

Modules older than 20 years: 2025 approx. 88.000 tons of End-of-Life modules in Germany expected => **corresponds to the amount seen on the recycling market.**

>20y old PV modules increase strongly from 2024 on.

Data of installed capacity: https://www.volker-quaschning.de/datserv/ren-Leistung-D/index.php

Data Watt / Module: from 2009 on: IT-RPV, before 2009: estimated.

Installed PV in Germany

>20y

Year	GW	Watt / M	Number	Weight / t
1999	0,01	185	43.243	865
2000	0,06	190	315.789	6.316
2001	0,12	195	615.385	12.308
2002	0,11	200	550.000	11.000
2003	0,12	205	585.366	11.707
2004	0,67	210	3.190.476	63.810
2005	0,95	215	4.418.605	88.372
2006	0,84	220	3.818.182	76.364
2007	1,27	225	5.644.444	112.889
2008	1,95	230	8.478.261	169.565
2009	4,4	235	18.723.404	374.468
2010	7,4	240	30.833.333	616.667
2011	7,5	245	30.612.245	612.245
2012	7,6	255	29.803.922	596.078
2013	3,3	265	12.452.830	249.057
2014	1,9	270	7.037.037	140.741
2015	1,5	275	5.454.545	109.091
2016	1,5	280	5.357.143	107.143
2017	1,8	285	6.315.789	126.316
2018	2,9	295	9.830.508	196.610
2019	3,75	300	12.500.000	250.000
2020	4,8	305	15.737.705	314.754
Summe	**54**		**212.318.214**	**4.246.364**

Material Composition of PV Modules

Dismantling of 22 tons of Modules at Fraunhofer CSP

Average Module Composition (based on 22 tons of EoL modules)

	[kg]	[%]
Module	**22,754**	**100**
Glass/Foils/Cells	19,327	85
Frame	3,037	13.3
Junction Box	216	0.9
Cabel	173	0.8
Screws	1	0.004

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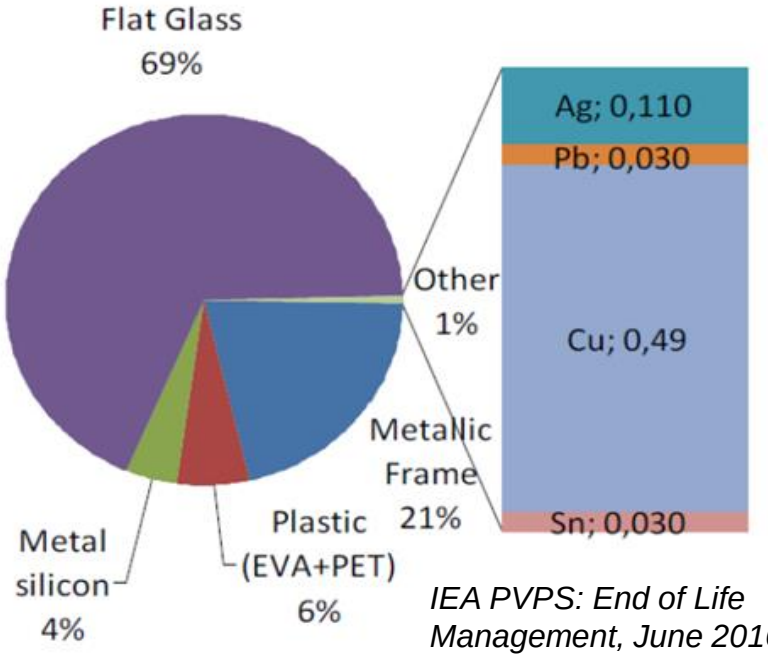
Glass/Foils/Cells	**85 [%]**
Glass	70
Cells	3.2
Foils	11.6



IEA PVPS: End of Life Management, June 2016

In general

1 t EoL-Modules	
125 - 200 kg	Aluminum
650 - 725 kg	Glass
25 - 35 kg	**Silicon**
60 - 110 kg	Plastics

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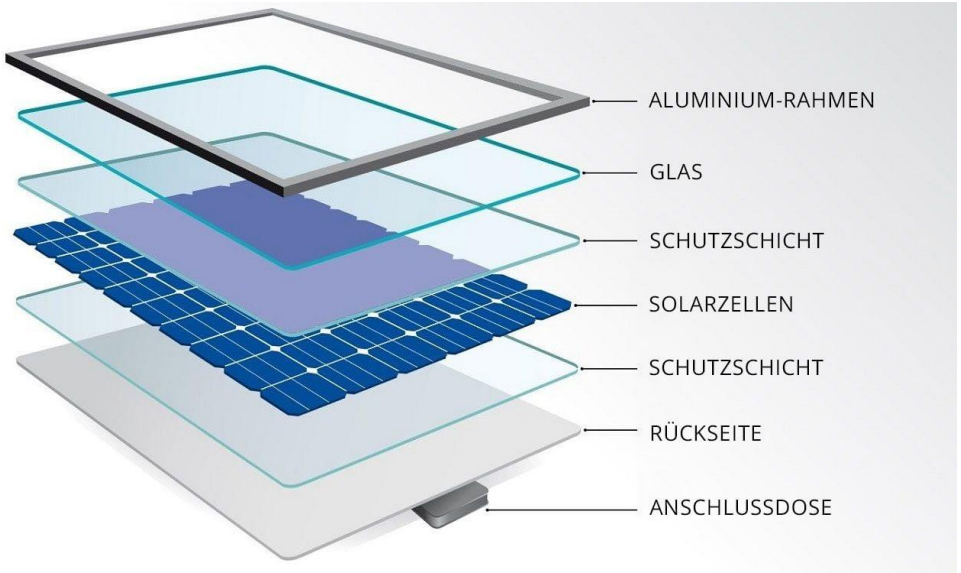
Recycling of PV Modules: Problems and Challenges

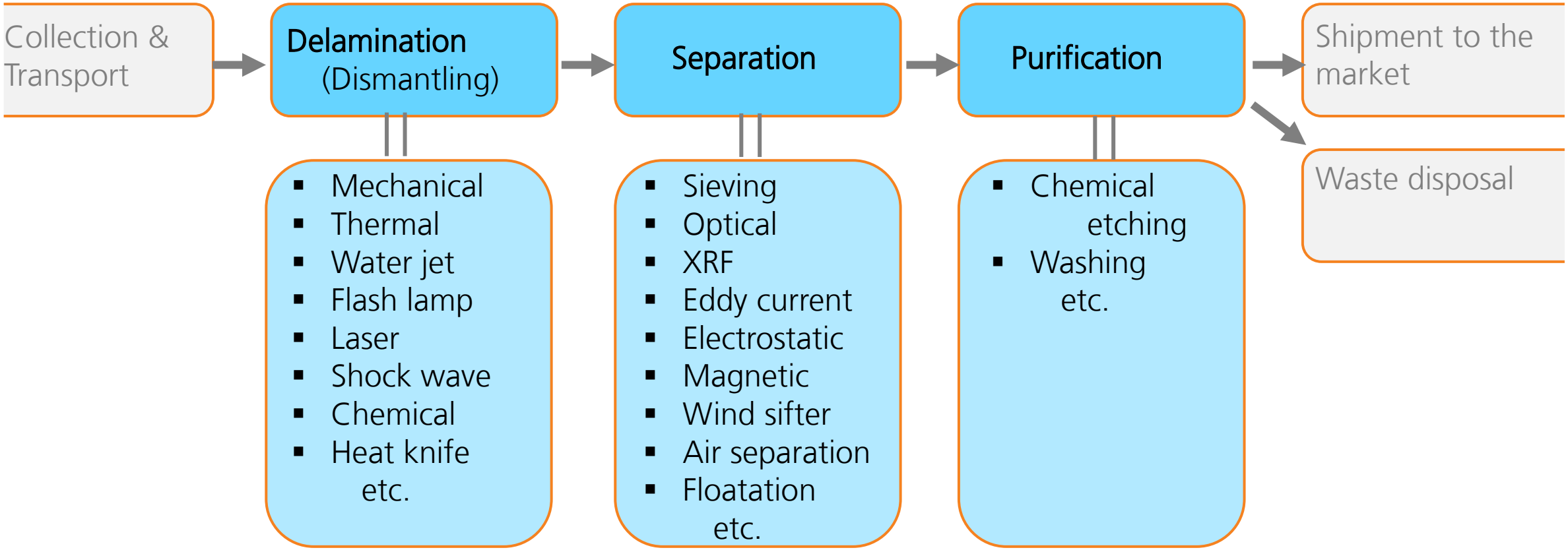


- Solar modules are build to withstand any weather conditions for at least 20 or 30 years!
- Solar cells are embedded between polymer-foils and covered with low-iron front glass
- Foil: due to lamination process, the structure changes and it can not be melted anymore
- Backside foil (e.g. Tedlar): contains fluoride, chemically inert

Globally spoken, the material value in total is very high –
but something like 10.000 t/y are required to form a good business case.

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?

Recycling of PV Modules

Actual Recycling Situation

Process:

Large scale

- In the moment, only mechanical shreddering is installed

Materials:

- **Aluminum**: completely recovered (“low hanging fruit”)
- **Glass**: partly recovered and send to alternative manufacturing industries, like insulation material, fibres, glass wool etc.; certain loss due to dust
- **Copper**: recycled
- All the rest (**silicon, silver, foils**): “ *thermal recycling* ” -> send to combustion plant (MVA)

Industrial Scale
Mechanical Shredder

Selective treatment of PV modules.

- Separation of cables, junction boxes and frames (Reiling GmbH).

Reiling Unternehmensgruppe

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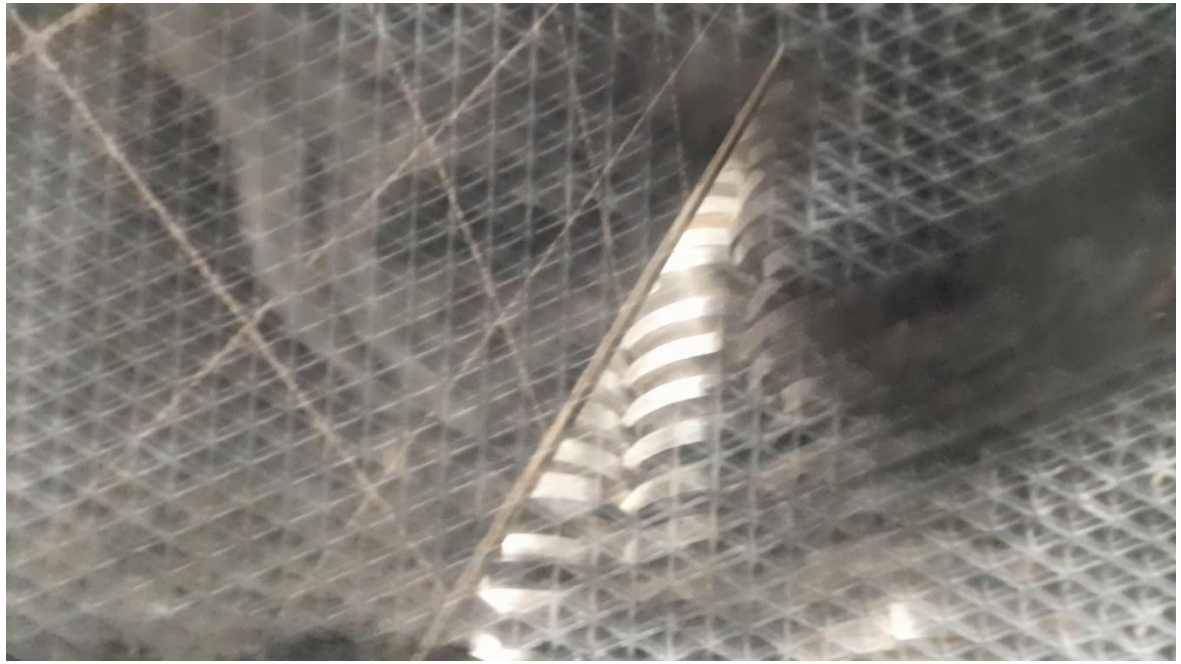
Industrial Scale
Mechanical Shredder

- Separation of glass, foils, cells etc. (Reiling GmbH).

Innovative Recycling Concepts @Fraunhofer IWKS and Fraunhofer CSP

4-Shaft Shredder



with frame

without

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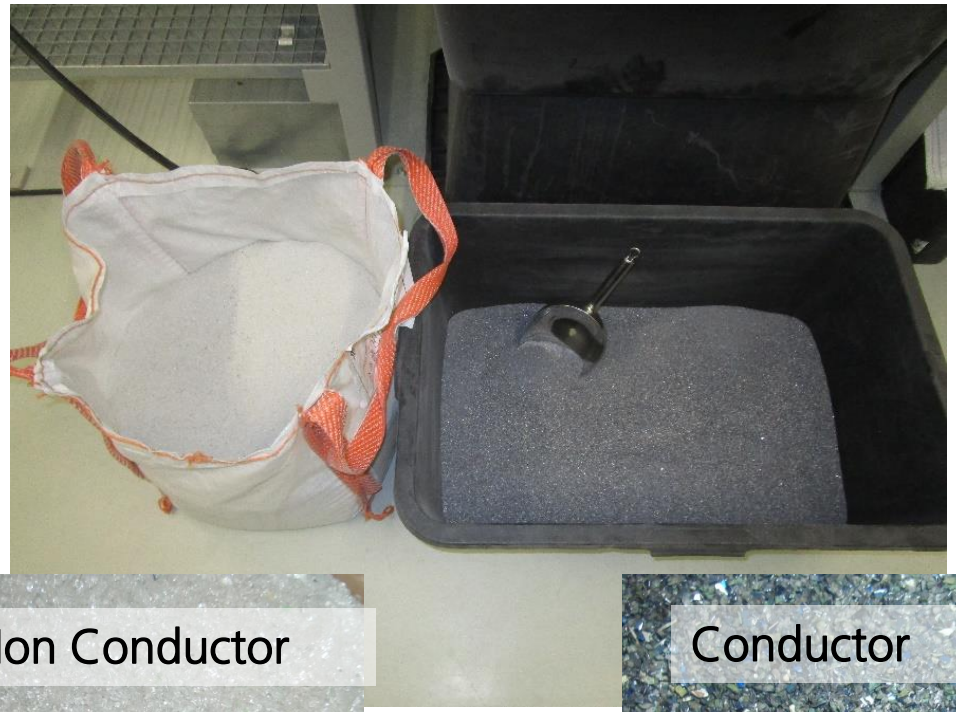
Innovative Recycling Concepts
Electrostatic Separation

Input



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

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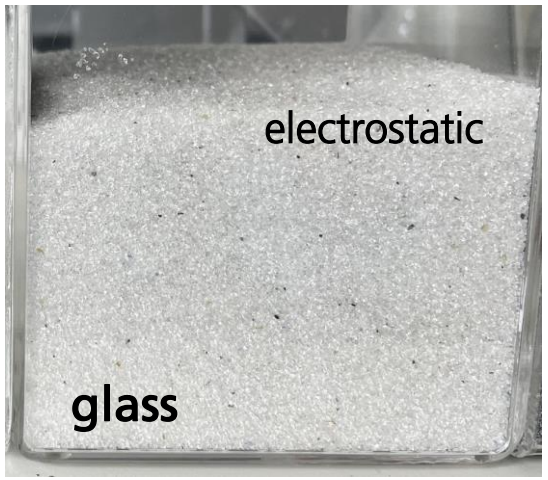
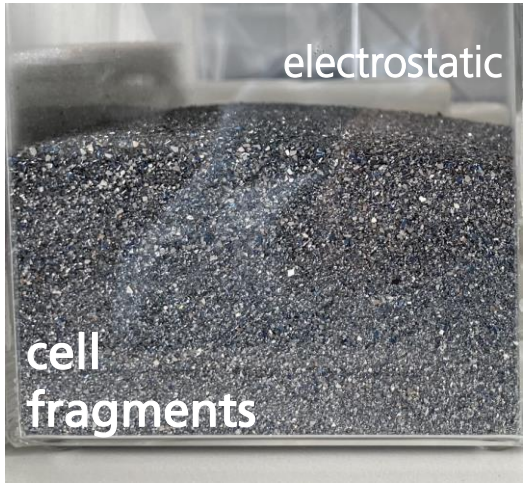
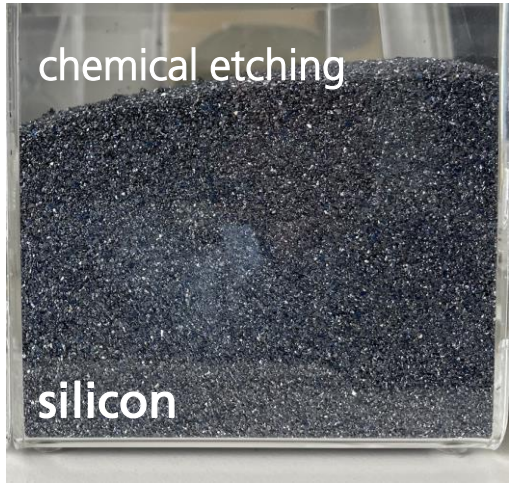
Recycling of PV Modules
Mechanical Delamination

- Separation and purifictaction of glass, foils, cells etc.



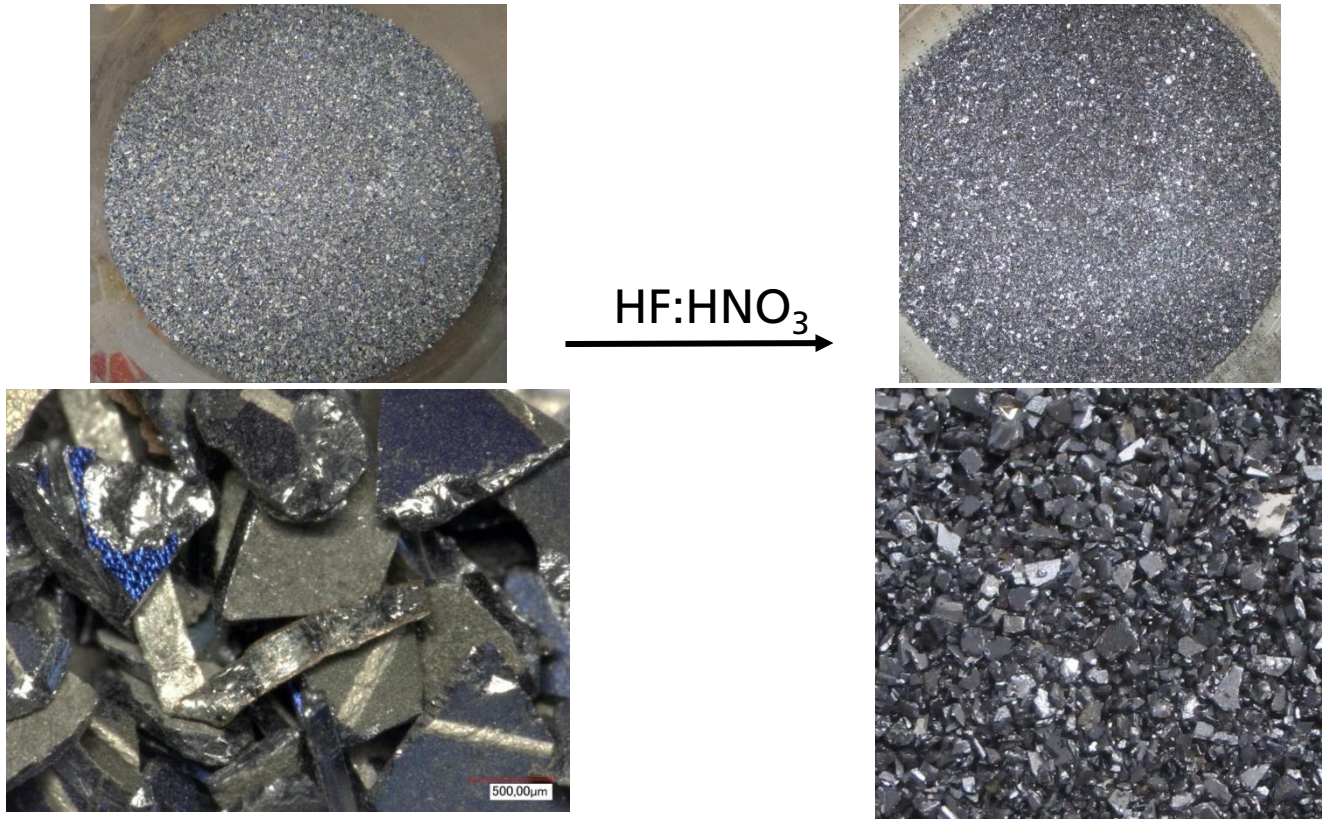




Innovative Recycling Concepts

Ingot Growth from 100% Recycling Silicon @Fraunhofer CSP

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



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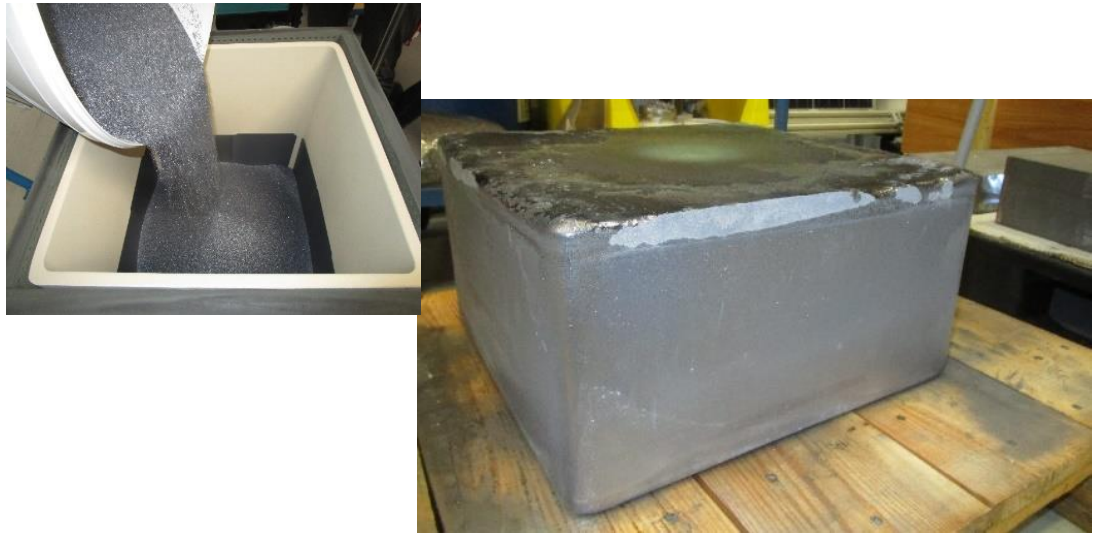
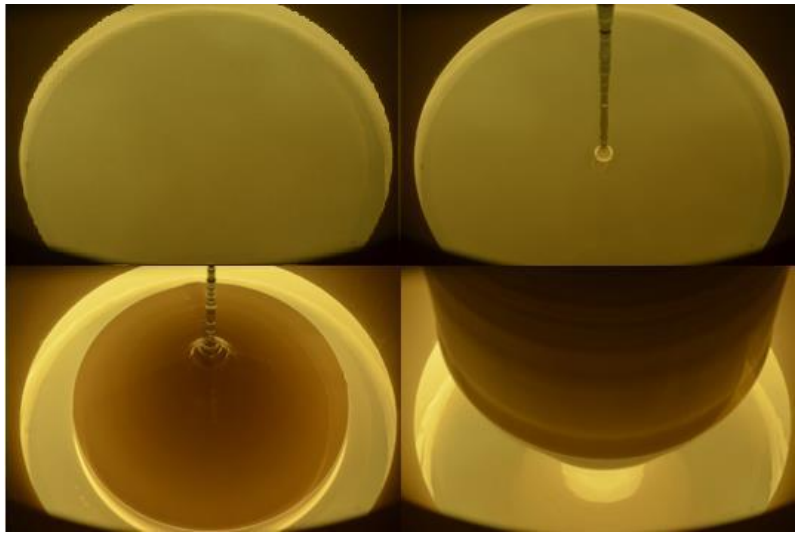
Innovative Recycling Concepts

Ingot Growth from 100% Recycling Silicon @Fraunhofer CSP



G2 brick, quasi-mono, 60 kg

- Growth of mono-like VGF bricks.
- Growth of mono ingots by the Czochralski method.



Czochralski-mono ingot from 100% SekuSil

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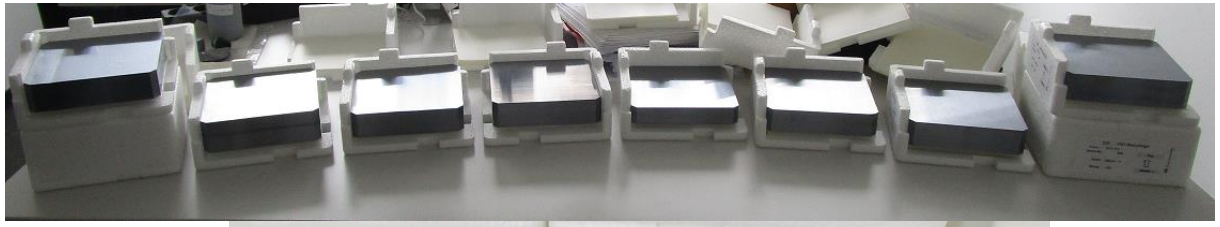
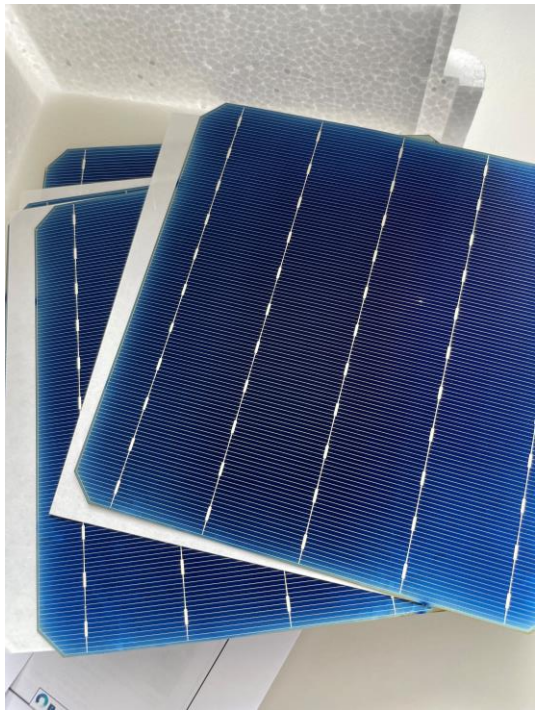
Innovative Recycling Concepts

Wafer and Cells from 100% Recycling Silicon @Fraunhofer CSP and ISE

Wafering process using diamond wire and Meyer-Burger multi-wire saw.





PERC-cells from 100% Recycling-Silicon: max. cell efficiency of 19.7% was reached in the first experiment.

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Innovative Recycling Concepts

Recycling von PV-Modulen @Fraunhofer

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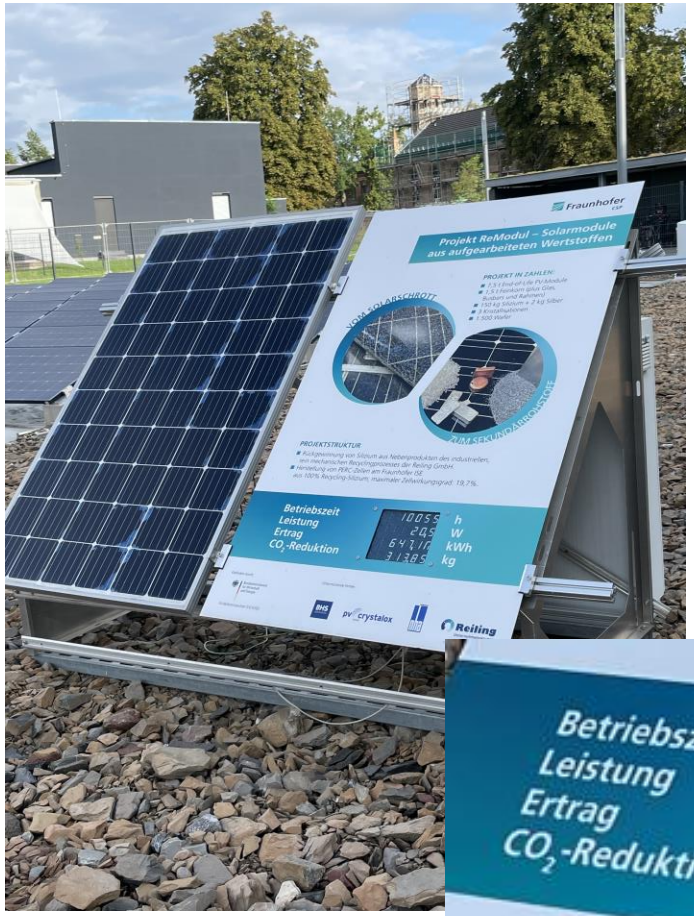

Demonstrator module
Running @CSP since 2022.

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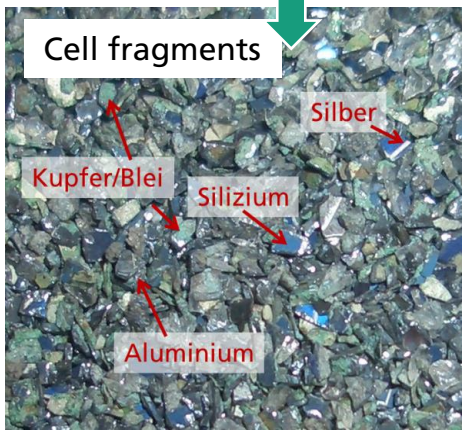
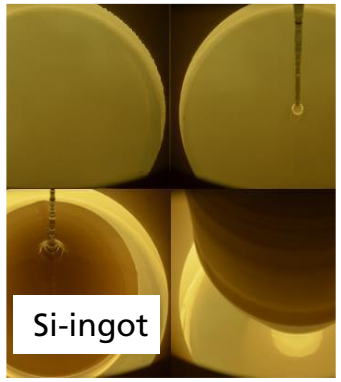
Innovative Recycling Concepts

2011-2025: Recycling von PV-Modulen @Fraunhofer





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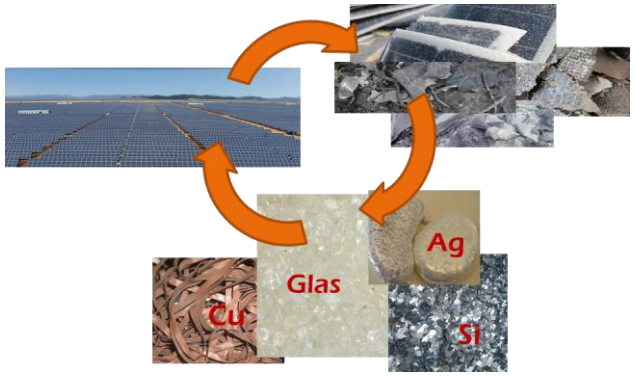
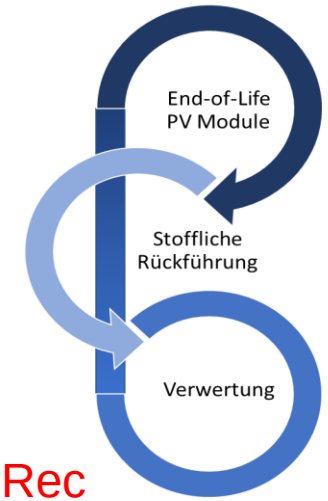
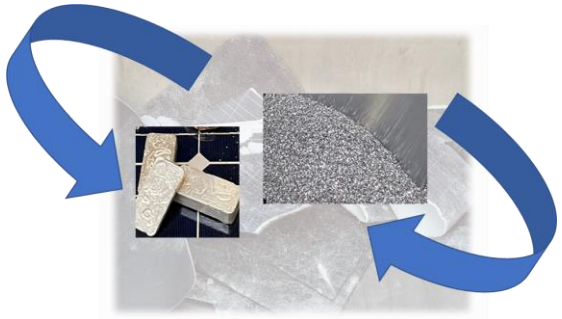
We Highly Acknowledge the Financial Support!



EoL-Cycle



Ko-Rec



SiSil

ReModul

Rescue, E², MetSeg, GeSiR etc.

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Thank you for your attention!