Research Project PVRe^2: Options to increase the sustainability of photovoltaic modules

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25.04.2023, Lebenszyklus und Recyclingstrategien für Produkte aus und mit Flachglas

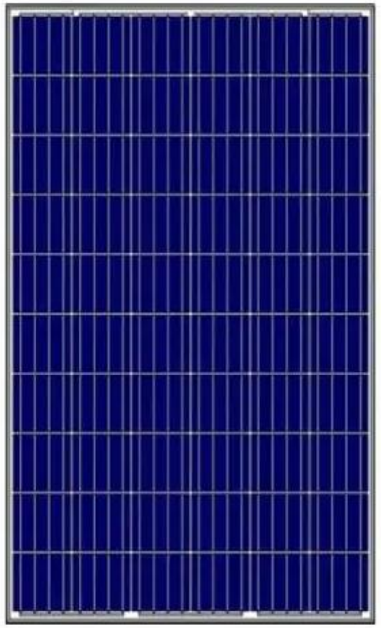
ENERGY RESEARCH 4TH CALL
TOPIC 5.5 PHOTOVOLTAICS

Photovoltaic Modules

Source: Wien Energie

- Several module technologies/types available on the market.
- PVRe² focuses on modules based on **crystalline silicon cells (c-Si)** as they have the highest market share.

c-Si (mono)

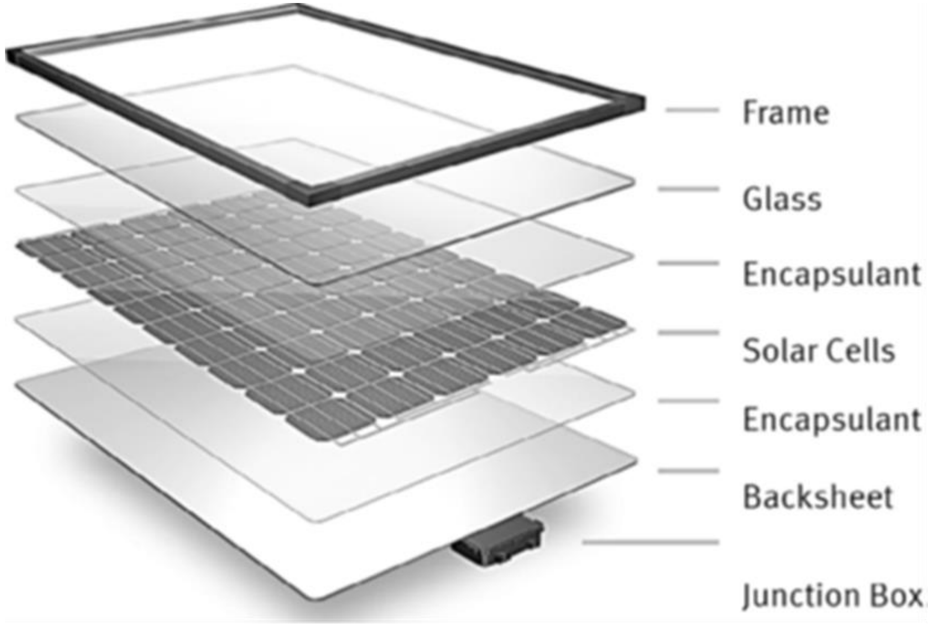


c-Si (multi)

Thin film

A closer look at c-Si PV modules

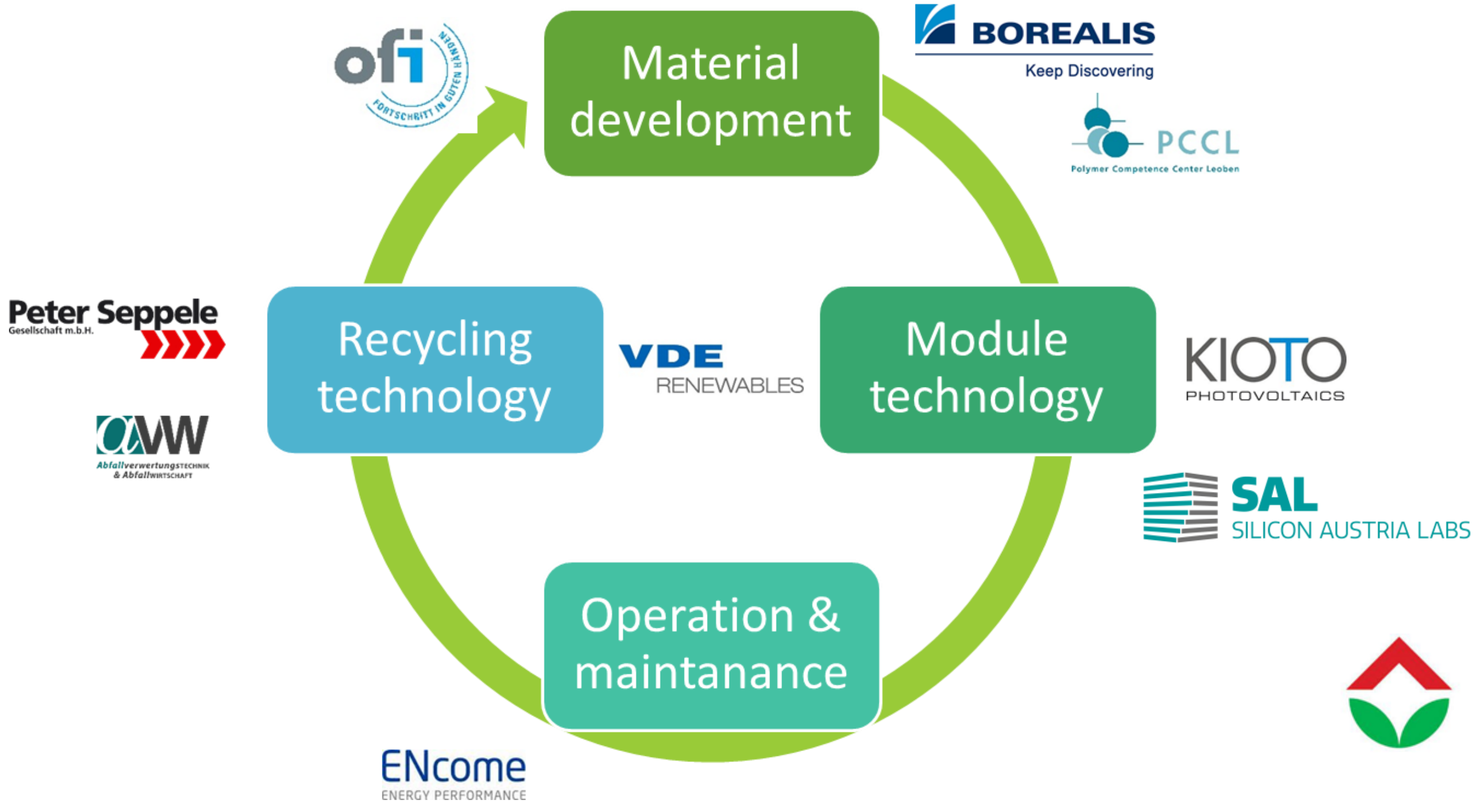
- Multi-material composite containing glass, polymers, semiconductors and metals.
- During PV module lamination the encapsulant melts and bonds all layers together.



Materials	Share [%]
Glass	70
Aluminium	15
Polymers	10
Silicon	3.5
Copper	0.50
Silver	0.07
Tin	0.05
Lead	0.05

PVRe² Project - Overview

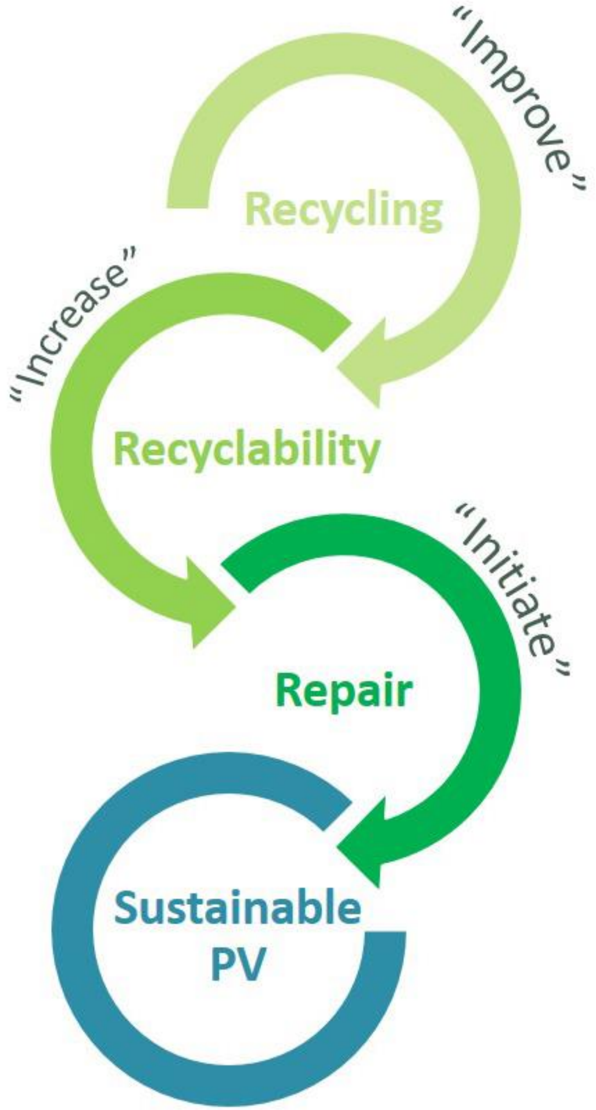
- Runtime: 3+ years (10/18 – 12/21)
- 9 partners covering the whole PV life cycle
- Funded by FFG (4. Ausschreibung – Energieforschung: Leitprojekte)



IBO as external partner for assessment tasks

PVRe² Project - Topics & Goals

- Recycling of PV Modules
- Sustainable PV Module Design
- PV Module Repair
- Environmental Impact & Economic Feasibility



WP2: Recycling of c-Si PV modules

- PV module waste
- State of the art recycling processes
- PVRe² solutions
- Outlook

Photovoltaic module waste in the EU (and Austria)

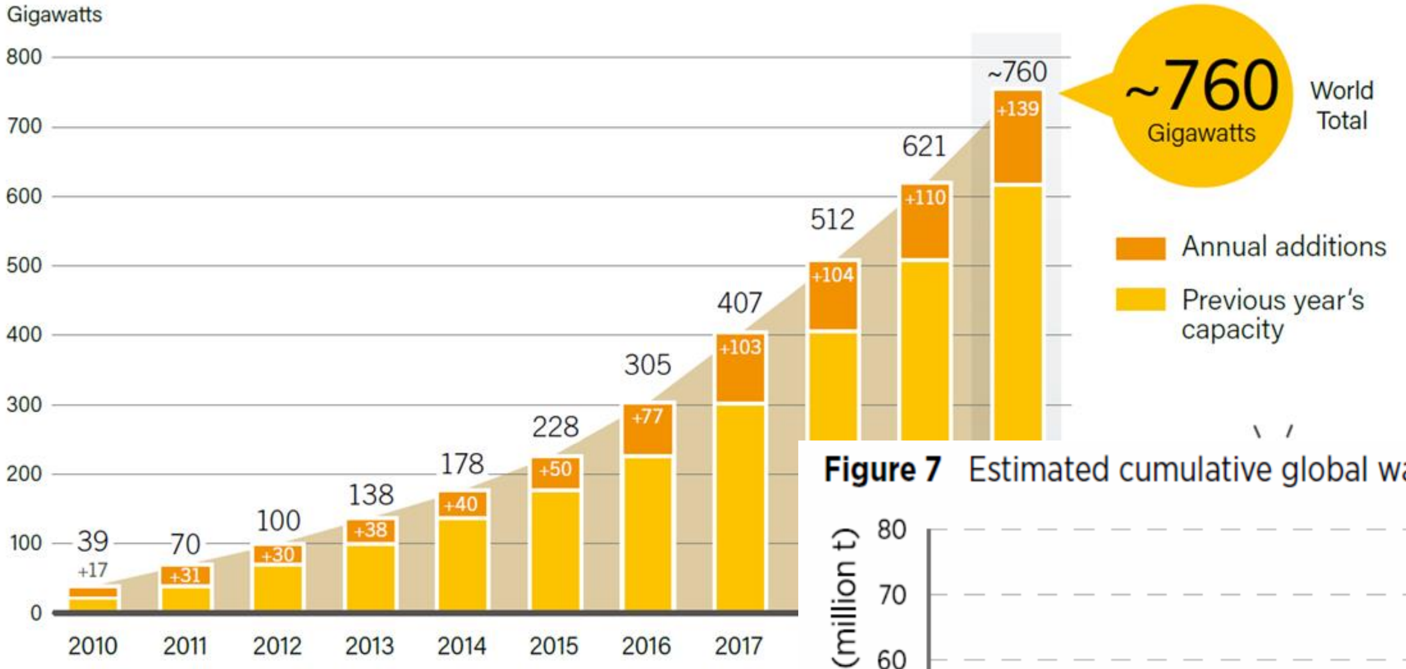
GEO \ TIME	2014	2015	2016	2017	2018
European Union - 27 countrie	:	:	: (z)	: (z)	: (z)
Belgium	:	:	242	117	168
Bulgaria	:	:	:	:	:
Czechia	:	39	129	7	16
Denmark	:	2	3	5	6
Germany (until 1990 former t	:	:	2,032	3,595	7,865
Estonia	:	:	:	:	:
Ireland	:	:	:	:	:
Greece	:	:	70 (d)	:	0
Spain	:	:	27	155	462
France	:	366	223	1,885	1,555
Croatia	:	:	:	:	:
Italy	:	:	:	:	1,350
Cyprus	:	0	0	:	:
Latvia	:	:	:	:	:
Lithuania	:	:	:	:	:
Luxembourg	:	:	:	:	0 (e)
Hungary	:	:	:	:	2,289
Malta	:	:	0	0	:
Netherlands	:	0 (d)	100	90	131
Austria	:	:	12	22	8
Poland	:	:	:	:	:
Portugal	:	:	:	0	:
Romania	:	0	0	0	0
Slovenia	:	:	:	:	:
Slovakia	:	:	0	0	14

Official numbers (collection) for Austria:

- 2015: no value
- 2016: 12t
- 2017: 22t
- 2018: 8t
- 2019: 3t
- 2020: 12t

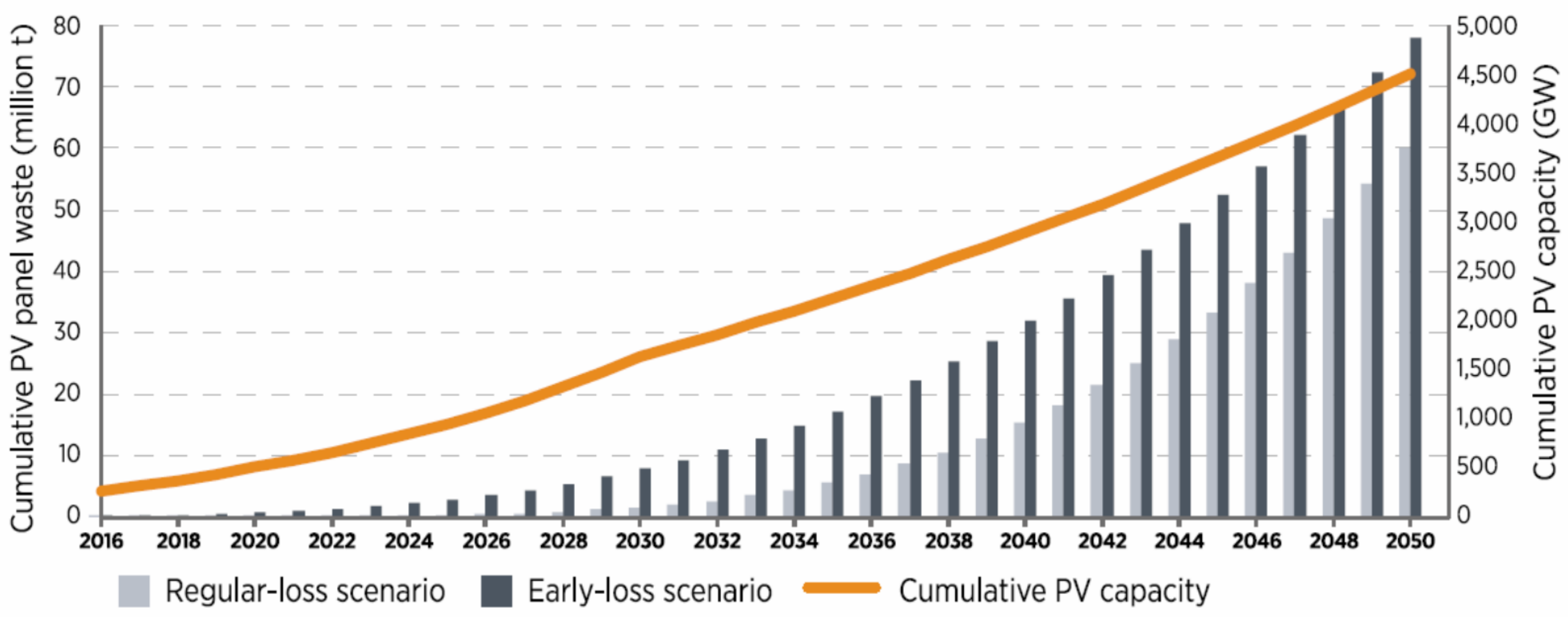
Real number is definitely higher - discrepancy due to current disposal practises and missing waste code (Schlüsselnummer).

Are proper EoL solutions even relevant?



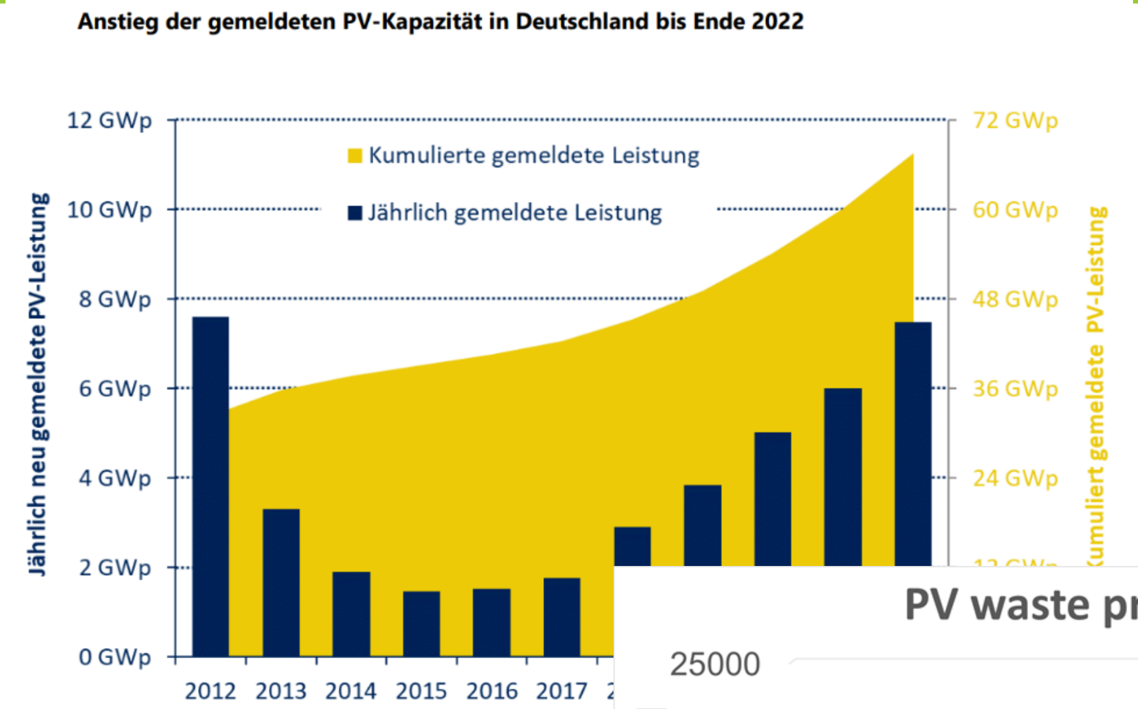
Source: REN21 – Renewables 2021 Global Status Report

Figure 7 Estimated cumulative global waste volumes (million t) of end-of-life PV panels

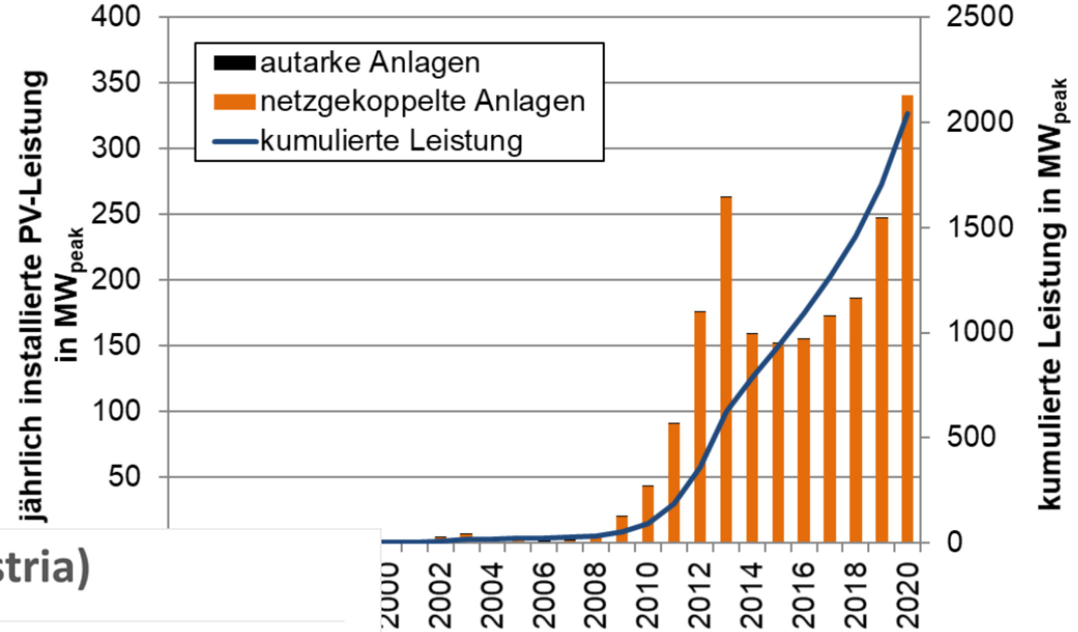


Source: IRENA & IEA-PVPS (2016) – End-of-Life Management Solar Photovoltaics Panels

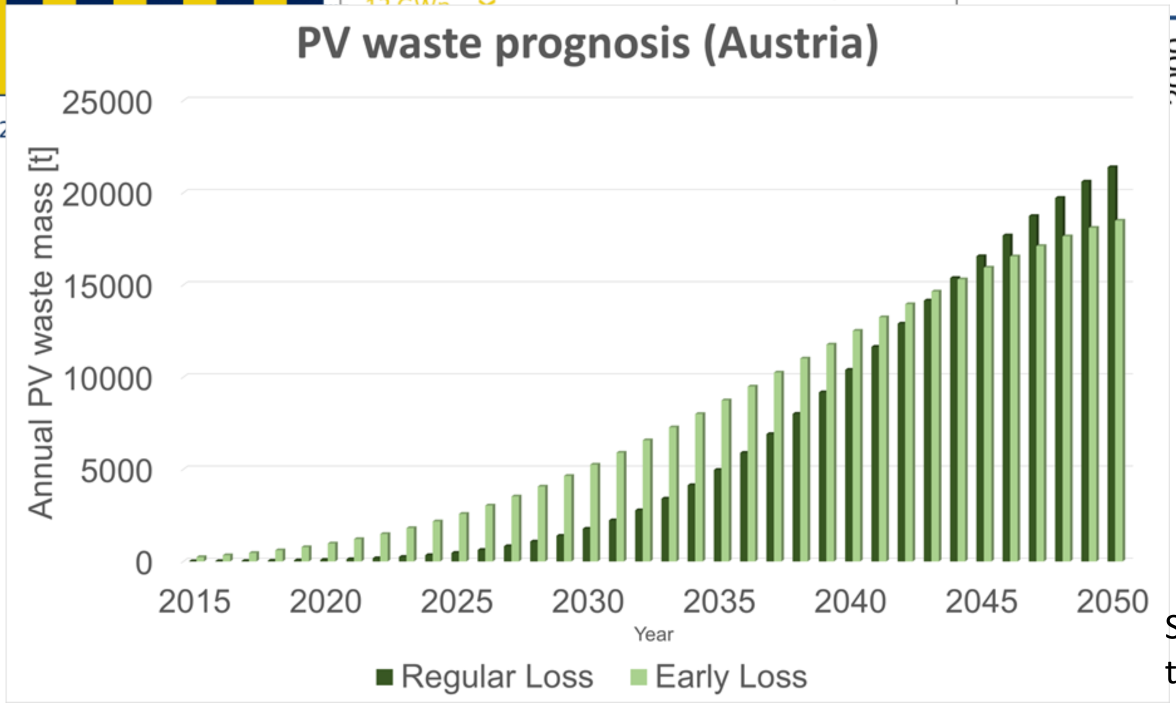
Situation in Germany/Austria



Source:
www.erneuerbareenergien.de

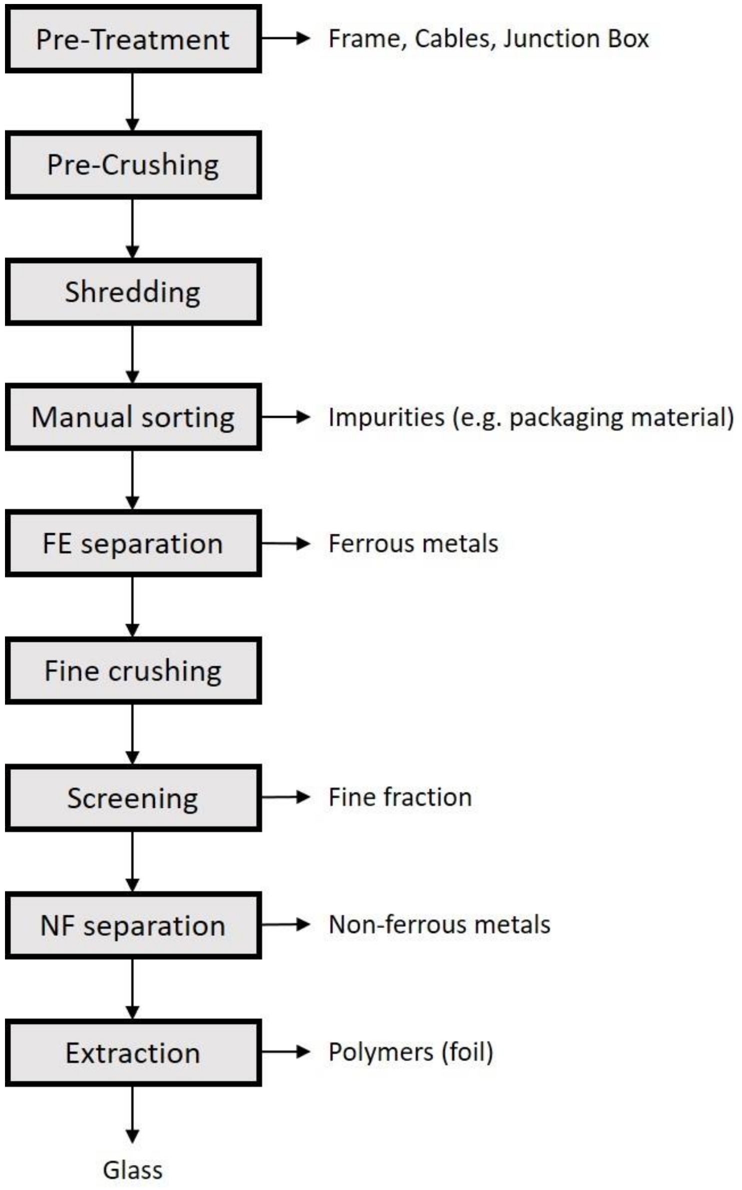


Source: Biermayr et al. – Innovative Energietechnologien in Österreich Marktentwicklung 2020



Source: Dobra et al. – Innovative Energie-technologien in Österreich Marktentwicklung 2020

State of the Art Recycling (in Europe)



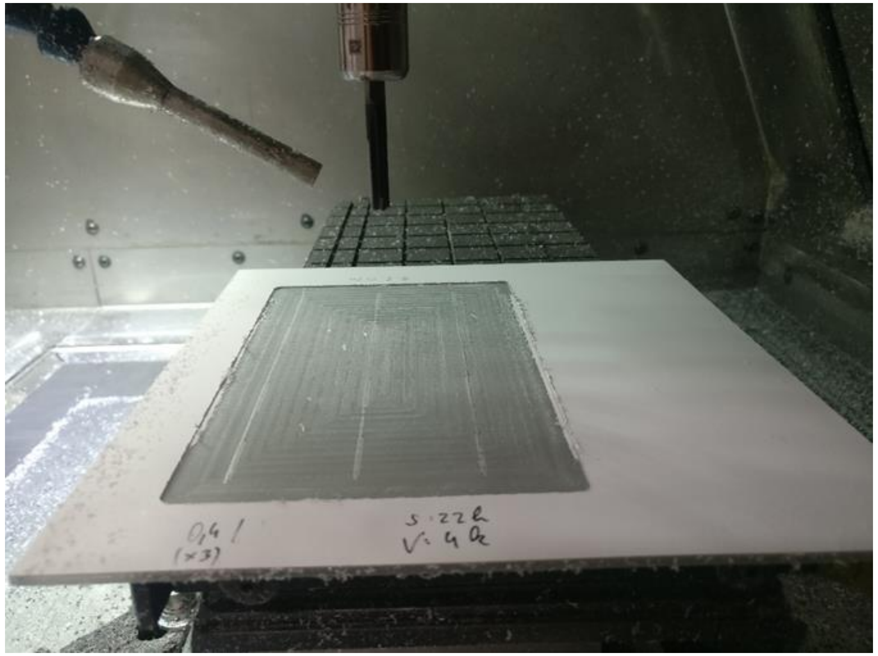
Flat glass recycling

+ Simple and cheap process
+ Proven technology
+ Treatment regardless of EoL condition (damages)
+ Fulfilment of legal requirements

- Downcycling of glass
- No recovery of Si, Ag
- Capacities of co-treatment limited

PVRe² approach: Selective mechanical delamination

Removal of layers from the module structure by machining processes such as milling, grinding, sawing, etc.:



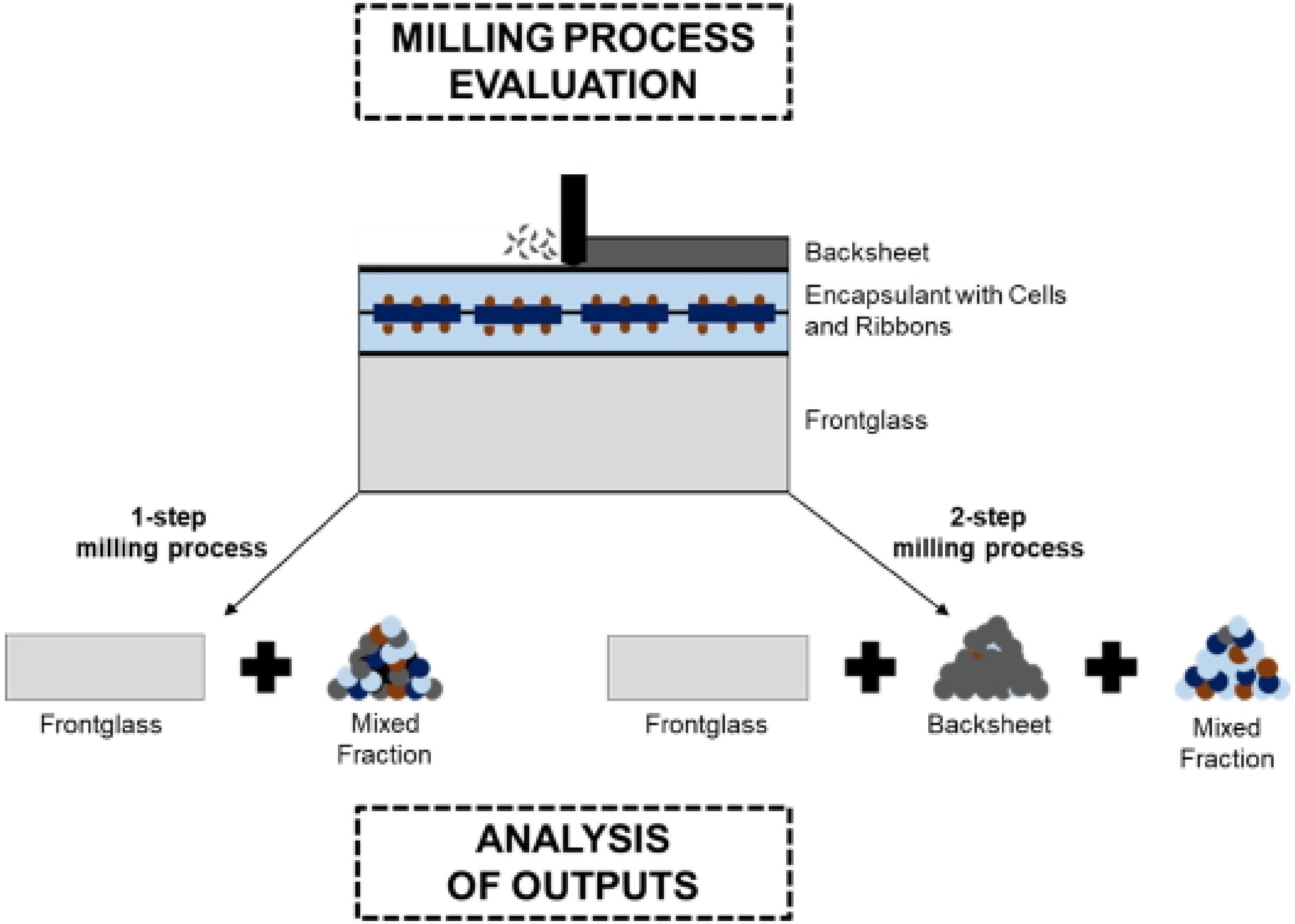
Advantages:

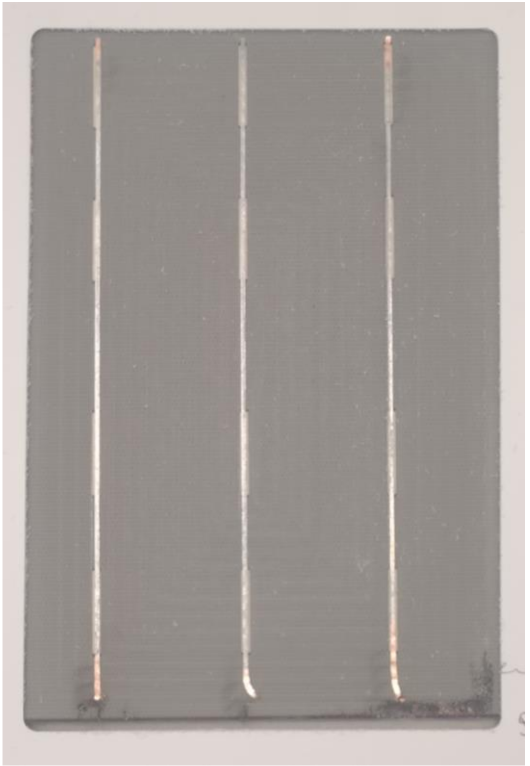
- Singular layer removal possible in principle
  → very high accuracy
- Negligible wear of equipment (if glass is not touched)
- Upscaling possible

Open questions/problematic aspects:

- Layer thickness measurement necessary
- Uneven layer distribution leading to no clean area/depth of separation
- Broken glass?

PVRe² approach: Selective mechanical delamination





More information in Dobra T., Thajer F., Wiesinger G., Vollprecht D., Pomberger R.:
Selective delamination by milling as a first step in the recycling of photovoltaic modules.
Environmental Technology (htpps://doi.org/10.1080/09593330.2022.2061380)

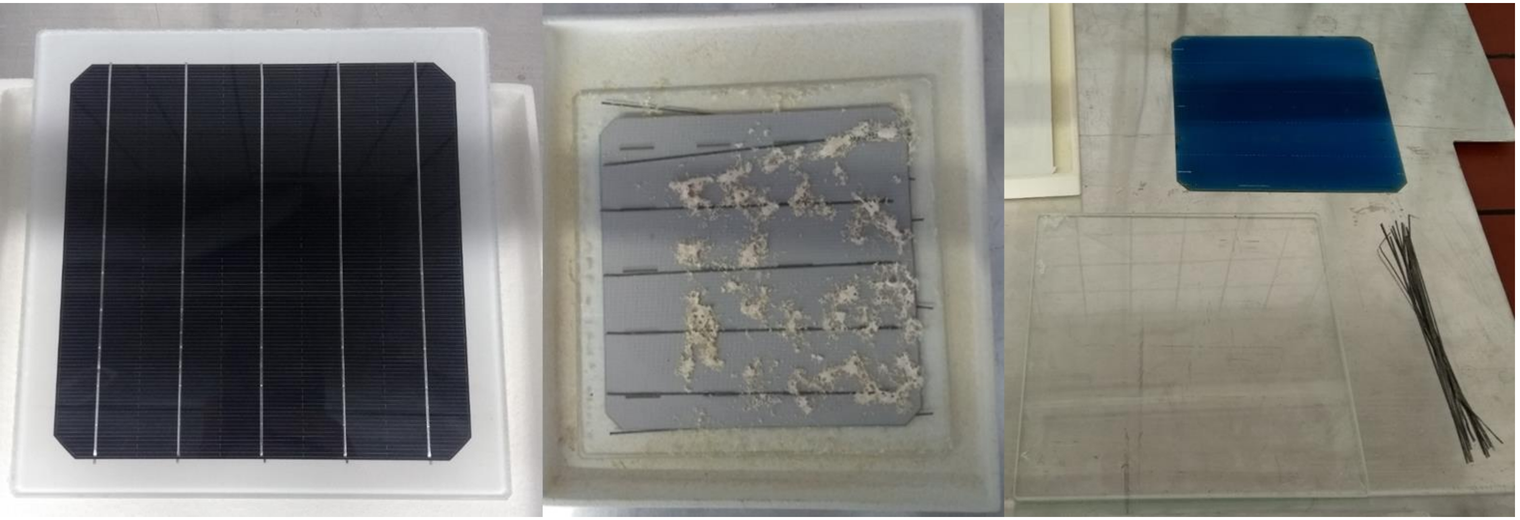
PVRe² approach: Thermal delamination

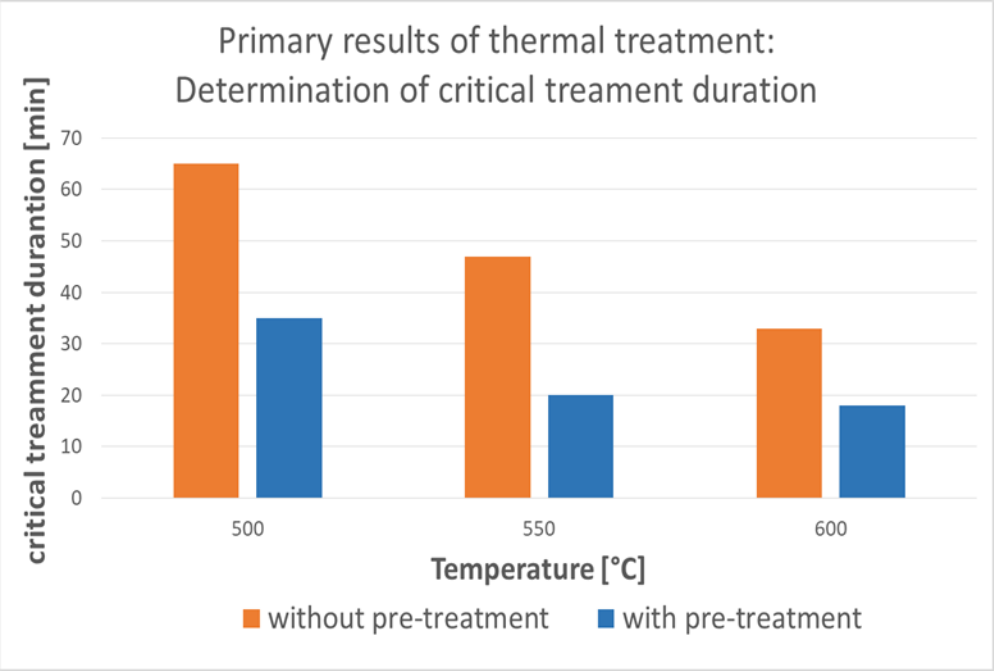
Removal of polymers from the module structure by increased temperature:

- Identification of correlation between treatment temperature and time
- Chemical analysis of solid outputs
- Flues gas discussion
- Mechanical pre-treatment

More information in Dobra T., Vollprecht D., Pomberger R.: *Thermal delamination of end-of-life crystalline silicon photovoltaic modules*. WM & R (https://doi.org/10.1177/0734242X211038184)

PVRe² approach: Thermal delamination



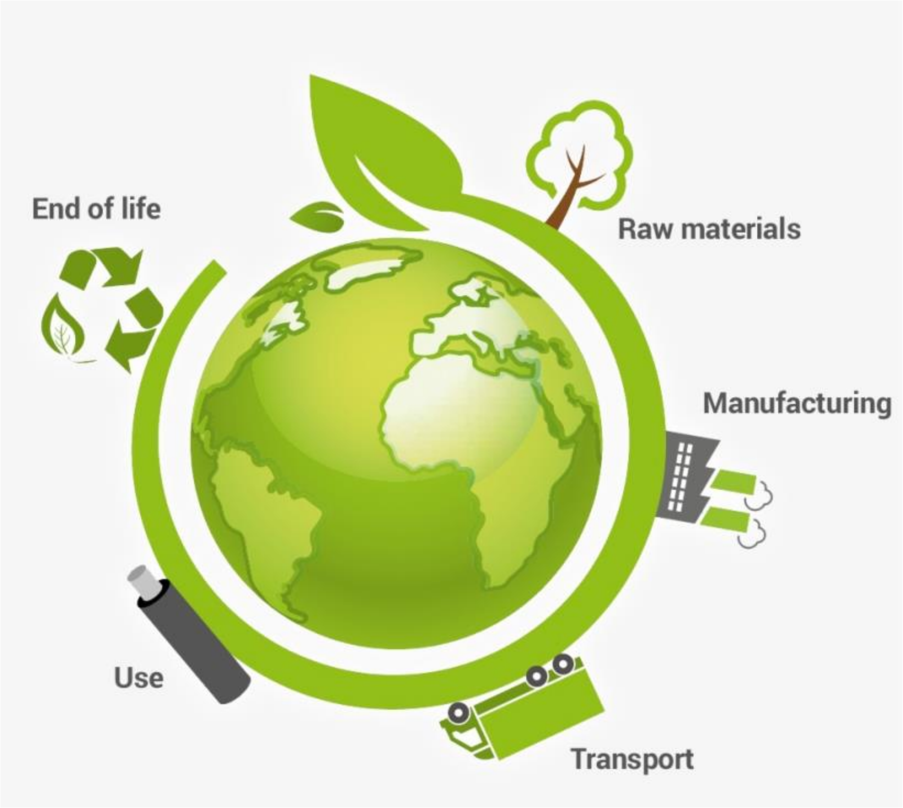


Outlook EoL Management/Recycling

- Substantial increase in waste amounts is expected in the upcoming years
- Research in regard to optimal delamination technology still ongoing
  - Collection of reliable data to enables holistic assessment/comparison
  - Selective mechanical delamination seems feasible from an economic and ecological standpoint
- Other EoL aspects - such as ReUse – might become more relevant

WP3: Sustainable PV Module Design

- Current limitation
- PVRe² solutions & assessment
- EoL Phase (Recyclability)
- Outlook



Module Structure (SotA for c-Si)

PVRe²

Front sheet

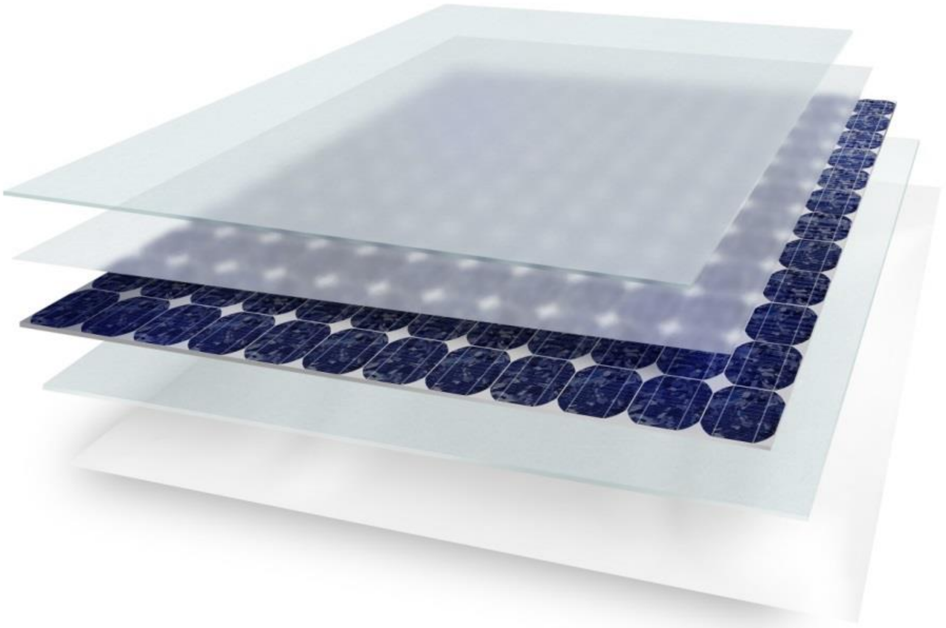
- *Low iron glass*

Solar cell encapsulant

- *Peroxide crosslinked Ethylene Vinyl Acetate (EVA)*

Crystalline silicon solar cells

- *Including silver grid and busbars on the front and metallization on the back*



Aluminum Frame

Cell interconnection

- *Flat copper ribbons coated with SnPb solders*

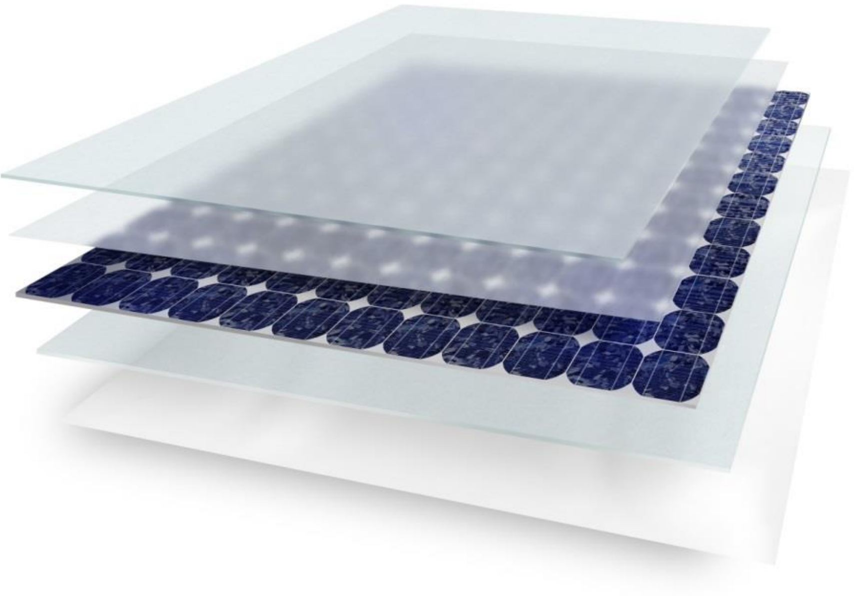
Junction box

Backsheet

- *Laminates consisting of PET and fluoropolymers (PVF, PVDF)*

Problematic Aspects (excerpt)

- **High Sb content of solar glass**
  - *Not usable in float glass recycling or for the production of glass beads for retroreflective coatings*
- **Difficult separation of chemically crosslinked EVA encapsulant from other module materials**
  - *EVA does not melt or dissolve, thermal and chemical separation methods do not have big impact*



- **Standard PV backsheets are not recyclable**
  - *Difficult separation of each layer*
  - *No recycling processes for fluoropolymers available*
- **Shredding of PV modules leads to contamination of certain materials by sawdust**
  - *Only downcycling of otherwise valuable components like solar glass due to metal contaminations*
- **Junction box**
  - *Removal of defunctive junction box often damages the backsheet*

How to make PV modules more environmentally friendly?

Considered module structures

- Changes especially for polymeric materials.
- (Most) components are commercially available, however compatibility between them is not always clear/needs to be assessed.

Module	std	eco1	eco2	eco-g
Front Glass	3.2 mm (with Sb)	3.2 mm (Sb-free)	2 mm (Sb-free)	2 mm (Sb-free)
Front Encapsulant	EVA	PE	PE	PE
Cell	standard	ROHS-certified	ROHS-certified	ROHS-certiefied
Inter-connection	Cu with SnPb	Cu with SnBi	Cu with SnBi	Cu with SnBi
Back Encapsulant	EVA	PE	combined back-sheet and encap-sulant (PE/PP)	PE
Backlayer	TPT backsheet	PP backsheet		2 mm glass

Quantitative Assessment

PVRe²

- Final results were calculated in the form of [impact/kWh] by relating the **Life Cycle Impacts** of a module to its **Lifetime Energy Production** (LEP).

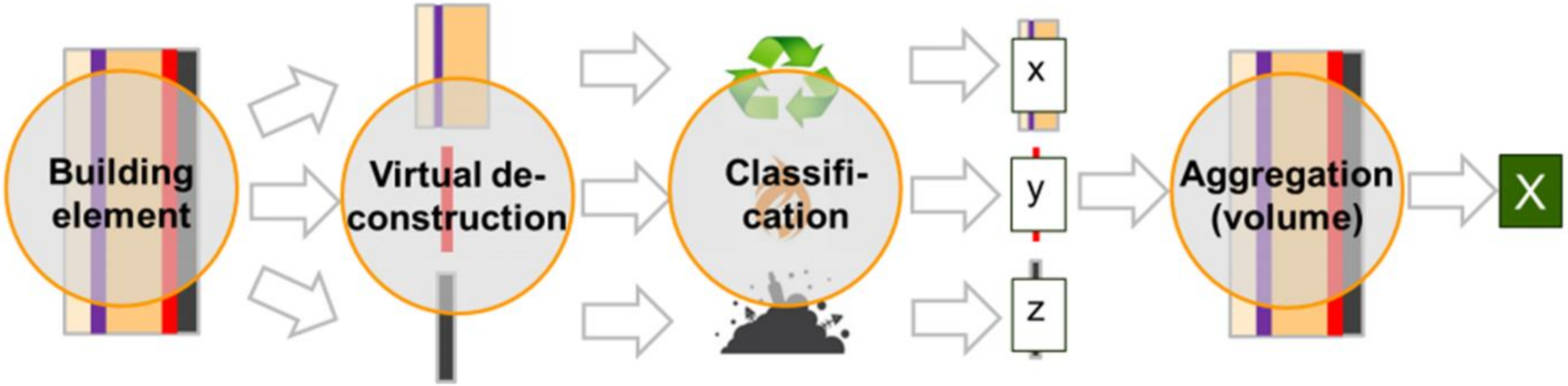
Module Type	LCI [kg CO_2-eq.]	P. [Wp]	RE [kWh/(kWp*a)]	t [a]	d [%]	**GWP [g CO_2-eq./kWh]**
std	230	300	1,000	25	0.5	**32.71**
eco1	227	300	1,000	30	0.4	**26.83**
eco2	220	300	1,000	30	0.4	**26.00**
eco-g	230	300	1,000	30	0.35	**26.97**

Reduction of 6 – 7 g CO_2/kWh

- Improved environmental performance is mainly caused by the enhanced use phase parameters (longer lifetime, lower degradation). Changes in LCI because of the alternate materials used during the production phase only make up a small amount of the benefits (max. 21 % for eco2).

Qualitative Assessment of End of Life Phase

Approach for building materials



H. Figl et. al: *A new Evaluation Method for the End-of-life Phase of Buildings*;
DOI: 10.1088/1755-1315/225/1/012024. Project funded by BMI/BBSR (Zukunft Bau)

Deconstruction:

- Current practice (real) and future scenarios (potential) as basis for classification
- Can also be evaluated/rated as a separate factor

Classification:

- For each fraction according to available technologies and material characteristics
- Differentiation between real/current situation & potential/future situation

Aggregation:

- Based either on volume or mass

Evaluation of separability (deconstruction)

PVRe²

Legend
Current situation for N.I.C.E modules
Future situation for standard modules
Current situation for standard modules

Class	Separability
A++	No compound, very easy to separate non-destructively, suitable for re-use
A+	Separable with minor damage (pure materials, largely non-destructive)
A	Pure materials, destructive separation
B	Not separable by material type/ usually not separated by material type

	std	eco1	eco2	eco-g
B	yes	yes	yes	yes
A[1]	yes	yes	yes	no
A+ (therm.)[2]	(yes)*	yes	yes	yes
A+ (chem.)[3]	no	yes⁺	yes⁺	yes⁺
A+ (new)[4]	yes	?	?	?

[1] Advanced mechanical (LuxChemTech, PVRe²)
[2] Thermal delamination (incineration, pyrolysis)
[3] Chemical delamination (solvent)
[4] New technologies, e.g. radiative (Flaxres)

Table refers to the laminate only

** Technically possible but questionable from an emission standpoint*

⁺ Investigation in regard to solubility still ongoing

Evaluation of recovery potential - Methodology

PVRe²

<table>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th></tr>
<tr><td>Reuse</td><td colspan="5">no preparation methods for reuse available</td></tr>
<tr><td colspan="4">Recycling</td><td colspan="2">no recycling</td></tr>
<tr><td rowspan="5">Closed loop (CL)</td><td>Recycling RC+ or CL with efforts</td><td>Recycling RC- or RC+ with efforts</td><td>Other utilisation or RC- with efforts</td><td colspan="2">no recycling procedure known or other utilisation with great efforts</td></tr>
<tr><td colspan="5">combustion</td></tr>
<tr><td rowspan="3">Derived fuels</td><td rowspan="3">Energy recovery +
(EV+)</td><td rowspan="3">Energy recovery -
(EV-)</td><td>Thermal (EB) disposal +</td><td>Thermal disposal -</td></tr>
<tr><td colspan="2">landfill</td></tr>
<tr><td>Landfill Class 0+I+II</td><td>Gypsum-Fibre-Organic</td></tr>
</table>

H. Figl et. al: *A new Evaluation Method for the End-of-life Phase of Buildings*; DOI: 10.1088/1755-1315/225/1/012024. Project funded by BMI/BBSR (Zukunft Bau)

Evaluation of recovery potential - Results

Current	std	eco1	eco2	eco-g
Frame	1 (CL)	1 (CL)	1 (CL)	1 (CL)
Cables	1 (CL)	1 (CL)	1 (CL)	1 (CL)
Glass	4 (AV)	4 (AV)	4 (AV)	4 (AV)
Ribbons	2 (RC+)	2 (RC+)	2 (RC+)	2 (RC+)
Cells*	5 (EB+)	4/5 (EV-/EB+)	4/5 (EV-/EB+)	4/5 (EV-/EB+)
Encapsulant*	5 (EB+)	4/5 (EV-/EB+)	4/5 (EV-/EB+)	4/5 (EV-/EB+)
Backsheet*	5 (EB+)	4/5 (EV-/EB+)	4/5 (EV-/EB+)	n.a.

Future	std	eco1	eco2	eco-g
Frame	1 (CL)	1 (CL)	1 (CL)	1 (CL)
Cables	1 (CL)	1 (CL)	1 (CL)	1 (CL)
Glass[1]	1/4 (CL/AV)	1/2 (CL/RC+)	1/2 (CL/RC+)	1/2 (CL/RC+)
Ribbons	2 (RC+)	2 (RC+)	2 (RC+)	2 (RC+)
Cells	3 (RC-)	3 (RC-)	3 (RC-)	3 (RC-)
Encapsulant[2]	3 (EV+)	2/3 (RC+/EV+)	2/3 (RC+/EV+)	2/3 (RC+/EV+)
Backsheet[3]	5 (EB+)	2/3 (RC+/EV+)	2/3 (RC+/EV+)	n.a.

* Thermal treatment of mixed fraction

- ✓ *Lower heating value > 11 MJ/kg*
- ✓ *Bulk density > 200 kg/m³*
- ✓ *Halogens 1 – 10 % (for standard)*
- ✓ *Mineral fraction > 15 % (for all)*

No significant advantages in current recycling system for ecodesigned modules.

[1] *Closed loop (PV glass) is indifferent to Sb-content but use for float glass is influenced.*

[2] *Recycling of PE/PP is SotA, although application to aged polymers is in question. EVA can't be recycled.*

[3] *Recycling of PE/PP is SotA, although application to aged polymers is in question. No recycling for fluoropolymers.*

Potential for higher recovery rates and improved secondary resource qualities when more specific recycling processes are established.

Outlook Module Design

- Ongoing evaluations to validate improved lifetime parameters.
- Economic feasibility (of ecodesign measures) needs to be proven for widespread implementation.
- Reduction of Life Cycle Impacts (during production) by technical and organizational measures should be focal point of future developments.
- Module lifetime is a key parameter in regard to sustainability and should also be of high priority → Projects aiming at 40 years module lifetime ongoing.

Research Project PVRe²:
Options to increase the sustainability of photovoltaic modules

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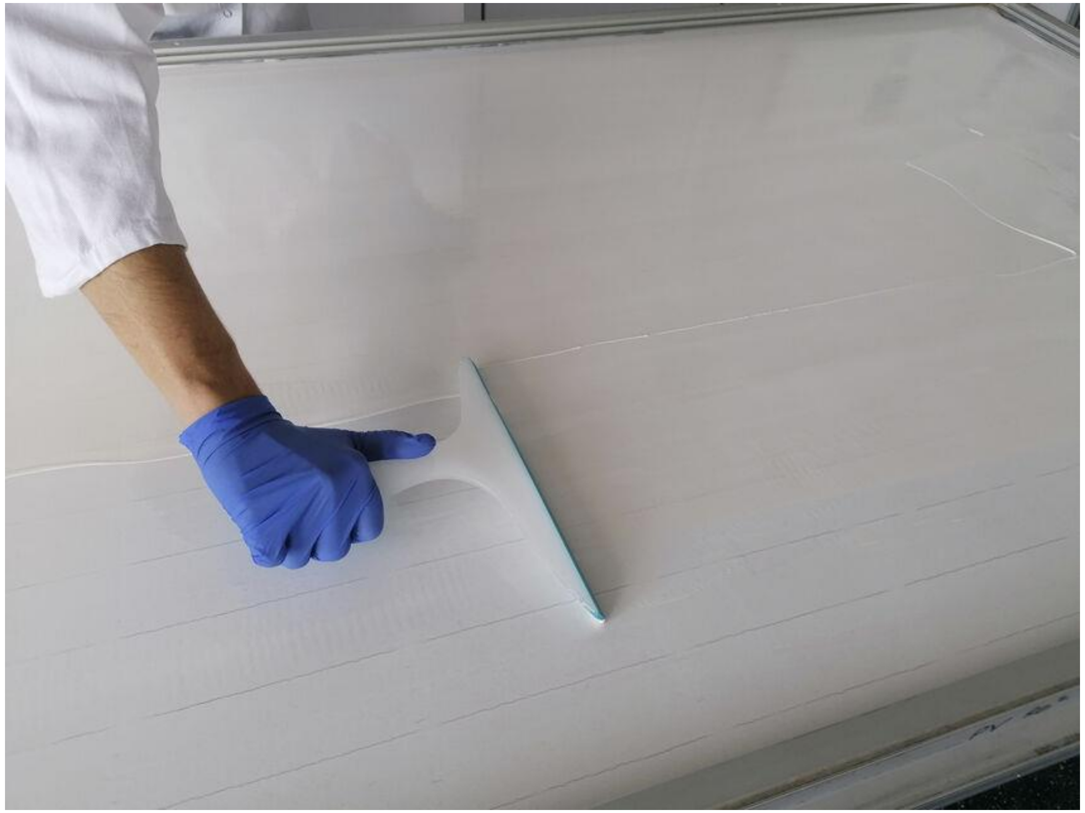
ENERGY RESEARCH 4TH CALL
TOPIC 5.5 PHOTOVOLTAICS

WP4: PV Module Repair

- Backsheet Cracking
- PVRe² solutions
- Assessment (ecological & economic)
- Outlook

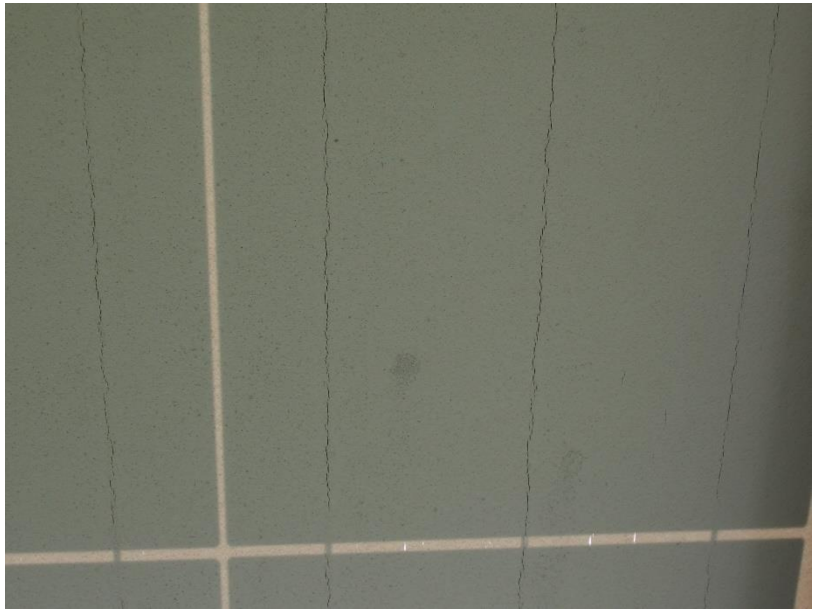


The problem

Failure mode: Backsheet Cracking

Can cause:

- accelerated degradation
- insulation failures
- shortened lifetime



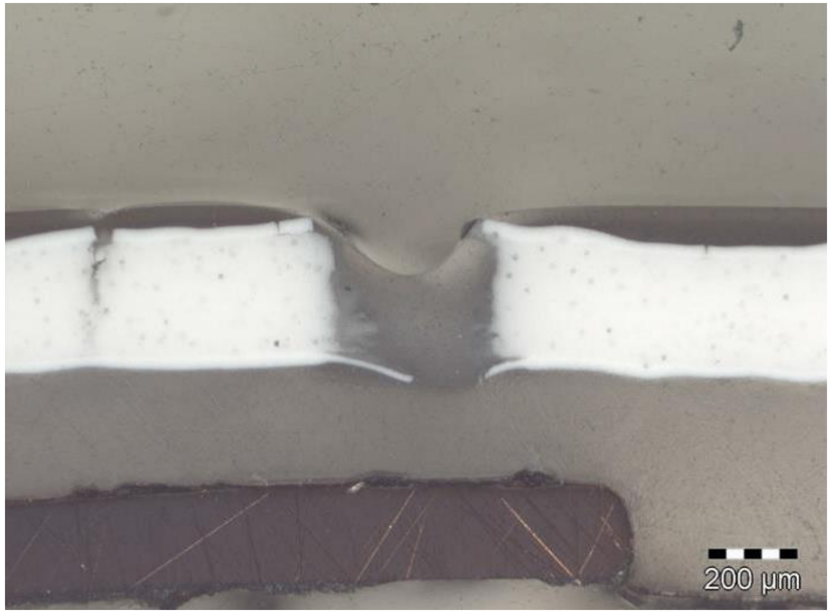
Source: Voronko et al. (2021)

The solution?

Repair solution based on coatings → Goal = Crack filling and sealing

Criteria for material selection:

- material compatibility
- applicability in the field
- long-term stability
- ***sustainability of the repair process***



Source: Voronko et al. (2021)

More details on the technical aspects in:
Voronko et al. (2021) - Repair options for PV modules with cracked backsheets, Energy Science & Engineering Vol. 9, Issue 9.

Aim of the study

Environmental and economic comparison
of different scenarios dealing with cracked backsheets

(A) **Repair** of defective modules

(B) **Disposal** of defective modules **without replacement**

(C) **Disposal** of defective modules **with replacement**

→ Calculation for real-life case studies with different framework parameters

Methodology

System Lifetime: 25 years

$$\frac{Environmental\ impacts}{Lifetime\ Energy\ Production^{\,*}} = \boldsymbol{Env.Performance}\ [\boldsymbol{Impact/kWh}]$$

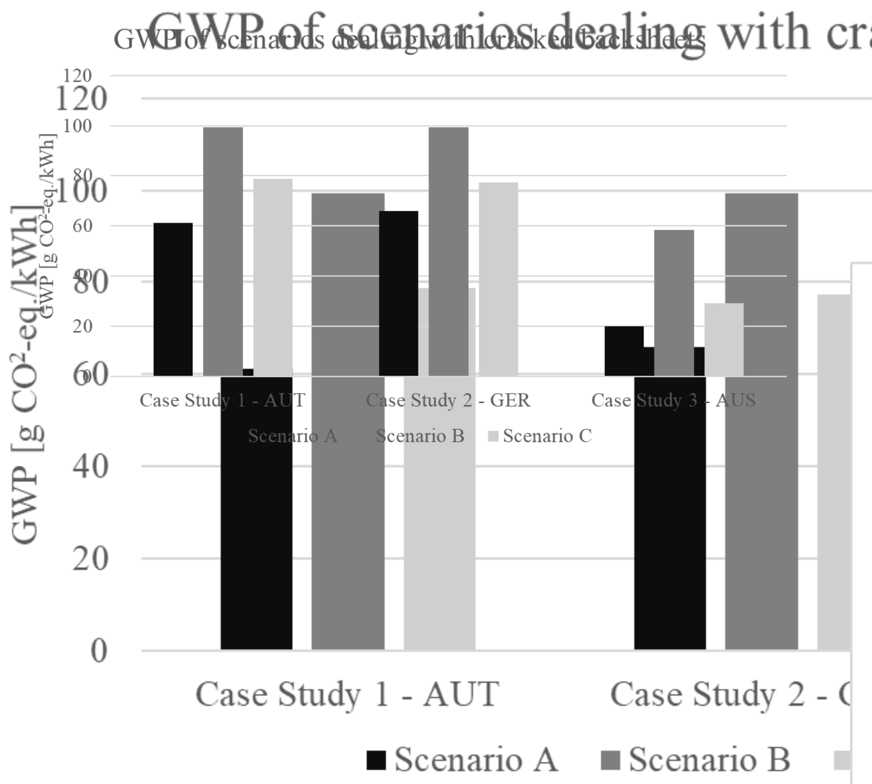
*Dependent on:

- Nominal module power [Wp]
- Yearly degradation before/after repair [%]
- Regional energy yield [kWh/(kWp*a)]
- Lifetime without repair [a]
- Lifetime with repair or additional life time [a]
- Time of repair [a]

$$(Lifetime\ Energey\ Production\ * Feedin\ tariff) - add.costs = \boldsymbol{Eco.Performance}\ [€]$$

→ Costs from plant owner perspective/decision maker

Results: Environmental Assessment

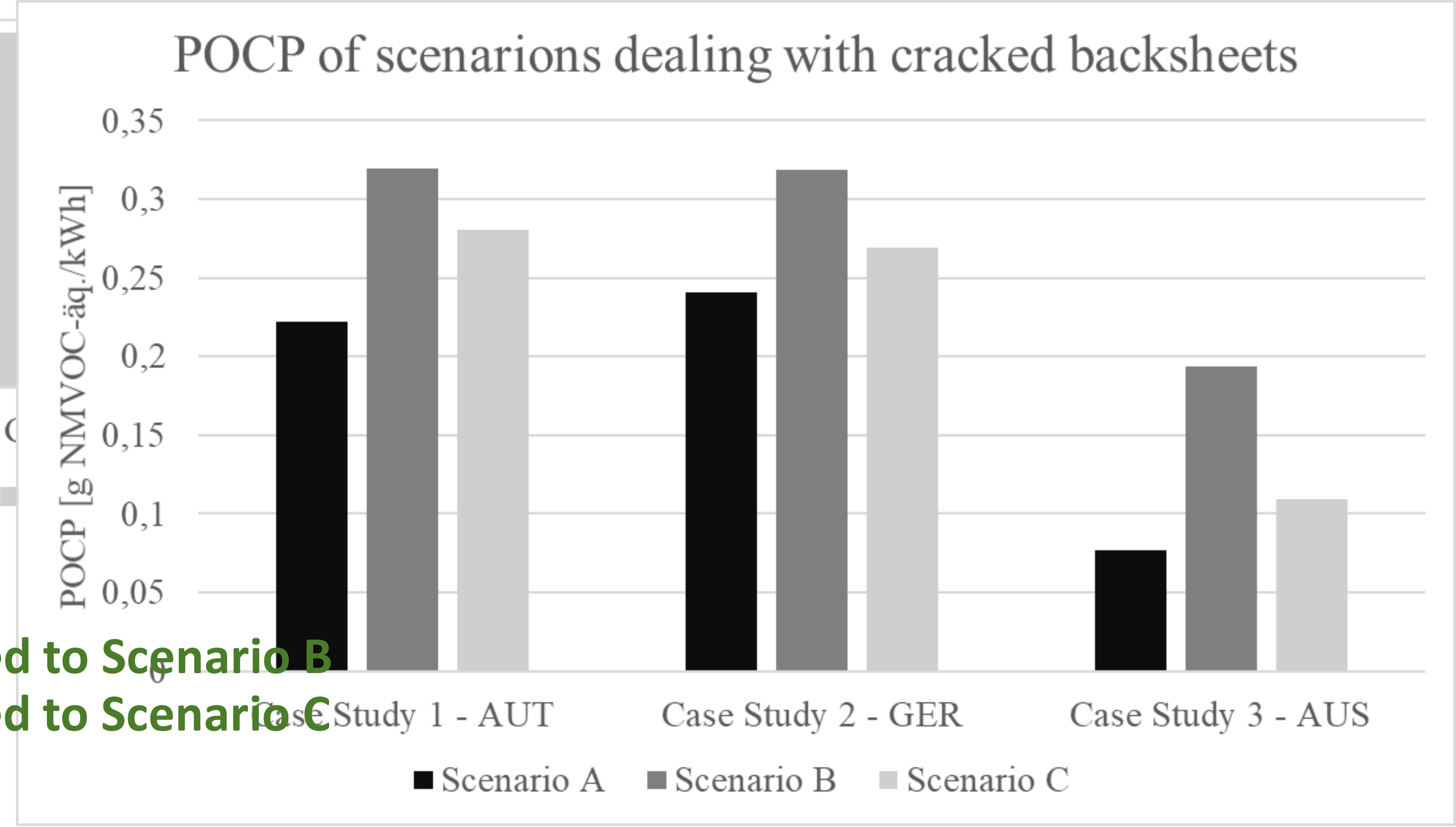


Repair:

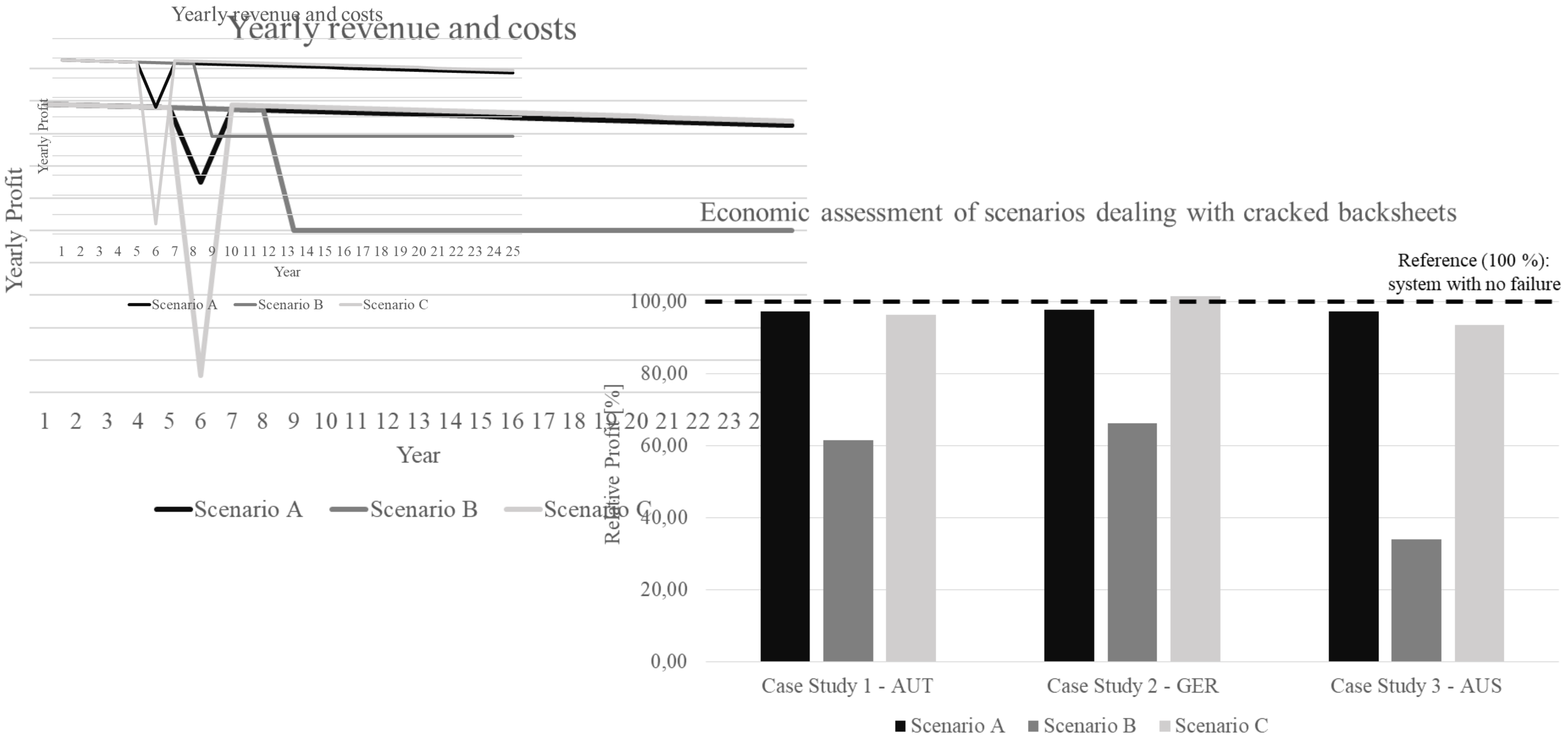
33 – 65 % reduction compared to Scenario B
15 – 31 % reduction compared to Scenario C

Repair:

24 – 60 % reduction compared to Scenario B
10 – 29 % reduction compared to Scenario C



Results: Economic Assessment



Summary of assessment results

- Doing nothing (“disposal without exchange”) is always the worst solution.
- From an environmental perspective “repair” is the most advantageous option for all considered case studies. The observed trends can be applied on a more general level.
- Economically speaking “repair” and “disposal with exchange” provide similar results. The assessment is quite complex and dependent on case-specific factors making individual evaluations advisable.

Outlook

- Ongoing evaluations of repaired modules in regard to long-term stability of coatings.
- Repair products developed in PVRe² have already been put on the market.
- Developed concept has received ÖGUT Umweltpreis 2021
- Establishment of a industrial repair process in order to enable widespread implementation at competitive costs.