Sustainable photovoltaics
Increasing recyclability of PV modules

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PV module technology

PV module composition

Multi-material composite containing glass, polymers, semiconductors and metal

Front sheet

- *Low iron glass*

Solar cell encapsulant

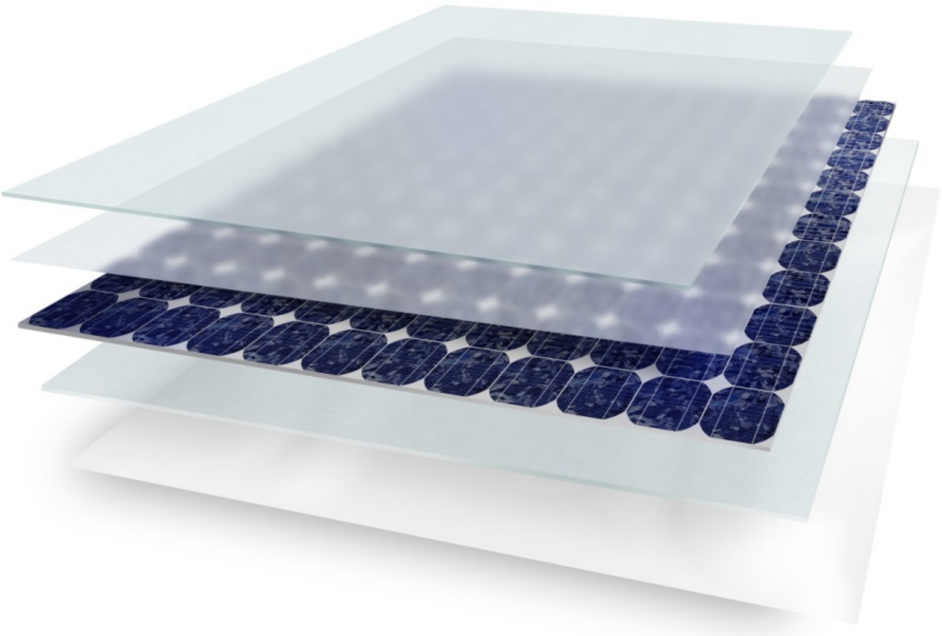
- *Peroxide crosslinked Ethylene Vinyl Acetate (EVA)*

Crystalline silicon solar cells

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

Cell interconnection

- *Flat copper ribbons coated with SnPb solders*



Backsheet

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

Frame

Junction box

Recycling?

During PV module lamination the encapsulant melts and bonds all layers together

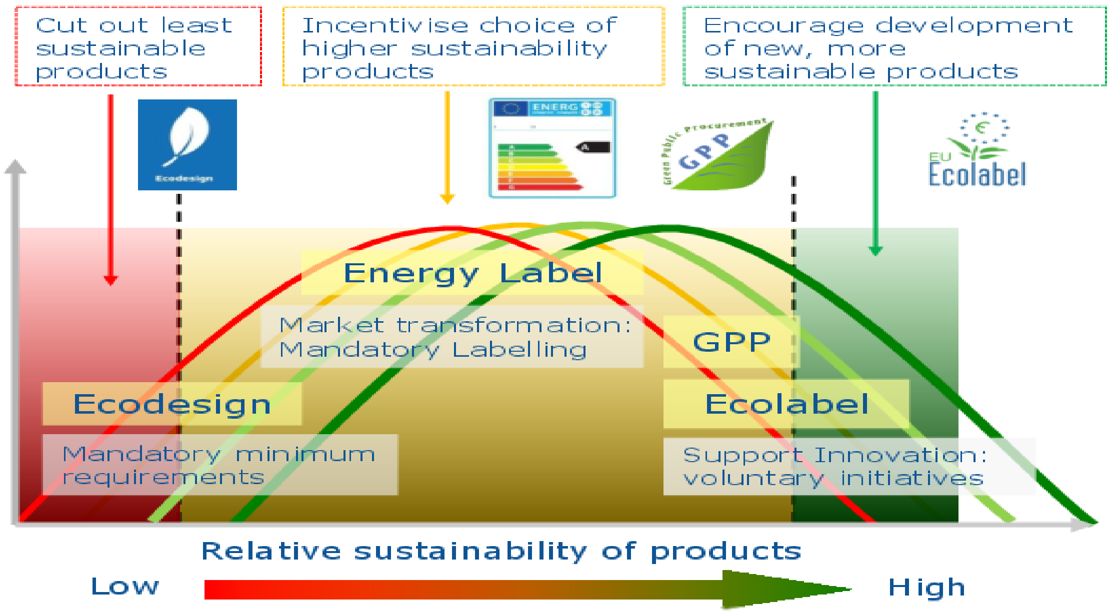
Sustainable PV Modules

Main objectives

1) *“Conceptual design of sustainable PV modules through recycling-friendly architecture/composition (detachable joints, easily demountable setup of laminate) and replacement of environmentally hazardous materials by non-toxic and easy-to-recycle ones”*
2) *Assessment of recyclability*

❖ Challenges

- *High cost pressure: Sustainable materials and components for PV modules must have same or lower price than standard components*
- *Required lifetimes of 25+ years: Compatibility of module materials is essential for long term stability*
- *No mature recycling processes available*



Ecodesign of PV: JRC Sevilla & JRC Ispra

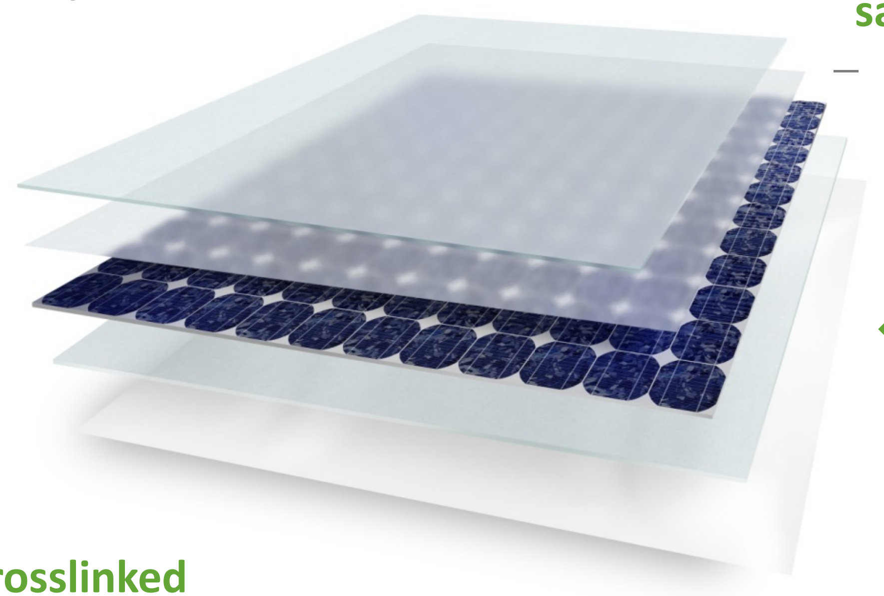
http://susproc.jrc.ec.europa.eu/solar_photovoltaics/index.html

PV module technology

How to make present day PV modules more environmentally friendly?

How to increase recyclability and reparability?

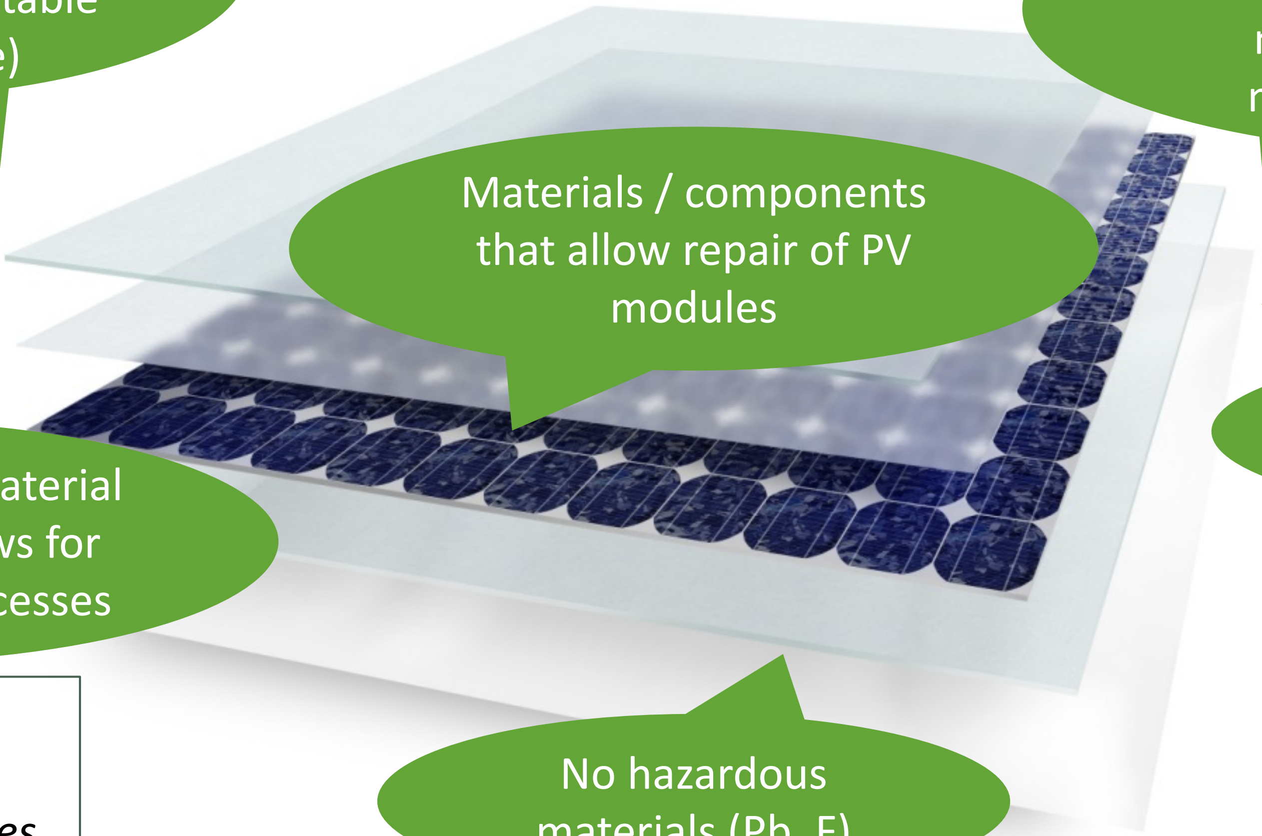
- **High Sb content of solar glass**
  - *Not usable in float glass recycling or for the production of glass beads for retroreflective coatings*
- **Standard PV backsheets are not recyclable**
  - *Difficult separation of each layer*
  - *No recycling processes for fluoropolymers available*
- **Difficult 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*



- **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*
- **Actual composition of the module is not considered in recycling process**
  - *Potential presence/release of environmentally harmful substances → Pb, F*

PV Re² Sustainable PV Module

Recycling friendly PV module design



Recycling-friendly architecture (detachable joints, easily demountable setup of laminate)

Reduced complexity of components advisable – less material composites / material combinations

Materials / components that allow repair of PV modules

Reduction of rare / high impact materials (Ag)

Module design and material selection which allows for various recycling processes

- *Mechanical processes*
- *Thermal processes*
- *Solution based processes*

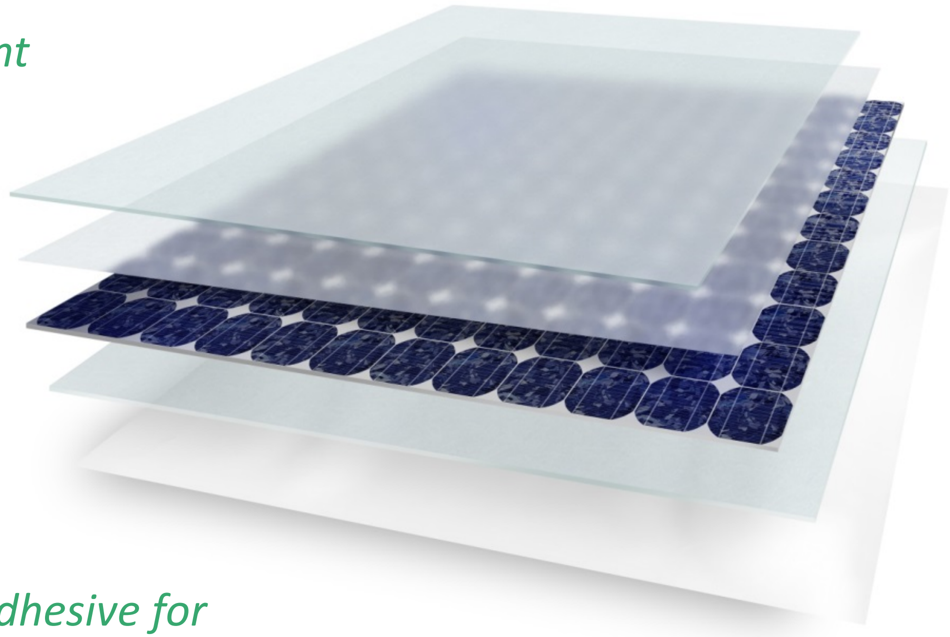
No hazardous materials (Pb, F)

Increased recyclability does not necessarily mean reduced carbon footprint

PV Re^2 Sustainable PV Module

PV Re^2 Module General criteria

No lead solders; No fluoropolymers; Reduced silver content; Recycling friendly materials



- *Hardened glass with low Sb content*
- *RoHS certified mono crystalline solar cells (5BB) with lead free metallization*
- *Thermoplastic PE based encapsulant*
- *Lead free interconnection*
- *Co-extruded PP backsheet*
- *Reversible adhesive for frame and junction box*

High durability PV module (Aspired lifetime: 25+ years)

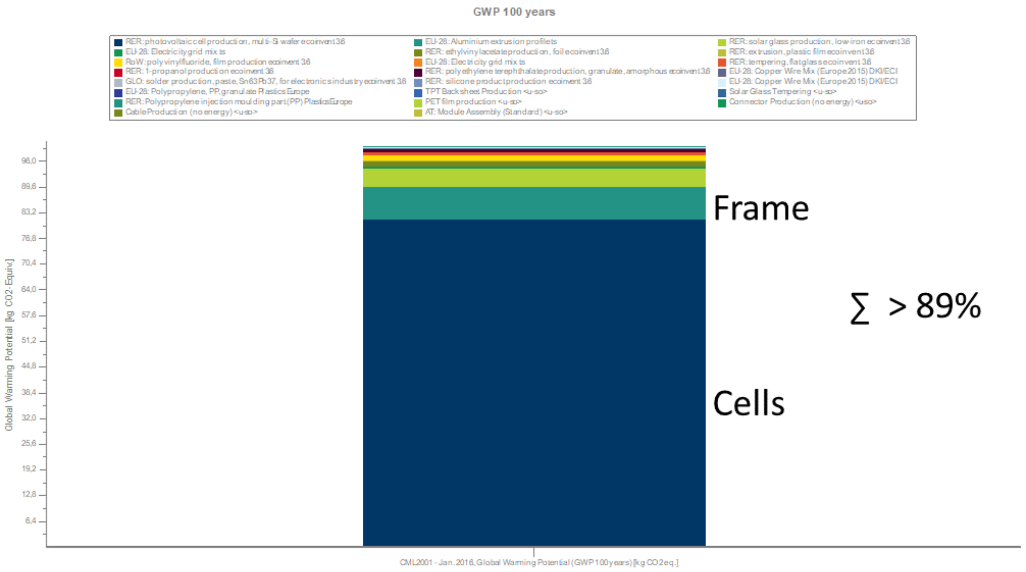
Framework of Life Cycle Assessment

- Comparison of 3 different module compositions - first focus on polymer packaging
  - ***Standard Module:*** *crosslinking EVA encapsulant, PVF/PET/PVF laminate as backsheet; 3.2mm front glass*
  - ***PV Re² Eco Module 1:*** *thermoplastic PE based encapsulant; co-extruded PP backsheet; 3.2mm front glass*
  - ***PV Re² Eco Module 2:*** *thermoplastic PE based front encapsulant; co-extruded back encapsulant / backsheet based on PE and PP; 2mm front glass*
- Functional unit: (production of) 1 Module (1.659 x 0.985 m)

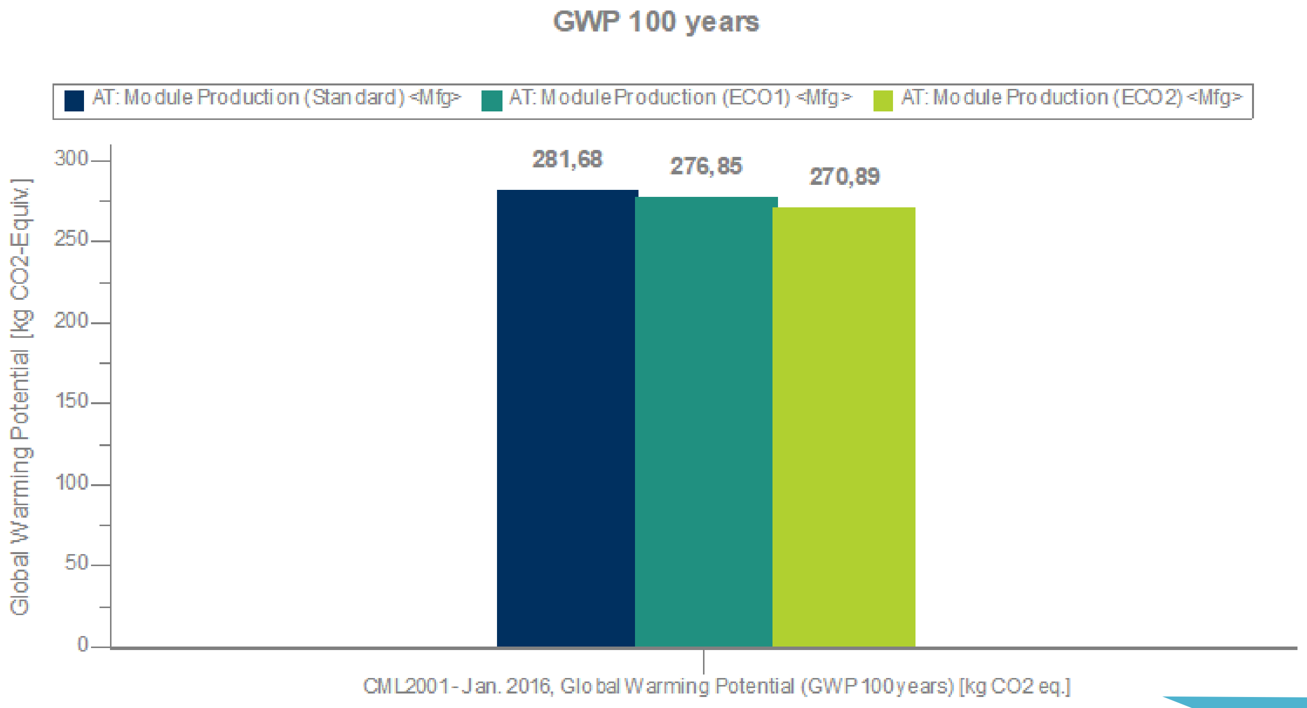
Framework:
Lifetime: *25 years*
Yearly Degradation: *0.8 %*
LCA (Lit.): *30 g CO_2 eq./kWh (southern European conditions)*
Energy Output: *38.250 kWh/kWp (1.700 kWh/(kWp*a))*

- Silicon solar cell and frame production (including upstream processes) dominate the environmental impacts of a PV Module
- Share of module production or the remaining module components (glass, cell connectors, polymers) significantly lower

→ **First assessment: PV Re² contents are difficult to represent in the classic LCA or, in the worst case, negligible**



Life Cycle Assessment



Results:
GWP: *10 kg CO_2 eq./Module saved (= 30 kg/kWp)*
Savings: *0.78 g CO_2 eq./kWh (= 2.6 %)*

Applied changes show a positive impact in all considered impact categories (e.g. global warming potential (GWP), acidification potential, eutrophication potential)

Pure technology comparison - location of production & energy mix not considered here

- **Relative improvement (in production phase) is rather small (2-3 %) due to no changes in the high impact areas**
- **Positive effects on use phase (prolonged lifetime) and end of life phase (better recyclability and repairability) are not included in the assessment yet**

How to assess recyclability?

Evaluation of recyclability

Approach for building materials

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*

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 recyclability - separability

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

Classification of separability (inspired by building industry)

	Standard	PVRe² Eco-1	PVRe² Eco-2	Glass/Glass
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	?	?	?

** Technically possible but questionable from an emission standpoint*

Table refers to the laminate only (not frame/cables)

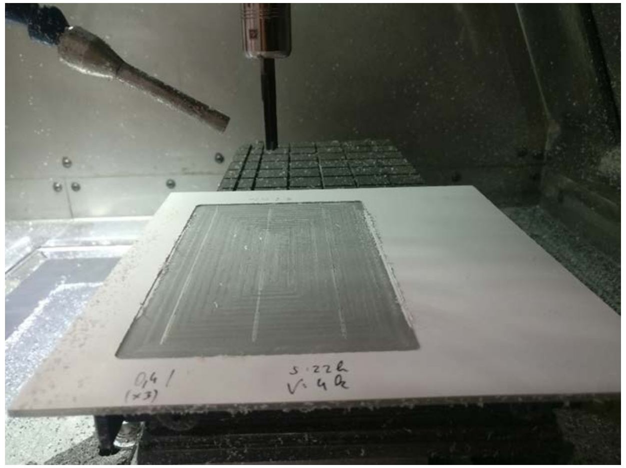
Potential separation technologies

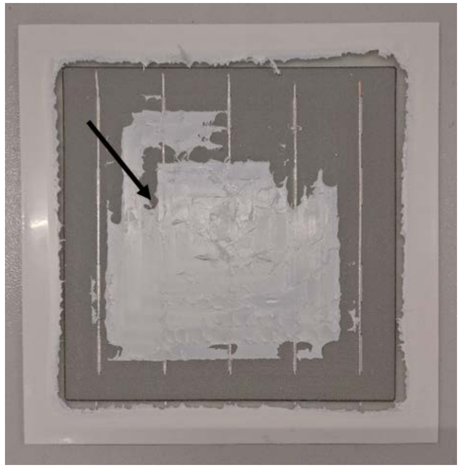
1) Advanced mechanical (e.g. LuxChemTech, PVRe²)
2) Thermal delamination (incineration, pyrolysis)
3) Chemical delamination (solvent)
4) New technologies, e.g. radiative

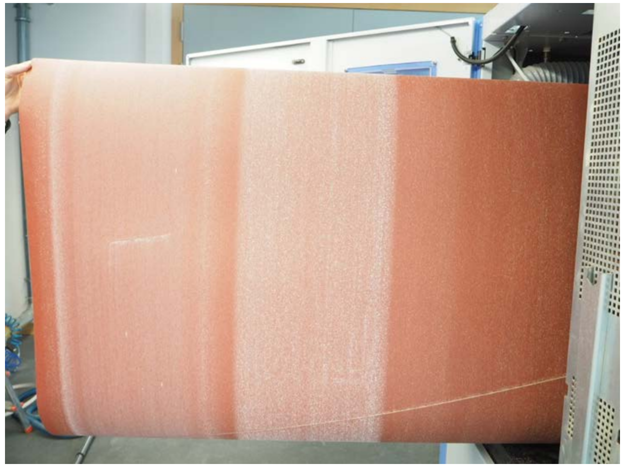
Outlook - potential mechanical separation technologies

Assessment of multiple mechanical delamination methods aiming at layer-by-layer removal

→ Wood processing technologies seem especially feasible (milling, grinding, etc.)







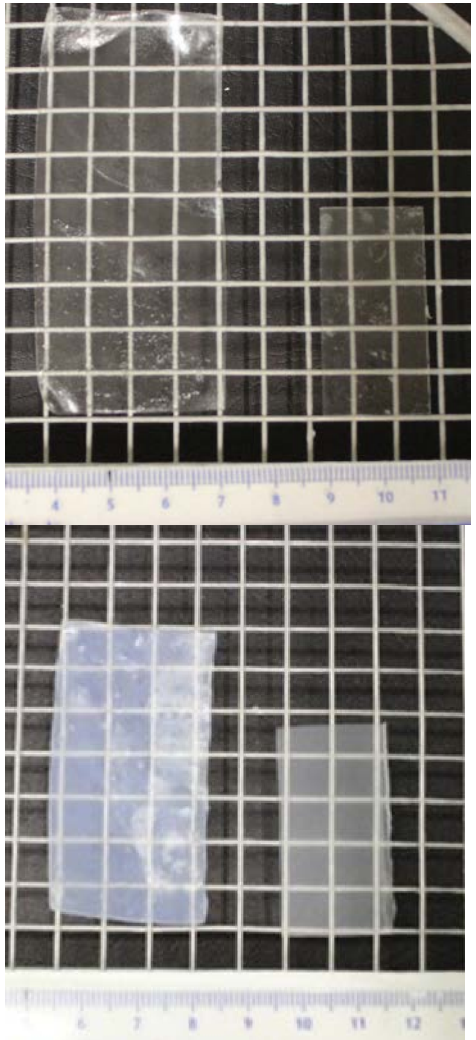
Technical feasibility of selective delamination shown but some open questions/potential drawbacks have also been identified and need to be considered more in-depth

→ Uneven layers, tool wear, throughput-rate, damaged modules

Follow up project planned to continue this work

Outlook - chemical separation

Swelling behavior

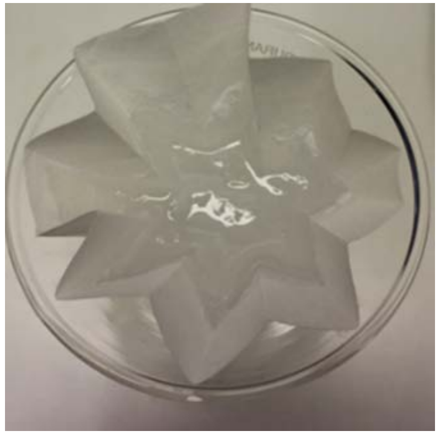


e.g. EVA (above) and BPO (below) at RT (left - swollen material)

Solubility behavior of EVA and BPO at RT, 60°C and 80°C

Solvent	RT		60°C		80°C	
	EVA	BPO	EVA	BPO	EVA	BPO
MEK	0.2	0.7	7	12	9	17
MIBK	1	2	10	33	13	38
Anisol	7	3	17	50*	18	26
THF	8	12	12	33	13	20
Toluene	7	15	13	43	14	70
Xylene	7	14	13	100	14	100
	BPO with DH treatment (1000h, 85/85) in xylene at 80°C for 1h					30

*outlier



Precipitated BPO material at room temperature after complete dissolution at elevated temperature (in xylene at 60°C and 80°C)

Damp heat treated BPO after solvation experiment in xylene at 80°C (not solved part very soft and swollen)

Evaluation of recyclability - recovery potential

<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.* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **225** 012024; DOI: 10.1088/1755-1315/225/1/012024. Project funded by BMI/BBSR (Zukunft Bau)

Comparison of module types for recovery potential

Current	Standard	PVRe² Eco-1	PVRe² Eco-2	Glass/Glass
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.

* Thermal treatment of mixed fraction - Assumptions

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

With current recycling technologies only energy recovery or thermal disposal are feasible

Future	Standard	PVRe² Eco-1	PVRe² Eco-2	Glass/Glass
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.

[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.*

Higher potential for material recovery with new recycling approaches

Summary

- Proposal for an Eco-designed PV module with increased recyclability and no hazardous materials used
- Applied changes show a positive impact in all considered impact categories, but relative improvement (in production phase) is rather small (2-3 %) due to no changes in the high impact areas (cell, frame)
- Positive effects on use phase (prolonged lifetime) and end of life phase (better recyclability and reparability) are not included in the assessment yet
- Recyclability can be evaluated using a qualitative approach from building materials using separability and recovery potential as main features
- High necessity for further research in **PV module separation and recycling technologies**

Recycling-friendly design of PV modules strongly dependent on available separation and recycling technologies

Acknowledgement

Thank you for your attention!

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