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

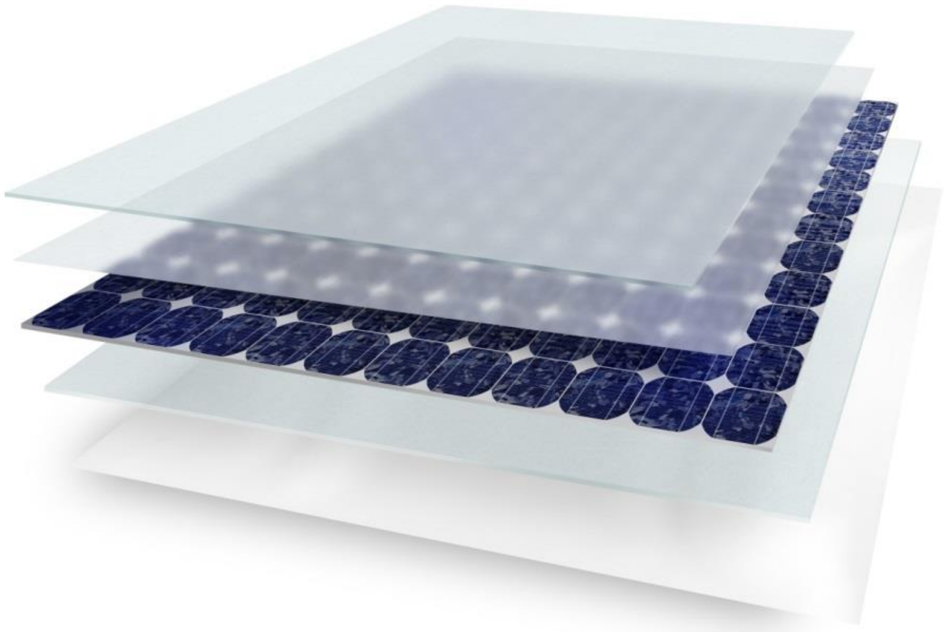
- *Low iron glass*

Crystalline silicon solar cells

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

Solar cell encapsulant

- *Peroxide crosslinked Ethylene Vinyl Acetate (EVA)*



Cell interconnection

- *Flat copper ribbons coated with SnPb solders*

Backsheet

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

Frame

Junction box

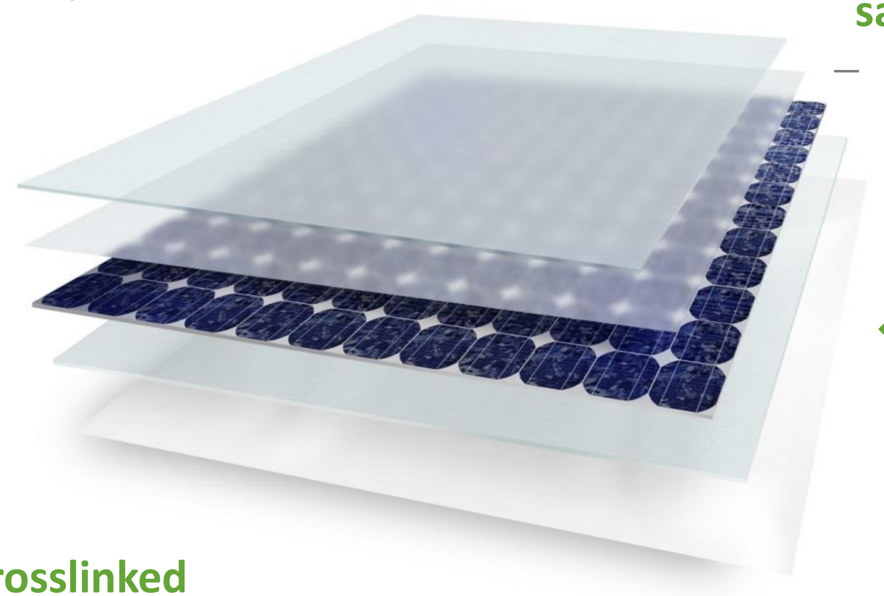
Recycling?

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

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*

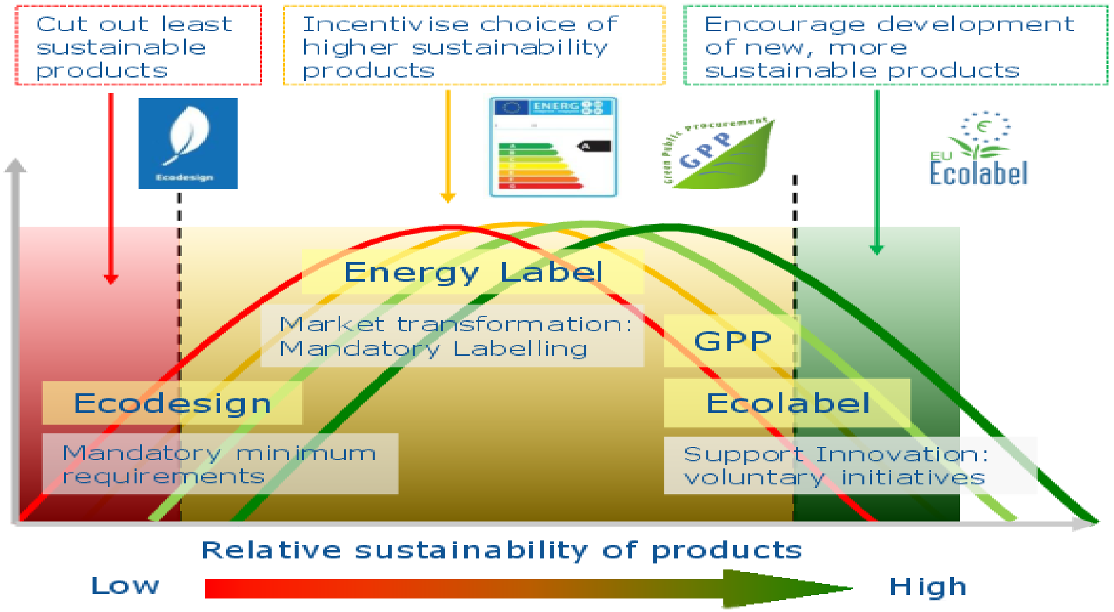
Sustainable PV Modules

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*



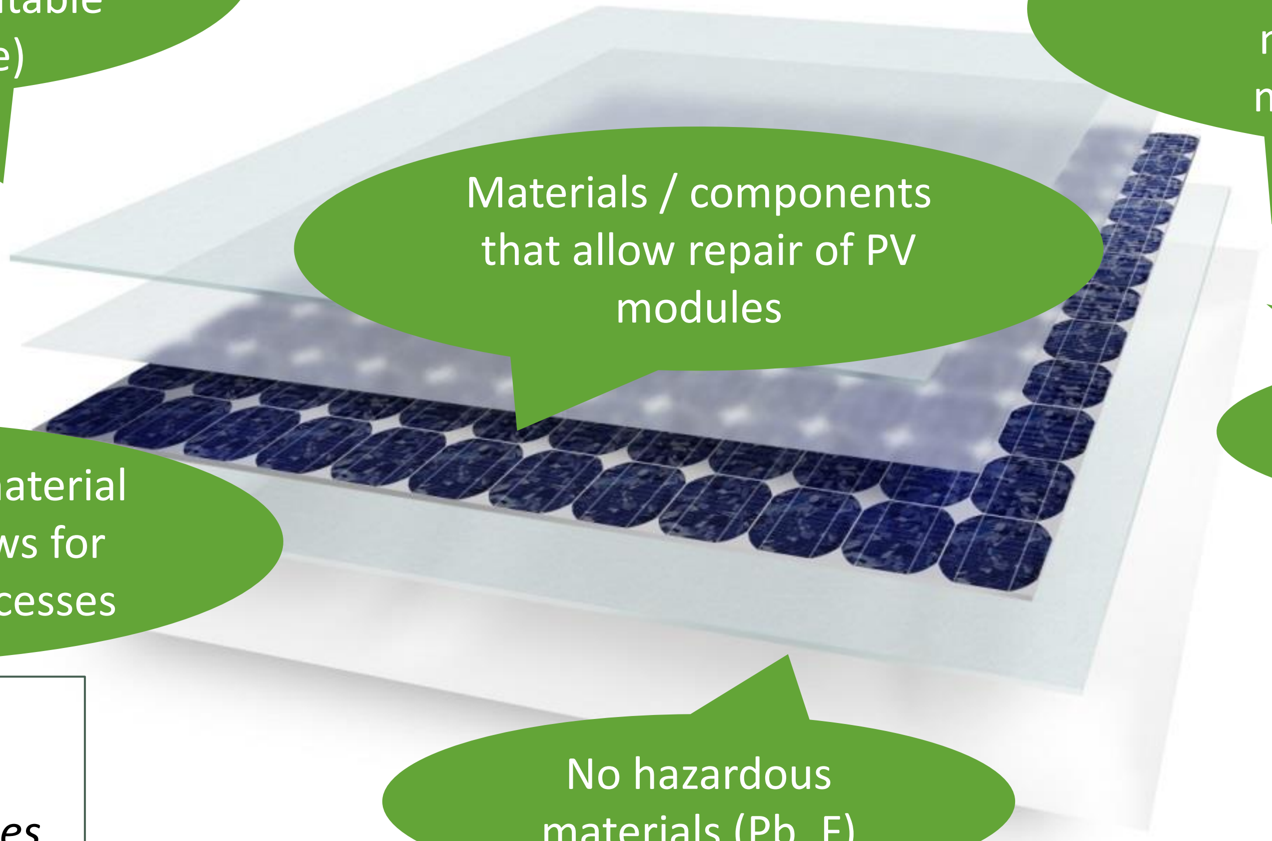
Ecodesign of PV: JRC Sevilla & JRC Ispra

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

PV Re² Sustainable PV Module

PVRe²

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)

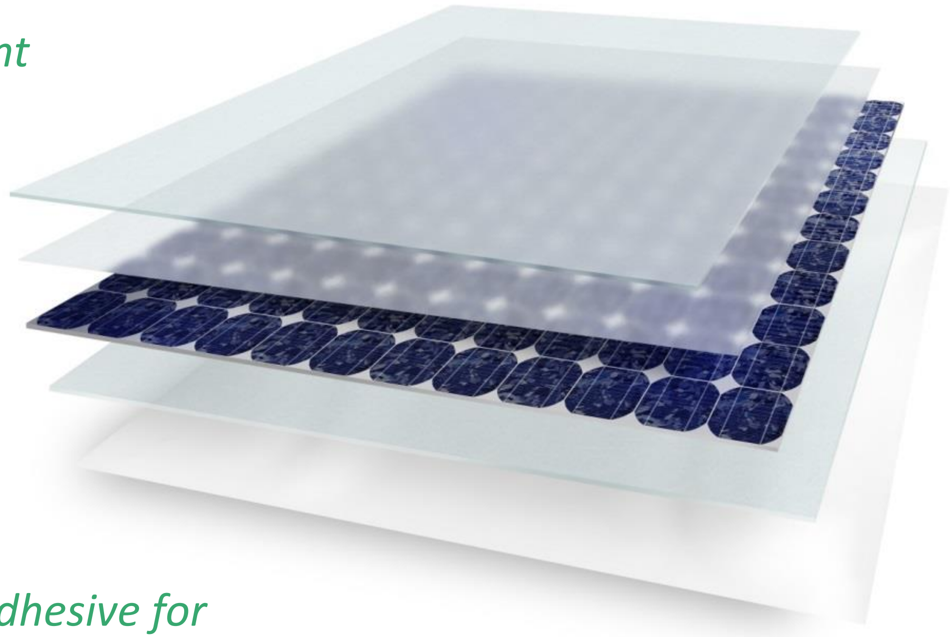
Increased recyclability does not necessarily mean reduced carbon footprint

PV Re² Sustainable PV Module

PV Re² 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

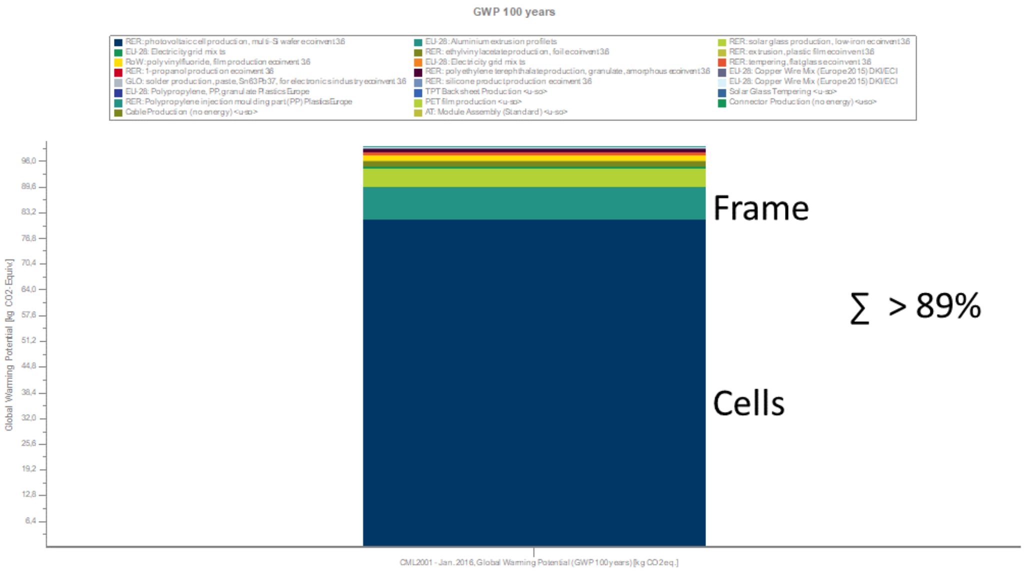
PVRe²

- **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)**

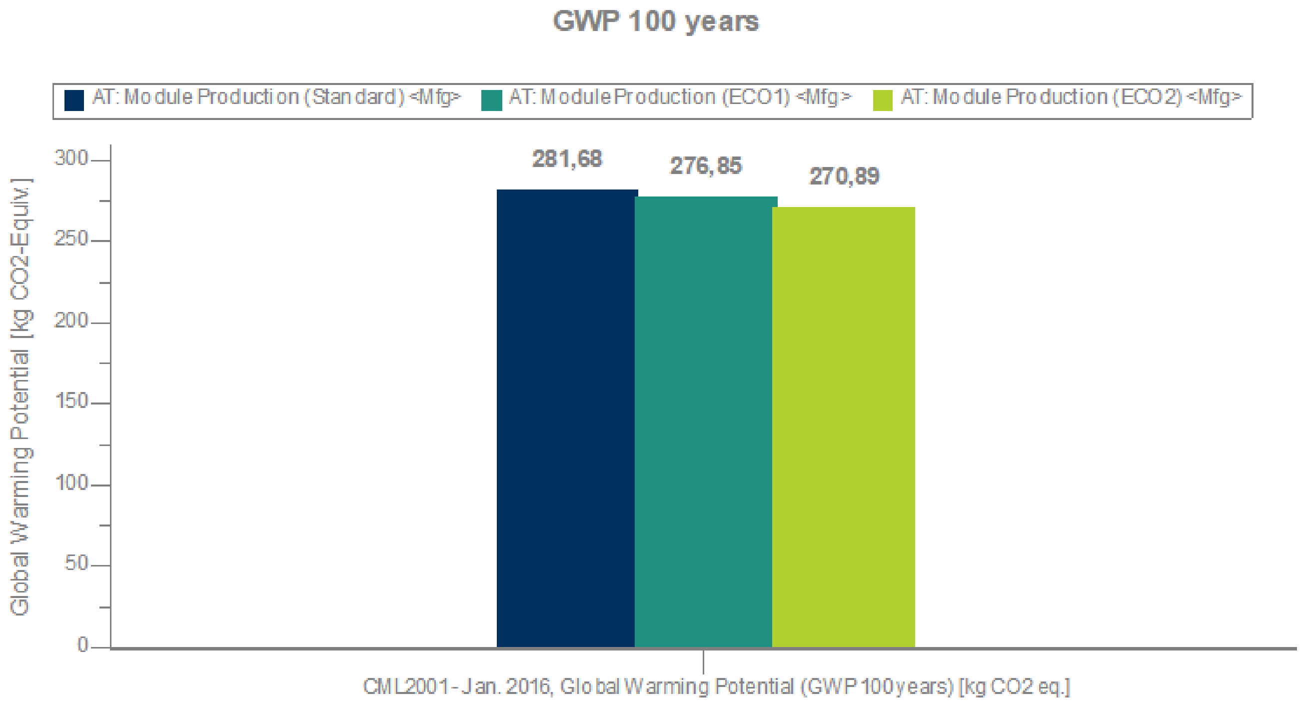
Framework:
Lifetime: *25 years*
Yearly Degradation: *0.8 %*
LCA (Lit.): *30 g CO_2 eq./kWh (southern European conditions)*
Energy Output: *38.250 kWh/kWp (1.700 kWh/(kWp*a))*

- **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 %)*

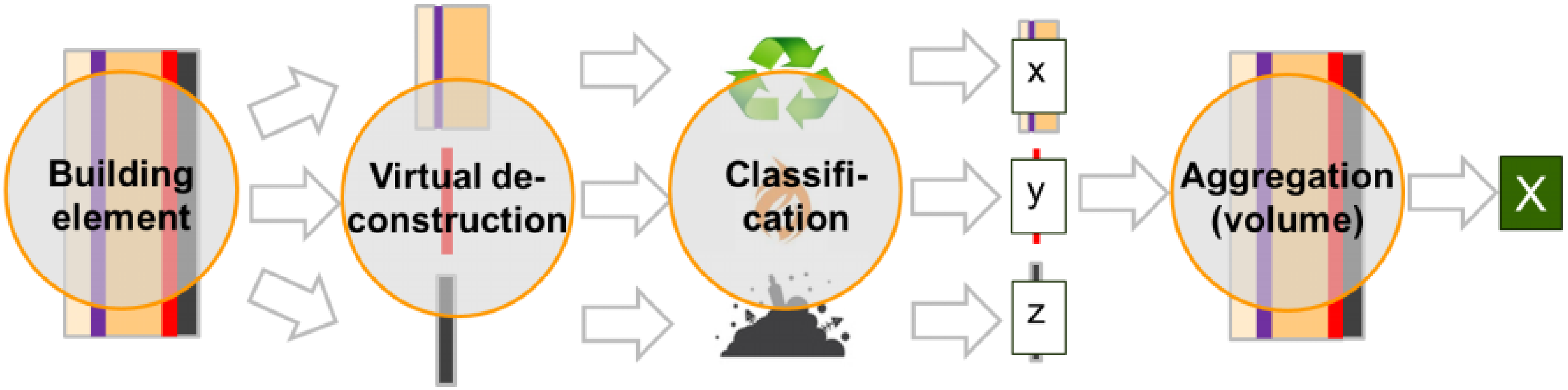
Applied changes show a positive impact in all considered impact categories (e.g. global warming potential (GWP), acidification potential, eutrophication potential)

- **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

PVRe²

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

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

PVRe²

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

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