Characterization of end-of-life modules for subsequent delamination and recycling

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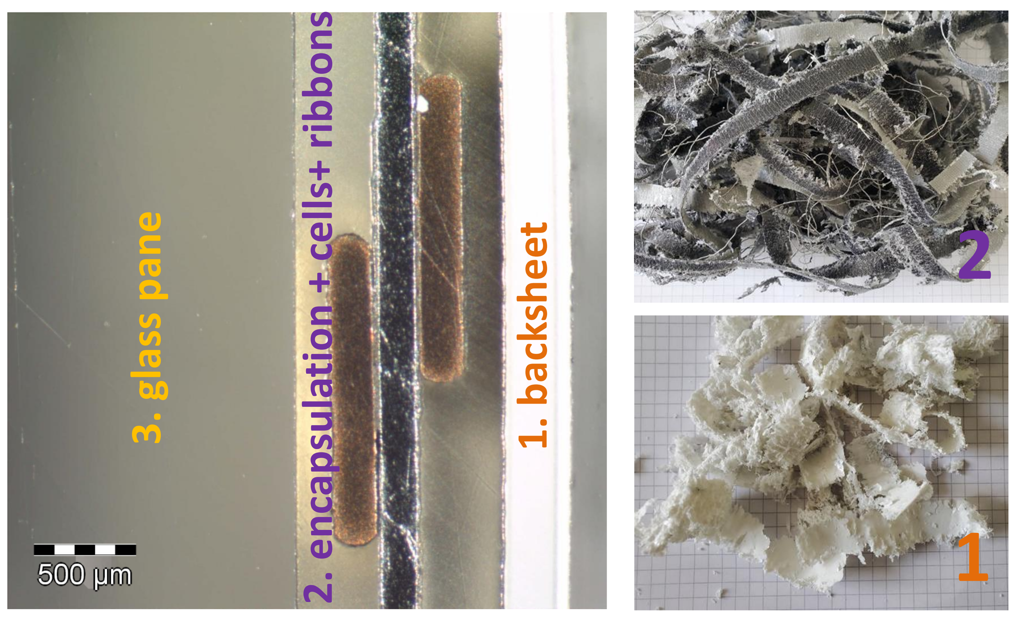
MOTIVATION

Although there are currently still small amounts of end-of-life (EoL) PV modules, a strong increase is to be expected in the next few years, for which it is important to be prepared accordingly. **As part of the PVReValue research project, the scientific and technical basics for a comprehensive layer-by-layer separation and recycling process for EoL PV modules are being developed and evaluated.**
The recycling process will consist of the following steps:
(i) input characterization
(ii) component separation
(iii) further processing of the separated fractions
(iv) output characterization
(v) finding recycling or reuse routes of the output fractions

With an innovative approach, the composite (multi-material laminate) is separated into the three main fractions
(1) Backsheet (BS),
(2) Encapsulation (EC) + solar-active semi-conductors and connections and
(3) glass (as a pane)
using mechanical delamination processes such as milling, water jet cutting or high-temperature sawing. To achieve this layered separation, in advance a thorough characterization of the installed components in terms of their **thickness** and **material identity** is necessary.
For this purpose, several analysis tools which enable a quick and qualified determination of the layer thickness of the backsheet (BS) and the encapsulation (EC) material are tested and evaluated. Since many BSs contain fluoropolymer layers (PVF, PVDF or F-coatings) that require special handling and separation during the recycling process, their possible presence must be clearly identified BEFORE the PV module is delaminated/separated.

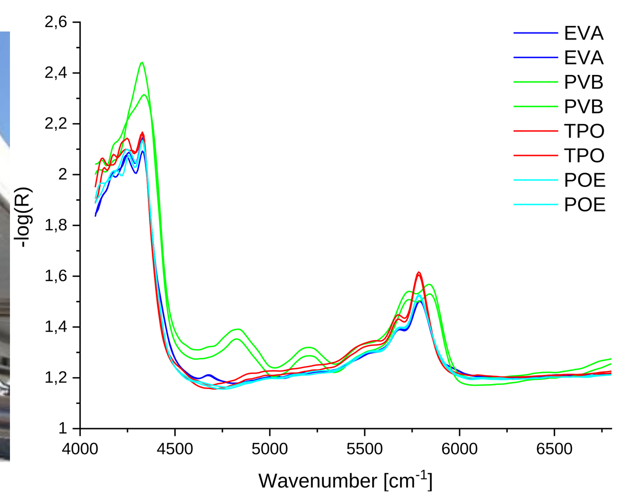


Polymer Material Identification

Material identification of the EoL modules is possible via vibrational spectroscopic methods:

- **ATR-IR (attenuated total reflection - infrared)**
  non-destructively and fast; surface sensitive
  -> identification only of the outer BS layer
- **Raman**
  through the transparent stack the focal point can be varied, and material identification of the EC is possible
- **NIR (near-infrared)**
  high penetration depth (through BS and EC -> cell) allowing the identification of all polymer layers

In a recycling line, short measurement times for the identification of all materials (BS and EC) are required; a sensor application is preferred.
-> NIR is the best suitable; with a large database and chemometric models, nearly all BS and EC used can be identified.



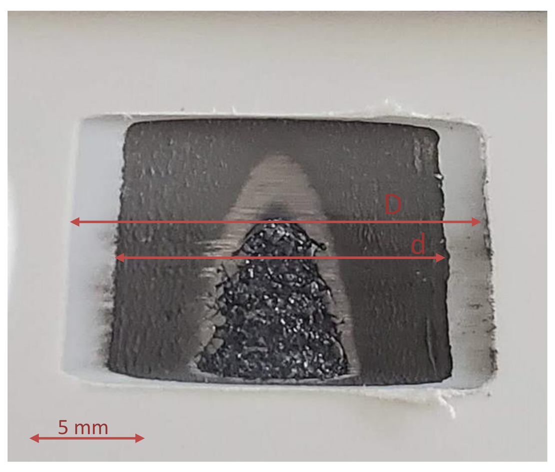
Layer Thickness Determination

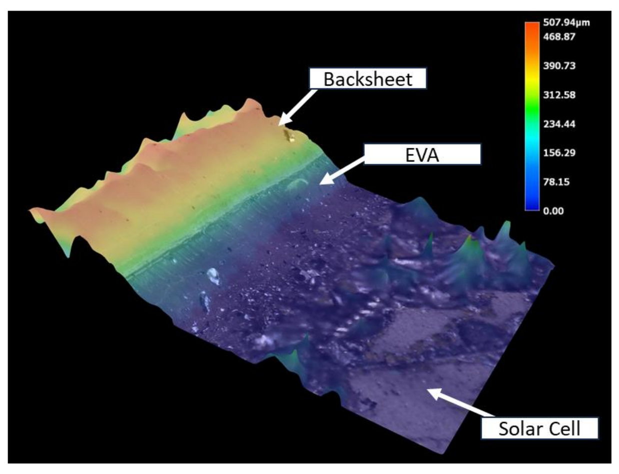
Destructive

- **Calotte grinding method** (left figure)
  - a grinding sphere (R) cuts a calotte-shaped scar from the backside into the module
  - an image is taken of the area with an industrial camera
  - BS thickness (t) calculation through an automated dimension measurement of the cut's borders

$$t = \sqrt{R^2 - \left(\frac{d}{2}\right)^2} - \sqrt{R^2 - \left(\frac{D}{2}\right)^2}$$

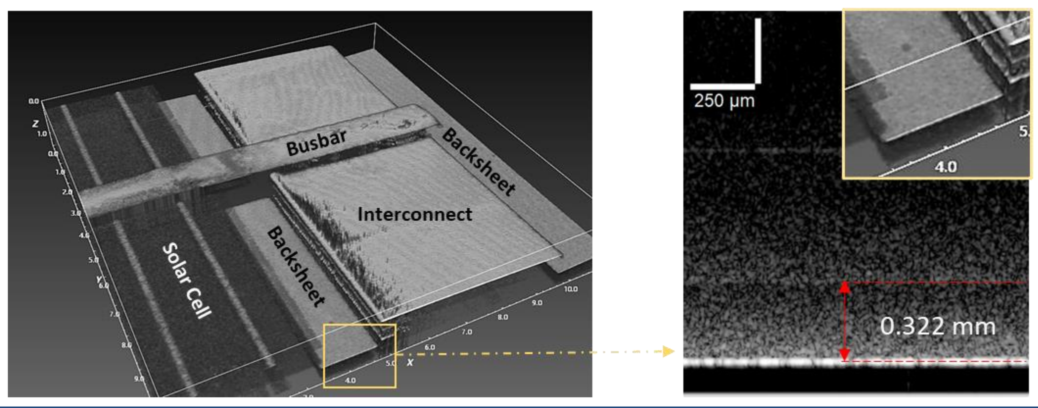
- **Optical 3D microscopy** (right figure)
  - oblique cut from BS side towards glass & removal of the material
  - optical 3D measurement inside the cut for determination of the layer thicknesses
  - depth-information of samples via focal point variation of z-stage





Non - Destructive

- **Ultrasonic thickness detection**
  - layer boundaries are identified by detecting changes in the characteristics of the reflected high-frequency sound waves at interfaces between different layers
- **Coaxial multicolor confocal measurement [2]**
  - optical sensing technique that utilizes multiple colors (400-700 nm) of light in a coaxial arrangement to perform precise distance measurements
  - combination of two-head & single-head configuration enables differential measurement of the BS thickness
- **Optical coherence tomography (OCT) [3] –** see figures
  - real-time, high-resolution images (also 3D mapping)
  - high penetration depth compared to other imaging methods (laser: 1300 nm wavelength)
  - sensitive to variations in refractive index, which is beneficial for characterizing different layers inside the (polymer) stack



RESULTS / EVALUATION

of potential methods/characterization tools in terms of time, cost, accuracy, lateral resolution as well as their suitability for the integration into an industrial separation process.

Measurement Method	Investment cost	Measurement time	Lateral Resolution	Measurement depth	Applicability (layers)	Advantages	Limits	industrial application
Coaxial Multicolor Confocal Measurement (CMCM)	~ 20 k€	real time	0.25 µm	up to several mm in transparent media	BS, TS, TT	fast, cheap, robust, accurate	BS thickness evaluation only applicable at TS; differential measurement necessary; structured glass may cause problems	yes
OCT (Optical coherence tomography)	~ 85 k€	~ 0.1 sec (2D)	14 µm (air)	up to several mm	BS, EC, Glass	fast, accurate, multilayer detection in PV module	BS thickness evaluation only from backside; industrial implementation & automated analysis is challenging	challenging
Ultrasonic thickness detection	~ 8 k€	10 sec	10 µm	7900 µm	BS, EVA	can detect all BS layers separately	point measurement; detailed database of all BS material is needed	yes
Calotte grinding + image processing	1 k€	1 min	tbd	several mm	BS	cheap implementation, possible for all BSs	requires image processing, samples preparation needed	yes
Cut + optical 3D microscopy	~ 30 k€	1 min	Dep. on front lens	µm – cm	BS, EVA, Si	fast, accurate, multilayer detection in PV module	requires image processing, samples preparation needed	yes
Mobile ATR-IR spectroscopy	~ 32 k€	10 sec	-	surface sensitive 1-2 µm	BS-outer layer	reliable polymer identification	surface sensitive method	no
Raman spectroscopy / probe	> 100 k€	30 sec	~ 10 µm	up to several mm in transparent media	EC BS-outer layer	measurement through transparent material	laser safety protocol required, fluorescence, slow	depending on task
NIR spectroscopy / probe	13 k€	10 sec	-	up to several mm	EC all BS-layers	useable for EC and all BS-layers	does not work for black materials and BSs including a metal layer	yes

TS= transparent Stack (EC + Glass); TT= Total Thickness

OUTLOOK

In order to achieve a layered separation using mechanical delamination processes such as milling, water jet cutting or high-temperature sawing, it is necessary to thoroughly characterize the installed components in terms of their thickness and material identity in advance. For this purpose – after evaluation of several analysis tools with all their advantages and shortcomings **– CMCM appears to be the best suited method to perform a quick and qualified determination of the individual thicknesses of all layers in the module stack.**
Molecular spectroscopic methods in general and **NIR in specific, equipped with probes, have the greatest potential for delivering reliable results for the identification of the polymer layers (EC, BS);** a highly qualified evaluation software and specific databases provided. Input characterization has to be a fast and reliable. Based on the material identification results of the NIR measurements and tabulated refractive index values highly accurate OCT analysis of the layer thickness of the backsheet is possible.
This work shows the results/evaluation of a screening of different measurement methods. The various mechanical delamination processes (for recycling) may require specific input information and measurement times. For this reason, after the final selection of the delamination process method, a more detailed analysis and implementation of the characterization tools is planned.

References
[1] TrinamiX; https://trinamixsensing.com/pv-modules
[2] Keyence, https://www.keyence.eu/products/measure/laser-1d/cl-3000/
[3] Thorlabs, https://www.thorlabs.com/

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