

Comparative Analysis of Layer Thickness Measurement Methods for Photovoltaic Modules: A Comprehensive Study

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The increasing volume of end-of-life (EoL) photovoltaic (PV) modules poses a significant challenge, necessitating efficient and sustainable recycling processes. In the PVReValue project, it is aimed to develop a comprehensive methodology for the systematic separation and recycling of EoL PV modules. Central to this effort is the precise determination of layer thicknesses, critical for effective characterization, and separation of input material. In this study, a comparative analysis of various industrial-applicable methods is conducted for measuring layer thicknesses in PV modules. Both destructive and nondestructive techniques are evaluated based on criteria such as time, cost, accuracy, and applicability. Methods such as optical coherence tomography (OCT), coaxial multicolor confocal measurement, and ultrasonic measurements are assessed alongside traditional approaches like calotte grinding and optical 3D microscopy. In these findings, it is indicated that while OCT and confocal measurement offer high accuracy and nondestructiveness, they are complex and costly. Conversely, calotte grinding, although less costly, provides only localized information and can be challenging for polymers. In this study, it is concluded with recommendations for the possible integration of these methods into an industrial recycling workflow, highlighting the potential for improving PV module recycling efficiency and sustainability.

increase in the volume of end-of-life (EoL) PV modules.^[2,3] This situation necessitates the development of efficient and sustainable recycling processes to manage the decommissioned modules. According to the Waste Electrical and Electronic Equipment Directive of the EU, at least 85% by weight of a PV panel must be recovered and at least 80% must be prepared for reuse and recycled.^[4] Addressing a more ambitious goal, a closed material cycles with a focus on reducing waste and using resources efficiently should be established.^[5] In addition to measures to extend the service life and promote the reuse of decommissioned but intact PV modules, a functioning circular economy requires a holistic recycling process, which includes the separation and recovery of all materials.^[6,7] Due to still low waste volumes in most countries, current recycling processes for PV modules are often unspecific and based on recycling methods designed for other products, e.g., flat glass. The initial size reduction process used in these pro-

cesses (shredding, drastic size reduction) poses a challenge for multi-material composites such as PV modules. The subsequent mechanical and physical processing is time-consuming and tends to lead to final fractions with low purity and therefore quality. Without further purification steps, the quality of these output fractions often prevents effective recycling of PV materials.^[8] More specific recycling processes tailored to the multi-material

1. Introduction

In the last years, photovoltaic (PV) has grown to one of the most important energy sources to enable a sustainable energy transition. Around the world, the installations have increased to a global cumulative capacity of 1.6 TW in 2023.^[1] Therefore, in the coming years, the PV industry is expected to face a significant

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laminates of PV modules are needed to improve the efficiency and quality of PV recycling.^[9] Some companies, startups and research groups around the world are currently developing new separation and recycling processes specially designed for PV modules. Currently, most of them still work on a test-facility scale.^[10] To enable a more holistic recycling, the Austrian research project PVReValue aims to develop a comprehensive processing and recycling methodology for EoL PV modules with a recycling rate exceeding 95% by weight, thus taking into account the importance of new innovative approaches to separation and material recovery. The targeted recycling process involves five key steps: input characterization, component separation, output characterization, and further processing of the output fractions, and recycling of the individual material streams. A primary objective within this framework is the identification and comparison of reliable and efficient techniques for determining the thickness of the individual layers within the multilayer laminate PV module. Accurate layer thickness determination is crucial for the subsequent mechanical separation processes studied within the research project focusing on a layer-by-layer separation. This layer-by-layer removal of the embedment materials in the PV module allows for the extraction of high-quality output

fractions. Consequently, the materials recovered during the mechanical separation processes like milling or material removal with water jet cutting are of higher purity. In turn, this enhances the value and usability of the secondary raw materials that are generated, making the recycling process more sustainable and economically viable. Without precise thickness measurements, the separation process could be less efficient, leading to contamination between layers, reduced material quality, and lower yields of reusable raw materials. Various nondestructive and destructive analysis tools (Figure 1 and 2) are tested to evaluate their applicability and efficiency in determining layer thickness.

The objective here is not to develop a new method for measuring layer thickness but to adapt and integrate existing techniques into a comprehensive methodology. This methodology aims to establish a systematic and automated approach for future recycling processes, where accurate layer thickness measurement is critical for addressing layer and component separation procedures. It is important to note that advanced techniques, such as optical coherence tomography (OCT) and coaxial multicolor confocal measurements, require substantial scientific development to be effectively incorporated into the framework of PV module recycling. These techniques may need to be recalibrated

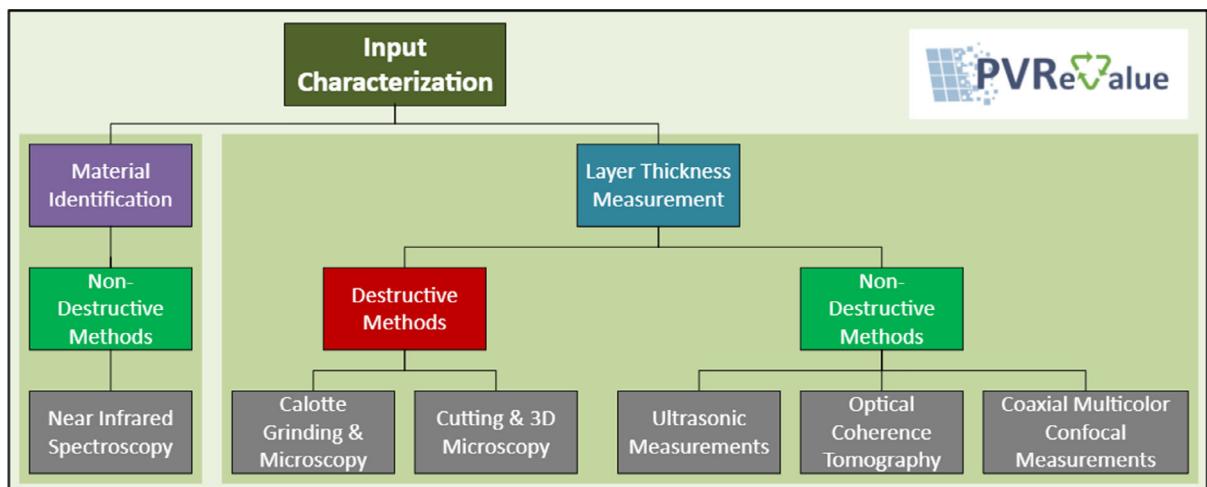


Figure 1. Overview of nondestructive versus destructive approaches for layer thickness measurements in PV modules.

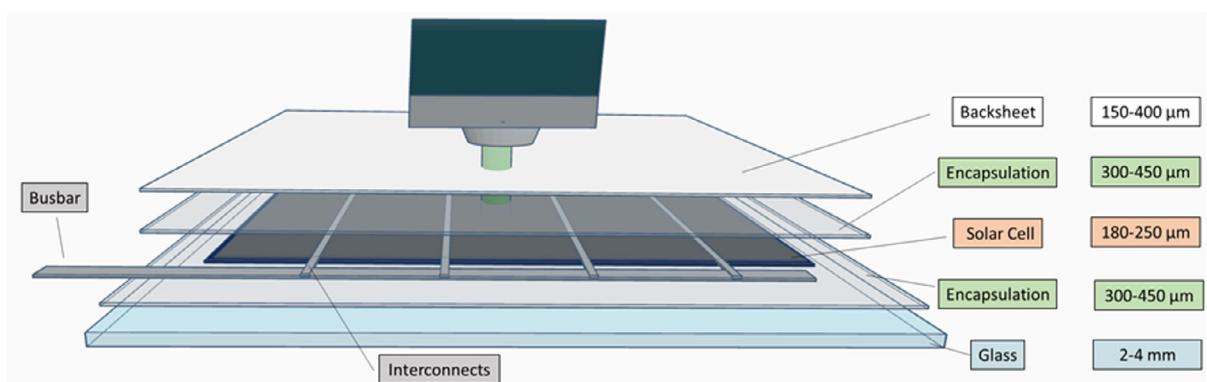


Figure 2. Schematic illustration of typical layers and respective thicknesses of a PV module.

to accommodate varying materials, such as encapsulations and backsheets (BSs), as well as environments and conditions that differ from their original applications, like medical imaging. Furthermore, these optical methods were not initially designed to address the specific properties of PV modules, which feature multilayered structures composed of materials with varying optical characteristics (e.g., glass, polymers, metals), where distinguishing between layers and measuring each one accurately requires advanced data processing and algorithms to separate overlapping signals. Each material introduces unique challenges, potentially impacting the accuracy and penetration depth of OCT and confocal measurements. Environmental influences, such as temperature, humidity, and surface roughness, can also impact the accuracy of spectroscopic measurements. Addressing these complexities will require further research and adaptation to ensure reliable performance. While PV module datasheets often provide thickness information for various components, these values typically represent a range that accounts for manufacturing variations. However, older PV module datasheets, if available with the EoL module, frequently lack specific thickness data altogether, making it more challenging to obtain accurate measurements for recycling purposes. Furthermore, some layer thicknesses are highly dependent on specific process parameters used in PV module production. Factors such as lamination temperature, duration, and pressure affect the viscosity and flow behavior of materials, leading to variability in the thickness of the encapsulation layer in the final product. Additionally, PV modules often exhibit thickness variations, such as the thinning of the encapsulation layer down to zero near the glass edge, marks or imprints from residues flaws inside the laminator, and elevations in the BS above the busbars.

The applied methods are assessed based on criteria such as 1) time, 2) cost, 3) accuracy, and 4) spatial resolution as well as 5) their suitability for integration into industrial recycling processes. Preliminary results have been presented, showcasing the potential of these techniques to enhance the recycling workflow.^[11,12] Currently, advancements in PV module recycling focus on recovering materials such as glass, silicon, silver, and copper. However, the separation and recovery of polymeric layers has received limited attention. A layer-by-layer composite separation process, utilizing sophisticated techniques like milling, water jet, or thermal delamination, aims to address this gap. This approach preserves the integrity and purity of the glass pane while generating high-purity pre-fractions of encapsulant and of BS early in the recycling process. Specifically, the BS layer, often containing fluoropolymers, requires intricate procedures for effective separation. Spectroscopic analysis tools can identify the polymer types of the individual polymer layers of an EoL PV module laminate, followed by layer thickness evaluation. This information forms an important input for the first separation step extracting the layers of the BS, which are then separated into distinct polymer fractions (F containing, F free). This is followed by a second separation step which removes the metal–semiconductor fraction and the encapsulation material from the glass pane. In the following purification step, the metals and Si are separated from the polymer, showcasing a novel approach to materials recovery.

The integration of these advanced techniques promises significant improvements in the efficiency and sustainability of PV

module recycling practices. Addressing the challenges of thickness determination as prerequisite for precise layer separation is crucial for advancing the industrial applicability and efficiency of PV recycling processes, paving the way for a more sustainable and resource-effective future.

2. Experimental Section

EoL modules could have different shapes, sizes, and—most importantly in our context—composition and material characteristics. This included on the one side the bill of materials (BOMs), the chemical identity of the various material layers, and on the other side the thickness of the individual layers within the multi-material laminate of a PV module. This fact required an automated module-by-module characterization of the incoming EoL modules, for a layer-by-layer separation, and it also showed that a wide test sample variety was required when developing new methods. Therefore, in the first step of method development, measurements were taken on specific test samples (with known BOM) to optimize the settings, parameters, and processes (=proof of concept) and then, in the second step, the developed measurement methodology was applied to samples with different BOM and evaluated. The materials were identified using near-infrared (NIR) spectroscopy (see Section 2.2).

2.1. Samples for Layer Thickness Measurements

The focus of the work presented was to determine the thickness of the glass front and the polymer back of the module. Small test samples (one cell; 200 × 200 mm) with known glass thickness, BS thickness, and composition were used to test the various possible measurement arrangements (see Table 1 and Figure 3).

2.2. Input Characterization

EoL modules arriving at a recycling plant must first undergo input characterization in terms of layer thicknesses and material identification to adapt the settings and parameters of the layer-by-layer separation method accordingly. In particular, it was important to know the layer properties of the multilayer polymer film for mechanical separation of the back layer using abrasive methods such as milling or water jet cutting to accurately adjust the offset of the milling head or water jet. In addition, the detection of fluoropolymers was crucial to ensure the proper recycling paths of the polymer fraction as fluoropolymers required specific EoL treatment.^[13] NIR was chosen as the best way to identify the polymer layers in a PV module noninvasively and quickly.^[14] This was due to the high penetration depth (mm to cm range) of the NIR radiation into polymer material.^[15] It allowed the identification of all polymer layers of the BS in one measurement step. NIR spectroscopy could also be used to identify the polymer type of the encapsulation layers beneath the transparent glass front pane. A portable NIR spectrometer from TrinamiX (model SYS-IR-R-P) with a spectral range of 1400–2500 nm (wavenumber range: 4000–7140 cm⁻¹) and a spectral resolution of 1% was used for this purpose.^[16] The measurements were performed in reflection mode, where polychromatic light was directed into the sample and generated specific absorptions of all NIR-transparent

Table 1. Overview—Composition of the sample set.^{a)}

		Sample S1	Sample S2	Sample S3	Sample S4	Sample S5
Glass	Thickness [mm]	3.2	2	3.2	2.3	2.3
Encapsulant	Material	EVA	POE	POE	EVA	EVA
	Thickness [μm]	480	400	400	460	460
Solar cell	Material	Mono-c Si	Mono-c Si	Mono c-Si	Poly-c Si	Poly-c Si
	Thickness [μm]	200	200	200	200	200
Backsheet	Material	PET-PET-F coating (PPF)	PET-PET-F coating	PP-PP-PP (TPO)	PET/PET/EVA	PET/AI/PET/EVA
	Thickness [μm]	310	310	290	375	390

^{a)}Al, aluminum; EVA, ethylene-vinylacetate; F, fluor (polymer coating); mono-c Si, monocrystalline silicon; PET, polyethylene terephthalate; PPF, PET-PET-F; POE, polyolefin elastomer; poly-c Si, polycrystalline silicon; PP, polypropylene.



Figure 3. Photos of the one-cell samples S1–S5 used for layer thickness measurements.

layers until it hit a material that was opaque in the NIR region (e.g., the solar cell). From the back of the PV module, the entire back stack and the back-encapsulation layer could be acquired. Measurements from the front (above the Si-cell) provided the spectra of the front encapsulation.

2.3. Destructive Layer Thickness Measurements

2.3.1. Calotte Grinding in Combination with High Precision Camera

A typical destructive measurement of very thin layers was the calotte grinding method. It was usually used for ceramic coatings and was described in the norm DIN EN ISO 26423.^[17] A rotating sphere with a defined radius created a mark/cut in the BS. Using a microscope or a high-precision camera, the dimension of the mark could be automatically detected in different measuring planes (corresponding to the interfaces of the layers) and then converted into the thickness of the layers according to simple geometric rules. Initial tests used a grinding machine and a light microscope on a measuring table. The setup could be extended to a production line using a camera and automatic image recognition software.

2.3.2. Cutting in Combination with 3D Microscopy

The second destructive option used a 3D microscope to assess the layer thickness on a sharply cut sample piece. Sampling was done with a v-type cutting knife which made an angled cut into the laminate—from the BS toward the glass—thereby exposing all layers within the material stack. This precise cut

allowed for the sample material to be removed and the sample to be prepared for further thickness measurements. A 3D optical microscopy measurement (Keyence VHX 7000) was conducted within the exposed cutting area to determine the thickness of each layer present in the sample (depth composition). For this, the focus of the microscope was automatically varied on the Z axis (confocal measurements), which enabled a detailed analysis of the internal structure of the sample at different depths.

2.4. Nondestructive Layer Thickness Measurements

2.4.1. OCT

OCT is an optical imaging technique that serves as a noninvasive equivalent to ultrasound, offering higher depth resolution but with lower imaging depth. It was ideal for analyzing heterogeneous samples, providing real-time 1D depth, 2D cross-sectional, and 3D volumetric data.^[18,19] By capturing reflections from layers with different refractive indices, OCT provided structural information of the sample.^[20,21] OCT systems could be integrated into real-time monitoring processes to enhance quality control and process optimization.^[22,23] OCT operates on principles of low-coherence interferometry, which measures the time delay and intensity of reflected light. Using a Michelson interferometer configuration, light was split into a reference beam and a sample beam which generated an interference pattern upon recombination. While in time-domain OCT, the reference mirror moved mechanically, in frequency-domain OCT—including the swept-source (swept-source OCT) used in this study—interference spectra were taken without moving parts, allowing for faster imaging.

2.4.2. Coaxial Multicolor Confocal Measurement

Coaxial multicolor white light confocal microscopy was a well-established optical method that used spectroscopic reflectometry to measure the layer thickness of transparent materials without interferences.^[24] The technique coaxially directed white light, typically in the visible (VIS) range from 400 to 700 nm, onto the sample.^[25] The reflected light was collected and analyzed with a spectrometer. A pinhole, placed in the optical path, acted as a spatial filter that allowed only light originating from reflections of the focal plane to pass through to the detector. Thus, out-of-focus light was blocked, and contrast enhanced. The measured spectrum contained peaks and patterns which were characterized by the layer's thickness and material properties. By fitting the observed spectral data to theoretical models that accounted for the material's refractive index and dispersion, the layer thickness could be accurately determined. This nondestructive method was in use in industrial settings, providing rapid and efficient measurements for applications in semiconductor manufacturing, coating industries, and biological research.

2.4.3. Ultrasonic Measurements

Ultrasonic measurements were often used for quality control of the layer thickness of coatings or paints on metals, but there were also known applications for plastic materials.^[26] An ultrasonic pulse was sent into the material to be measured and was reflected at the interfaces between layers of different sound propagation speeds. If the speed of sound of a material was known, the thickness could be calculated from the measured travel time of the sound. A QuintSonic T was used to measure the thickness of the BS and encapsulant.^[27] It could detect layers thicker than 10 µm with an accuracy of $\pm 1 \mu\text{m}$.

3. Results and Discussions

In this section, the findings from the layer thickness and depth analysis of PV modules using both destructive and

nondestructive methods are presented. All methods were evaluated for their performance and suitability for determining the layer thickness and compared in an evaluation matrix.

3.1. Destructive Layer Thickness Measurements

3.1.1. Calotte Grinding in Combination with High Precision Camera

Sample S1 (PPF BS) was used for the first tests of the method (Figure 4). The grinding wheel used has a radius of $R = 60 \text{ mm}$. By measuring the 2D data d and D in the surface plane using Formula (1), the thickness t can be calculated

$$t = \sqrt{R^2 - \left(\frac{d}{2}\right)^2} - \sqrt{R^2 - \left(\frac{D}{2}\right)^2} \quad (1)$$

Based on Equation (1), the BS thickness of sample 1 resulted in $310 \pm 8 \mu\text{m}$.

In an automated recycling process line, the microscope can be switched to an automatic high-precision camera that detects the edges of each layer and calculates the thickness. Difficulties can arise due to the elastic properties of the polymer. This can lead to the grinding wheel wearing out quickly and is a drawback for industrialization. An advantage is that it is very cheap to implement, as no expensive hardware is needed.

3.1.2. Cutting in Combination with 3D Microscopy

The use of cutting and 3D optical microscopy provided accurate measurements of the layer thicknesses within the test modules. By making an angled cut starting from the BS toward the glass, the individual layers become visible and measurable. To demonstrate this technique, we performed analyses at two positions of the test module 1) outside of the cell area (BS, 2x encapsulation, glass; Figure 5 top), and 2) above the center of a cell (BS, encapsulation, solar cell; Figure 5 bottom). It was found that small

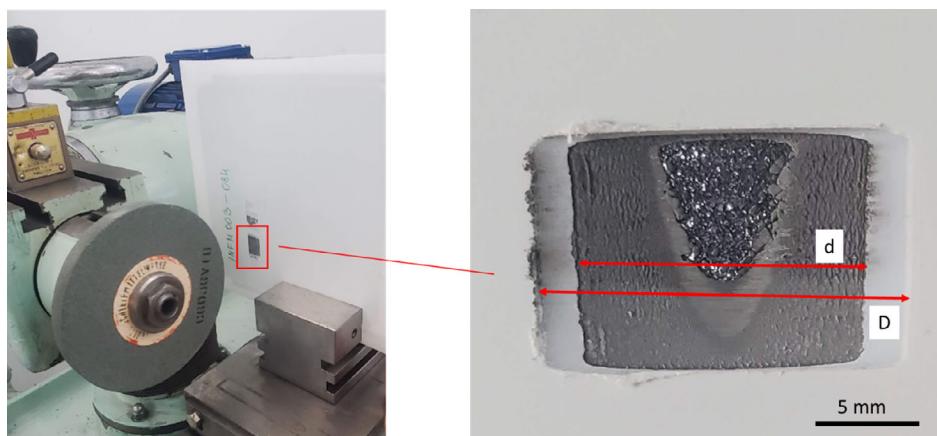


Figure 4. Calotte grinding for exposing individual layers of PV modules and subsequent layer thickness calculation; $d = 14.705 \text{ mm}$; $D = 19.075 \text{ mm}$.

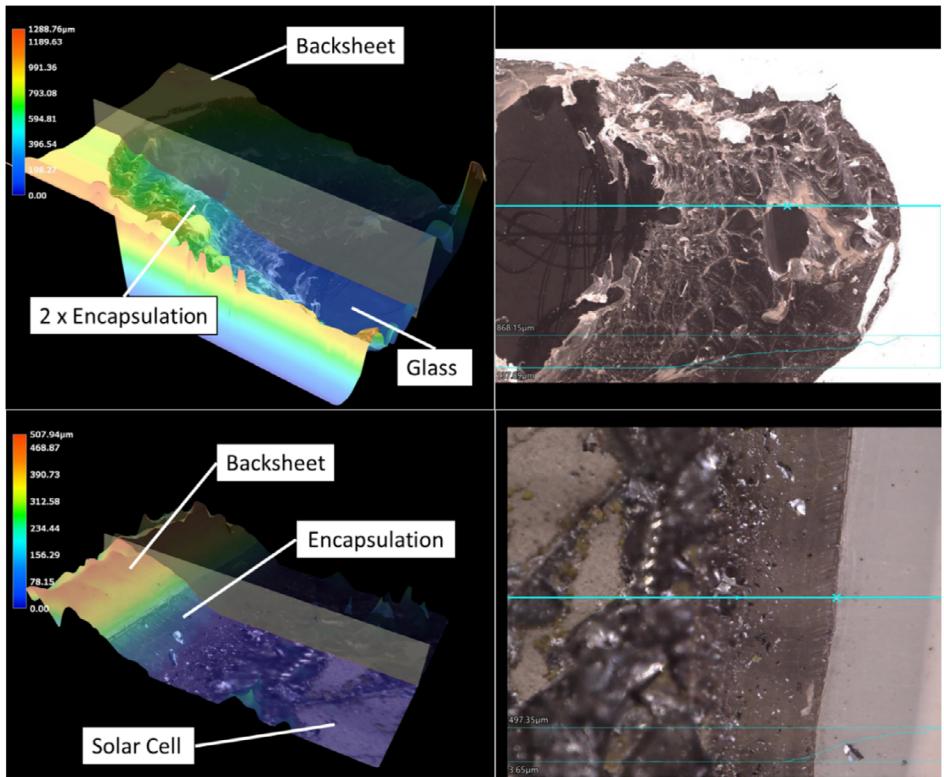


Figure 5. 3D analysis for two locations of a test module resulting from an angular cut through the backsheet; top: outside of the cell area; bottom: above the center of a cell; and turquoise line resembles 2D measurement path for focus adjustment.

angles for the cuts gave significantly better thickness results than steep angles. This may be due to the automatic focus adjustment (depth composition mode) of the 3D optical microscope working more effectively with shallower cuts. Small angles allow a smoother and more gradual transition between layers, allowing the microscope to maintain a consistent focus at each depth and accurately record the layer thickness measurements. It should also be noted that the 3D measurements were taken for demonstration and visualization purposes only; the present layer thickness analysis is based on 2D line measurements as shown in Figure 5 (right).

3.2. Nondestructive Layer Thickness Measurements

3.2.1. OCT

For our study, we used a SweptSource Vega VEG210C1 (Thorlabs) OCT imaging system to measure OCT data, utilizing a laser source at 1300 nm. With an A-scan rate of 100 kHz, the theoretical imaging depth is \approx 11 mm in air. The lateral resolution is 20 μ m, while the axial resolution varies depending on the material. For air, it is in the range of 14 μ m. Our analysis focused solely on the 2D images displayed in Figure 6. These images were captured using a

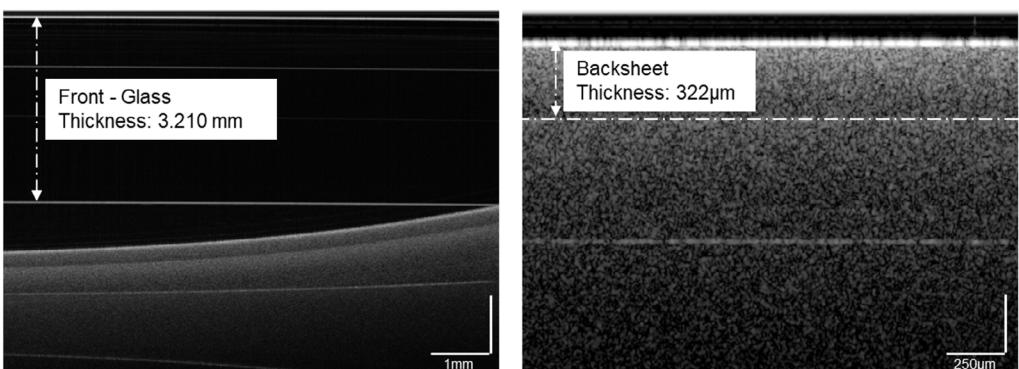


Figure 6. (Left) 2D-OCT scan at the edge of one test module from the front side (transparent stack) and from the back side (backsheet) with the corresponding measured layer thicknesses.

depth slice that spanned 3 mm and had a spatial resolution of 2.93 μm . The measurement depth reached 1.44 mm with a depth resolution of 5.22 μm . For measurements taken from the backside, a refractive index of 1.63 was used, while measurements approaching from the glass side utilized a refractive index of 1.51.

Figure 6 (left) shows an OCT scan from the front side, showcasing the boundaries between the front glass and the encapsulant. The most prominent reflection originated from the interface between the encapsulant and the BS. The image also demonstrated that as one approaches the edge of the PV module, the thickness of the encapsulant material decreases due to the lamination process during assembly. Furthermore, when measuring from the front side, OCT can determine a glass thickness of 3.21 mm, slightly deviating from the nominal value of 3.2 mm provided by the supplier. Figure 6 (right) shows an OCT scan of the BS, revealing the surface of the BS and the first reflection between the BS and the encapsulant material. Despite the weak reflections, a thickness of around 322 μm could be measured.

3.2.2. Coaxial Multicolor Confocal Measurement

For our measurements, we used a Keyence CL-3000 displacement sensor to measure the layer thickness of the BS. The system generates multicolor light by using a blue laser that irradiates a fluorescent element that emits, compared to white light-emitting diodes (LEDs), homogenous more stable, brighter light. The higher light intensity levels ensure a higher light homogeneity at all points in the measurement range, allowing for higher accuracy analysis. Figure 7 (left) showcases the measurement system to conduct measurements in the lab. The system is equipped with a motorized linear stage (LTS300, Thorlabs) for the sample movement to simulate industrial conditions. The system utilizes a pair of synchronized Keyence CL-3000 measurement heads, positioned above and beneath the sample. The sensor on the top captures two reflections—one from the glass surface and another from the BS surface. Concurrently, the sensor on the bottom records a reflection from the backside of the BS. By analyzing variations in the readings from these probes, the system calculates the BS thickness by subtracting the distance information of both sensors. For optimal accuracy, the system requires initial calibration using a standard measure

of known thickness. Operating at a sampling rate of up to 10 kHz, the system enables real-time, nondestructive measurement of the BS layer thickness. Figure 7 (right) shows a measurement result the total module thickness of a test module. The plot clearly shows a height variation along the module width which can be attributed to positions with the underlying interconnects.

Figure 8 presents line scans of the BS and total module thickness along the edge of measurement samples S1–S5. The data highlights significant variations in both the BS material and the overall module thickness across the modules. The BS materials range from ≈ 290 to $330 \mu\text{m}$, while the front glass thickness varies from 2.35 to 3.23 mm.

These values were also compared to microscopic cross-section measurements shown in Figure 9. When comparing the measurement results of the industrial measurements with the microscopic images of the cross sections, one can see that the measurement error is larger for sample S5 compared to samples S1–S4 (Table 2). A notable difference for the samples is in the used BS, which corresponds very well with the datasheet values. Differences could also be explained by slight variations in the refractive indexes of the used glass.

Table 2 shows the overall comparison of the measured and datasheet values for the different BSs and front glasses. For samples S4 and S5, it needs to be added that the BS contains a transparent adhesive layer toward the inside, which cannot be detected by utilizing the current measurement approach (no reflection at interference layer between transparent adhesive and encapsulation). Hence, only the BS layer thickness without this layer can be analyzed. Although the system can measure slight thickness differences of the used materials, our observations reveal that it is highly sensitive to external influences such as surface contamination and other parameters affecting the surface. Notably, the fluctuations in the total module thickness of S1 in Figure 8 (right) can be linked to measurements taken on the busbar, where the system encounters multiple reflections that distort the fitting accuracy due to poor peak selection. It is important to note that such measurement errors can potentially be mitigated through advanced signal processing techniques when integrated into an industrial system; however, these were not within the scope of this study. Overall, there is a good correlation between the reference data and the measurements, demonstrating that the

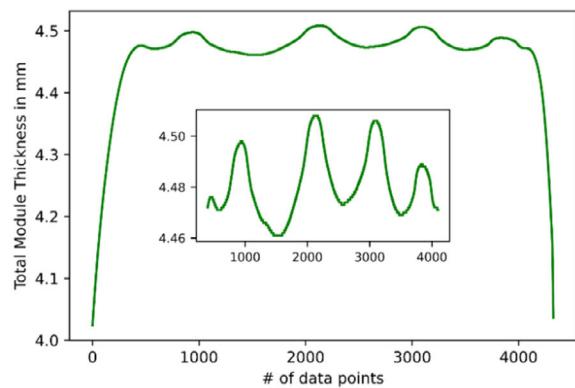


Figure 7. (Left) Measurement system for measuring total module thickness and the backsheet layer thickness; (right) measurement result of the total module thickness of a test module. The insert shows a zoom of the thickness variation along the module width.

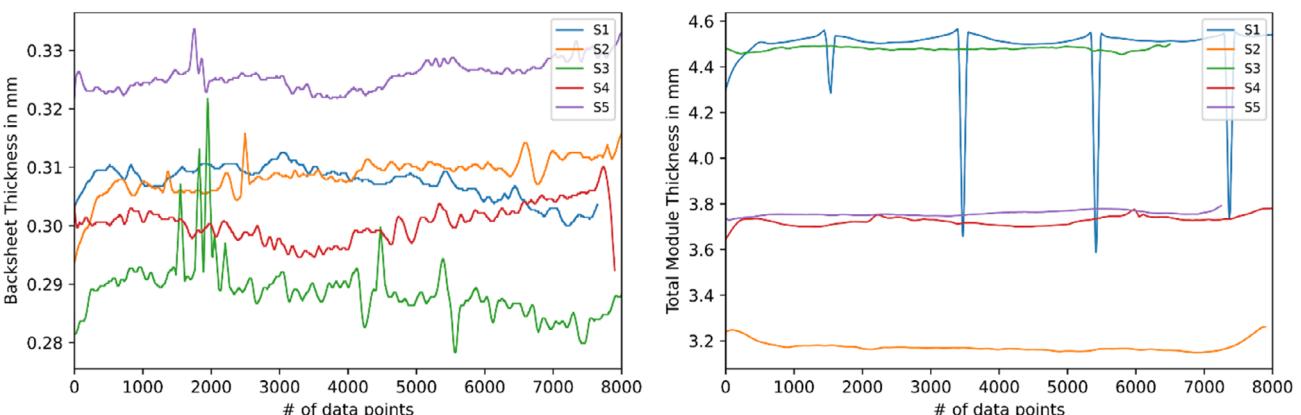


Figure 8. (Left) Measured backsheets thickness and (right) corresponding total module thickness of five test modules.

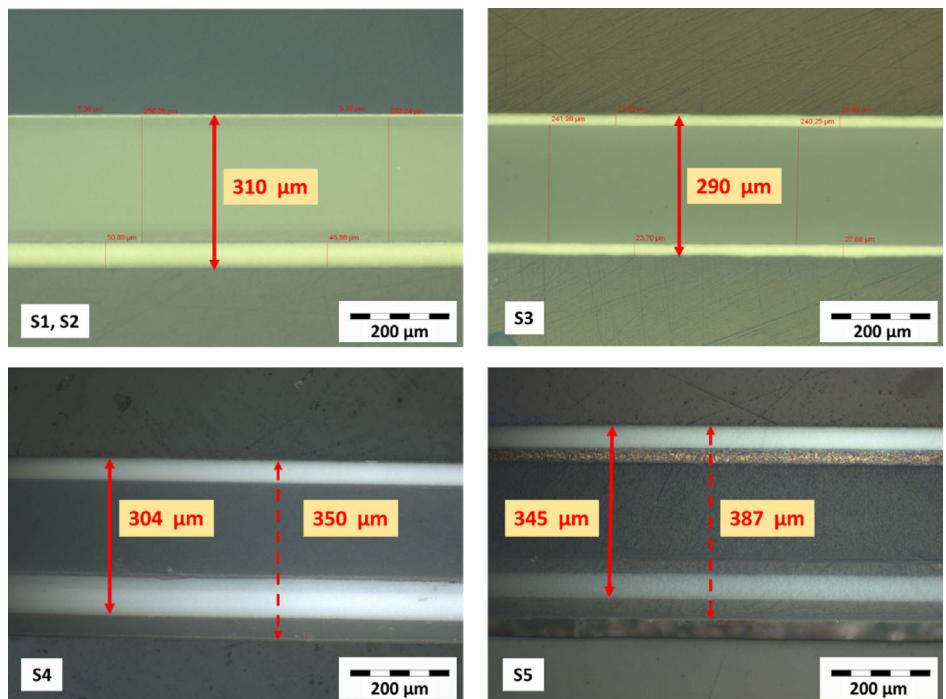


Figure 9. Light microscopy image of cross sections of the backsheets.

Table 2. Measurement results of different backsheets materials and front glasses using the Keyence CL-3000 displacement sensor.

	S1	S2	S3	S4	S5
BS—measured average thickness [mm]	0.307	0.309	0.288	0.300	0.326
BS—datasheet thickness [mm]	0.31	0.31	0.29	0.375	0.39
BS—cross-section measurement [mm]	0.31	0.31	0.29	0.304	0.345
Glass—measured average thickness [mm]	3.229	1.890	3.108	2.343	2.348
Glass—datasheet thickness [mm]	3.2	2.0	3.2	2.3	2.3

system is a very promising tool for real-time thickness measurements of the BS.

3.2.3. Ultrasonic Measurements

The ultrasonic equipment was tested on different BS materials. The three layers of a PPF BS (PET + filler-PET-F-polymer coating) or a Tedlar BS (PVF-PET-PVF) could be detected meaning that for each interface a signal could be detected. However, for a correct determination of the layer thickness, the sound velocity of

each individual layers must be known and used for the evaluation. This requires precise calibration and the knowledge of the BS composition (determination, e.g., by NIR measurements) beforehand. This complicates a potential use in a recycling line. Furthermore, the change in composition of only one of the layers already affects the overall results. Thus, it was decided not to further investigate this method for use in a recycling line.

4. Discussion

Several destructive and nondestructive methods for measuring the layer thickness of polymer foils incorporated in PV module laminates were tested and compared. **Table 3** provides an overview of the comparative data gathered for each method, each of them coming with its own strengths and limitations.

Two widely used destructive methods are calotte grinding combined with optical microscopy and optical 3D microscopy using an angular cut of the material. Calotte grinding combined with optical microscopy is known for its cost-effective implementation, making it accessible for routine quality control and research purposes. Its versatility allows it to be applied to a wide range of materials, providing flexibility in different industrial and laboratory environments. However, this method has its limitations, as grinding polymers can result in relatively rapid wear of the grinding wheel. It also relies on accurate image processing to determine layer thickness, which can be difficult and time-consuming to calibrate. Proper sample preparation, i.e., probe mounting, alignment, and subsequent imaging analysis, is critical to obtaining reliable results, adding extra steps to the process. The resolution of the resulting thickness measurement also depends heavily on the optics used to analyze the spherical section. In addition, the technique provides only localized information on layer thickness, which may not be representative of the entire sample/PV module, and upscaling can be difficult. The industrial, automated integration will be an additional drawback for considering it as efficient method for the proposed recycling approach. In contrast, optical 3D microscopy in an angular cut can be recognized for its high accuracy in measuring layer thickness, making it suitable for applications where precision is critical, though this varies again depending on the optics used. High precision objectives enable a detection of complex surface topographies and layer thicknesses simultaneously with sub-micron resolution. Additionally, it provides 3D depth profiling up to several centimeters, depending on the (open) cut depth.

It is particularly effective in detecting and measuring multiple layers in complex structures, where layers of different materials and colors are present. Similar or identical color layers are difficult to distinguish. This method also requires sophisticated image processing to extract precise thickness measurements. However, as shown, there are tools available specifically designed for this purpose. These tools have built-in vision capabilities and do not require highly trained personnel, but they are expensive. Like calotte grinding, this method provides only local information about layer thickness, which may necessitate multiple measurements at different locations to obtain a comprehensive understanding of the whole measurement sample, resulting in long measurement times. Considering inline measurements, surface topology can be assessed, including total thickness variations of samples. However, layer thickness analysis requires cutting and multistep sample preparation, which is disadvantageous for a scalable and efficient recycling process.

Nondestructive methods for layer thickness measurements offer several advantages, including preserving the integrity of the sample and often providing faster results compared to destructive techniques. OCT is known for its speed and accuracy, also within this work for detecting multiple layers within PV modules. Material identification must be done in a first step to select the refraction indices accordingly for the exact evaluation of the layer thicknesses. In addition to the glass thickness, OCT can also be employed to measure the thickness of polymer layer such as BSs or encapsulants. Its measuring beam can penetrate multiple layers, providing detailed cross-sectional images in the millimeter range with a depth resolution in the micrometer range. Additionally, it is capable of measuring 3D volumetric data. However, the implementation and especially the automatic analysis and interpretation of OCT data can be complex and expensive, posing challenges for its widespread adoption in industrial settings. Substantial development efforts are necessary to adapt the system, and data analysis requires expert knowledge due to potential multiple reflections within the material stack. Coaxial multicolor confocal measurement is fast, affordable, robust, and accurate, making it highly feasible for industrial applications. The system offers high penetration depth through transparent layers of up to several millimeters. However, it has its limitations as it requires two sensor heads, positioned on the top and bottom of the sample to be measured to differentially measure the BS layer thickness. Moreover, textured glass can cause focusing problems, potentially affecting the accuracy

Table 3. Evaluation matrix of potential methods for layer thickness measurements.

Method	Cost [k€]	Measurement time per point [s]	Lateral resolution	Measurement depth	Applicability (layers) ^{a)}	Industrial application
Calotte grinding + optical microscopy	≈1	60	Depending on lens & calotte	μm-mm	BS	Yes
Cut + optical 3D microscopy	≈30	60	Depending on lens & cut	μm-mm	BS, EM, Si	Yes
Ultrasonic thickness detection	≈8	10	10 μm	μm-mm	BS, EM	Yes
Optical coherence tomography	≈85	≈0.1 (2D)	14 μm (Air)	Up to several mm	BS, EM, glass	Difficult
Coaxial multicolor confocal measurement	≈20	Real time	0.25 μm	Up to several mm in transparent media	BS, TS, TT	Yes

^{a)}BS, backsheet; EM, encapsulation material, Si, silicon; TS, transparent stack; TT, total thickness.

Table 4. Advantages and disadvantages of methods for layer thickness measurements.

Method	Advantage	Disadvantage
Calotte grinding + optical microscopy	High precision in layer thickness measurement ($\pm 1 \mu\text{m}$; potential dependence on optics). Can measure multiple layers simultaneously. Cheap system costs.	Destructive method due to grinding through layers. Time-consuming and requires sample preparation (up to several minutes). Inline integration hardly possible.
Cut + optical 3D microscopy	High-resolution imaging for layer thickness ($\pm 1 \mu\text{m}$ possible; potential dependence on optics). Can detect complex surface topographies and layer thicknesses simultaneously (sub μm range). 3D depth profiling up to several cm (depending on cut depth).	Destructive method due to cut. Limited to small sample areas (mm^2 range) and requires sectioning of the module. Time-consuming due to multi step approach (several minutes). Inline measurement just for surface topology (total thickness variations of samples).
Optical coherence tomography	High-resolution, nondestructive and fast for 2D imaging ($\pm 1 \mu\text{m}$). Measuring beam can penetrate multiple layers (mm range) and provide detailed cross-sectional images with depth resolution of ($\pm 5 \mu\text{m}$). Capable to measure 3D volumetric data.	Limited penetration depth depending on material (e.g., polymers typically 1 or 2 mm, glass several mm). Additional material parameters (e.g., refractive index) necessary to measure correctly. Expensive/high system costs. Requires considerable development efforts to adapt the system data analysis requires expert knowledge due to possible multi reflections.
Coaxial multicolor confocal measurement	Very high resolution for surface and near-surface layers ($\pm 1 \mu\text{m}$). High penetration depth through transparent layers up to several mm. Contact-free and nondestructive. Industrially implemented for similar applications. Multiple sensor heads can be used in parallel to cover large areas.	Limited to transparent or semitransparent layers. Nonreflective surfaces (porous, optical absorbers, etc.) prevent measurements and provide wrong measurement readings. Complex calibration required for different materials (refractive indices of measured materials need to be known). Distance between sensor and measurement sample need to stay within reference distance.

and reliability of the measurements. Additionally, multiple sensor heads can be used in parallel to cover large areas and integrate the system into industrial applications.

Ultrasonic thickness measurement is a versatile technique often used for thin layers such as coatings or paints on metal or polymer surfaces. In terms of PV modules, it allows for detecting of all sub-layers of the BS (multilayer laminate). However, to achieve accurate results, a comprehensive database of all BS materials is required, as well as detailed qualitative information on the samples material composition, including the sound propagation velocity for all materials involved. The varying material properties cause signal reflection and attenuation, leading to inaccurate readings. This need for extensive data is a significant limitation, as it necessitates thorough prior knowledge and characterization of the samples. As with other methods, this point measurement technique provides precise thickness information at specific locations on the sample.

The choice between these methods depends on the specific requirements of the application, including the need for cost-effectiveness, accuracy, and the ability to detect multiple layers. **Table 4** gives a summarizing overview of respective advantages and disadvantages for each method (ultrasonic measurements excluded due to its impracticality for [industrial] layer thickness measurements).

5. Conclusion and Outlook

Since more and more PV systems are being installed and the quantities of EoL modules are increasing—with a delay of around

20 years—efficient separation processes and recycling routes must be found for all materials used in the PV modules. In addition to the metal frame and the glass, the multilayer composite made up of encapsulation, BS, Si wafers, and connectors is increasingly becoming the focus of research and development activities. Holistic recycling processes aim to recover the components of this composite material as pure as possible and with a high mass yield. Only then can it be ensured that the materials obtained are used again as high-quality secondary raw materials in the production processes of new PV modules or equivalent replacement products and that material cycles are closed. To achieve layer-by-layer separation through physical (mechanical and/or thermal) delamination processes such as milling, water jet cutting, or high-temperature sawing/cutting, a thorough characterization of the installed components in terms of their thickness and material identity is required in advance. For layer thickness determination—after evaluating several analysis tools with all their advantages and disadvantages—coaxial multicolor confocal measurement appears to be the most suitable method to achieve 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 on the material identity of the polymer layers (encapsulation, BS)—a highly qualified evaluation software and specific databases provided.

For industrial use, input characterization has to be fast and reliable. Coaxial multicolor confocal measurements are fast, affordable, robust, and accurate and thus suited for industrial

applications. A two-step procedure comprising first material identification by NIR spectroscopy (and tabulated refractive index values) highly accurate analysis of the layer thickness of the BS with OCT are also possible.

Overall, this study contributes to the understanding of the advantages and shortcomings of different analysis tools used to identify composite layer characteristics of PV modules. The various mechanical delamination processes (for recycling) require specific—and sometimes deviating—input information and measurement times.

The presented comparative method evaluation is intended to show the possibilities of characterizing the materials installed in EoL or decommissioned PV modules in terms of identity and layer thickness. The obtained information is crucial to identify EoL PV modules which are potentially damaged, (partially) broken, soiled, or covered with biofilm, mosses, lichens, and/or algae. Additionally, this knowledge is not necessarily limited to use in recycling, where the delamination process has to be adjusted to the material composition of the present PV module, but also to the testing process for PV reuse and refurbishment, where information about material composition and constitution is crucial for proper handling of PV modules with restrictions in quality and expected lifetime. Building on the findings of this study, the promising analysis methods will be evaluated on a pilot scale to investigate and assess the industrial applicability, especially with regard to i) the variety of PV modules and ii) the influencing factors of real processing environments. Possible restrictions are being developed. Future research must also deal with the combinability of measuring sensors and delamination tools on the equipment side. Furthermore, it must be ensured that the layer separation can be controlled and optimized in real time, that the process can be adapted to layer and surface irregularities and that the quality of the separated starting material fractions can then be improved.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Lukas Neumaier: Conceptualization (lead); Data curation (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Visualization (lead); Writing—original draft (lead); Writing—review and editing (equal). **Martin De Biasio:** Conceptualization (equal); Data curation (equal); Software (equal); Visualization (equal); Writing—original draft (equal); Writing—review and editing (Supporting). **Anika Gassner:** Conceptualization (equal); Data curation (equal); Methodology (equal); Visualization (equal); Writing—original draft (equal); Writing—review and editing (equal). **Gabriele C. Eder:** Data curation (equal); Methodology (Supporting); Supervision (lead); Writing—original draft (supporting); Writing—review and editing (lead). **Thomas Nigl:** Conceptualization (supporting); Project

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Research data are not shared.

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