Solar-NIRT: Identification of PV-module backsheets in the field with natural sunlight

Oleksandr Stroyuk, Claudia Buerhop-Lutz, Jens Hauch, Ian Marius Peters

Abstract
Reliable and durable solar power plants require PV modules with high-grade polymer encapsulants and backsheets (BSs). For performance analyses of PV installations fast, reliable and non-destructive methods for determining composition and degradation state of polymer components need to be developed. Here, we show that the structure of some common polymer BSs can be determined in the field in real time by analyzing near-infrared transmission (NIRT) spectra collected under illumination with natural sunlight. The potential of this “Solar-NIRT” method was probed by field measurements on a multi-MW PV power plant where four major BS types were identified by multispectral cross-sectional Raman imaging. Additionally, degradation of a particular BS type was found to result in distinct changes in NIRT spectra allowing the degraded BSs to be classified as a separate type. Principal component analysis (PCA) applied to a collection of 62 Solar-NIRT spectra allowed to create a map of five clusters, each corresponding to a particular BS type. The feasibility of using the PCA cluster map for the identification of unknown samples was shown on a test set of 13 different BSs. The Solar-NIRT is relatively fast, non-invasive, selective, can be upgraded to a non-contact regime making it a promising tool for high-throughput characterization.

1 | INTRODUCTION

Degradation of polymer components of silicon PV modules is currently recognized as one of the major issues resulting in module under-performance, failures, and shortened lifetime.1–5 Both organic encapsulant surrounding the silicon wafers and organic module backsheets (BSs) protecting the module from adverse climatic effects can be subject to chemical and mechanical degradation caused by UV irradiation, broad and rapid temperature variations, and attacks by atmospheric gases. The degradation processes in the encapsulant and the underlying BS mutually affect and accelerate each other.2,4–6 As mechanisms of degradative processes can be specific for different encapsulant and BS materials, any proper analysis or monitoring of the degradation status of PV modules should start with the determination of the chemical composition of these materials. Such analysis is also important for the initial quality check of the PV modules before their commissioning because manufacturers typically do not reveal bill of materials used in their products.

The analysis of the chemical composition of encapsulants and BSs should comply with a set of requirements, including a non-contact (or at least non-destructive) character, high speed, reliability, and feasibility of large-scale field measurements. In view of these requirements, infrared spectroscopic methods, such as Fourier-transform (FTIR) and Raman spectroscopy provide unique analytic capabilities, allowing most of the PV-relevant polymer types to be identified and their degradation state to be evaluated with no mechanical or chemical intrusions into the PV modules.6–11 However, both FTIR and Raman are mostly laboratory techniques, with only a few recent

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Both methods are limited by the depth within the material from which data can be gained and can consequently not provide accurate information on multi-layer BS materials. The Raman spectroscopic identification of polymers in aged PV modules can also be impeded by fluorescence from the BSs and encapsulants and is mostly confined to new modules. By all these reasons, there is still a demand for new reliable spectroscopic approaches for fast and non-destructive field identification/inspection of polymer components of PV modules.

Recently, we have reported on a high potential of near-infrared absorption (NIRA) spectroscopy for chemical identification of polymer components of PV modules. This method can be applied to the operating modules directly in the field with no particular preliminary preparations and can provide analytical information on the entire polymer BS and encapsulant layers from a single measurement. By combining NIRA with multi-spectral Raman imaging, we have shown the feasibility of applying this technique for the identification of the structure and composition of more than 10 different configurations of multi-layer BSs based on polyethylene terephthalate (PET) core insulation layers.

Here, we further extend this approach and show that NIRA can be used for the spectroscopic analysis of PV module BSs with no additional excitation light sources, by only using natural sunlight transmitted through the modules. As the characteristic vibration bands of many PV-relevant polymers do not overlap with the absorption bands of atmospheric gases (H₂O, CO₂), we were able to distinguish between four exemplary BS types found on a multi-MW power plant used for testing the method. Additionally, degradation signs were detected for one of the BS types showing the potential of such “Solar-NIRT” spectroscopy for evaluating the degradation status of the module BSs. We expect the presented results to constitute a basis for future development of Solar-NIRT into a non-contact and high-throughput characterization tool.

2 | METHODS

Raman spectra and multispectral maps were collected using a WITec alpha700 confocal Raman microscope coupled to an UHTS 300 spectrometer in a spectral range of 130–3,700 cm⁻¹ with 532-nm laser excitation. Spectral maps were constructed by scanning 1-mm² sample sections using characteristic spectral Raman ranges of BS constituents. Raman mapping was performed on BS cross-section samples produced by detaching a piece of BS from a PV module and cutting the cross-section edge along the BS length. FTIR transmission spectra were recorded from the BS air-sides with a Vertex 70 spectrometer (Bruker) with an attenuated total reflection (ATR) diamond accessory.

The Solar-NIRT spectra were recorded with a FT-NIR Rocket 2.6 spectrometer (Arcoptix) in a spectral range of 900–2,600 nm using natural sunlight. Typically, 20 NIRT spectra were collected consecutively by placing an optical fiber end as a probe to a module air-side spot where sunlight can penetrate the BS and averaged for noise reduction.

3 | RESULTS AND DISCUSSION

3.1 | General description of measurements

The present data were collected during a field measurement campaign on a multi-MW PV power station in Germany during the August–September season of 2020. The field is composed of the 60-cell PV modules from a single major manufacturer and features a broad variation of nominal power classes. More than 500 single modules were tested with NIRA spectroscopy during the campaign using the conventional reflectance mode and sample illumination with a NIR light source.

Along with NIRA, measurements with natural sunlight were carried out. The PV modules were probed from the air-side by placing a free end of an optical fiber to a BS spot between the wafers where sunlight penetrates the module. A “clear-sky” Sun irradiation spectrum was measured by directing a free end of the optical fiber toward Sun unobscured by clouds. In this way, 75 spectra were collected for four different BS types. The verification set (13 samples) was collected on another large PV installation in Northern Germany in June–July 2021.

Simultaneously with the NIR measurements, a collection of BS samples (35 samples) was taken for a detailed Raman study from discarded modules, which contained each of the module types that could be found on the PV power plant. The BS cross-sections were characterized in the lab by multispectral Raman mapping, as discussed in detail in Stroyuk et al., revealing a variety of possible BS structures and compositions. A part of the modules exhibited coextruded polyamide (PA) BSs with outer rutile titania-enriched PA layers and a core layer of a rutile-depleted mixture of PA and polypropylene (PP) reinforced with glass spheres. The rest of the tested modules had multi-layer laminated BSs with a rutile-filled fluoropolymer air-side layer, PET core layer, and an inner layer composed of rutile-filled polyolefins, in particular polyethylene (PE) or PP. The BS samples were categorized into four groups (Table 1) including group A of polyamide BSs and three groups of multi-layer BSs: group B with polyvinyl fluoride (PVF) air-side layer, group C with polyvinylidene fluoride (PVDF) air-side layer, and group D with an air-side formed by fluorinated acrylate-polyurethane copolymer coating (FC).

3.2 | Raman characterization of the BS cross-sections

The polyamide type-A BS cross-section is composed of a single 350–400 μm layer (Figure 1, sample IA) attached to a low-contrast layer of ethylene vinyl acetate (EVA) encapsulant. Raman spectra of type-A BSs (Figure 1, sample IIA) taken from both cross-section edges (points 1 and 3) are identical and show characteristic PA vibrations.
Table 1: Summary of the BS cross sections studied in the present work

| Type | Structure | Air-side (μm) | Core layer (μm) | Inner layer (μm) | Total (μm) |
|------|-----------|---------------|----------------|-----------------|------------|
| A    | R-Polyamide | 350–400       |                |                 |            |
| B    | R-PVF/PET/R-PE | R-PVF (30–40) | PET (160)      | R-PE (50)       | 240–250    |
| C    | R-PVDF/PET/R-PE | R-PVDF (30–40) | PET (330)      | R-PE (80)       | 440–450    |
| D    | R-FC/PET/R-PP  | R-FC (5–10)   | PET (160)      | R-PP (140)      | 305–310    |

The type-B BSs (Figure 1, sample IB) shows Raman bands characteristic for rutile-filled PVF (IIB), in particular a C–H doublet at 2,940/2,960 cm⁻¹ and a C–F vibration at 1,145 cm⁻¹. The core layer was identified as PET, while the inner layer shows characteristic features of rutile-filled PE.

The type-C BSs (Figure 1, sample IC) was identified as rutile-filled PVDF based on characteristic peaks at 800/880 cm⁻¹ and the shape of C–H band (Figure 1, IIC) both typical for crystalline PVDF. Similar to type B, the core and inner layers were identified as PET and rutile-filled PE. A multispectral Raman map of type C BS (Figure 1, IIC) shows thicker core PET and inner PE layers as compared to type-B (see Table 1).

The air-side Raman spectrum of type-D BSs (Figure 1, sample ID) is very similar to the spectrum of PET with some additional minor

![Figure 1](https://example.com/figure1.png)
peaks and distinct rutile series (Figure 1, IID, curve 1), indicating that this layer is too thin to be reliably identified by Raman spectroscopy. Additional probing of the air-side layer with FTIR spectroscopy (Figure 1, IID, curve 4) revealed the presence of two C=O species (bands at 1,720 and 1,680 cm\(^{-1}\)) assigned to free and amide carbonyls as well as CF\(_2\) and CF\(_3\) fragments seen by C-F vibrations at 1,146/1,240 cm\(^{-1}\).\(^{8,21,26}\) Basing on these observations, the air-side polymer was identified as a rutile-filled fluorinated copolymer coating (FC).\(^{18}\)

The core layer of type D BSs is typical PET (Figure 1, IID, curve 2), while the inner layer shows characteristic signs of rutile-filled PP.

### 3.3 Solar-NIRT spectra

Sunlight passes through the BS and is collected by a NIR spectrometer. The fraction of the transmitted light depends on thickness and scattering capacity of each BS (Figure 2). Typically, a cross point between four neighboring Si wafers was used to collect the transmittance spectrum as indicated by points marked "1" in Figure 2. A reference solar irradiation spectrum was measured together with each transmittance spectrum, typically using a gap between adjacent PV modules (point 2 in Figure 2).

Additionally, a conventional NIR reflectance spectrum was measured for each BS by using the lamp excitation and converted into a NIRA spectrum. In this way, for each BS, a set of three spectra was collected including NIRA, Solar-NIRT, and reference solar spectrum.

The “clear-sky” Sun NIR irradiation spectrum used as a reference shows intense water absorption bands at 1,350–1,500 nm and 1,800–1,960 nm, as well as sharp CO\(_2\) absorption bands at about 2,000 and 2,060 nm (Figure 3A-D*, curve 1). However, in the range of 1,500–1,800 nm, a gap exists in absorption by atmosphere gases allowing this range to be used for analytical purposes. The range of 1,950–2,200 nm can also reveal vibration bands of polymer materials not entirely masked by relatively sharp CO\(_2\)-related absorption bands.

In the case of PA type A BS, both BS and EVA encapsulant are expected to contribute to Solar-NIRT spectrum. The corresponding contributions can be inferred from conventional NIRA spectra. In particular, PA shows a characteristic C–N–H vibration band at 2,045 nm as well as a combination of aliphatic C–H vibration bands at 1,700–1,800 nm.\(^{13,17}\) (Figure 3A, curve 2). Both these components can be expected in the Solar-NIRT spectra. The EVA encapsulant shows a characteristic C=O vibration band at 2,140 nm as well as aliphatic C–H series at 1,700–1,770 nm (Figure 3A, curve 3) which should also be observable in the Solar-NIRT spectra.

The PVF-based type B BSs show a low sunlight transmittance (Figure 2B) and a noisy NIRA spectrum (Figure 3B, curve 3) most probably due to the rough air-side morphology, strongly contributing to the NIR light scattering. The NIRA spectrum reveals a weak aromatic=C–H vibration band at 1,660 nm and a triplet at 2,120–2,190 nm originating from the PET core layer and a C–H series at 1,700–1,800 nm found for almost any organic polymer. These features can also be observed in the Solar-NIRT spectrum despite the low transmittance (Figure 3B, curve 2). In particular, weak bands at 1,660, 2,130, and 2,160 nm allow this BS to be definitively identified as a multi-layer PET-based material.

The case of PVDF-based type C BSs most vividly exemplifies the benefits of the Solar-NIRT spectroscopy as compared to conventional NIRA. When probed by lamp excitation in the reflectance mode, this BS reveals a complex interference pattern hindering any meaningful analysis of the NIRA spectrum (Figure 3C, curve 3). At the same time, the Solar-NIRT spectrum of this BS shows PET-related characteristic features at 1,660, 2,130, and 2,160 nm as well as a C–H series at 1,700–1,740 nm (curve 2), clearly distinguishable against the reference Sun spectrum (curve 1). The relative intensity of 1,660-nm PET-related band is higher in this case as compared to type B BS. The types B and C BSs have roughly the same thickness of air-side fluoropolymer layer (Table 1) but distinctly different air-side
morphology—rough for the B type BS and very smooth and uniform for the C-type BSs. In this view, the difference in the intensity of PET-related signals was assigned to a lower light scattering by the surface of type C PVDF-based BSs.

The type D BS shows the most pronounced PET features in the NIRA spectrum (Figure 3D, curve 3) among all PET-based BS samples, because this BS type has the thinnest air-side fluoropolymer layer. By this reason, the NIRA spectrum of a type D BS is dominated by $\pi-\pi^*$ vibration bands. Additionally, a sharp aliphatic $\text{C}==\text{H}$ doublet at 1,710 and 1,730 nm, C-O-C vibration at 1,950 nm, and a water-related $\text{O}==\text{H}$ vibration band at 1,910 nm can be observed. The Solar-NIRT spectrum of type D BSs expectedly shows clear PET-related bands at 1,660, 2,130, and 2,160 nm (Figure 3D, curve 2) with a perfect correspondence to NIRA.

The above examples show that both PET- and PA-based BSs can be identified by their spectral signatures even despite the presence of EVA-related features in the Solar-NIRT spectra. By this reason, we did not discriminate contribution of EVA to the Solar-NIRT spectra and used them as-registered for further spectral analyses.

Some of the PV modules with type-D BSs showed signs of discoloration (browning) of the BS material, indicative of BS degradation (type $D^*$). Such modules can be easily distinguished by characteristic brown coloration both from the PV module front and from the back of the module in the transmitted sunlight (compare D and $D^*$ in Figure 2). NIRA testing on unaffected sections of the air-side BS revealed it to be type D FC-based material.

The browning of PET-based material is a well-reported degradation mode resulting from UV irradiation alone or combined with other climatic factors and is assumed to originate from photochemical fragmentation of PET chains and formation of additional conjugated fragments. This assignment is supported by our NIRA findings which show a much higher relative intensity of $\pi-\pi^*$ vibration bands of $D^*$ BSs as compared to non-degraded D samples (compare curve 3 in Figure 3D and $D^*$).

These degradation-induced changes can also be observed in the Solar-NIRT spectra (compare curve 2 in Figure 3D and $D^*$). The Solar-NIRT spectrum of $D^*$ shows a much more pronounced $\pi-\pi^*$ feature at 1,660 nm indicating a higher contribution from aromatic species in

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**FIGURE 3** (A–$D^*$) Examples of Solar-NIRT spectra of BSs of different type A–$D^*$ registered using both lamp NIR light and natural sunlight. Curve 1, NIR spectrum of Sun at the measurement site; curve 2, Solar-NIRT spectra; curve 3, NIRA spectra measured with a lamp. (E) Solar-NIRT spectra registered by contacting the probe fiber with BS (curve 1) and from a 5 cm distance (curve 2).
D* as compared to type D samples. These observations indicate that both NIR and Solar-NIRT can be used not only for the identification of BS composition and structure but also be useful for the analysis of degradation of PET-based BS materials.

In comparison to more conventional NIR spectroscopy, the Solar-NIRT approach can potentially be used for remote identification of BS materials by collecting and analyzing the solar light penetrating the semi-transparent BSs from a distance. We probed the feasibility of such measurement regime on the example of a D-type module collecting the solar light between the silicon wafers on a distance of 5 cm from the BS surface with the optical fiber aligned normally to the module air side. The Solar-NIRT spectra registered by touching the BS surface with the probe (Figure 3E, curve 1) and from the distance (curve 2) were found to be identical in terms of structure showing almost the same intensity of analytical signals. This example illustrates the feasibility of applying Solar-NIRT for remote inspection of PV plants.

### 3.4 Multivariate analysis of NIRT data

The Solar-NIRT spectra of different multi-layer PET-based BSs show a similar structure, only varying in relative intensities of aromatic \( \equiv \text{C} - \text{H} \) and aliphatic \( \text{C} - \text{H} \) vibration bands (Figure 3). These differences are difficult to evaluate directly from the spectra but can be uncovered using multivariate analysis.\(^{27}\) In particular, principal component (PC) analysis allows evaluating the variance among Solar-NIRT spectra and allows presenting them as a set of clusters.

The PC analysis was performed on a collection of 75 Solar-NIRT spectra for BSs from types A to D and D*. A portion of the Solar-NIRT spectra were selected as a test set, totally 13 spectra from each of five above-described different BS types (A, B, C, D, and D*) to verify the applicability of the PC analysis results for the BS identification. The Solar-NIRT spectra were analyzed in the range of 1,400–2,300 nm with a step of 5 nm taking each wavelength as a variable. A set of PCs was calculated, reflecting the variance between the Solar-NIRT spectra and was arranged by significance as PC1, PC2, etc.

The “PC1 versus PC2” plot presented in Figure 4a shows that all tested BS types can be reliably distinguished by the position of their respective clusters. Each point on the graph represents a single Solar-NIRT spectrum and belongs to one of the clusters according to their specific spectral features. A scree plot presented in Figure 4b shows that the first two principal components, PC1 and PC2, are responsible for almost 90% of variance observed between the tested Solar-NIRT spectra. In this view, we can neglect further PCs and analyze the Solar-NIRT spectra by using 2D “PC1 versus PC2” plots without major losses in variance. A loading plot of PC1 and PC2, that is, the distribution of variance as a function of wavelength (Figure 4c), shows that variance among the Solar-NIRT spectra is concentrated in characteristic PET-related features at 1,660 nm and 2,130/2,150/2,180 nm.

Type A polyamide BSs show no PET-related signals, and, in this respect, they differ from other BS types in the most decisive way. The corresponding cluster (A) stands apart from other clusters (Figure 4a). Types B and C have similar Solar-NIRT spectra, and the corresponding

![Figure 4](https://via.placeholder.com/150)

**Figure 4** (a) PC analysis plot showing clustering of the Solar-NIRT spectra of various BS samples; (b) scree plot showing contribution of PCs into the total variance among the Solar-NIRT spectra; (c) component loading plots for PC1 and PC2 along with an exemplary Solar-NIRT spectrum of a degraded type D BS; (d) results of the identification of the test set samples using PC analysis.
clusters are close but still in different quadrants, distinctly resolved by their geometric position.

Cluster D stands apart both from PA BSs and from samples B and C, due to the very thin air-side fluoropolymer layer, resulting in distinct PET-related features in the Solar-NIRT spectra. The PV modules with degraded type D* BSs show even higher intensity of the aromatic =C−H vibration bands and form a separate cluster. The results show that the geometric position of any D-type BS in the PC plot relative to the centers of clusters D (non-degraded BSs) and D* (strongly degraded BSs) is indicative of the degree of this particular type of degradation. We are currently in the progress of collecting type D BS samples from different solar fields with a different browning depths to test this assumption experimentally.

By using the categorization of BS types based on multi-spectral Raman mapping, as well as the library of 62 Solar-NIRT spectra presented in the PC plot (Figure 4a), we can now determine the BS type (and the BS degradation state for the case of type D) for any PV module installed on a given PV field only from the Solar-NIRT spectrum of the tested sample. We only need to add a tested spectrum to the library of spectra (“library +1”) and perform the PC analysis again to determine the geometric position of the tested spectrum on the PC plot.

The feasibility of the Solar-NIRT identification using the principle “library +1” was probed by using a test set of 13 PV modules representative of all five BS types studied in the present work. The results of the test (Figure 4d) showed all samples within the expected clusters. Further work is in progress to collect more statistical information on the studied BS types by field measurements.

If the geometric place of the tested sample differs from all presented clusters, we can conclude that we encounter a new BS type or a strongly degraded A-D BSs. In this case, we need to perform an additional multi-spectral Raman study of the new BS cross-section, associate the structure of such BS with its Solar-NIRT spectrum, and add the spectrum to the presented PC plot. The library of cataloged BS types can be constantly expanded increasing the accuracy of the Solar-NIRT analysis.

The Solar-NIRT identification is performed using ambient sunlight with no additional NIR light source required to probe the sample, and therefore, it may potentially be carried out in a non-contact way by collecting the sunlight coming through the backsheets distantly by a system of lenses. A combination of this capacity with a relatively high acquisition and processing speed of the Solar-NIRT spectra (totally less than 1 min per PV module), a high selectivity of the PC analysis evidenced by the present report and portable character of the measuring equipment makes the Solar-NIRT a promising tool for the non-invasive and non-contact high-throughput characterization of PV power plants.

4 | CONCLUSIONS

The composition and structure of some of common polymer BSs of commercial silicon PV modules can be determined in the field by analyzing NIR transmission spectra collected using illumination with the natural sunlight (“Solar-NIRT” spectra).

The Solar-NIRT spectra were found to provide as much analytical information as conventional NIRA spectra registered by using NIR light sources in a reflectance mode. The applicability of the Solar-NIRT analysis is shown on an example of a large multi-MW PV power plant where four major BS types were identified and their composition and cross-sectional structure determined by using Raman spectroscopy. In particular, we focused on polyamide-based single-layer BSs as well as on multi-layer PET-based BSs having different air-side fluoropolymer (PVF, PVDF, FC) and inner polyolefine (PE, PP) layers. These four BS types revealed characteristic differences in the Solar-NIRT spectra, which can be uncovered by applying a multivariate PC analysis allowing all four types to be reliably distinguished.

We found that photoinduced browning of FC-based BSs results in distinct spectral changes in NIR range allowing this particular degradation event to be tracked by the proposed analysis as well.

The proposed Solar-NIRT approach is expected to evolve into a selective, non-destructive and non-contact method for human-assisted or automated high-throughput characterization of large PV installations.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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