

Evolution of inverter ground impedances for PV modules with various backsheets types

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Abstract

Herein, we present results that emphasize the importance of retaining high insulation resistance in polymer backsheets for the reliable operation of photovoltaic installations. By correlating inverter monitoring data, meteorological data, and spectroscopic information from backsheets materials of photovoltaic modules, we derive performance and degradation rates for inverters connected to photovoltaic modules with several backsheets types. The feasibility of evaluating the degradation status of photovoltaic modules in the field through spectroscopic analysis of the water content in backsheets and encapsulant is demonstrated. We show that an increase in water content is a sign for reduced leakage resistance. Ground impedance was measured alongside relative humidity and temperature for three specific backsheets types. Inverters with polyamide and fluorinated coating/polyethylene terephthalate backsheets showed a significant drop in ground impedance at high humidity, $RH > 70\%$. A loss rate of $-2 \text{ k}\Omega/\text{day}$ in ground impedance was found for inverters connected to modules with certain fluorinated backsheets. This value is twice as high as for inverters connected to modules with polyamide backsheets. Time series show that the sensitivity to moisture and water ingress increases with time, especially for modules with polyamide and certain fluorinated backsheets. The worst degradation scenario observed had an annual yield loss of 27% due to inverter outages on humid days. About 25% of inverter trip alerts after 8 years of operation included modules with the specific fluorinated backsheets. In general, the study revealed a distinct backsheets impact on ground impedance and operation of inverters and the resulting yield showing an important role of the choice of polymers for reliable and long-lasting photovoltaic systems.

KEYWORDS

degradation, ground impedance, insulation resistance, near-infrared spectroscopy

1 | INTRODUCTION

Inverters are a key component in green energy production by photovoltaic (PV) power stations. They invert DC to AC, and they ensure grid integration of PV power stations and feed-in of the produced energy. At the same time, inverters collect and provide numerous monitoring data, including general performance indicators and ground impedance (GI), the latter characterizing cumulative insulation resistance of the modules serviced by each specific inverter. The safe and continuous operation of inverters is a prerequisite for the successful implementation of PV energy conversion, and this task is regulated by numerous international and national standards covering inverter operation, performance measurements, safety, installation mode, and so forth.^{1–3}

While inverters are supposed to operate safely and efficiently, their operation depends on the performance and insulation state of each PV modules connected to it. Numerous standards and limitations are in place to ensure safe operation of the inverters, in particular, a minimal threshold insulation resistance (or GI) of 1 M Ω . Often, manufacturers specified an even lower preset GI threshold, for example, 400 k Ω . If the measured GI falls below the preset threshold, the inverter does not start and does not connect to the grid, resulting in noticeable losses in PV yield and revenue, if countermeasures are missing.

Recently, degradation of protective polymer backsheets (BSs) of PV modules has been recognized as a major reason for the loss of insulation resistance (R_{iso}) on the module level.^{3–6} Despite the fact that the R_{iso} loss typically is not directly resulting in losses in power efficiency, yield is still lost. A single module with critical low R_{iso} is enough to prevent the inverter from starting and from connecting to the grid. Depending on the preset inverter configuration, there are repeated attempts for grid connection or a limited number of attempts. In a best case scenario, the inverter restarts successfully after a short period necessary for the affected modules to dry under solar illumination and restore their insulation resistance. In a worst-case scenario, the inverter is shut down for the whole day if countermeasures are not set in place.

Monitoring data on inverters of moderately aged PV plants (6–10 years) show clear signs of weather-dependent behavior, with some inverters not functioning properly during humid seasons and days, rainfalls, snow deposits, and so forth.¹ As we found recently, different BS types vary in their resistance to metal corrosion and water ingress, reflecting different mechanisms and dynamics of environmental degradation.^{5,6} These observations indicate that the weather-dependent behavior of inverters can originate from differences in the composition and structure of BSs of PV modules connected to the affected inverters.

The present study addresses two major aspects: (i) how field aging and degradation of polymer components of the PV modules, in particular, backsheets (BS), provide driving forces for inverter outages and tripping alerts and (ii) to which extent the degraded BSs evolve into a risk factor for yield and income of PV installations.

Our approach relies on a dataset of BSs collected from about 5,000 PV-modules from 68 inverters in one multi-MWp PV power station. Historic monitoring data recorded by inverters were collected for this BS dataset and linked with public weather data. Correlating weather and ground impedance data enhanced the extraction of BS-specific rates of insulation resistance loss.

Environmental moisture is a powerful driving force for the development of various failure modes of PV modules, including potential-induced degradation (PID) of silicon cells, corrosion of metal interconnects, as well as oxidation and delamination of polymer encapsulants and BS components, the polymer degradation strongly enhanced when moisture ingress is combined with other stress factors.^{4,7,8} To address this issue, we combined lab and field studies of water ingress into BSs of different types and its effect on the measured insulation resistance of moisture-affected modules. As a result, we provide an outlook of how different polymer backsheet materials in PV-modules influence the operation of inverters in the field with respect to relative humidity. As a summary, a worst-case scenario is presented that addresses a potential impact of BS degradation on the expected yield of a PV plant.

2 | METHODS

2.1 | Insulation resistance measurements

The insulation resistance (R_{iso}) of PV modules was measured in the lab conditions at 23–24°C by completely immersing a PV module into a bath with aqueous electrolyte.⁵ In kinetic experiments, the module was left immersed in the bath at a constant temperature, and R_{iso} was measured periodically without extracting the module from the bath. Six PV modules were tested in this way with three different BS structures (FC1, PA, and PVDF1; see explanation of the abbreviations below) and two identical modules per BS type. All six modules were from the same tier-one manufacturer, with equal power class, age, and deployment history. The initial R_{iso} loss rate was determined as a decrement of the insulation resistance during the first hour of immersion.

2.2 | Spectral measurements

The BS type was identified non-destructively by using near-infrared absorption (NIRA) spectroscopy.⁹ The NIRA spectra of BSs were registered from the air-sides and the BS type identified by comparing the measured spectra with the earlier reported BS database providing unambiguous BS identification.¹⁰

Kinetic lab measurements of R_{iso} were supplemented by NIRA tests showing the dynamics of water ingress and evaporation.⁵ The water ingress was tracked by periodically extracting the module from the aqueous electrolyte bath, registering NIRA spectrum of the BS, and placing the module back into the electrolyte bath. The water

evaporation was tracked by periodically measuring the NIRA spectra of the BS of a module that was extracted from the electrolyte bath and left drying at 23–24°C and relative humidity of 40%.⁵

The tested module was subjected to several cycles of water immersion and drying with periodical measurements of NIRA spectra during both immersion and drying stages focusing on the first 3–4 h of water ingress/evaporation.

The water content was determined from NIRA spectra as a ratio of intensities of water-related absorption band at 1,910 nm and a reference C-H band at 1,730 nm using an established procedure.⁹ The rates of water ingress/evaporation were determined as an increment/decrement of the relative intensity of water-related 1,910 nm band during the first hour of immersion/drying, respectively. Field measurements of water content were performed by registering pairs of NIRA spectra from the air side (water identification in BS) and frontal side (water identification in EVA encapsulant) of the PV modules in the lower rows of the PV plant. The pairs of air/frontal NIRA spectra were collected for 311 PV modules during 2 weeks of measurements under the same weather conditions.

2.3 | Dataset

A dataset consisting of modules with known BSs and inverter GI was collected and combined with public weather data. The dataset was generated from a 6.8 MWp PV power station commissioned in 2012 including information about the BSs of all 28,030 PV-modules, collected through field analysis using NIRA spectroscopy⁷ as well as the historic GI data of 423 inverters. Seven BS types were identified: one non-fluoropolymer and six single-fluoropolymers differing in composition and layer thickness (differing single fluoropolymers [PVF, PVDF,

FC] marked by index 1 and 2). Details about these BSs can be found elsewhere.² Table 1 gives a summary of BS composition and occurrence.

For studying the BS-related GI evolution, 68 inverters with exclusively one BS-type were selected, namely, PA, FC1, and PVDF1; see Table 2, addressed as PA-inverters, FC1-inverters, and PVDF1-inverters (the other 355 inverters had multiple BS types). For these BS-labeled inverters, the GI values were linked to averaged daily humidity data.

For the statistical analysis of the GI evolution, 2,792 days (slightly less than 8 years) of historic data were available. These data were linked with publicly available weather data.¹¹ The weather conditions at the site of installation analyzed on an annual base can be described as follows: mean daily temperature $\bar{T} = 11.1 \pm 8.2^\circ\text{C}$, range of daily relative humidity $RH = 34\text{--}95\%$; see Figure 1A (median $RH_{p=0.5} = 77\%$), mean daily rainfall $\bar{r} = 0.01 \pm 0.01 \text{ kg/m}^2$, mean daily irradiance $\bar{E} = 3.62 \pm 2.4 \text{ kWh/m}^2$; see Figure 1B (median $E_{p=0.5} = 3.1 \text{ kWh/m}^2$, 5%-percentile $E_{p=0.05} = 7.6 \text{ kWh/m}^2$, 95%-percentile $E_{p=0.95} = 0.4 \text{ kWh/m}^2$). The dataset was binned with respect to relative humidity (RH).

3 | RESULTS AND DISCUSSION

In the present paper, we focus on three representative BS types, PA, FC1, and PVDF1, that totally account for almost 80% of PV modules included in our dataset (see Table 1). The representative field-aged modules with these BS types identical to those inspected on the PV power plant were first subjected to lab insulation resistance tests. The R_{iso} tests were performed in exaggerated conditions, that is, by complete immersion of the modules in the aqueous electrolyte for many

TABLE 1 Overview of identified BSs and their occurrence

	Identifier	Air layer	Core layer	Inner layer	Fraction
Non-fluoro-polymer	PA	PA	PA	PA	19%
Single-fluoro-polymer	FC1	FC	PET	PP	28%
	FC2	FC	PET	PP	6%
	PVF1	PVF	PET	PE	4%
	PVF2	PVF	PET	PE	3%
	PVDF1	PVDF	PET	PE	30%
	PVDF2	PVDF	PET	PE	9%

Abbreviations: FC, a fluorinated coating; PA, polyamide; PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PVDF, polyvinylidene fluoride; PVF, polyvinyl fluoride.

TABLE 2 Overview of aggregated data in terms of BSs and inverters for inverters with exclusively PV modules with one BS type, PA, FC1, and PVDF1

BS type	No. of modules per inverter	No. of inverters	No. modules
PA	69	14	966
FC1	69	34	2,346
PVDF1	69	20	1,380
total		68	4,692

hours, resulting in an accelerated water ingress and providing the general overview of water ingress dynamics and insulation behavior of such BS types.

As a second step, we provide an analysis of GI monitoring for selected inverters that service exclusively PV modules with PA, FC1, and PVDF1 BSs showing a good correspondence between trends observed in the lab and in the field. This analysis is supported by field measurements of water content in PV modules with PA, FC1, and PVDF1 BSs, showing clear differences in the insulation behavior among these BSs and specifically a prominent liability of FC1-type modules to the insulation loss.

Finally, we provide an analysis of expected yield and yield losses with respect to local weather conditions and identify the worst scenario of humidity-related yield losses depending on the BS type.

3.1 | Lab tests of water effect on PV modules with different BS types

The insulation state of PV modules with three different BS types, FC (corresponds to FC1 in Table 1), PA, and PVDF (corresponds to PVDF1 in Table 1), was probed in the lab by total-immersion leakage resistance test coupled with NIRA measurements.⁵ In a typical test, the module was completely submerged in an aqueous electrolyte at controlled temperature (22°C), and the initial R_{iso} was measured. As we were interested mostly in the effect of BS type on the insulation resistance and R_{iso} loss, the submersion was limited to ~5 h, and afterwards, the module was extracted and NIRA spectra registered periodically from the air side to collect data on the kinetics of drying.

Six samples were subjected to R_{iso} tests, two per each BS type, all modules produced by the same tier-one manufacturer and having the same power class, age, and field history. We found that both the initial R_{iso} and the rate of R_{iso} loss depend on the BS type of the tested modules. Samples with PVDF-type BS revealed the highest initial R_{iso} of ~250 MΩ and the lowest R_{iso} loss rate of ~4 MΩ/h (Figure 2, green diamonds). Modules with FC-type BS showed the lowest initial R_{iso} in the range of 10–50 MΩ and the highest R_{iso} loss rate of more than 10 MΩ/h (Figure 2, red circles). Modules with PA-type BS occupy an intermediate place with initial R_{iso} in the range of 160–180 MΩ and the R_{iso} loss rate of 6–7 MΩ/h (Figure 2, blue squares). Considering the same history of the modules as well as the same EVA encapsulant as shown by NIRA, the differences in the insulation behavior can be directly related to different BS materials. Some additional factors potentially affecting R_{iso} , for example, a variation of EVA properties due to the presence of small amounts of additives, cannot be excluded completely as well, but detection of such additives in EVA is currently beyond the sensitivity limit of our spectroscopic approaches.

Recently, we have shown that water ingress/drying can also be tracked by NIRA spectroscopy of the air sides of the tested modules using the characteristic 1,910 nm band of water.⁵ In particular, water ingress can be detected by a growth of the intensity of the water band during immersion with all other spectral features remaining unaffected. When the module is extracted from the electrolyte bath and left for drying, the process of water evaporation from the module can be tracked by NIRA in the similar manner. This cycle of water ingress/drying can be repeated many times (four cycles presented in Figure 3A) showing a reversible character of water penetration into the PV module. In the present work, we used much shorter

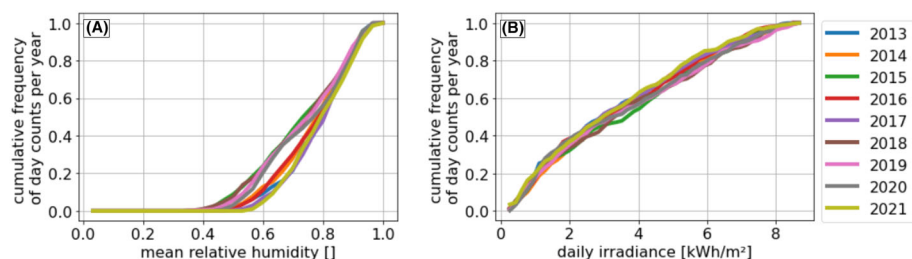


FIGURE 1 Cumulative frequency of daily relative humidity (A) and daily irradiance (B) for 9 years of operation

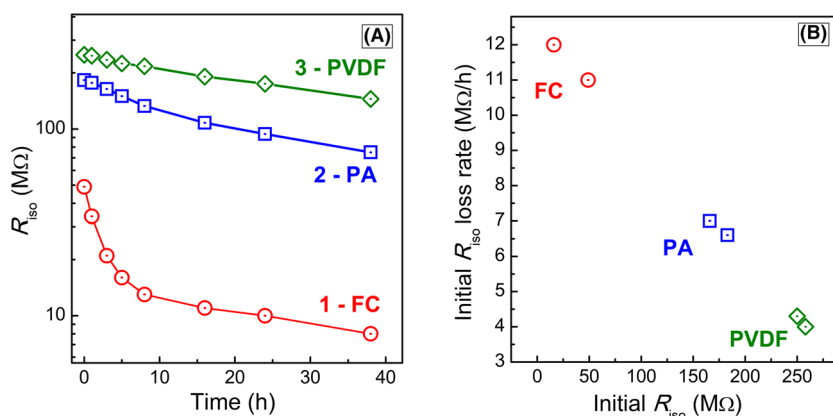


FIGURE 2 (A) Kinetic curves of R_{iso} loss during the immersion of PV modules with FC-type (curve 1), PA-type (2), and PVDF-type (3) BSs in an aqueous electrolyte bath. (B) Initial rate of R_{iso} loss as a function of the initial R_{iso} for three different BS types

submersion periods as compared the previous report,⁵ and, therefore, NIRA measurements during the water ingress stage can be compromised by partial drying of the module during spectral measurements. By this reason, we evaluated only the drying rates, which are also BS-dependent and proportional to the rates of water ingress.⁵

It was found that the modules with FC-type BSs show the highest drying rate (Figure 3B, red circles). Coupled to their lowest R_{iso} , this observation indicates FC-BSs could be expected to be most penetrable for the environmental moisture. The modules with PVDF-type BSs showed the lowest drying rate (Figure 3B, green diamonds) and the highest R_{iso} , indicating that BS poses a more reliable barrier both for the ingress of water and for subsequent drying. The modules with PA-type BSs again showed an intermediate rate of drying (Figure 3B, blue squares).

Summarizing the lab observations, we conclude that the dynamics of water penetration into field-aged modules depends quite

considerably on the BS type. The insulation efficiency increases from FC- to PA- to PVDF-type BSs. The case of FC BSs showed the highest rates of water ingress and evaporation allowing to expect the highest dependence of the electrical behavior of such modules on the environmental conditions, in particular, relative humidity.

3.2 | Analysis of ground impedance

Figure 4A visualizes the distribution of all inverters of one BS-type for several particular days for different years. It shows the trend how the GI distribution shifts throughout 9 years of operation. In particular, the GI distribution of PA and FC1 inverters is reduced significantly within this period. GI falls below the threshold of $GI = 400 \text{ k}\Omega$ for many FC1-type inverters. In contrast, PVDF1 remains on a relatively high GI-level.

FIGURE 3 (A) Kinetic curves of NIRA water signal rise/fall recorded for PV module with FC BS at for four consecutive immersion/drying cycles (immersion events are marked with blue bars). (B) PV module drying rate as a function of the initial R_{iso} for three different BS types

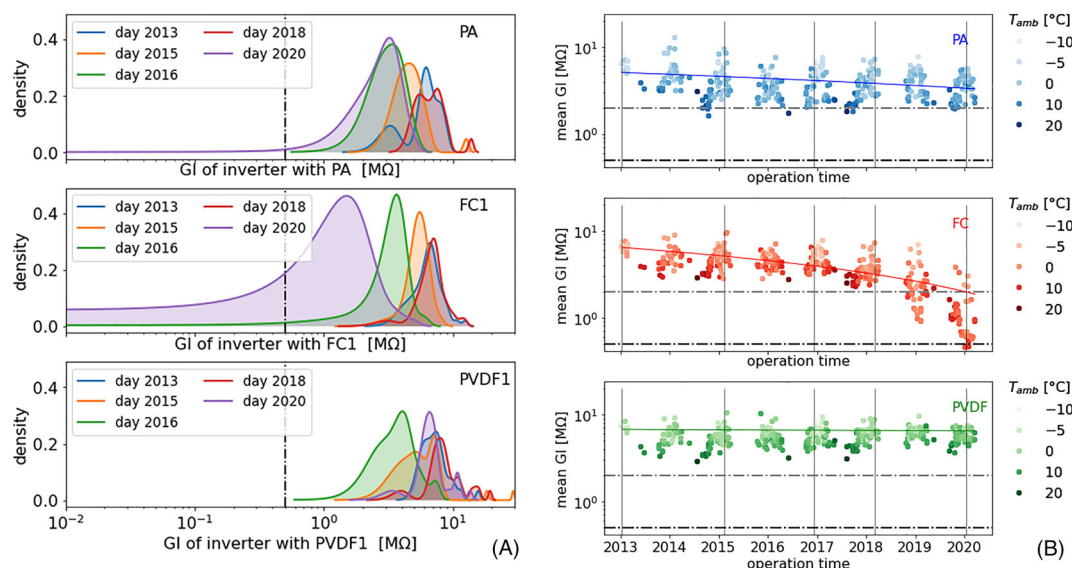
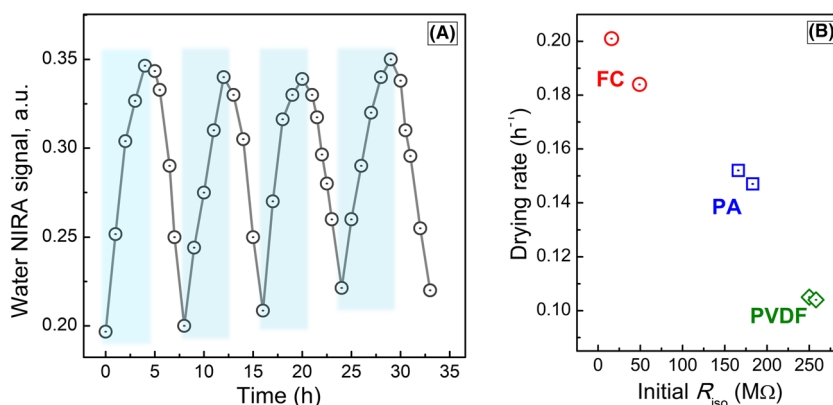


FIGURE 4 (A) GI evolution at bin of $RH = 85\%$ for three different BS-types, PA, FC1, and PVDF1, at 1 day in 5 years. Dashed line marks the GI-threshold, $GI = 400 \text{ k}\Omega$. (B) Evolution of mean GI at bin of $RH = 85\%$ for three different BS types, PA, FC1, and PVDF1, including trend lines. Dashed line marks the GI threshold of the inverters, $GI = 400 \text{ k}\Omega$. Vertical lines mark days of visualized GI distributions in Figure 4A.

The expected steady shift to lower GI values with operation time is not fully recognizable for PVDF1 but statistically significant on a 5% level according to Student's *t* test for PA and FC1 inverters. Possible explanation can be either in replacement of PV modules or in the binning criteria being over-simplified.

The operation of inverters depends on the ambient temperature, as well. At high temperatures, inverter efficiency and ground impedance drop. In summer, the ground impedance is much lower than in winter. The temperature in the morning, when the inverter checks for connection to the grid, is in the range from -12°C to 23°C . At the same instances, GI varies between 7 and 10 M Ω (PA: 1.7–11.7 M Ω , FC: 2.3–9.4 M Ω , PVDF: 2.7–9.7 M Ω) for the first 5 years of operation with a decreasing trend. These seasonal GI variations are common for the tested inverters regardless of BS type and have not been discussed in the literature so far. Possible explanations for the low GI values at elevated temperatures could be, for example, a temperature drift of measurement components in the inverters or/and the voltage temperature coefficient of the PV-module. In particular, following the suggested measurement procedure of R_{iso} for inverters in Müller,¹² the reduced GI can be explained by the voltage temperature coefficient. At increased temperatures in summer, the module voltage and respectively the string voltage drop. This temperature-driven voltage reduction results directly in a low R_{iso} . This temperature-driven voltage reduction results directly in a low R_{iso} . For a deeper insight in the temperature and humidity dependence of GI, further field investigations and measurement data are necessary.

The evolution of GI since commissioning in 2012 is displayed in Figure 4B for RH = 85%. GI evolutions differ depending on the BS type. For PA inverters, GI diminishes slightly. A similar behavior is observed for FC1 inverters. However, after 6 years of operation, GI drops notably. In 2020 (8th year of operation), GI values frequently drop below 400 k Ω . In contrast, PVDF1 inverters remain on a high GI level since commissioning.

To study the performance at other weather conditions, we calculated the regression slope $\Delta\text{GI}/\Delta t$ for all bins in the range $35\% \leq \text{RH} \leq 100\%$. Figure 4B shows that PA, FC1, and PVDF1 inverters reveal a distinct GI evolution. For PA and FC1 inverters, the gradient is always negative; that is, GI is diminishing for low as well as for high RH. GI of FC1 falls heavily for RH $\geq 80\%$ (Figure 4B). However, GI recovers when RH goes down, e. g. in the summer, but does not reach the original values. The slope is (slightly) negative.

For PA inverters, GI does not depend on RH as strong as it does for FC1 inverters. Because the slope is always negative, GI falls independent on humidity. Even though in PA inverters most PV modules (60–80% per inverter) have macroscopic cracks in the BS, the GI drop with $\Delta\text{GI}/\Delta t = -1.0$ k Ω /day is lower than for inverters with FC1, $\Delta\text{GI}/\Delta t = -2.0$ k Ω /day for RH = 95%.

For PVDF1-based inverters $\Delta\text{GI}/\Delta t$ is mainly positive for RH < 80%. For days with higher humidity, we see an upcoming slight negative trend.

Even though the dataset is limited to 68 inverters, the difference between BS types appears to be statistically significant (Figure 5). The consequence is that after 10 years of operation (3,650 days), GI of

FC1 inverters drops (from 20.2 ± 15.5 M Ω in 2013) statistically on average by $\Delta\text{GI} = -1.47$ k Ω /day whereas PA inverters (starting from 39.7 ± 9.7 M Ω in 2013) show an averaged $\Delta\text{GI} = -0.74$ k Ω /day. We note that in case of a low initial GI, the PV modules fail already in the middle of the expected lifetime due to early degradation of the polymer material.

In year eighth of operation (2020), GI of 35% of inverters dropped below the threshold for periods between 1 and 78 days (Table 3). Mostly, FC1 inverters, which suffer more on humid days, trip alerts. The number of affected inverters and days would even be higher, if countermeasures, such as deactivating (“bridging”) PV modules with low insulation resistance had not been implemented. Yield losses (at humid and dry days) are the direct consequence.

On the basis of the above analysis of the temporal GI evolution, we conclude that FC1 inverters have a higher risk for insulation issues and therefore inverter issues compared to PA or PVDF inverters as shown for a subset of 68 of inverters with one BS types (16% of 6.8 MWp PV power station).

3.3 | Field tests of water content in PV modules using NIRA spectroscopy

The lab tests showed the potential of NIRA spectroscopy for tracking water balance in PV modules in the field. The field measurements were performed in July 2021 on a multi-MW PV plant in Germany

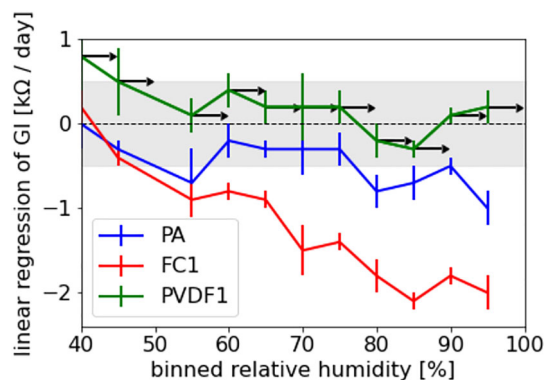


FIGURE 5 linear regression for GI with time for distinct bins of relative humidity for PA, FC1, and PVDF1 inverters. Error bars represent the standard error of the slope. Black arrows mark the bin size of 5% of relative humidity.

TABLE 3 Evaluation of affected inverters and days falling below the threshold of GI < 400 k Ω in year eight of operation

BS type	Inverters	Instances within 8th year
PA	2 (14%)	Up to 30
FC1	30 (88%)	Up to 1,009
PVDF1	0	-

under intermittent rain. In this view, we adopted two kinds of spectral measurements: (i) trying to track changes in the water content during rain events and (ii) collecting statistical data on the water content in PV modules depending on the BS type during relatively long dry periods.

In the first case, we found that FC1-type BSs indeed show a labile water content and can accumulate water during the rain events. Figure 6A presents two NIRA spectra of the FC1-BS air side before (curve 1) and after (curve 2) a strong rain shower. We note that both spectra were collected on the same module after complete drying of the BS surface. A distinct increase of the characteristic 1,910 nm water band can be observed after the rain indicating the presence of residual water in the module even after 4 h drying under direct sunlight. No significant changes were detected in this regime for PA-type BSs, most probably due to lower water ingress (as shown by the above-discussed lab tests) as well as a considerable broadening of water band on PA increasing the experimental uncertainty. No meaningful information was collected also from PVDF BSs because of strong interference patterns in NIRA spectra as discussed in our recent reports.^{6,10}

In a separate experiment, we observed water ingress into an FC1-type BS directly during the rain, starting measurements within 10 min after the rain start and recording NIRA spectra of the air side each 5 min. At that, the measuring head was held tightly on the BS surface, and no direct contact of rain water with the air side was observed close to the measurement spot. We found that the intensity of the 1,910 nm water band increases gradually during the rain (Figure 6B), indicating feasibility of real-time water ingress monitoring using NIRA. We stopped the experiment after 20–25 min because of scattered droplets penetrating the measurement spot.

Another approach to evaluate the BS effect on the water content in PV modules is in collecting NIRA spectra from multiple modules in dry weather and in roughly the same environmental conditions. For each particular module, two NIRA spectra were collected—the air-side spectrum indicative of the BS type and a spectrum of EVA encapsulant over a metal interconnect as described in Buerhop et al.⁶ Using metal interconnect as a mirror, we were able to register highly resolved EVA spectra and identify several meaningful features, including water-related band at 1,910 nm. In view of the above-discussed

labile equilibrium between water ingress and evaporation in the BS material, we assumed the water content in inner EVA encapsulant layers to be more representative indicator as compared to the water content in the BS itself.

In this manner, 311 pairs of BS/EVA spectra were collected, including 174 FC1-type, 71 PA-type, and 66 PVDF1-type modules, and analyzed with the aim of identifying a relationship between the water content in EVA and BS type. The results are presented in Figure 6C as a “violin” plot showing relative water content in the tested module types as well as statistical distributions of the data. In general, the FC1-type modules show the highest water content in the EVA encapsulant with a broader distribution as compared to other types. The lowest water content was found for PVDF1-type modules, while PA-type samples occupied an intermediate position. These results are in a good correspondence with our lab observations made during the R_{iso} /NIRA tests.

3.4 | Expected yield depending on local weather conditions

For annual income and yield, the prevailing weather conditions are of relevance. Data of humidity and of daily solar irradiance for 9 years of operation are statistically evaluated for the specific site; see Figure 7. At 182 days of a year it is fairly humid and wet with daily average $RH = 77\%$. The irradiance data show that there are 109 sunny days (29%) with daily mean $E > 5 \text{ kWh/m}^2$. The expected annual yield is calculated as $Y = 1.285 \text{ kWh/m}^2$ by summation of the daily irradiance.

For estimating the impact of inverter outages due to low GI, we did some assumptions. For a worst case scenario, we assume, first, that for $RH > 77\%$ GI drops always below the critical value $GI = 400 \text{ k}\Omega$ for FC1 inverters, and second, that the FC1-inverter fails connecting to the grid for that day and inverter outage is the consequence. At that, compare, the yield is diminished at $RH > 77\%$ by $\Delta Y_{RH > 77\%} = Y_{RH > 77\%}/Y = -27.7\%$ (Figure 7) throughout the year without countermeasures.

The data also point out that there are 78 sunny summer days (41% of the days with high humidity) with high irradiance as well as

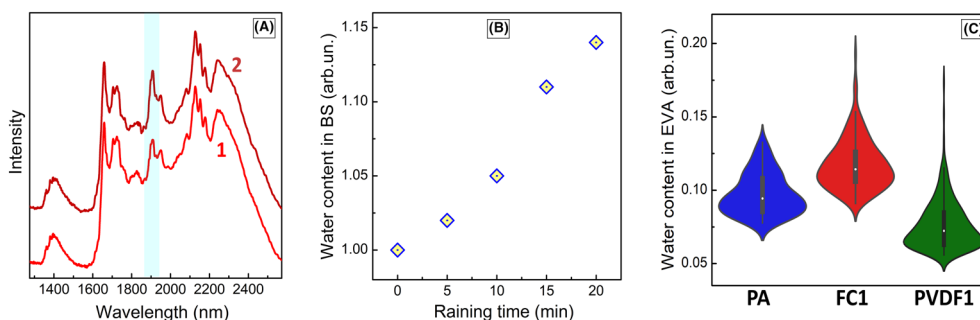


FIGURE 6 (A) NIRA spectra of a FC1 BS registered before a rain (curve 1) and in 4 h after the rain. (B) Increase of water content during a rain event registered for a FC1 module by NIRA. (C) “Violin” plots of distributions of water content in EVA encapsulant for three different BS types. PA, 74; FC, 174; PVDF, 66

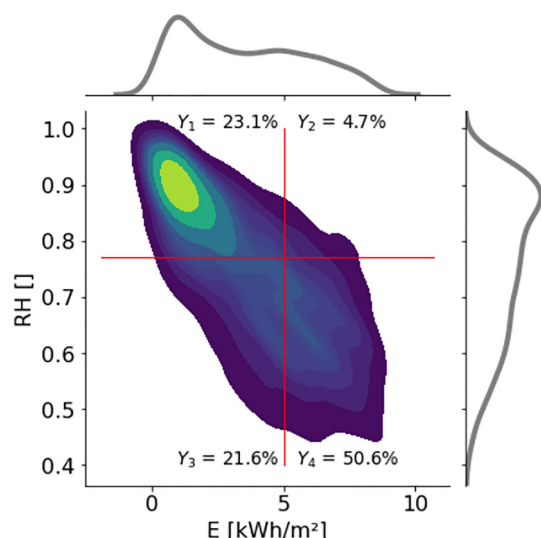


FIGURE 7 Joint plot of distribution of daily mean relative humidity and daily irradiance with density distributions of relative humidity (right) and irradiance (top). Y_1 to Y_4 is the fraction of expected yield in the quadrant related to RH and E calculated for 1 year.

high RH. At these days, the annual yield reduction accumulates to ΔY ($RH > 77\%$, $E > 5 \text{ kWh/m}^2$) = Y ($RH > 77\%$, $E > 5 \text{ kWh/m}^2$)/ Y ($RH > 77\%$) = -16.8% or with respect to the complete annual yield to ΔY ($RH > 77\%$, $E > 5 \text{ kWh/m}^2$) = Y ($RH > 77\%$, $E > 5 \text{ kWh/m}^2$)/ Y = -4.7% .

If we consider progression of degradation with increasing sensitivity of the BSs to moisture, insulation issues are expected at increasingly lower humidity year by year affecting more days. For FC1 inverters, we observed this trend in the data since the sixth year of operation. Summer days with high temperatures and high humidity (e.g., rainfall and morning dew) have an increasing risk for inverter outages, especially for FC1 inverters according to our current knowledge. Data of PA and PVDF1 inverters until year nine of operation do not give evidence for the same kinetics of GI drop in identical operating conditions field.

4 | CONCLUSION

The present results emphasize the importance of insulation properties and durability of polymer BSs in PV modules for long-lasting and sustainable green energy production. Our BS-labeled dataset combined with relevant electrical field performance data of a PV power station is unique, and the first of its kind, to the best of our knowledge.

By correlating inverter monitoring data with weather data and BS materials of all involved PV modules, we derived BS-specific performance and degradation rates for inverters. As a single inverter is typically connected to PV modules with various BS types, 68 inverters out of 423 with available monitoring data could be used in this analysis. These inverters serviced exclusively PV modules with three different backsheet types, denoted PA, FC1, and PVDF1.

By combining lab and field spectroscopic and electrical studies, we demonstrated the feasibility of quantifying the degradation status of PV modules in the field by measuring the water content in BS and EVA encapsulant. We found that water content in different BS materials is strongly correlated with the insulation status, with greater water content resulting in a lower insulation.

Ground impedance of the selected inverters was analyzed with regard to relative humidity. While PVDF1 inverters operate on a constantly high GI level, for PA and particularly FC1 inverters, GI drops at high humidity $RH > 70\%$. For PA inverters, although many BSs show cracking, GI is only slightly reduced at high humidity. The degradation rate for FC1-inverters increases significantly for $RH > 75\%$. The GI-loss for FC1-inverters with $-2 \text{ k}\Omega/\text{day}$ is twice as high as for PA-inverters. Time series show that the sensitivity to moisture and water ingress increases with time, especially for PA and FC1 inverters. At high humidity, e.g., during or after rainfall, the insulation properties are lost as shown by an increased water content in the polymer BS by NIRA spectroscopy.

Statistical analysis of the weather data reveals that for half a year, humidity on the inspected multi-MW PV power plant is high with $RH > 77\%$. Considering a worst-case scenario for FC1 inverters in year 8 of operation results in an annual yield loss of 27% in case of inverter outages at humid days. Our results bring a specific attention to PET-based BSs with a thin air-side FC layer (FC1-type BSs), which appear intact at a first glance, but at a closer inspection reveal inner micro-cracks, potentially resulting in corrosion and most likely causing inverter issues due to a low insulation resistance. About 25% of inverters trip alerts after 8 years of operation, all including modules with FC1-BS.

In summary, this study revealed that degradation of BSs differs. There is a BS-specific impact on the ground impedance and operation of inverters and the resulting yield. The choice of polymers of PV-modules plays an important role for reliable and long-lasting PV-systems for the energy transition.

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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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