Received: 2 September 2021 | Revised: 28 September 2021 | Accepted: 29 September 2021

DOI: 10.1002/pip.3492

EU PVSEC PAPER

PROGRESS IN PHOTOVOLTAICS WILEY

Repair and preventive maintenance of photovoltaic modules with degrading backsheets using flowable silicone sealant

Guy Beaucarne[1] | Gabriele Eder[2] | Emmanuel Jadot[1] | Yuliya Voronko[2] | Wolfgang Mühleisen[3]

[1]Dow Silicones Belgium SRL, Building and Infrastructure Technical Support & Development, Seneffe, Belgium

[2]OFI, Austrian Research Institute for Chemistry and Technology, Materialanalytik & Umweltsimulation / Werkstoffanwendungen, Vienna, Austria

[3]Silicon Austria Labs, Sensor Applications, Sensor Systems, Graz, Austria

Correspondence
Guy Beaucarne, Dow Silicones SRL, Seneffe, Belgium.
Email: guy.beaucarne@dow.com

Funding information
Austrian Research Promotion Agency (FFG); Austrian Climate and Energy Fund

Abstract

Photovoltaic (PV) modules with a degrading backsheet pose a challenge for solar park operators and other players in the PV value chain. Some types of backsheets are known to develop cracks because of an aging-induced change in the mechanical characteristics of the material during operation in the field, which result in a loss of insulation resistance. In this work, we present a solution for repair and preventive maintenance based on a single component flowable silicone sealant. The method fills the cracks present in the backsheet with an insulating material, restoring insulation resistance, and provides a protective layer to avoid subsequent degradation. The solution was successfully implemented on the back of PV modules with co-extruded polyamide backsheet ('AAA'), which showed deep cracks following degradation 5–7 years of operation in a solar park. The repaired modules had a restored insulation resistance of several hundred MΩ as observed with wet leakage testing and maintained a high resistance after accelerating aging. This repair technology can be done in the field and is an alternative solution to module replacement.

KEYWORDS

backsheet, degradation, repair, silicone

1 | INTRODUCTION

Over the last few years, several solar park operators have observed a premature degradation of some photovoltaic (PV) modules. These modules were manufactured and installed between 2010 and 2015 using co-extruded polyamide AAA backsheets, which turned out to degrade in the field in spite of passing accelerated tests at the time of manufacturing.[1,2] Under the influence of climate and weather conditions, these backsheets tend to crack, leading in the worst case to a loss of electrical insulation. The leakage currents can either result in unsafe situations or cause the electrical safety systems to trip, leading to unforeseen outages and long duration downtime. In the longer term, cracked backsheets might also lead to other problems such as delamination, encapsulant degradation, and corrosion of solder joints and metallization, resulting in a decrease in module performance. There have been reports of similar though less acute problems with other types of backsheets, including those with PVDF or stabilized PET outer layers.[3,4]

When such an issue occurs, it causes trouble for several players in the value chain: first the solar park operator, then the engineering, procurement, and construction (EPC) company, which originally built the solar park and which faces guarantee claims, and ultimately the PV module supplier, which is required to provide a solution. Module producers usually offer to replace the failing modules but often this is not an optimal solution: (i) the cost of installing new modules is high (new module cost plus the related logistic costs); (ii) the module model may no longer be produced, which can lead to problems for straight replacement (different dimensions, different nominal voltage, and current); and (iii) finally, there is no guarantee that the modules of the same type—which are not yet affected—will not, at some point, start to degrade as well. Clearly, there is a need for a cost-effective, easy-to-implement solution, not only for the failing modules but also for those modules that are still operational but likely to develop backsheet-related failures. Apart from the cost, the environmental impact of prematurely discarding PV modules long before their normal end-of-life is substantial and should be avoided.

An alternative approach to replacing modules with a failing backsheet is to repair them. Several repair solutions have been proposed and are being studied.[5,6] Some solutions involve applying a tape or a new backsheet with incorporated adhesive on top of the damaged backsheet, whereas others simply consist in a coating material that is applied on the backsheet to create a new insulation and protective layer. These procedures can be applied on modules with already degraded backsheets, or as preventive maintenance on modules that are suspected to be prone to backsheet degradation. Different coating materials are being developed and tested, including epoxy, polyurethane, acrylic, nitrile rubber, and silicone materials. Initial results and first conclusions are presented in Voronko et al.,[5,6] and follow-up studies by the same team will provide complementary information.

In this paper, we study the use of a flowable silicone sealant for the purpose, and discuss the material, the application, and the first results.

2 | EXPERIMENTAL DETAILS

2.1 | Flowable silicone sealant

Silicone materials are known to the PV industry because they are commonly used in PV module manufacturing for frame sealing, junction box bonding, and junction box potting. Usually polydimethylsiloxane (PDMS) polymers are used, which consist of molecules with Si–O–Si–O … backbone and two CH_3 groups bonded to each Si atom; see Figure 1. The Si–O bond in the silicone backbone is much stronger than the C–C bond in the backbones of organic polymers, with a bond energy of 452 versus 346 KJ/mol, respectively. This makes the material intrinsically more stable under UV irradiation and at high temperatures.

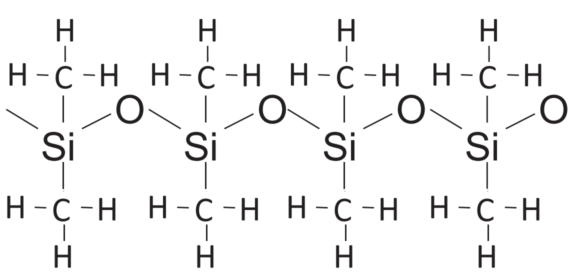

FIGURE 1 Chemical structure of polydimethylsiloxane silicone

The material that was used in this study is a flowable silicone sealant called *DOWSIL™ 7094 Flowable Sealant*. Just like silicone frame sealants, it is a single component material that consists of a mixture of a filler (calcium carbonate particles) and a PDMS polymer that will cross-link ('cure') upon exposure to ambient moisture. However, in contrast with frame sealants, it is formulated to be flowable rather than a paste. The moisture cure system results in an inward directed curing process starting from the surface in contact with air, with the cure rate slowing down as the barrier for moisture diffusion becomes wider. After cure, the material is a solid elastomer with a high elongation at break, which develops good adhesion to backsheet materials. The white version of this material was preferred for this application as it reflects light better and helps keeping a lower module operating temperature. In addition, the fillers and pigments in the flowable sealant protect the backsheet from UV exposure. Table 1 gives some material properties of the flowable sealant.

The silicone coating used for repair in this work is sufficiently liquid to enable easy coating yet viscous enough to enable crack-filling and barrier coating of backsheets that are at an angle, facing downward. The rheology is such that a one-coat application is possible.

2.2 | Tests at backsheet level

In order to study the adhesion of the material on backsheet materials, peel test samples were prepared. Various backsheet materials were tested, as listed in Table 2.

The backsheets (as received, not aged) were cut into 2.5-cm-wide and 10-cm-long rectangular strips. The flowable silicone sealant was

TABLE 1 Material properties of the flowable sealant used in this study

Material property	Value
Before cure	
Viscosity	28 000 mPa s
After cure	
Cure time at 23°C, 50% relative humidity	
0.20 mm thick	45 min
0.40 mm thick	1 h 15 min
0.84 mm thick	3 h 0 min
Hardness	19 shore A
Tensile strength	1.2 MPa
Elongation at break	400%
Secant modulus at 100% elongation (force at 100% elongation divided by cross-sectional area)	0.36 MPa
Resistivity	4.8×10^{15} Ohm cm
Dielectric strength	20 kV/mm
Relative Thermal Index (RTI, as determined by method in UL 746B)	105°C

applied onto one of those strips, on the airside of the backsheet material. Then, a second strip, airside down, was placed on top of the first one and pressed so that the silicone material between the two backsheet strips had a thickness of about 1 mm. The excess silicone material was removed from the side, and the samples were left to cure at 23°C, 50% relative humidity for 28 days. After curing, some samples were placed in a climate chamber at 85°C and 85% relative humidity for 1000 h. The samples were then tested in a mechanical test rig of the make Zwick in a T-peel test configuration. The ends of the two strips were placed into test grips such that the lower strip was pulled downwards over 10 cm at a speed of 50 mm/min while the end of the upper one was kept immobile and the bonded area stuck out horizontally. The maximum force measured during a peel test was recorded for each sample. After the peel test, the surface of each of the test samples was studied and the percentage of the surface area that failed cohesively was noted down (100% CF if failure was only cohesive, 0% CF if the failure was totally adhesive). Three peel test samples were tested for each condition, and an average of the three samples was reported.

TABLE 2 Backsheet types studied (PVF stands for polyvinyl fluoride, PVDF for polyvinylidene fluoride, PET for polyethylene terephthalate)

Backsheet type code	Backsheet structure
AAA	Co-extruded polyamide
TPT	PVF—PET—PVF
KPK	PVDF—PET—PVDF
PPPr	PET—PET—primer

2.3 | Tests at module level in the laboratory

The flowable sealant was applied on the back of PV modules with AAA backsheets that had previously been operating in a PV-plant in southern Europe for 7 years and had developed deep longitudinal cracks,[1] leading to leakage currents and decommissioning from the plant. Before repair, these modules exhibited an insulation resistance of 0 MΩ. Photos of such a module is shown in Figure 2.

The coating took place in the laboratory, with the modules lying horizontally. The modules were first cleaned by wiping the backsheet surface with a wet, wringed cloth and after that dried immediately with a dry cloth. Then, the flowable sealant was dispensed on the areas of the backsheet with the cracks. With a spatula, then material was pushed to fill the cracks and then spread and smoothened into a uniform flat layer over the whole surface as shown in Figure 3. The amount of material used in these experiments was in the order of ~200 g/m^2 (corresponds to a layer thickness of ~150 μm).

After curing, the backsheet surface was studied with optical microscopy. Surface observations were made using a portable USB-light microscope (magnification 20×). In order to determine the coating thickness and the degree of crack filling, some pieces of one laminate with areas of coated backsheet cracks were cut and prepared for

FIGURE 2 Photos of the backside of a module with degraded backsheet as a result of outdoor exposure for 7 years; deep longitudinal cracks above the busbars of the solar cells are observed

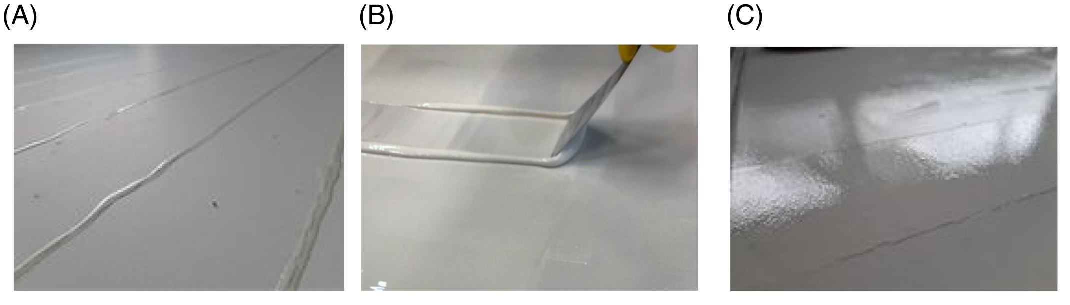

FIGURE 3 Application of the silicone sealant on a PV module in the laboratory. (A) Dispensing sealant over areas with cracks, (B) spreading of sealant with spatula, (C) back surface of the module right after application

cross-sectional microscopy. The samples were embedded in an epoxide resin, polished in cross-sections and finally studied with a reflected- light microscope (Olympus, bi- ocular) with 100× and 200× magnification.

The repaired PV modules that were not sacrificed for cross-sectional microscopy were electrically measured. The insulation of one of the modules was tested according to IEC 61215-1-1 (MQT 15, 'wet-leakage testing'), which involves shorting the terminals of the module, immersing the back of the module in water, applying a large voltage difference between the terminals and the water, and measuring the electrical resistance. After that measurement, the module was placed in a climate chamber at 85°C and 85% relative humidity for 1000 h (damp heat storage). After leaving out the module to dry for a few days, a wet leakage test was carried out again.

Electroluminescence mapping measurements of modules before and after damp heat aging were also carried out.

2.4 | Tests at module level in the field

The repair procedure was implemented on a few PV modules in a solar park in Southern Germany. Here the modules were not dismantled but directly coated in the plant (see Figure 4). The silicone was applied from a cartridge and then distributed and smoothened over the whole surface via a broad spatula. The repaired modules were left to operate in the field for about 2 months (April–May–June 2021) after which they were dismounted and transported to the laboratory for measurements: (i) microscopic measurements to check for complete crack filling and surface coverage and (ii) electrical measurements to test for the insulation resistance.

3 | RESULTS AND DISCUSSION

3.1 | Results of tests at backsheet level

An example of the peel test measurement on backsheets is given in Figure 5. The three curves correspond to the three samples for the same condition, which were measured one after another. After an initial rise, the peel process reaches a steady state, but there is some local variations, leading to an irregular plateau.

The complete results of the adhesion study on backsheets can be found in Table 3.

As can be seen, the material provides good adhesion on all the different types of backsheets, including AAA backsheets, with 100% cohesive failure in all cases. The peel forces are in the same range than those found between PET core layers and fluorinated polymer films in backsheets (peel strength in the order of 0.5 N/mm[7]). Exposure to damp heat did not change the situation fundamentally. Good adhesion was retained, with 100% cohesive failure on all types of backsheets studied. The peel forces seem to increase somewhat with damp heat aging for the AAA samples, and to decrease for the other backsheets, but they remained sufficiently high.

It should be pointed out that these tests were carried out on backsheet samples that had not been aged, whereas the repair solution is applied on aged backsheets. During the module tests, adhesion on the backsheets of aged modules appeared good. Dedicated adhesion studies on aged backsheet will be carried out in the future to substantiate this impression.

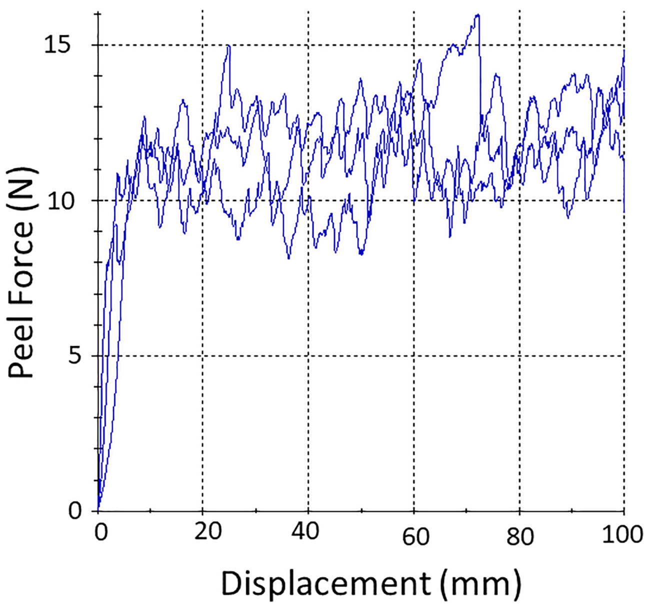

FIGURE 5 Peel tests curves for the AAA samples, after cure but without any accelerated ageing

FIGURE 4 Application of the silicone sealant in the field without dismounting the modules

TABLE 3 Results of the adhesion study

	After cure		After cure and 500 h at 85°C, 85 RH		After cure and 1000 h at 85°C, 85 RH	
Backsheet type	$F_{peel,max}$ (N/mm)	St. dev. (N/mm)	$F_{peel,max}$ (N/mm)	St. dev (N/mm)	$F_{peel,max}$ (N/mm)	St. dev (N/mm)
AAA	0.60	0.04	0.74	0.18	0.80	0.14
TPT	0.74	0.14	0.71	0.07	0.59	0.05
KPK	0.99	0.08	0.75	0.10	0.63	0.06
PPPr	0.87	0.30	0.68	0.13	0.49	0.11

Note: Failure mode: 100% cohesive for all samples in all tested conditions.

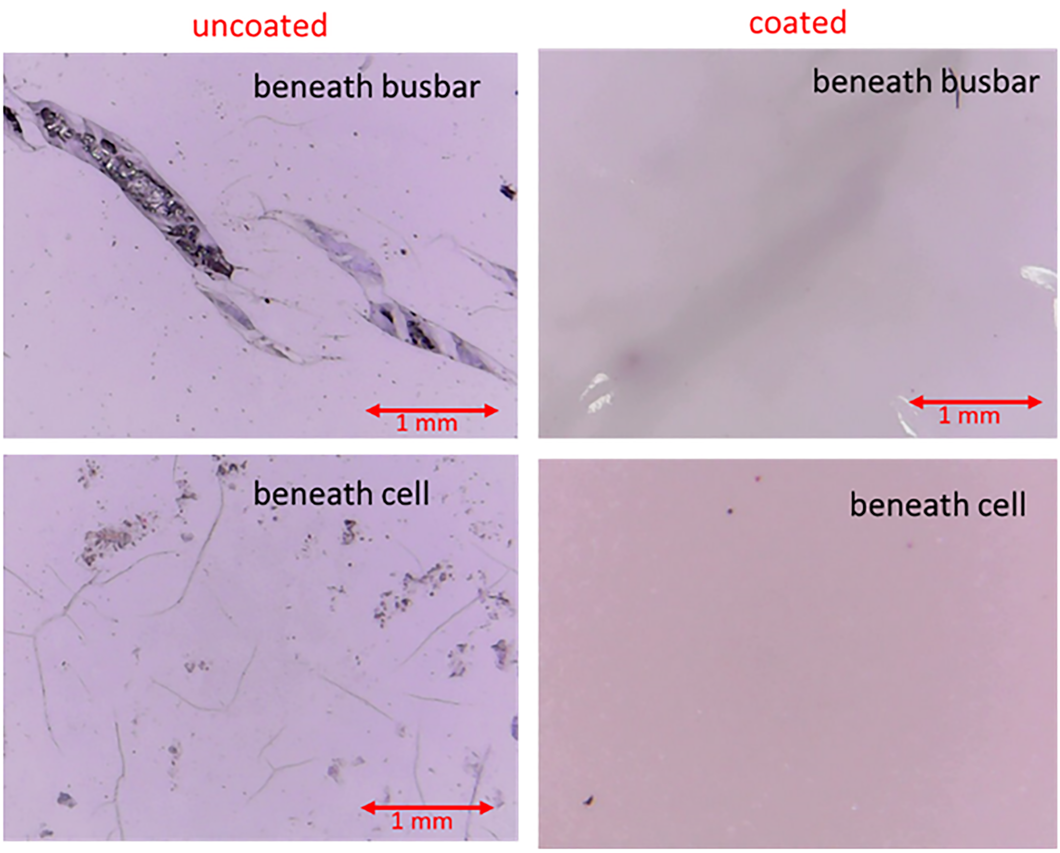

FIGURE 6 Optical microscope pictures of an aged backsheet surface before and after coating

3.2 | Results of tests at module level in the laboratory

Figure 6 shows optical microscope pictures of the surface of a cracked backsheet after application of the flowable silicone sealant. The surface is now flat, and only the deep cracks are still visible as somewhat darker areas. The small cracks are no longer visible.

Figure 7 shows an optical microscope picture of the cross-section of a cracked and coated backsheet sample. It can be seen that the final average layer thickness was in the range of 100–200 μm. However, there are locally places with much more material. In the cross-section, a crack in the backsheet can be seen that has clearly been filled with the flowable silicone sealant.

The PV module that underwent the repair procedure was electrically measured showing a restored insulation resistance, above the resistance requirement for safe operation. After damp heat treatment, the module maintained a high insulation and again passed the wet leakage test (see Table 4). The measured insulation resistance values were far above the minimum required of about 25 MΩ for this module size.

Note that before repair, such modules with deep longitudinal cracks can show high insulation resistance if they are dry, but completely lose electrical insulation under wet conditions.

Such a large contrast cannot be observed with just electroluminescence measurements. The EL images of modules before and after 1000 h of damp heat storage displayed no evidence of degradation

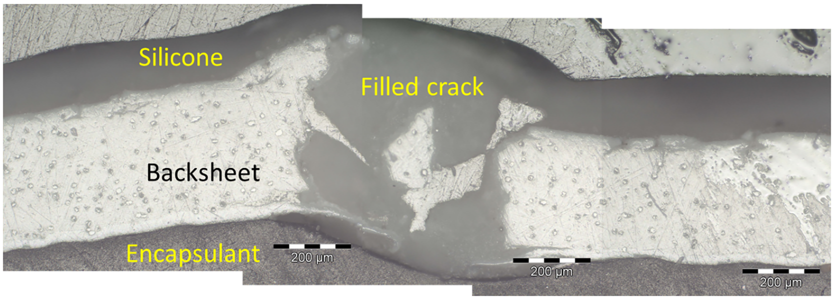

FIGURE 7 Cross-section of aged backsheet after coating with flowable silicone sealant

TABLE 4 Electrical measurements of module under study before and after repair

Before repair		After repair	
'Dry' $R_{insulation}$: measurement following MQT 15 but without water immersion	Wet leakage test result MQT 15	Wet leakage test result MQT 15	Wet leakage test result MQT 15 after 1000 h at 85°C, 85 RH
>1000 MΩ	Failed $R_{insulation} = 0$ MΩ	Passed $R_{insulation} > 1000$ MΩ	Passed $R_{insulation} = 254$ MΩ

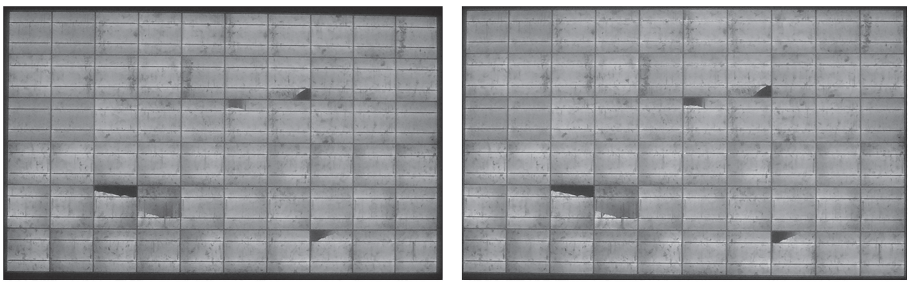

FIGURE 8 EL-image of a PV-module with cracked PA-backsheet directly after repair with silicone sealant (left) and after 1000 h of damp heat storage (right)

such as corrosion, with or without repair coating. The EL images for a repaired module before and after damp heat storage are shown in Figure 8.

3.3 | Results of tests at module level in the field

Figure 9 shows photos of one of the modules used for the study of in-field repair.

The protective layer on the back of the repaired modules showed no sign of cracking or coming off. The microscopy study showed similar 'filled cracks' features (Figure 10) as the modules that had been repaired in the laboratory.

The modules showed a high insulation resistance in the wet leakage test MQT 15, with values of 750 MΩ or above, and functioned normally.

4 | DISCUSSION

The data obtained so far on the repair solution with the flowable silicone sealant indicate that it is effective in restoring electrical insulation and enabling continued operation. Early results also indicate that the module status is stabilized, but further long-term testing is needed.

It should be noted that silicone sealants have an outstanding track record in durability, which is actually one of the reasons why they have been selected as the material of choice for frame sealing and junction box bonding. In the field of construction, reliable operation of silicone seals for more than 50 years has been demonstrated. It is therefore unlikely that the repaired module would start degrading again as a result of the degradation of the protective layer.

It is unclear whether the repaired backsheet provides the same barrier to moisture as the original, undamaged backsheet. While silicone is an extremely effective barrier to liquid water, it is more permeable to water vapor than typical backsheet materials. However, on most of the area of the repaired backsheet, the original backsheet is still present, and in those regions the stack backsheet/silicone coating will provide a somewhat larger barrier to moisture penetration. Only in the small surface area corresponding with the cracks, locally the barrier will be weaker as it consists of only silicone. The EVA encapsulant below and around the crack will provide some barrier to moisture spreading. The nett effect in terms of moisture protection should be studied further, possibly with damp heat exposure of

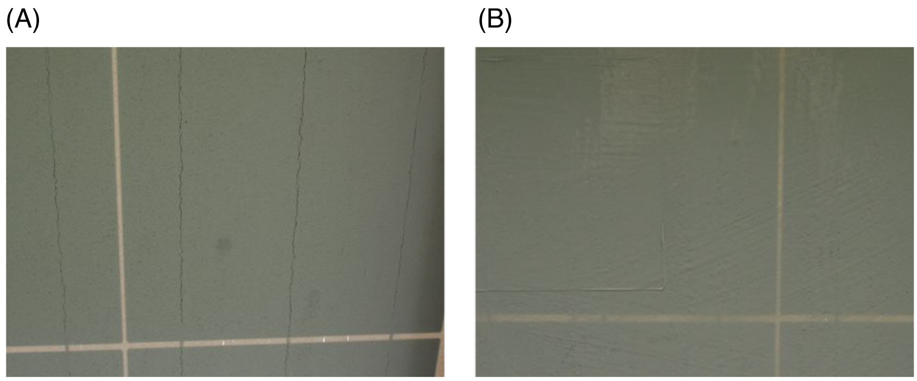

FIGURE 9 Photos of the back of a module with cracked backsheet used in the study of in-field repair. (A) before in-field repair, (B) after repair and two months of operation

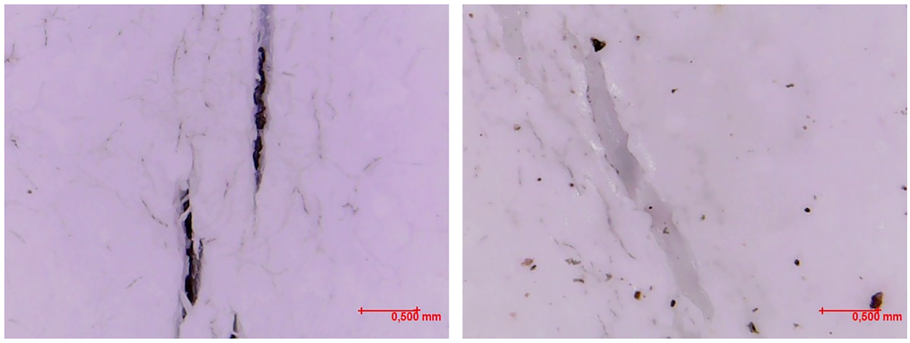

FIGURE 10 Microscopic images of cracked backsheets (AAA) before and after coating with flowable silicone sealant in the field

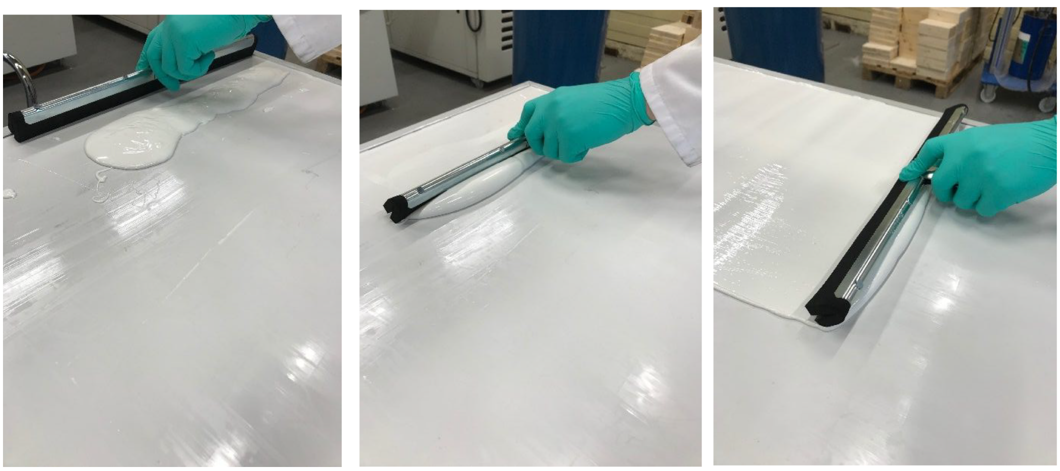

FIGURE 11 Application of flowable silicone sealant on a backsheet using a squeegee

repaired and non-repaired modules beyond the 1000 h of damp heat treatment that was carried out in this study.

5 | OPTIONS FOR APPLICATION

For a large-scale implementation of the solution presented in this paper, the optimal way of applying the material must be determined and two main options seem possible.

5.1 | Dismounting and applying the silicone on horizontally laid down modules

The inclined position, backsheet facing down of a module makes the application of a coating challenging. If the module can be dismounted and placed sunny-side down, the material can be more easily applied and the repair duration can be reduced to a very short time. In Figure 11, we show a convenient procedure in which the material is poured on the backsheet and spread over the surface with a

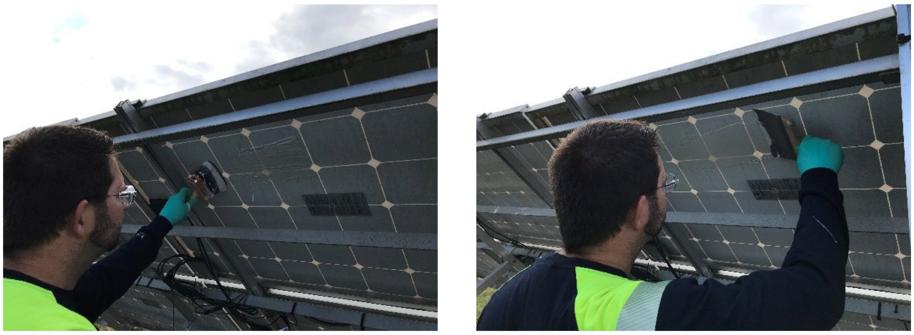

FIGURE 12 Application of flowable silicone sealant without module dismounting combining paintbrush application and spreading with spatula

squeegee. This procedure allows a module to be coated in less than a minute.

Note that this method can be envisaged not only in a repair workshop, but also in the field, as it can be done quickly without any specialized equipment, and the modules can be mounted again right after application.

5.2 | Application in the field on installed modules

As demonstrated in Section 2.4, it is possible to coat the module backsheets without dismounting them. This has the advantage that labor is not needed to dismount and, after repair, remount the modules, but also that the whole procedure can potentially be done with less qualified workforce. In Section 2, the procedure that was used involved dispensing a bead of sealant with a caulk gun and then spreading with a spatula. In Figure 12, we show a similar procedure where the flowable silicone sealant is applied by brush and immediately smoothened using a spatula. In both cases, the material remains as a thin coating and does not flow down.

An alternative, faster application is to spray the silicone sealant onto the back of the module as shown in Figure 13. The flowable silicone sealant is sprayable either with a pneumatic cartridge gun with a spray nozzle powered by compressed air, or with a dedicated system that pumps the flowable silicone sealant from a pail or a drum and drives it through a spray nozzle.

The surface of the silicone material after spray coating is not smooth but shows little hills and valleys. For best coating quality, smoothening with a spatula is recommended. It not only leads to a better coating uniformity but also helps pushing the sealant into the cracks.

FIGURE 13 Application of flowable silicone sealant without module dismounting by spraying

6 | CONCLUSION

In this work, we presented a solution for repair and preventive maintenance based on a flowable silicone sealant. The method fills the cracks present in the backsheet with an insulating material, restoring insulation resistance, and provides a protective layer to avoid subsequent degradation. This repair solution can be done in the field and can lead to a much lower cost than module replacement or off-site repair. The repaired modules maintain their insulation resistance after accelerated aging and during post-repair outdoor exposure so far.

As there is an estimated 12 GW of installed modules with AAA backsheets, a large part of which will develop issues in the coming years, this solution, both as module repair and preventive maintenance, could lead to massive savings for various players in the value chain.

ACKNOWLEDGEMENTS

The work at OFI and SAL was supported by the Austrian "Energy Research Program" project "PV Re2 - Sustainable Photovoltaics" (FFG No. 867267) funded by the Austrian Climate and Energy Fund and the Austrian Research Promotion Agency (FFG).

DATA AVAILABILITY STATEMENT

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

ORCID

Gabriele Eder https://orcid.org/0000-0003-0397-8453
Yuliya Voronko https://orcid.org/0000-0002-8122-1213

REFERENCES

1. Eder G, Voronko Y, Oreski G, et al. Error analysis of aged modules with cracked polyamide backsheets. *Sol Energy Mater Sol Cells*. 2019; 203:1-14.
2. Owen-Bellini M, Moffitt SL, Sinha A, et al. Towards validation of combined-accelerated stress testing through failure analysis of polyamid-based photovoltaic backsheets. *Nat Sci Rep*. 2021;11(1):1-13.
3. Hu H, Gambogi WJ, Choudhury K, Garreau-Iles L, Felder T, MacMaster S, Fu O & Trout T-J Field analysis and degradation of modules and components in distributed PV applications, in 35th European Photovoltaic Solar Energy Conference Brussels, 2018, 1072-1075.
4. Tracy J, Khatri R, Xia S, Hu H, Borne A, Gambogi W, Roy K. Failure modes of backsheets in field and laboratory aged PV modules (POSTER), in European Photovoltaic Solar Energy Conference Online, 2020.
5. Voronko Y, Eder G, Breitwieser C, Mühleisen W, Neumaier L, Sonja F & Oreski G Repair options for PV modules with cracked polyamide backsheets (POSTER), in 37th European Photovoltaic Solar Energy Conference online, 2020.
6. Voronko Y, Eder G, Breitwieser C, et al. Repair options for PV modules with cracked backsheets. *Energy Sci Eng*. 2021;00(9):1-13.
7. Oreski G, Wallner GM. Delamination behaviour of multi-layer films for PV encapsulation. *Sol Energy Mater Sol Cells*. 2005;89(2-3):139-151.

How to cite this article: Beaucarne G, Eder G, Jadot E, Voronko Y, Mühleisen W. Repair and preventive maintenance of photovoltaic modules with degrading backsheets using flowable silicone sealant. *Prog Photovolt Res Appl*. 2022;30(8): 1045-1053. doi:10.1002/pip.3492