INTRODUCTION

Polymeric photovoltaic (PV) backsheets are designed to protect the active components of the module (solar cells, electrical connectors) from environmental stress and act as an electrical insulator to protect people and animals from electric shocks. Several variations of backsheet compositions are available on the market, mainly laminated multilayer stacks and coextruded foils. When looking at the reliability of glass/backsheet modules, it was noted that the most frequent backsheet failures are cracking, delamination, and yellowing.
Within the last years, an enhanced occurrence of backsheet cracking was observed in the field (after only 4-7 years operational time) and reported at several conferences and publications.\(^4\)\(^,\)\(^8\)-\(^13\) Especially polyamide (PA), but also polyvinylidene fluoride (PVDF) and polyethylene terephthalate (PET)-based backsheets were affected (see Figure 1).

A detailed error analysis of aged modules with cracked PA backsheets\(^4\),\(^12\),\(^13\) revealed that the main drivers for the formation of cracks in coextruded PA-based backsheets are the daily and seasonal temperature changes and their corresponding thermomechanical loads/stresses due to different thermal expansion coefficients of the different PV module layers. The main factor for crack initiation—which is often accompanied by chalking—can be found in the described physical aging process of PA\(^12\),\(^14\) which significantly reduces the ability for plastic deformation of the backsheet, visible in the significant decrease of strain-at-break values.\(^4\)

Depending on the type and severity of crack formation,\(^4\) defective backsheets primarily impose a safety risk due to failing wet leakage insulation.\(^9\),\(^15\)-\(^17\) Additionally, backsheet cracks may accelerate various PV module degradation modes such as delamination, corrosion, potential induced degradation (PID) or polymer hydrolysis by providing gateways of moisture ingress into the modules.\(^8\),\(^16\),\(^18\)-\(^20\) This could result in a performance loss over time and the modules therefore must be replaced or—preferred for sustainability reasons—repaired in order to be able to meet the expected operating time of 25 years.

The development of reliable repair solutions for defective backsheets to increase the operational lifetime is not only a sustainability issue, but may also have a cost advantage. Furthermore, it is often difficult to find identical replacement modules for a given plant. From the economic point of view, restoring PV modules with cracked backsheets by in-field-repair options could be attractive for the owner.

Even though repair of backsheets is a topic of interest in the PV community and is discussed in commercial reports and communications since several years,\(^21\)-\(^24\) so far, no scientific work on repair of defective backsheets has been published. However, several companies are offering repair solutions for cracked backsheets, mostly based on repair tapes\(^25\),\(^26\) or weathering layer repair liquids.\(^27\),\(^28\)

The main objective of this paper is (i) to provide a comprehensive overview on possible repair strategies and (ii) to describe first test results on potential solutions for the repair of cracked backsheets based on polyamide. The detailed damage analysis of PA backsheet cracks done by the same group of authors\(^4\) served as the basis for the development process. The paper covers the following aspects of the repair process:

(i) material compatibility,
(ii) applicability of the repair material in the field,
(iii) sustainability of the repair process (ideally no hazardous or toxic materials),
(iv) penetration of the repair coating/adhesive into the cracks,
(v) adhesion of the repair material to the weathered backsheet surface,
(vi) restoration of electrical insulation.

The very important topic of long-term stability/reliability of the repaired modules is currently under investigation and will be published in a subsequent separate contribution.

2 | EXPERIMENTAL APPROACH

In the first screening step, suitable materials for full (coatings) and partial repair (tapes/foils) of cracked PA-backsheets were identified. Two different repair objectives have been addressed:

**FIGURE 1** Photos with different levels of detail of an aged backside of a PV module with cracked backsheet (deep longitudinal cracks)
1. **Damage repair:** The backsheet is fully cracked and the electrical insulation properties have to be restored. Apart from backsheet cracking, the modules should not exhibit significant power loss due to any other degradation modes like delamination or corrosion.
2. **Prevention:** The module only shows microcracks or surface near cracks and the electrical insulation of the module is still intact. The objective is to seal the small cracks and prevent further crack growth.

In a second step, a repair strategy was developed including the following steps: (i) cleaning, (ii) pretreatment—if needed—and (iii) repair process (crack filling and sealing). A repair matrix including all selected materials and the cleaning and repair steps were elaborated and implemented in the laboratory.

Several defective PV modules with cracked polyamide backsheets showing chalking and microcracks (see Figure 2), which were dismounted from the field, served as the basis for the experimental work. In this case, the repair aims at prevention of crack propagation. The optimized repair processes with four selected coating materials were tested on defective/aged modules directly in the field and in parallel in the laboratory.

The field modules (still operative) are currently undergoing field testing (natural weathering test) for one year at the PV site (Carinthia/Austria, climate classified as Cfb by the Köppen-Geiger system). After a first characterization step (methods described in chapter 3) directly after the repair process, an intermediate evaluation step of the repaired modules was performed after 6 months and a second one will take place after 12 months. Aged modules taken from the same plant and coated in the laboratory are currently subjected to accelerated aging tests with intermediate sample characterization after each aging test procedure.

Furthermore, the repair process was also tested on aged PV modules with deep longitudinal cracks (see Figure 3) from a PV plant in southern Europe. These modules exhibited an insulation resistance of 0 MΩ and thus had to be replaced in the plant due to safety reasons. Four of these defective modules were fully coated with selected repair material and then again tested for their insulation behavior and reliability.

### 3 | EXPERIMENTAL METHODS

#### 3.1 | **Visual assessment**

Visual inspection of the backsheet outer surfaces was performed by the naked eye and using a portable microscope (magnification 20×). Due to the direct attachment of the microscope to the computer via USB port, it is possible to capture images at any point of module surface in the laboratory and also on site.

#### 3.2 | **Adhesion testing**

In the first step, a peeling test with a specified test tape (Tesa Tape 4651, width of 25 mm) was used for testing the adhesion of a coating to the weathered backsheet surface. Then, the adhesion strength of the coatings to the weathered and cleaned surface was tested with a portable, hand-operated “Positest AT-A Automatic Adhesion Tester.” This device is equipped with an electronically controlled hydraulic pump which applies smooth and continuous pull-off pressure, which significantly reduces user effort and the risk of influencing the pulling process. The diameter of the used aluminum dollies was 20 mm. Fixing of dollies was made by using epoxy adhesive (2K) and measurements were done after 72 hours under normal climate 23°C and 50% r.H.

#### 3.3 | **Scratch and hardness testing**

The scratch resistance of the coating was tested with a classical scratch testing such as scoring orthogonal hatch marks through the coating and counting the squares that went missing was performed. To measure the hardness of the surface protective layers, a hardness test pencil (Erichsen, Modell 318 S) was used.

#### 3.4 | **Light microscopy**

The film thickness (coverage of the cracks) and the penetration of the coating into the crack (filling) were analyzed by using light microscopy (LM) on polished cross-sections of the samples (PV module/coating), embedded in an epoxy resin. The recording of images of the backsheets/coating cross-section in the cracked regions was performed with a reflected-light microscope (Olympus, bi-ocular) with 100× and 200× magnification. In order to increase the visualization of crack filling, an UV-fluorescent additive was added to the coatings.

#### 3.5 | **Color measurements**

In order to determine the aging-induced color changes of the backsheets, additional CIELAB color difference measurements on the backsheets environmental surface were performed. A portable spectral photometer (Datacolour CHECK II PLUS) was used, and the measurements were performed according to standard EN ISO 11664-4 making use of the CIE L*a*b* color scale. For the assessment, the delta values ($\Delta E^*, \Delta L, \Delta a$, and $\Delta b$) between the original and aged samples were utilized. The total color difference is usually expressed by $\Delta E$, which includes lightness (+)/darkness (−)
(ΔL), redness(+) / greenness(−) (Δa), and yellowness(+) / blueness(−) (Δb).30

3.6 | Infrared spectroscopy

Potential material degradation of the polymeric coating after indoor and outdoor aging at the environmental side (outer surface of the coating) was analyzed by attenuated total reflection (ATR) Fourier transform (FT) infrared (IR) spectroscopy. For the measurements, a portable ATR-FTIR spectrometer system (A2 Technologies; EXOSCAN) was used. The system is equipped with a diamond ATR-crystal in single reflection mode with a diameter of 2 mm. The depth of penetration is wavelength-dependent and lies between 1.5 μm and 2.5 μm in the mid IR region (2 μm at 1700 cm⁻¹). The spectra were recorded with a resolution of 4 cm⁻¹. Three spectra at independent measurement points were taken for each sample.

3.7 | Electrical characterization

For the electrical characterization, current voltage (I-V) curves (outdoor measurements, STC-corrected; HT Instruments, device IV 400), electroluminescence (EL) images (modified Canon EOS 700D camera), and insulation resistance (Fluke 1654B) were measured. The PV modules were measured before and after the repair process in the field and in laboratory. The electrical characterization was also performed after each step of the reliability testing (climatic chamber accelerated aging, see Section 3.10).

3.8 | Insulation test

A wet leakage current test in accordance to the standard IEC 61215-1-1 (MQT 15) was performed for the aged/defective and the repaired modules. For this test, the module specimen
was immersed in water to achieve wetting of the backsheet. The standard specifications of at least 3500 Ohm/cm and a water temperature of (22 ± 2)°C were fulfilled and checked using an appropriate device.

3.9 | Natural weathering

For the evaluation of the predefined coating approaches and the respective repair procedure on-site, a PV plant comprising PV modules with defective PA backsheet and starting degradation (strong chalking and backsheet microcracks) was chosen. The plant (~1 MWp) is located in Carinthia/Austria and was built up in 2011 (see Figure 4).

In a comprehensive field test in summer 2020, the repair solutions were applied on a set of PV modules. An initial characterization of the coated modules was conducted directly after the application (visual inspection, electrical characterization, EL, FTIR, light microscopy, color measurement, and adhesion testing) and will be repeated in a 6-month cycle. For comparison, a set of four untreated modules is being monitored in parallel in order to monitor crack propagation and progression of degradation without repair.

3.10 | Artificial weathering

Six aged PV modules were dismounted from the same PV plant and coated in the lab. After characterization, they were subjected to artificial weathering tests according to the standard IEC 61215-1-1:2021: at first, the coated modules were exposed to damp heat conditions (DH, MQT 13). In the second step, temperature cycles (TC) was performed according to MQT 11. Finally, a dynamic mechanical load test (DML) was carried out. A detailed parameter overview of the ongoing accelerated aging test program is given in Table 1.

4 | RESULTS AND DISCUSSION

A detailed failure analysis in order to identify the drivers leading to the unexpected behavior of the PA multilayer composites was performed and published last year. These findings of the main factors for the formation of different types of cracks were the basis of the repair work described in this paper. Besides local backsheet cracking caused by individual hot cells or hot spots, three different types of cracks were identified with PA-based backsheets:

- microcracks (in the outer backsheet layer; often accompanied by chalking); MC
- tile-shaped, square cracks (along the intercellular spacings); SC
- longitudinal cracks (beneath the busbars of the cells); LC

These crack-failure modes usually affect the entire backside of the module and crack formation occurs with increasing operational time, starting after 4-7 years of outdoor exposure (dependent on climate, module design and encapsulant used). The main driver for the formation of cracks (MC, LC, and SC) in coextruded PA-based backsheets are the daily and seasonal temperature changes and their corresponding thermomechanical loads/stresses due to different thermal expansion coefficients of different PV module layers. A detailed description and discussion on the effect of aging-induced chemical and structural changes of the PA-backsheet on the formation of different cracking modes are given in the study cited herein.

Microcracks develop randomly at local notches with slightly higher stress concentrations. But these cracks were found to appear only in surface near regions. Sometimes, microcracking is accompanied by a partial delamination of the outer layer and/or chalking. The longitudinal cracks are directly located below the ribbons (busbars; ~200 µm in height), which impose additional tensile stress in the backsheet. The resulting cracking from the airside of the backsheet into the core gets more pronounced in length and broadness with aging time and can pass the core layer of the coextruded backsheet, in the worst case leaving the encapsulant unprotected from open contact with the atmosphere.

4.1 | Material screening—Requirements for repair solutions

First of all, potential repair solutions for cracked backsheet have to be chemically compatible with the outer backsheet surface for the bond strength to be sufficient and stable over time. In this study, we focused exclusively on PA backsheets, but in the future, also solutions for PVDF or PET will be investigated. Furthermore, any candidate material for repair in general has to fulfill the same requirements regarding

| TABLE 1 | Accelerated aging test program |
|----------|-----------------------------|
| **Storage** | **Temperature** | **Relative humidity** | **Pressure** | **Duration** |
| Damp heat (DH) | 85°C | 85% | - | 1000 h |
| Temperature cycles (TC) | −40/45°C | - | - | 50 cycles (300 h) |
| Dynamical mechanical load (DML) | - | - | 1000 Pa | 1000 cycles |
weathering stability and electrical insulation (dielectric strength) as backsheet films themselves. Outgassing materials in the repair solution should not have a negative impact of the module materials (e.g., corrosion of interconnector or cell grid).

Any repair solution has to provide a similar (or better) stability toward environmental influences, which include temperature and temperature cycles, humidity, UV, mechanical and thermomechanical loads, as well as other media. Ideally, the repair layer also mimics the properties of the layer underneath. The coefficient of thermal expansion (CTE) should preferably be in the same range as the backsheet or show enough flexibility in order to avoid CTE mismatches and related internal stresses. Also, resistance to acetic acid, which is a side product of EVA degradation, and diffuses out of the module through the backsheet, is desired.

Additional requirements arise from application and handling during the repair process itself. The main aim of the project is to develop repair solutions which are easily applicable in the field, without any special knowledge or training in chemistry. This is especially challenging for coating solutions, which have to be mixed (2 components), applied, and cured. Hence, materials exhibiting curing chemistries depending on special conditions such as elevated temperature, high pressure or certain humidity levels are not suitable. Also, special surface treatments apart from simple cleaning steps are not wanted. Preferably, curing takes place at ambient temperature in terms of minutes or hours. The viscosity of the material has to be in a range, where crack filling is possible, but no dripping during application occurs. Also dimensional stability after curing and during operation is essential. The coating should especially not exhibit shrinkage after curing, which can lead to internal stresses within the backsheet. For employee safety and sustainability reasons, also coating systems that do not rely on evaporation of solvents are preferred.

4.2 Cleaning

For ensuring a correct and reasonable application of the specific repair materials, the PV modules with cracked backsheets need to be cleaned in advance. Besides expected soiling effects, resulting from several years of operation on site, also strong chalking was observed at the test modules. In order to establish a proper cleaning procedure including practicability, effectiveness as well as economic and ecological aspects, three cleaning options were investigated: (i) wiping with water, (ii) wiping with isopropyl alcohol, and (iii) mechanical cleaning with dry sponge. For the validation of the effectiveness of the cleaning, the modules were subdivided into separate test areas and respective cleaning procedures were performed (see Figure 5). After a drying phase, all surfaces were coated with various materials and the adhesion was tested with test tape, the adhesion tester, and the scratch needle.

Comparing the results for the 3 different cleaning procedures reveals only minor differences in the adhesion of the coatings to pretreated surfaces. Thus, cleaning with water (wet, soft cloth turned) was chosen as the most easy and practical approach and was thus used for all subsequent repair tests.

4.3 Material identification and preselection

Material screening under consideration of the required properties (as described in Section 4.1) gave a number of possible material types for PA backsheet repair which were available as commercial products in the market (listed in Table 2). Concerning the application of these materials onto the weathered surfaces of cracked backsheets, (i) brush-coating, (ii) spray coating, and (iii) adhesive tapes application are possible. Coatings were tested for full/continuous deck application, adhesive tapes/films due to practical reasons for local repair only.

After cleaning of the aged backsheets with a wet towel and a drying step, the materials were applied (with a painting brush, sprayed or with a broad spatula in the case of the tapes) in horizontal position with upward-faced backsheet (“sunny side down”) in a first laboratory test. All materials were applied in one layer.

For the characterization of the adhesion of the repair material to the aged backsheet surface visual assessment, peel tests and scratch resistance tests were performed. An overview on the results obtained in this first material screening/test run is given in Table 3. No significant defects such as blistering or delamination were detected. The adhesion strength of the coatings to the weathered and cleaned surface was tested with tesa tape 4651 and showed good performance without delamination or material detachment for all selected materials. However, scratch resistance testing revealed material clipping from the backsheet in the case of products Re04 (acrylate-based coating) and Re07 (epoxy-based coating). Thus, these two products were not investigated further.

In a next step, the film thickness (coverage of the cracks = sealing) and the penetration of the coating into the crack (filling) were analyzed on the cross-sections of the PV module/coating stack via light microscopy (LM). For this purpose, coated backsheet samples were cut out from the module with a utility knife/scalpel. It should be noted that not for all materials/products cross-section samples could be prepared in such a way. Especially for the adhesive tapes, no penetration of the adhesive into the crack could be found, they just formed a surface protection layer, but were not anchored in the crack. The repair options Re12 and Re13 which mainly
mimic a backsheet adhered via an adhesive layer (Re12) or an encapsulant (EVA, Re13) did not pass the peel test and the scratch test and were thus excluded from the test program.

Crack filling was successful when using materials Re03 (2-K, PU), Re05 (silicone), Re08 (nitrile rubber), and Re09 (liquid rubber) already in the first test run. For materials Re01 (1-K, epoxy) and Re02 (2-K, PU), crack filling had to be optimized on the material level (by addition of a wetting agent) and in the application process (by variation of the viscosity). In order to reach the targeted film thickness of 50-60 µm, a variation in the viscosity and an increase in the number of coating layers had to be performed for some products.

In the optimized process, all coatings except for Re05 (silicone) were applied in two layers. Best results were obtained with a low viscosity coating in the first step (= crack filling) and a higher viscosity application of the same material in the second step (= sealing). Two examples for the optimized coating application in two layers are given in Figure 6.

As far as the adhesion of the coating to the backsheet is concerned, for some products (e.g., Re01, see Figure 7A), the adhesion strength was found to be rather independent of the viscosity of the coating and the number of coating layers; for other materials (e.g., Re03, see Figure 7B), the adhesion strength increased significantly, when two layers were applied.

Although coating Re08 (based on nitrile rubber) has met all requirements regarding adhesion and crack filling, this product had to be removed from the test program for optical reasons (brown color and inhomogeneous appearance).

**TABLE 2** Overview of materials for repair activities

| Sample ID | Application type | Material type | Solvent | Curing | Color        |
|-----------|------------------|---------------|---------|--------|--------------|
| Re01      | Brush-coating    | Epoxy         | Yes     | 1-K, RT| Transparent  |
| Re02      | Brush-coating    | Polyurethane  | Yes     | 2-K, RT| Transparent  |
| Re03      | Brush-coating    | Polyurethane  | Yes     | 2-K, RT| Transparent  |
| Re04      | Brush-coating    | Acrylate      | No      | 1-K, UV, RT| Transparent |
| Re05      | Brush-coating    | Silicone      | No      | 1-K, RT| Transparent  |
| Re06      | Brush-coating    | Epoxy         | No      | 2-K, RT| Transparent  |
| Re07      | Brush-coating    | Epoxy         | No      | 2-K, RT| Black        |
| Re08      | Spray coating    | Nitrile rubber| Yes     | 1-K, RT| Brown        |
| Re09      | Spray coating    | Liquid rubber | Yes     | 1-K, RT| Black or white|
| Re10      | Tape/film        | PU + Acrylate | No      | RT     | Transparent  |
| Re11      | Tape/film        | PVC + Acrylate| No      | RT     | White        |
| Re12      | Tape/film        | TPT + Adhesive| No      | RT     | White        |
| Re13      | Tape/film        | PET + EVA     | No      | RT     | White        |

Abbreviations: 1-K, 1 component; 2-K, 2 components system; EVA, Ethylenevinylacetate; PET, Polyethylene terephthalate; PU, Polyurethane; PVC, Polyvinylchloride; RT, room temperature; TPT, Tedlar-Polyester-Tedlar.

**FIGURE 5** (Left) Segmentation for cleaning procedure evaluation; (right) module after cleaning
The most promising materials for full-surface repair were the coatings Re01, Re03, Re05, and Re09; local repair could be performed by using the adhesive tapes Re10 and Re11. These materials were selected for the up-scaled repair test in the field.

4.4 Preventive repair process for modules with microcracks

In a next step, the optimized repair solutions were applied to aged modules (with backsheets showing chalking and microcracking) directly in the field without dismounting. For comparison, a set of four untreated modules is being monitored in parallel in order to monitor crack propagation and progression of degradation without repair. Six additional modules of the same type were dismounted and repaired in the laboratory and subsequently put in the climate chamber for artificial aging tests (DH, TC, DML, listed in Section 3.10).

After visual and electrical pre-characterization, all test modules were cleaned with a wet towel, and coated with the selected materials Re01, Re03, Re05, and Re09. On one test module, the adhesive tapes Re10 and Re11 were applied. Electrical characterization (IV-curves, EL) was repeated after the repair process and showed that the repair process did not cause any cell breakage (see Figure 8), also the P_{MPP} was unchanged between 172 Wp and 180 Wp for all test modules. In order to evaluate the effect of the coating on the crack propagation with time, light microscopic images of the cracked surface were recorded after coating. IR-spectra and color measurements of the coated backsheets were taken and will be used as reference data for the analysis of chemical degradation after the natural weathering and artificial aging tests (see Section 4.6).

Material consumption and time required for the repair process were monitored for all repair options and are summarized in Tables 4 and 5. The amount of material required (without diluent) was ranging from about 50 g to 100 g per module (area = 1.5 m²) in order to achieve satisfactory crack filling and sufficient sealing of the whole backside. Also, first material cost estimations were done, ranging from 1.2 € to 3 € per module. These values were calculated based on wholesale prices of the coatings.

| Sample | Visual | Tape peel test | Scratch test | Crack filling | Sealing film thickness [µm] |
|--------|--------|----------------|-------------|---------------|-----------------------------|
| Re01   | ✓      | ✓              | ✓           | ✓             | Optimization step required 18-21 |
| Re02   | ✓      | ✓              | ✓           | ✓             | Optimization step required 12-16 |
| Re03   | ✓      | ✓              | ✓           | ✓             | 16-61                       |
| Re04   | ✓      | ✓              | Chipping    | -             | -                           |
| Re05   | ✓      | ✓              | ✓           | ✓             | 30-50                       |
| Re06   | ✓      | ✓              |            | ✓             | -                           |
| Re07   | ✓      | ✓              | Chipping    | -             | -                           |
| Re08   | ✓      | ✓              | ✓           | ✓             | 30                          |
| Re09   | ✓      | ✓              | ✓           | ✓             | 42                          |
| Re10   | ✓      | ✓              | ✓           | -             | 300 + 60*                   |
| Re11   | ✓      | ✓              |            | -             | 90 + 35°                    |
| Re12   | ✓      | -              | -           | -             | 270 + 30°                   |
| Re13   | ✓      | -              | -           | -             | 300 + 300*                  |

*For the adhesive tapes/films (Re10-Re13) the film thickness gives the value of the tape liner + the adhesive thickness.

Table 3 Characterization results of the first test run (application of 1 layer of coating)

Figure 6 Light microscopic images of cross-section of repaired backsheets showing crack filling and sealing (materials: left Re03 with fluorescent additive, right Re09 rubber; 2 coating steps)
Time consumption for cleaning was ~2 minutes/module, and application of each coating layer took 2-4 minutes in the field and lab tests. The authors estimate that with experienced personnel and appropriate application method, these times can possibly be halved. Between the applications of the first and the second layers of the brush-coated materials Re01 and Re03, 10-15 minutes drying time was used. For the spray-coated material (Re09), a drying time of 30 minutes after primer application has to be considered.

4.5 Repair procedure for modules with longitudinal cracks and collapsed insulation resistance

The repair process was also tested on aged PV modules with deep longitudinal cracks and collapsed insulation resistance. Such modules have to be replaced in the plant for safety reasons (see Figure 1). Four of these defective modules were fully coated with the selected repair materials Re03 (2-K PU), two types of silicone (Re05 and a high-viscosity material), and Re09 and then again tested for their insulation behavior. The crack filling and sealing behavior of the coatings were again characterized by light microscopy on cross-sections (for Re03 depicted in Figure 9). Complete filling of the broad longitudinal cracks could be achieved and the insulation resistance of the backsheet (>1000 MΩ) restored. Also, these modules undergo accelerated aging tests (DH, TC, and DML) currently.

4.6 Long-term stability of repaired modules

The test modules repaired directly in the field are currently being monitored for 1 year (natural weathering); the test modules repaired in the laboratory are subjected to accelerated aging tests (DH, TC, and DML). The intermediate results taken after 6 months in the field reveal good stability of the coatings in respect to adhesion and material stability.

Discoloration of the naturally weathered PA backsheet when subjected to DH-testing was observed for the uncoated and coated modules (see Figure 10). For the assessment, the delta values between the original (=freshly coated) and aged (after 1000 h DH exposure) samples were used.

A complete and comprehensive description of the chemical, optical, and electrical characterization of the repaired modules after the first year of natural weathering test phase and the complete accelerated aging test will be given in a subsequent paper.
DISCUSSION AND CONCLUSIONS

Two different repair strategies have been addressed within this paper: (i) damage repair with restoration of electrical insulation properties and (ii) prevention of further growth of surface near microcracks.

From the technical point of view, several of the investigated repair solutions fulfilled the defined requirements regarding compatibility and applicability. Nearly all coatings were easy to apply and showed sufficient adhesion strength and scratch resistance. However, only for a few materials, satisfactory crack filling could be achieved, both for microcracks and fully cracked backsheets (longitudinal cracks).
Only materials that showed full crack filling lead to a restoration of the electrical insulation properties. Repair tapes sealed the surface and only covered the cracks, because the adhesive did not enter the cavities that had opened up through the cracks in the backing material. In addition, the application of larger areas of adhesive films/tapes in the field was very difficult, and tapes that were not applied optimally showed blisters and delamination from the edges already after several weeks. Therefore, repair tapes are considered unsuitable for repairing full surface damage and permanently restoring electrical properties to cracked surfaces.

In comparison, it is more difficult to evaluate the effectiveness of preventive repair coatings. This is because the successful filling and covering of existing cracks do not rule out further crack growth or even the formation of new cracks in the backing layer per se. Long-term observations are required here and are still in progress.

Since the technical feasibility has now been demonstrated, the greatest challenge remains the economic expense of repairing the backsheet on site. A first rough estimation leads to material costs between one and three Euros and a processing time of approx. 10 minutes per module (application time for two coating layers). It is very likely that there is considerable potential for further cost reductions through economies of scale and optimization of the repair process. However, since the long-term behavior of the repair solutions and their life-extending effect of PV modules are not known at this point of the investigations, it cannot yet be clearly stated whether a repair or replacement of PV modules with torn backsheets makes more sense from an ecological and economic point of view.

ACKNOWLEDGMENT

This work was conducted as part of 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).

ORCID

Yuliya Voronko https://orcid.org/0000-0002-8122-1213
Gabriele C. Eder https://orcid.org/0000-0003-0397-8453
Gernot Oreski https://orcid.org/0000-0003-4223-9047

REFERENCES

1. Geretschläger KJ, Wallner GM, Fischer J. Structure and basic properties of photovoltaic module backsheet films. Sol Energy
2. Omazic A, Oreski G, Edler M, et al. Increased reliability of modified polyolefin backsheet over commonly used polyester backsheets for crystalline PV modules. J Appl Polym Sci. 2020;137:48899. https://doi.org/10.1002/app.48899

3. Omazic A, Oreski G, Halwachs M, et al. Relating between degradation of polymeric components in crystalline silicon PV module and climatic conditions: a literature review. Sol Energy Mater Sol Cells. 2019;192:123-133. https://doi.org/10.1016/j.solmat.2018.12.027

4. Eder GC, Voronko Y, Oreski G, et al. Error analysis of aged modules with cracked polyamide backsheets. Sol Energy Mater Sol Cells. 2019;203:110194. https://doi.org/10.1016/j.solmat.2019.110194

5. Gambogi W, Heta Y, Hashimoto K, et al. A comparison of key factors of photovoltaic module failures on the field. Prog Photovolt Res Appl. 2019;27(1):44-54. https://doi.org/10.1002/pip.3038

6. Halwachs M, Neumaier L, Vollert N, et al. Statistical evaluation of PV system performance and failure data among different climatic zones. Renewable Energy. 2019;139:1040-1060. https://doi.org/10.1016/j.renene.2019.02.135

7. Köntges M, Oreski G, Jahn U, et al. Assessment of Photovoltaic Module Failures in the Field: Report IEA-PVPS T13-09:2017; 2017.

8. Tracy J, Choudhury KR, Gambogi W, et al. Survey of material degradation in globally fielded PV modules. In: IEEE 46th Photovoltaic Specialists Conference (PVSC). IEEE; 2019:874-879.

9. Tracy J, Gambogi W, Felder T, et al. Survey of material degradation in globally fielded PV modules. In: Conference Record of the IEEE Photovoltaic Specialists Conference; 2019. https://doi.org/10.1109/PVSC.2019.8981140

10. Fauberthor A, Boyd M, Lyu Y, et al. Differential degradation patterns of photovoltaic backsheet at the array level. Sol Energy. 2018;163:62-69. https://doi.org/10.1016/j.solener.2018.01.072

11. Lin C-C, Lyu Y, Jacobs DS, et al. A novel test method for quantifying cracking propensity of photovoltaic backsheet after ultraviolet exposure. Prog Photovolt Res Appl. 2019;27(1):44-54. https://doi.org/10.1002/pip.3038

12. Lyu Y, Fairbrother A, Gong M, et al. Drivers for the cracking of multilayer polyamide-based backsheets in field photovoltaic modules: in-depth degradation mapping analysis. Prog Photovolt Res Appl. 2020;28:704-716. https://doi.org/10.1002/pip.3260

13. Lyu Y, Kim JH, Fairbrother A, Gu X. Degradation and cracking behavior of polyamide-based backsheet subjected to sequential fragmentation test. IEEE J Photovolt. 2018;8(6):1748-1753. https://doi.org/10.1109/JPHOTOV.2018.2867389

14. Geretschläger KJ, Wallner GM, Hintersteiner I, Buchberger W. Damp heat ageing behavior of a polyamide-based backsheet for photovoltaic modules. J Sol Energy Eng. 2016;138(4):41003. https://doi.org/10.1115/1.4032977

15. Gambogi W, Yu B-L, Felder T, et al. Development of accelerated test sequences to assess long term durability of PV modules. In: IEEE 46th Photovoltaic Specialists Conference (PVSC). IEEE; 2019:2406-2410.

16. Köntges M, Kurtz S, Packard CE, et al. Review of Failures of Photovoltaic Modules. Report IEA-PVPS T13-01:2014; 2014.

17. Kempe MD, Lockman T, Morse J. Development of testing methods to predict cracking in photovoltaic backsheets. In: 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC); 2019:2411-2416.

18. Bruckman L, Wang Y, French R, et al. Backsheets: Correlation of Long-Term Field Reliability with Accelerated Laboratory Testing. 2019. https://doi.org/10.2172/1529111

19. Quintana MA, King DL, McMahon TJ, Osterwald CR. Commonly observed degradation in field-aged photovoltaic modules. In: Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, May 19–24, 2002. Hyatt Regency, New Orleans, Louisiana; 2002:1436-1439.

20. Trout TJ, Gambogi W, Felder T, et al. PV module durability-connecting field results, accelerated testing, and materials. In: 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC). IEEE; 2017:2312-2317.

21. Brakels R. Solar Panel Backsheet Defects Rising Says DuPont PV Reliability Report; 2019. https://www.solarquotes.com.au/blog/solar-panel-backsheet-defects/. Accessed December 18, 2020.

22. Chaturvedi V. How Backsheet Quality Impacts Modern Solar PV Modules; 2020. https://www.solarmoduleworld.com/2020/07/how-backsheet-quality-impacts-modern-solar-pv-modules/. Accessed December 18, 2020.

23. Pickeler K. Solar’s Silent Killer: Backsheets are Shortening Some Project Lifespans. https://www.solarpowerworldonline.com/2020/01/solars-silent-killer-backsheets-are-shortening-project-lifespans/. Accessed December 18, 2020.

24. Schwarzburger H. Repairing Solar Modules: Sometimes Easier Than Buying New Ones; 2017. https://www.pveurope.com/solar-generator-repairing-solar-modules-sometimes-easier-buying-new-ones. Accessed December 18, 2020.

25. Accessories Backsheets from Krempel. https://www.krempel-group.com/en/solar-materials/accessories-backsheets/. Accessed December 18, 2020.

26. Zhou Q, Chen H, Uno K, Wu X. Repair Adhesive Tape Sticking Process for Photovoltaic Module Back-sheet and Application Thereof (WO2019/024165); 2017.

27. CYBRID TECHNOLOGIES INC. Development History; 2019. https://en.cybrid.com.cn/news/16. html. Accessed December 18, 2020.

28. Liu L, Lu X, Zhang Z, Chen L. Solar Cell Backsheet Repair Solution; H01L3/18(CN10433849B); 2017.

29. ISO. Colourimetry — Part 4: CIE 1976 L*a*b* Colour Space. 1st ed; 17.180.20 Colours and Measurement of Light (ISO/CIE 11664-4:1999); 2019. https://www.iso.org/standard/74166.html Accessed 07.01.2021.

30. Voronko Y, Edler GC, Knauz M, Oreski G, Koch T, Berger KA. Correlation of the loss in photovoltaic module performance with the ageing behaviour of the backsheet used. Prog Photovolt Res Appl. 2015;23(11):1501-1515. https://doi.org/10.1002/pip.2580

31. IEC. Terrestrial Photovoltaic (PV) Modules - Design Qualification and Type Approval - Part 1-1: Special Requirements for Testing of Crystalline Silicon Photovoltaic (PV) Modules (IEC 61215-1:2021). https://webstore.iec.ch/publication/61346. Accessed April 14, 2020

32. Czanderna AW, Pern FJ. Encapsulation of PV modules using ethylene vinyl acetate copolymer as a potting agent: a critical review. Sol Energy Mater Sol Cells. 1996;43(43):1040-1060. https://doi.org/10.1016/0927-0248(95)00150-6
33. Oreski G, Mihaljevic A, Voronko Y, Eder GC. Acetic acid permeation through photovoltaic backsheets: influence of the composition on the permeation rate. *Polym Testing*. 2017;60:374-380. https://doi.org/10.1016/j.polymertesting.2017.04.025

34. Gebhardt P, Pitta-Bauermann L, Philipp D. Backsheet chalking - theoretical background and relation to backsheet cracking and insulation failures. In: *Proceedings 35th European Photovoltaic Solar Energy Conference and Exhibition*, pp. 1097-1100.

**How to cite this article:** Voronko Y, Eder GC, Breitwieser C, et al. Repair options for PV modules with cracked backsheets. *Energy Sci Eng*. 2021;00:1–13. https://doi.org/10.1002/ese3.936