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Comparison of Commercial TOPCon PV Modules in Accelerated Aging Tests

Paul Gebhardt, Simone Marletti, Jochen Markert, Ulli Kräling, Mai Tu, Ingrid Haedrich, and Daniel Philipp

***Abstract*—Tunnel oxide passivated contact (TOPCon) is set to become the new mainstream cell technology despite pending reliability concerns. This work compares commercially available TOPCon photovoltaic (PV) module types from five different manufacturers in a variety of electrical characterization and accelerated aging tests. This case study represents a selection process of PV modules for larger PV installations. Therefore, the work features an in-depth comparison of the electrical performance (energy rating) that can serve as a reference for state-of-the-art TOPCon modules. The aging results confirm previously reported degradation mechanisms of the TOPCon technology due to humidity ingress. In the case of UV aging, a new pattern of strong degradation (up to –12% after 60 kWh/m^2;) and subsequent recovery after humidity freeze test is presented, which could have implications on the results of certification tests (IEC61730-2, Sequence B). Though not directly connected to the TOPCon cell technology, the mechanical load tests revealed weaknesses of several module types, related to module dimensions, frame height, and glass properties. Based on the results, the necessity for more focused testing and technological development is highlighted.**

***Index Terms*—Accelerated aging, corrosion, degradation, energy rating, mechanical load, PV Modules, TOPCon, UV.**

I. Introduction

TUNNEL oxide passivated contact (TOPCon) solar cells are set to become the new mainstream cell technology, seeing rapid growth in market share [1], while at the same time driving the change toward n-type wafer material [2]. Early reports evaluated TOPCon to be equally or more reliable compared with PERC [3], [4]. However, due to the novelty of the technology, there is staggeringly little experience concerning the reliability of photovoltaic (PV) modules based on this technology. Although experiences so far suggest that TOPCon might be less prone to light- and elevated-temperature-induced degradation (LeTID) and light-induced degradation (LID), some concerns have been raised concerning the susceptibility of TOPCon against polarization-type potential-induced degradation (PID-p) [5], corrosion [6], [7], [8], and UV-induced degradation [9]. Despite the long-term effects these processes could have, most manufacturers of TOPCon-based modules promise higher yield and a lower degradation rates (typically 0.4%/a) compared to conventional PERC-based modules [10], which could lead to a widespread usage without the consideration of the possibly higher risks. Therefore, a third-party evaluation of the current state of TOPCon-based PV modules, as they are currently available on the market, is urgently needed. This work analyzes the performance and aging behavior of commercial state-of-the-art Tier 1 TOPCon modules also in the context of similar data obtained from modules based on the PERC technology in order to assess:

1) how the observed degradation of TOPCon compares to other technologies;
2) if the observed degradation effects are intrinsic to the technology or only seen for individual module products;
3) the general spread of degradation of different module types.

II. Methods

The module types were selected from five different manufacturers. The modules were sampled randomly from the production line by an independent third party. The module type selection also includes different wafer formats to account for the behavior of different form factors (Table I).

Based on first findings [6], [9], [11] and anecdotal evidence about the reliability of TOPCon, modules Fraunhofer ISE compiled a customized aging sequence, efficiently addressing the major concerns in Fig. 1. It consists of an in-depth electrical characterization, including light stabilization, determination of temperature coefficients, spectral response, low-light behavior, and angle of incidence modifier, and energy rating according to IEC 61853, followed by aging tests run in parallel.

Stabilization against LID was done by light soaking according to IEC 61215-2:2021 gate 1.

Potential-induced degradation (PID) tests were performed according to IEC 61215-2:2021 MQT 21 for 192 h for two modules per module type at positive and negative potential, respectively. Final stabilization/recovery according to MQT 19.2 (i.e., UV irradiation) was *not* performed after the aging test.

LeTID tests were performed according to IEC TS 63342:2022 for 2 × 162 h at $I_{SC} - I_{MPP}$.

Damp heat (DH) testing was done according to IEC 61215-2, for 2 × 1000 h with interim characterization.

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TABLE I
OVERVIEW ON ENCAPSULANT MATERIALS

Module type	Encapsulant	Material	UV	Material	UV	Number of cells	Cell format	Glass	Dimensions (mm)	Frame height (mm)
Type 1	Mfr. E1	EPE	Pass	EPE	Block	144	M10	2x2 mm	2278 x 1134	30
Type 2	Mfr. E1	POE	Pass	EVA	Block	144	M10	2x2 mm	2278 x 1134	30
Type 3	Mfr. E2	POE	Pass	EVA	Block	144	M10	2x2 mm	2278 x 1134	30
Type 4	Mfr. E1	POE	Pass	EVA	Block	132	G12	2x2 mm	2384 x 1303	33
Type 5	Mfr. E1	EPE	Pass	EVA	Block	132	G12	2x2 mm	2384 x 1303	33

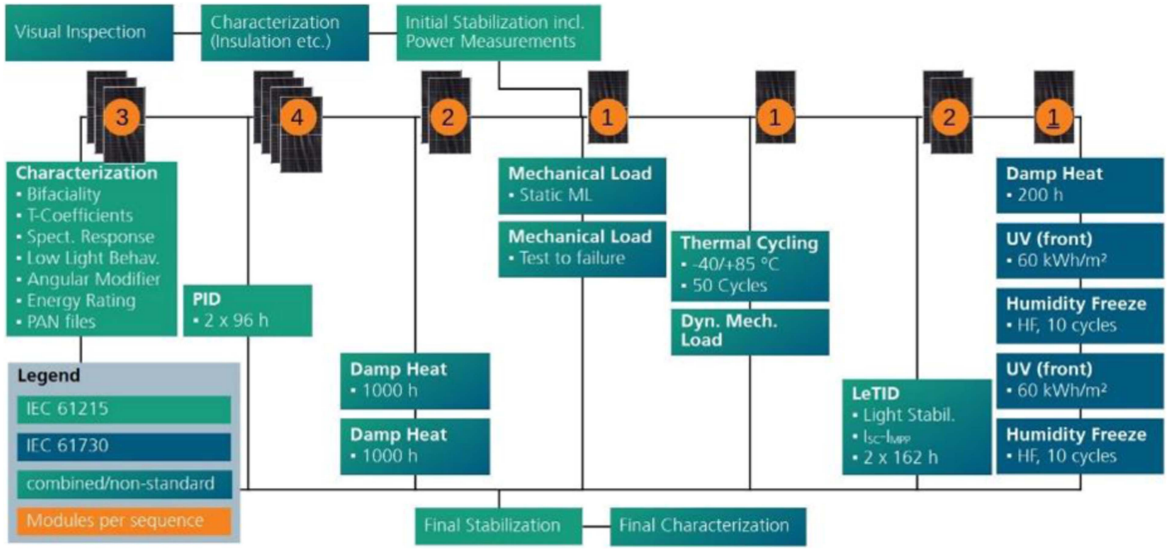

Fig. 1. Conducted test sequence at Fraunhofer ISE specifically customized for TOPCon PV modules. The orange numbers indicate the number of modules tested per module type.

The combined test sequence consisting of 200 h DH (85 °C/85% RH) followed by two cycles of UV aging by 60 kWh/m^2; (front), UV-A fluorescent tubes were used as light source, and ten-cycle humidity freezes (HF 10) between –40 and +85 °C with 85% RH during the hot phase. This sequence was adapted from IEC 61730-2 to apply both UV irradiations from the front side and included interim characterization steps in the individual aging test [12].

In addition, the modules underwent a custom mechanical load (ML) test sequence. One module per type was compared under similar static loads (2100 Pa) for all module types and subsequently tested until breakage. Another module of each type was subjected to a sequence of cyclic ML (IEC 61215-2, MQT 20) followed by thermal cycling (50 cycles –40/+85 °C). For all ML tests, a 1P Tracker setup, with bolt fixation at a distance of 400 mm, was used.

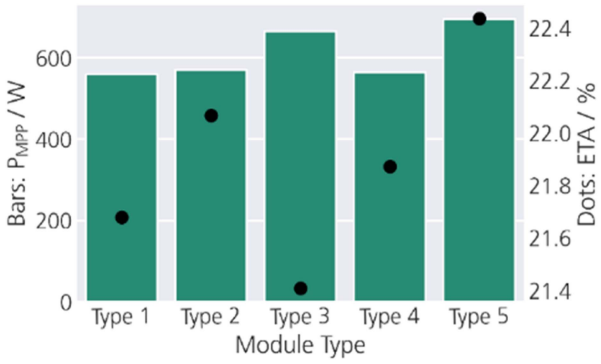

Fig. 2. Nameplate performance and efficiency values of module types in this study.

III. RESULTS

A. Performance and Energy Rating

The nameplate performance of the investigated modules lies between 560 and 665 W, with efficiencies between 21.4% and 22.07% (Fig. 2). The measured initial performance (before testing) of the modules shows a significant negative deviation from the label values, with the exception of module type 3 (see Fig. 3). This general trend was also observed previously and seems to be independent of cell technology [13].

The thermal coefficients for P_{MPP} lie between –0.33 and –0.30%/K and are thereby slightly better than corresponding values for PERC, which typically lie around –0.35%/K [14].

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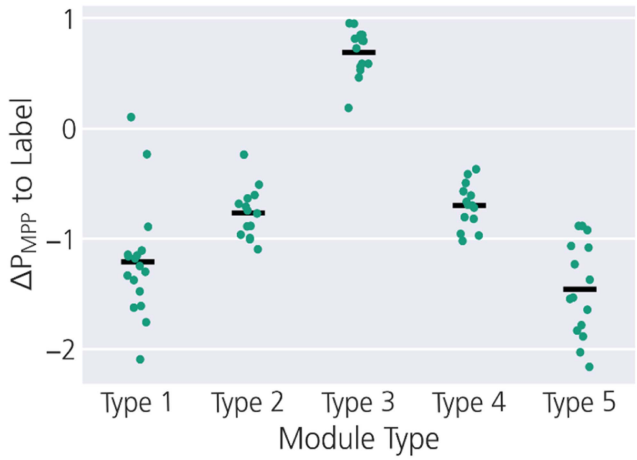

Fig. 3. Deviation of the initial power measurement (P_{MPP}) from nominal (label) values. The horizontal bars represents the median deviation.

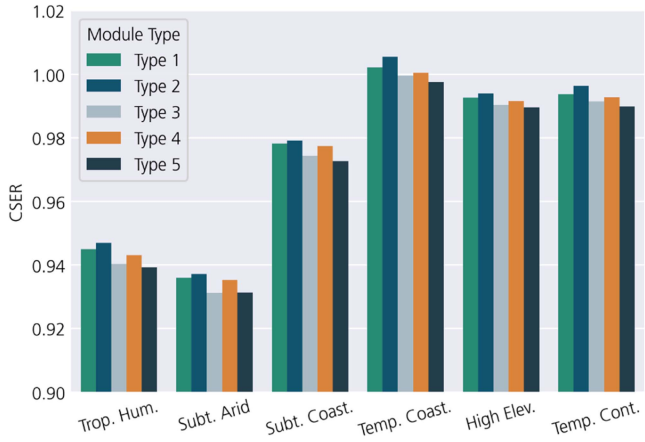

Fig. 4. Results of the climate-specific energy rating. The x-axis represents different reference climates.

Similarly, the average bifaciality of 77.5% lies higher than typical PERC values (∼75% [15]).

Consequently, the energy rating shows consistent results with a ranking of module types (from best to worst) 2, 1, 4, 3, and 5 (Fig. 4). The highest and lowest ratings are obtained for the temperate coastal and subtropical arid reference climates, respectively.

B. Light-Induced Degradation and Light- and Elevated-Temperature-Induced Degradation

The effects due to LID and LeTID were very minor in all the investigated module types. In the case of LeTID, the measured degradation of $< 0.25\%$ lay in the range of measurement reproducibility; therefore, no significant effect can be established. This demonstrates an advantage to previous module types based on the PERC technology, although it has to be said that latest PERC types (after 2022) typically also show very minor degradation due to LID or LeTID.

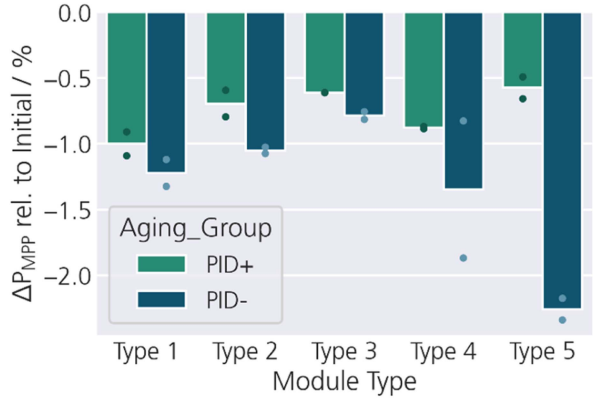

Fig. 5. P_{MPP} degradation relative to the initial measurement after PID testing.

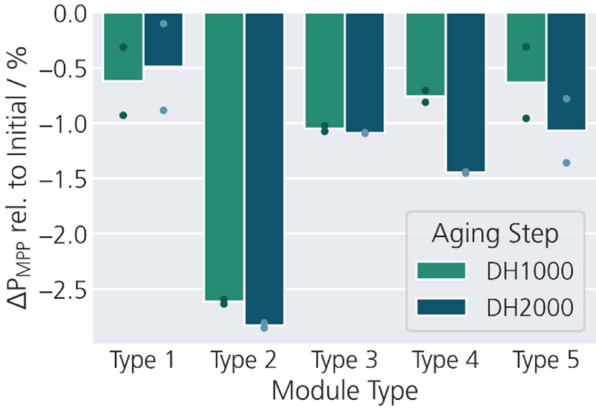

Fig. 6. P_{MPP} degradation relative to the initial measurement after DH aging.

C. Potential-Induced Degradation

The PID tests show minor degrees of degradation with the exception of module type 5 (see Fig. 5). Some TOPCon modules are reportedly prone to PID-p [16], which is triggered at negative potentials. This fits well with the strongest degradation of type 5 in the test at negative potential. Taking into account the drastic degradation reported in some cases, the extent of the observed degradation of type 5 can be characterized as moderate, but significant. Overall, no different sensitivity or severity toward PID than PERC modules could be established based on the obtained results, although there could be a shift from shunting-type potential-induced degradation (PID-s) to PID-p as the most relevant mechanism for TOPCon in contrast with PERC. Regardless of this, we recommend to retain a focus on PID in TOPCon module testing.

D. Damp Heat

DH (85 °C/85% RH) results show varying degradation of up to –2.6% after 1000 h (see Fig. 6). The second run of 1000 h DH does not translate strong further degradation in most cases. With a mean degradation of –1.13%, these results show a slightly stronger degradation compared with comparable PERC

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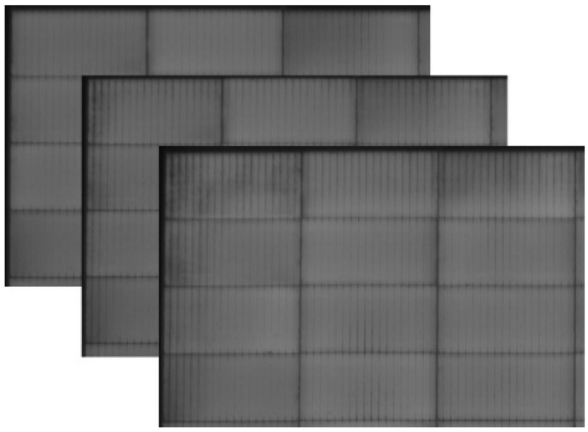

Fig. 7. Detailed EL images (top left of PV module) of type 3 initially (left), after DH1000 (middle), and after DH2000 (right) reveals corrosion of cell metallization or connectors, most pronounced at the module edges.

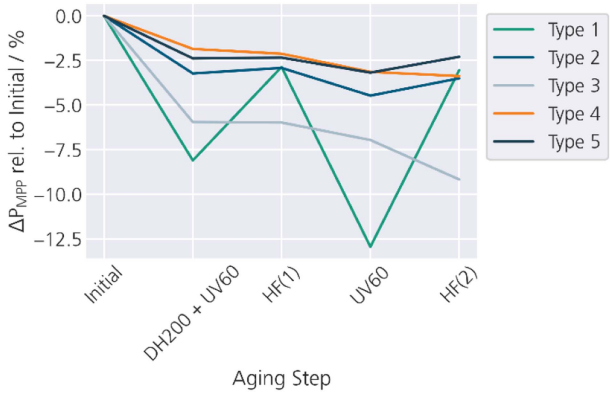

Fig. 8. Performance loss (P_{MPP}) relative to the initial value after aging following modified sequence B (IEC 61730-2).

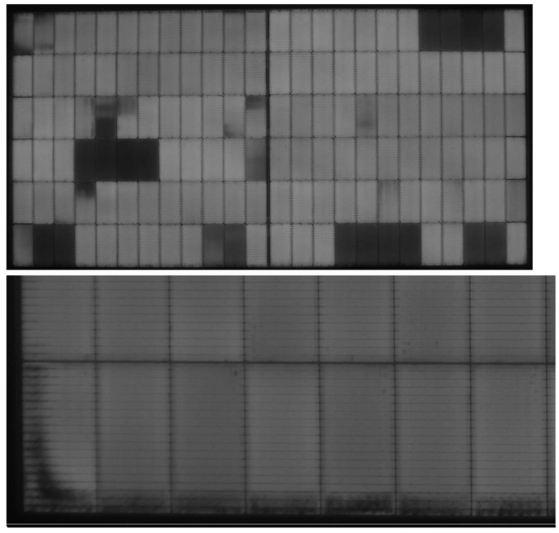

Fig. 9. EL Images after final aging step of type 1 (top) and type 4 (bottom, partial) in the sequential UV/HF sequence.

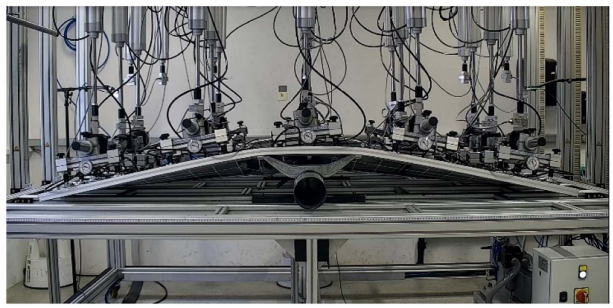

Fig. 10. Photograph of the PV module with bent frame after static ML test.

modules, which usually show significantly less than 1% power degradation [17].

The electroluminescence (EL) images of some of the modules showed the darkening of cell metallization or connectors after DH aging. This was most clearly observed on type 3 (see Fig. 7) and generally toward the edges of the modules, which is to be expected because this is the main entry point for moisture into the module. However, the observations in EL did not correspond to the measured power loss. The darkening was observed for types 3–5, with types 3 and 5 exhibiting the weakest and strongest darkening, respectively, while the type with the strongest power degradation exhibited no corrosion features in EL.

According to the proposed degradation mechanism, cell metallization on the front of the cell is corroded in the presence of moisture [6], [7], [8]. Similarly to mechanisms of previous cell technologies [18], this mechanism is accelerated by acetic acid that can be formed inside the encapsulant, as well as other chemicals like polymer additives or flux can play a role [8]. The module types in this study contain different combinations (front and rear) of encapsulant types (Table I) such as ethylene vinyl acetate (EVA), EPE, and polyolefin elastomer (POE), with POE generally exhibiting the lowest tendency of acetic acid formation [19]. Notably, module types 2 and 4 contain the same encapsulant materials, but only type 2 exhibits a strong power degradation.

E. UV Aging

Another striking result was the UV-induced aging shown in some module types during the sequential UV/HF test following sequence B (IEC 61730-2): The modules showed strongly varying degradation of up to –8.1 and –12.9% after 60 and 120 kWh/m^2; cumulative front UV irradiation, respectively. However, after the intermittent HF aging, the performance *recovered* to values around –3% except for module type 3 (Fig. 8). Even the module types with less absolute degradation showed the same degradation–regeneration pattern (“W-pattern”). The degradation and regeneration mainly corresponded with changes in V_{OC}.

After UV aging, two distinct degradation features can be observed: types 1–3 show a chess-patterned darkening of individual cells after the first UV aging step (see Fig. 9 , top). Similar patterns are typically observed for other degradation mechanisms, such as PID or LeTID and points to different sensitivity

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TABLE II
RESULTS OF THE STATIC ML TESTS

Module type	Module size (mm)	Frame (mm)	Specified Load Profile* (Pa)	Applied Load (Pa)	Failed at (Pa)	Deflection on short side, center (mm)
Type 1	2278 x 1134	30	±1800	±2100	2100**	54
Type 2	2278 x 1134	30	±2400	±2100	1880	105
Type 3	2278 x 1134	30	±2100	±2100	1980	131
Type 4	2384 x 1303	33	±2200	±2100 to failure	Pass 3689	61 75
Type 5	2384 x 1303	33	+2100 /−1900	±2100 to failure	Pass 3702	58 79

*The specified load profile corresponds to a one-axis tracker system.
**The marked result was reproduced on a second module of the same type with very similar results.

for individual cells in a module, which could be caused during the module production process. The EL images only change slightly upon further aging, but the recovery/degradation cycles can be observed by the brightness of the affected cells. Notably, no additional cells darken upon further power degradation. On the other hand, type 4 shows a similar appearance as the corrosion features after DH at the module edges (see Fig. 9, bottom; compare Fig. 7).

Concerning the test approach, this test sequence exemplifies the importance of custom test design for new technologies. Notably, the applied UV test sequence deviates from other popular extended test schemes (e.g., IEC TS 63209-1:2021) that propose UV irradiation from the rear side only—or from the IEC 61730, which is lacking interim power measurements. Both standardized tests would likely not have revealed the possible issue of UV-related degradation.

It is, however, important to note that at this stage, the real-life implications of these results are not yet fully understood. The acceleration factor of the stronger UV irradiation (according to IEC 61215-2) is currently unknown. Furthermore, operating conditions during the aging tests could play a role since the cell strings were in short circuit during the UV tests. To further investigate this issue and its real-life implications, tests under different indoor and outdoor conditions on the most strongly affected module type 1 are currently being carried out and will be the subject of a future publication.

F. Mechanical Load

The issue of mechanical stability is generally regarded as independent of the TOPCon cell technology, but rather tied to the general trend toward large module dimensions, thin module frames, and varying glass quality [20].

While no significant performance degradation was measured after the dynamic ML test and TC50 sequence (not shown), the results of the static ML tests revealed generally critical behavior (Table II).

Module types 1–3 failed the static ML test at 2100 Pa (Fig. 10). Although type 1 was only specified for a load of ±1800 Pa for the tested configuration, these results raise concerns about the durability of the tested configuration because the load can generally be regarded as low, since the minimum required load to pass the IEC 61215 MQT16 is defined with ±2400 Pa.

Module types 4 and 5 passed the test and exhibited a failure load of ∼3700 Pa. Thereby, the module deflection increased along the short and decreased along the long module side, which is assumed to influence the location of highest principal stresses in the glass significantly. Since the determined prestresses of the front and rear panes appeared comparable for all modules—with glass in the heat strengthened range according to EN 1863-1 (∼60 MPa) on the front, and higher prestressing (≥86 MPa) on the rear sides—this could be caused by different frame profiles and height.

In addition, the module bending of types 4 and 5 caused a contact between central junction boxes and the torque tube, which is assumed to additionally support the mechanical stability in this case but could cause other problems under more realistic operation scenarios.

In general, first principal stresses in the glass and associated failure loads might appear significantly different under realistic inhomogeneous loads [21], [22], [23] or by changing the mounting configuration [24], [25], which is why it is crucial to consider the latter in module testing.

IV. CONCLUSION

This work used electrical characterization and accelerated aging tests to evaluate representative PV module types, including the TOPCon technology from different tier 1 manufacturers.

However, considering the experiences from this and similar studies, the test sequence for future test could still be refined, e.g., by shifting the focus from LeTID and LID to UV and ML tests.

This work could confirm the promise of modern PV modules based on the TOPCon cell technology of higher performance and projected yield, as demonstrated in the electrical characterization and energy rating calculations. Specifically, the investigated TOPCon module types were superior to typical PERC in terms of efficiency, bifaciality, and temperature coefficients. Similar to latest PERC generations, no elevated sensitivity toward LID, LeTID, or PID could be found in the TOPCon module types.

However, the investigation also revealed critical degradation effects with respect to moisture ingress, UV irradiation, and

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static ML, which stand in striking contrast with the ambitious warranty conditions offered by the manufacturers. The sensitivity of current front metallization pastes is a reported issue of TOPCon that can hopefully be reduced for next-generation materials. Interestingly, the use of POE as front encapsulant was not sufficient to suppress the corrosion. Furthermore, corrosion patterns, which could be observed in the EL images, did not correspond to the measured power loss.

The UV test sequence showed a "W-pattern" of strong degradation during UV, followed by recovery during the HF test. The corresponding EL images showed two different feature patterns. The issue, however, requires further research to help advance the understanding of the degradation mechanism to determine the relevance for outdoor exposure and possible implications for sensible testing procedures.

The observed ML issue can be seen as independent of the cell technology, but rather generally critical for large modules with thin frames and varying glass properties. The results highlighted the importance to consider the local circumstances (e.g., support structure and climate).

Based on the results of this study, we recommend the testing of specific module types (specific to the BOM if possible) with a focus on DH, PID, UV, and ML, before buying a larger number of TOPCon modules from the current market.

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