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Reliability of Commercial TOPCon PV Modules – An Extensive Comparative Study

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I. ABSTRACT

Tunnel oxide passivated contact TOPCon is poised to emerge as the predominant technology in photovoltaic (PV) cells, yet accelerated aging tests point towards significant reliability issues that remain unresolved. This study conducts a comparative analysis of 20 TOPCon PV module types, utilizing a range of electrical characterization and accelerated aging assessments. This investigation provides a detailed evaluation of the electrical performance, resulting in an Energy Rating of the modules, establishing a benchmark for cutting-edge TOPCon technology. While some failure modes, such as LeTID, appear to be non-critical, the findings confirm previously identified degradation pathways in TOPCon modules due to moisture penetration. During UV exposure, a novel degradation pattern was observed during the indoor tests, showing severe losses (up to -12% after 120 kWh/m^2), followed by recovery after humidity freeze-testing, which may influence outdoor performance and the outcomes of certification tests (IEC61730-2, Sequence B). The results highlight the areas of need for more targeted testing and technological refinement.

II. INTRODUCTION

Tunnel oxide passivated contact (TOPCon) solar cells are rapidly gaining market share [1] and are driving the shift towards n-type wafer material. While its advantages are higher performance compared to previous technologies, there have been conflicting reports about its reliability, with some stating that it is at least as reliable as PERC [2,3] or less reliable [4]. However, due to its recent introduction, there is a notable lack of extensive experience with the reliability of PV modules utilizing this technology. Although preliminary evidence indicates that TOPCon may be more resistant to degradation by LeTID and LID, concerns persist regarding its vulnerability to PID [5], corrosion [6-8], and UV-induced degradation [4,9]. In contrast to these potential long-term issues, manufacturers of TOPCon-based modules often claim higher yields and lower degradation rates (typically -0.4% per annum) compared to conventional PERC modules, which might encourage widespread adoption without full consideration of potential increased risks. Consequently, an independent evaluation of the current offerings of TOPCon-based PV modules on the market is needed.

This research examines the performance and aging characteristics of commercial state-of-the-art modules to determine a) the comparative degradation of TOPCon versus other technologies, b) whether the degradation observed is inherent to the technology or only certain module types and c) the overall variability in degradation across different module types.

III. METHODS

The module's selection was done according to different methodologies according to the project context. While in some cases, they were randomly selected from a production line by a third party, other occasions had them selected directly by the (OEM) manufacturer. Preliminary observations and anecdotal data that was available until mid-2024 regarding the reliability of TOPCon modules reliability led to the design of a tailored aging sequence (Figure 1). It starts with comprehensive electrical characterization including light stabilization, temperature coefficient assessment, spectral response evaluation, low-light performance, incidence angle effects, resulting in an energy rating according to IEC 61853. The sequence continues with parallel aging test sequences that were carried out as described in the following if not indicated otherwise.

Light-induced degradation (LID) stabilization was carried out through light soaking by 30 kWh/m^2 as specified in IEC 61215-2:2021 gate 1.

Potential-induced degradation (PID) assessments were conducted in accordance with IEC 61215-2:2021 MQT 21 for 192 h for two modules per type at both positive and negative potentials,

Table 1: Number of manufacturers and commercial module types per test in this study

Test	Manufacturers	Module Types
Energy Rating	12	13
LID	14	14
LeTID	9	10
PID	11	12
Damp Heat	14	17
UV	10	14

respectively. No final stabilization/recovery post-aging test, such as UV irradiation according to MQT 19.2, was performed.

Light and elevated temperature degradation (LeTID) tests adhered to IEC TS 63342:2022, involving 2 cycles of 162 h at 2 x I_{SC}-I_{MPP}. In contrast to the technical specification, the preceding BO-LID stabilization was done by light soaking instead of current injection.

Damp heat (DH) testing followed IEC 61215-2 standards for 2 cycles of 1000 h with interim characterization.

The combined aging sequence included 200 h of damp heat (85°C/85% RH), two cycles of UV aging with 60 kWh/m^2 exposure using UV-A fluorescent tubes as the light source (Figure S6), and 10 interim cycles of humidity freeze (HF 10), fluctuating between -40 and +85 °C with 85% RH during the hot phase, between the UV stress. During this test, the modules were subjected to a testing current of ~100 mA. This sequence was modified from IEC 61730-2 to feature UV irradiation from the front and incorporate interim characterization steps between individual tests.

The outdoor exposure of two modules of type 16 was carried out in Freiburg, Germany between January 04 and July 8, 2024. During the exposure the modules were mounted at 45° angle facing south. Interim measurements (performance measurements at standard test conditions and EL measurements) were carried out once a month. Since the exact wavelength range relevant for UVID was unknown, the UV dose was estimated to be 5 % of the total irradiance as measured by a pyranometer mounted close to the modules.

The mechanical load tests are an important part of any qualification test of current modules, especially in light of the currently reported increase in mechanical failures from the field [10]. Indeed, many of the tested modules showed critical behavior in the static mechanical load test. However, because these are not specific to the TOPCon cell technology, this topic lies outside the scope of this article and is expanded upon in a different investigation [11].

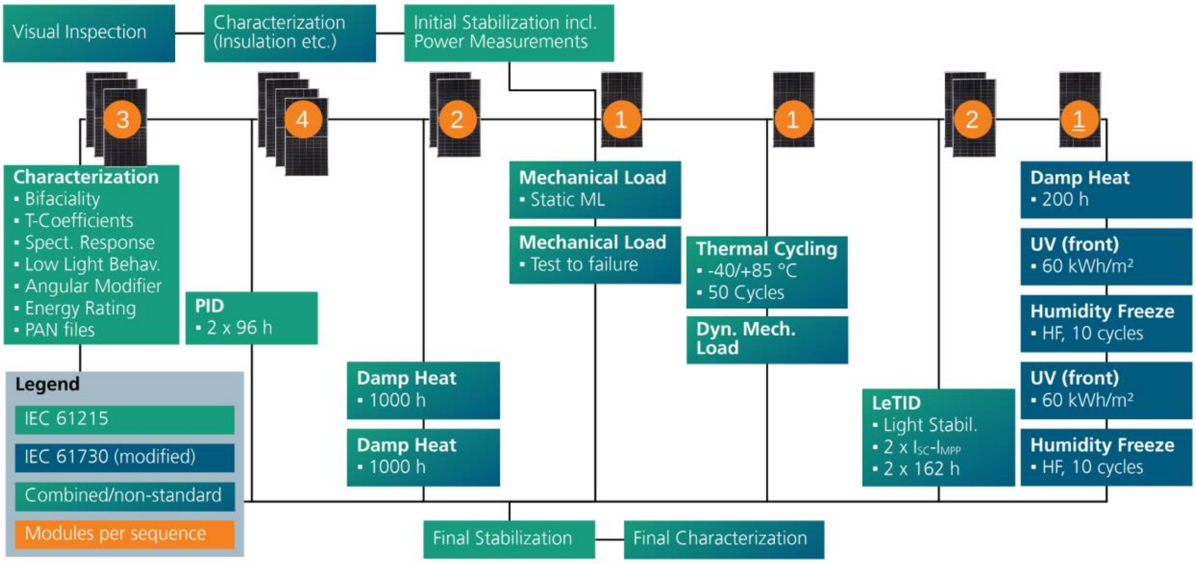

Figure 1: Test scheme used in this study

IV. RESULTS

1. Performance and CSER

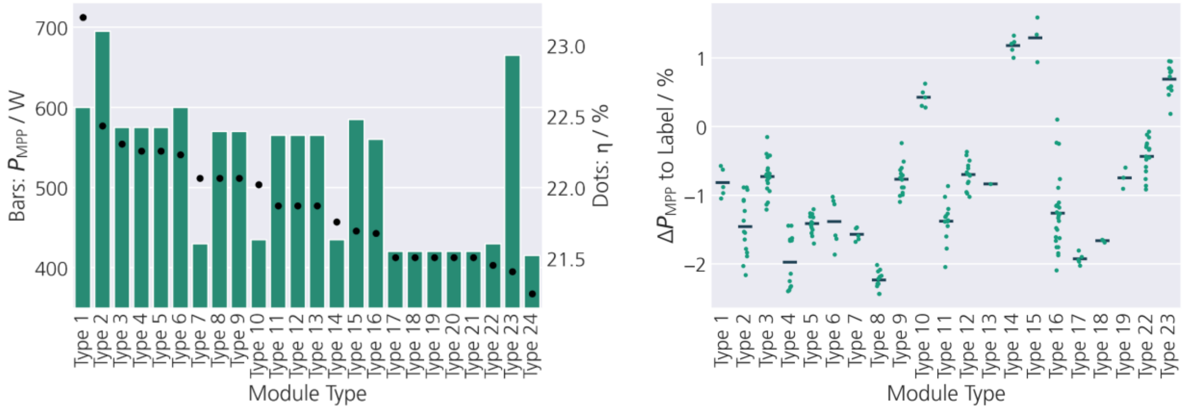

Figure 2: Performance and efficiency of the PV modules in this study (left); Deviation of out-of-the-box power measurement from label (right)

The nominal power output of the modules examined ranged between 415 and 695 W, with efficiencies varying from 21.2 to 23.2 % (Figure 2, left). Initial performance measurements (prior to testing) indicated a notable negative discrepancy from the labeled values for most module types, except for types 10, 14, 15 and 23 (Figure 2, right). This deviation has been consistently noted in previous studies and appears to be independent of the cell technology employed [12]. The median thermal coefficients for P_{MPP} lie around -0.308 %/K (Figure S1), see supporting information (SI), which shows a slight improvement over typical values for PERC cells, which are reportedly generally around -0.35 %/K [13]. The average bifaciality recorded was 76.4 % (Figure S2), which is higher than the average for PERC modules, typically around 75% [14]. Additional details from the electrical characterization are available in the supplementary information (Figure S2, S2). The energy rating yields mostly consistent trends within the module type selection, with Type 9 performing best in all reference climates. The lowest values are obtained for types 3, 5 and 11, with slight variations; for example, type 5 yielded particularly relatively low values for the temperate coastal reference climate, and type 11 yielded relatively high values for the alpine reference climate.

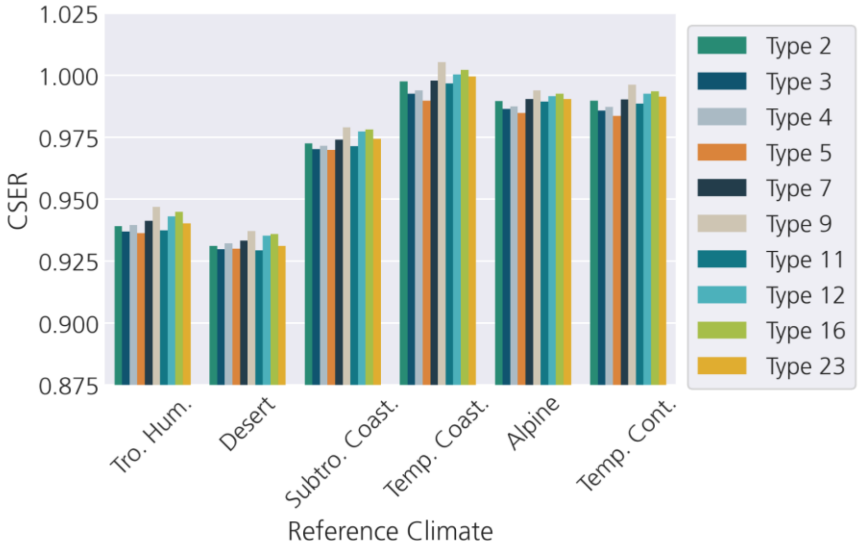

Figure 3: Climate-specific energy rating (CSER)

2. Light (and elevated Temperature)-Induced Degradation (LID and LeTID)

The impacts from light-induced degradation (LID) and light- and temperature-induced degradation (LeTID) across all tested module types were minimal: For LeTID, observed degradation was less than -0.3%, falling within the range of measurement reproducibility, thus indicating no significant effects (Figure 4). This suggests an improvement compared to earlier modules based on PERC technology, though it is noteworthy that the latest PERC models (post-2022) generally also exhibit minor degradation due to LID or LeTID.

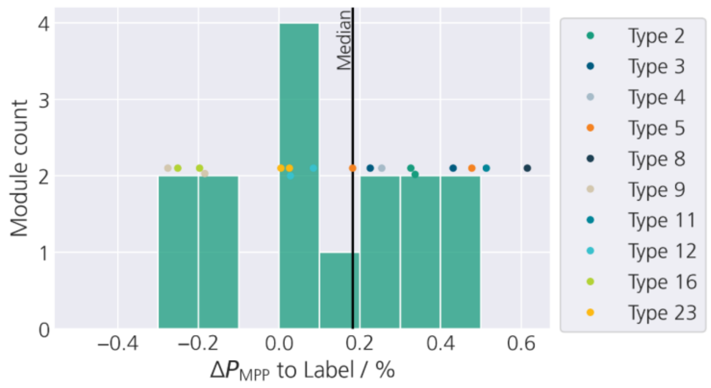

Figure 4: Degradation relative to initial measurement after 2x 162 h LeTID test at 2x I_{SC}-I_{MPP}

3. Potential-Induced Degradation (PID)

The potential-induced degradation (PID) assessments revealed minimal degradation across many of the tested module types. Types 15 and 19 showed more than -2 % degradation. The generally observed trend of stronger degradation at negative potential aligns with earlier reports suggesting susceptibility of some TOPCon modules to polarization type PID (PID-p) [5]. While some literature indicates severe impacts, the degradation observed in this study was moderate. Overall, the sensitivity and severity of PID in TOPCon modules is therefore evaluated as comparable to those in PERC modules. However, compared to previous PERC types, there may be a tendency for the primary degradation mechanism in TOPCon to shift from PID-s to PID-p. Based on these findings, continued emphasis on PID evaluation in TOPCon module testing is recommended.

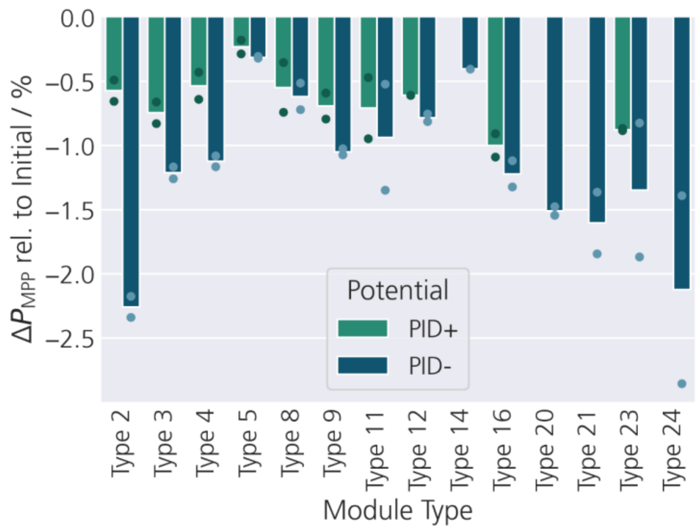

Figure 5: Degradation relative to initial measurement after 2x 96 h PID test

4. Thermal Cycling

The applied test sequence only features a small amount of thermal cycling (TC50), even compared with a conventional standard testing approach, i.e. TC200 according to IEC 61215-2. Consequently, no significant power loss was observed after the tests (not shown). However, EL images after some of the tests showed noteworthy features, such as metallization finger detachments (Figure 6, left) or dark lines parallel to the longer cell edges (Figure 6, right). The latter effect most likely represents an insufficient bond between the cell connectors and the outermost contact pad, as previously observed [15,16]. Although this failure mode was only observed in some module types (3, 4, 5, 8, 9), it seems to occur more frequently since the introduction of TOPCon cells and the properties of the respective metallization pastes. Prolonged testing, beyond 200 cycles, should be applied to investigate the long-term effect on the module performance in the future.

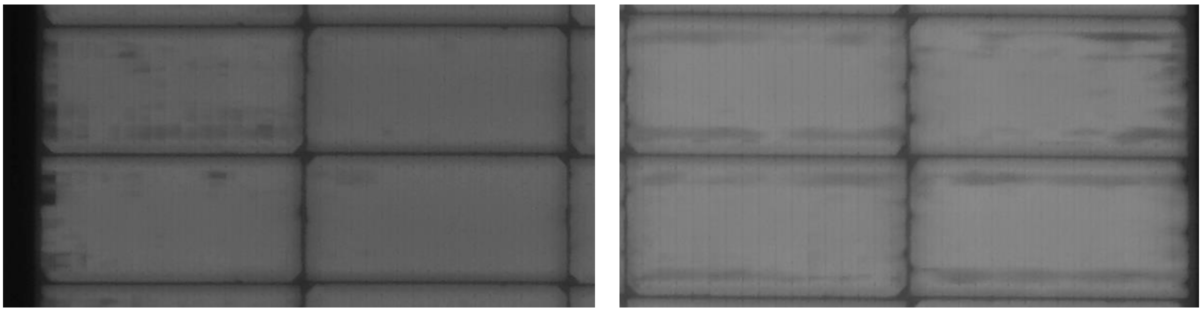

Figure 6: Partial EL images of modules with metallization finger detachments in type 8 (left) and dark lines parallel to the cell edge on type 4 (right) after TC50 testing.

5. Damp Heat aging

The damp heat (DH, 85 °C/ 85 % RH) testing caused varying degrees of degradation, with a median degradation of -1.7 % after 1000 h (Figure 7, left). Within the tested modules, a significantly stronger degradation can be observed for modules with polymeric backsheet (mean = -5.0 % P_{MPP}), which allow a higher amount of humidity ingress compared to glass-glass modules (mean = -1.0 % P_{MPP}) (Figure 7, right). A subsequent DH test, resulting in 2000 h in total, generally did not result in significant additional degradation in P_{MPP}. However, a comparison of the performance parameters of glass-glass modules after the individual degradations steps (Figure S3-S5) reveals that the first 1000 h mainly cause a loss in I_{SC}, which could be due to a change in the optical properties of the respective encapsulants, e.g. triggered by the influence of high temperature. In contrast, the degradation during the second run of 2000 h is strongest in *FF*, which could be explained by corrosion effects that are only triggered after ingress of a significant level of moisture.

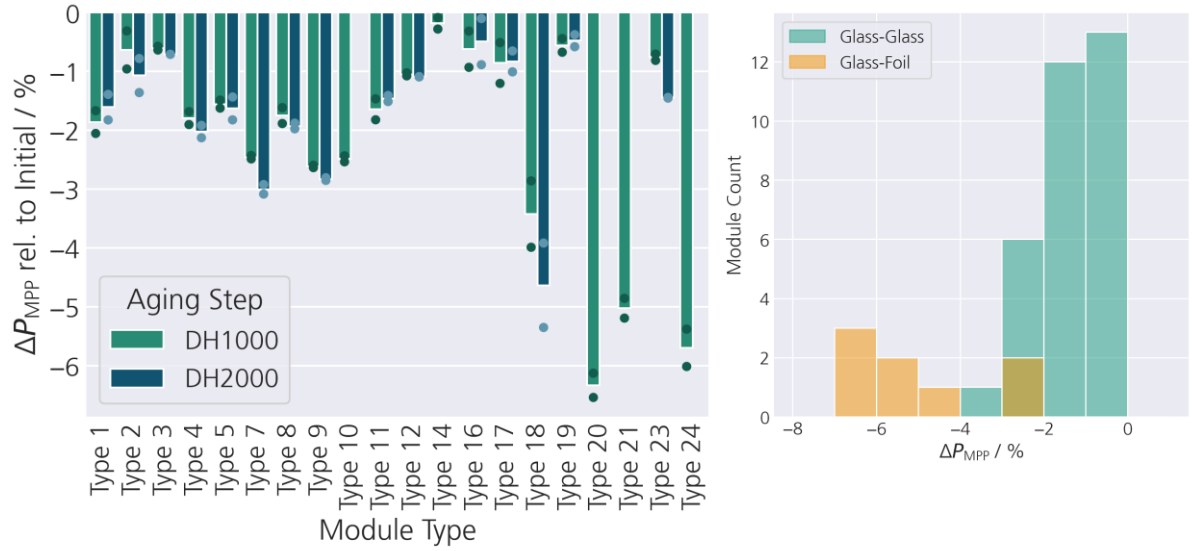

Figure 7: Deviation of performance loss (P_{MPP}) after DH1000 and DH2000 tests (left); Distribution of power loss (P_{MPP}) of PV modules with glass-backsheet and glass-glass configurations after DH1000.

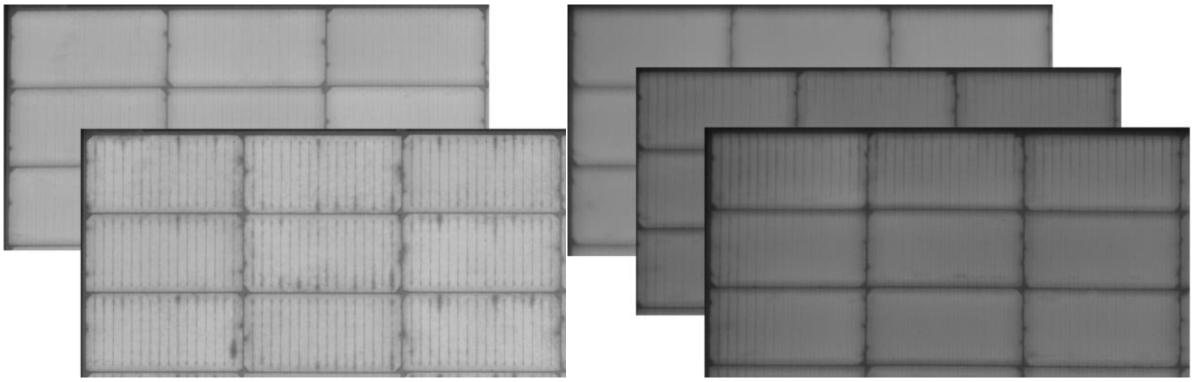

Figure 8: Exemplary partial EL images (top left corner) of glass-backsheet module (type 21) initially and after DH1000 aging (left); of glass-glass module (type 4) initially and after DH1000, DH2000 aging (right).

Overall, the average degradation of TOPCon module types is higher than previously observed for PERC, where degradation typically remains well below -1 % [17]. Electroluminescence (EL) imaging revealed darkening in the cell metallization or connectors after DH aging, which was particular pronounced in most cells of the glass-backsheet modules (types 18-21(Figure 8, left), 24) and only evident towards the module edges of glass-glass types 2, 4(Figure 8, right), 7, 8,12,14 and 23. However, in case of the glass glass modules, these EL observations did not correspond with the a higher power loss in the performance measurements.

According to the hypothesized degradation mechanism, the front cell metallization is susceptible to corrosion when exposed to moisture [6–8]. This process is similar to those observed in previous cell technologies [18] and can be exacerbated by the presence of acetic acid, which may form within the encapsulant. In this study, the module types used various combinations of encapsulant materials on the front and rear, including EVA, EPE, and POE, although the exact combination was unknown in many cases. POE typically shows the least tendency for acetic acid formation. Out of the cases, where the used encapsulant was known, it did not correlate with the power loss: For example, although module types 9 and 12 use the same encapsulant materials, only type 9 exhibited significant power degradation. This underlines the possible influence of other chemicals such as polymer additives or solder flux [8].

6. UV Aging

During the combined UV/HF testing following a modified sequence B from IEC 61730-2 (details see method section), some module types exhibited significant UV-induced aging. The modules displayed degradation, with 40 % of the modules showing more than -5 % P_{MPP} loss after a front UV irradiation of only 60 kWh/m² (Figure 10). This is evaluated as a strong degradation, considering that the UV dose corresponds to roughly one year in moderate climates [19]. However, during the following intermittent HF aging, performance partially recovered to above -5 % before dropping again during the next UV aging step, describing a distinctive degradation-regeneration 'W-pattern' (Figure 9, left).

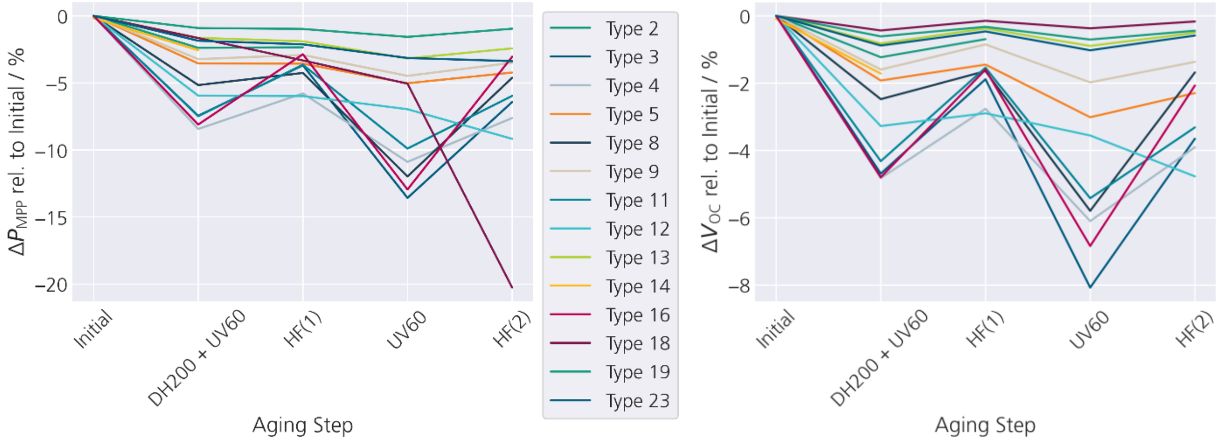

Figure 9: Degradation relative to initial during combined UV/HF test sequence; P_{MPP} (left) and V_{OC} (right).

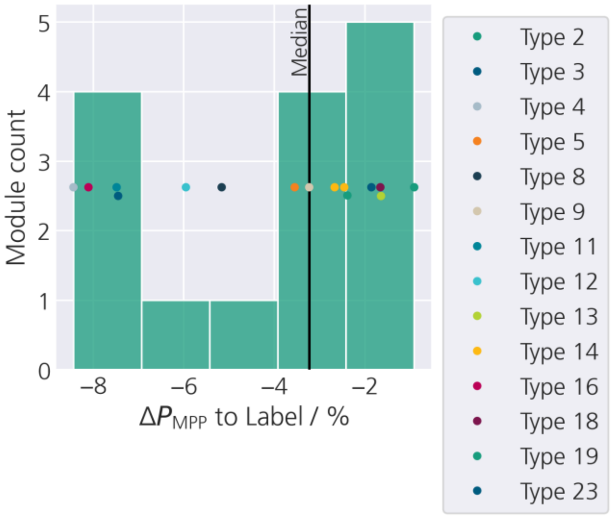

Figure 10: Distribution of power loss after the first UV test of 60 kWh/m²

This behavior was primarily associated with changes in V_{OC} (Figure 9, right). Two module types (12 and 18) showed deviations from this pattern due to additional corrosion effects, that produced EL images similar to those after damp heat. This could be related to the tests incorporating moisture, i.e. the initial damp heat and intermittent HF10 test. (not shown).

In EL, two distinct degradation features were observed: most types demonstrated a checkerboard-pattern darkening of individual cells after the initial UV aging phase (Figure 11). Subsequent EL imaging showed only small changes, but the degradation and recovery cycles were evident in the varying brightness of the affected cells (Figure 11) upon careful observation.

This test sequence underscores the importance of tailored test designs for emerging technologies: Notably, the UV test protocol used here differs from other extended test schemes like IEC TS 63209-1:2021, which suggest UV irradiation solely from the rear, or sequence B from IEC 61730-2, as carried out in the context of module certification, which lacks interim power measurements. Therefore, these widely applied standard tests might not have identified the potential UV-related degradation issues observed here.

Subsequent tests focused on the observed degradation and partial recovery towards a better understanding of the different influences of the indoor stress tests as well as its relevance for a more realistic outdoor scenario. Modules of type 16 were used, since it had shown a distinct ‘W-pattern’ in the tests described above. Firstly, several modules were submitted to a UV test for 55 kWh/m² with or without previous DH200 aging (Figure 12, left). This also confirmed the possibility to reproduce the UV-induced aging effects previously observed. Independently of the presence or absence of the initial

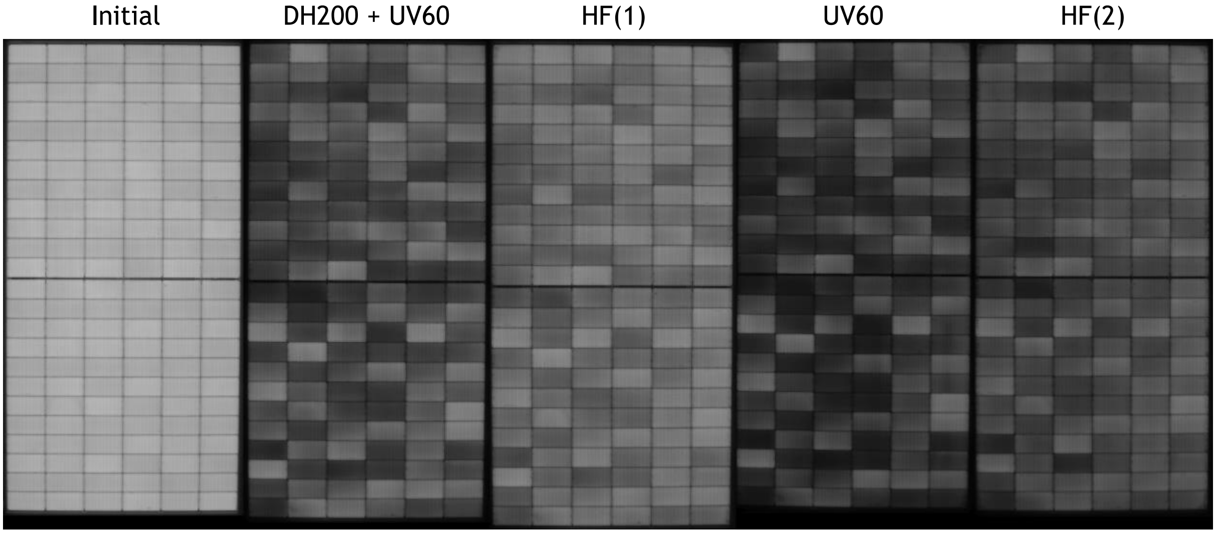

Figure 11: EL images of module type 11 during combined DH/UV/HF test sequence reveals checkerboard pattern with varying intensity affected by the 'W-pattern' of degradation and recovery.

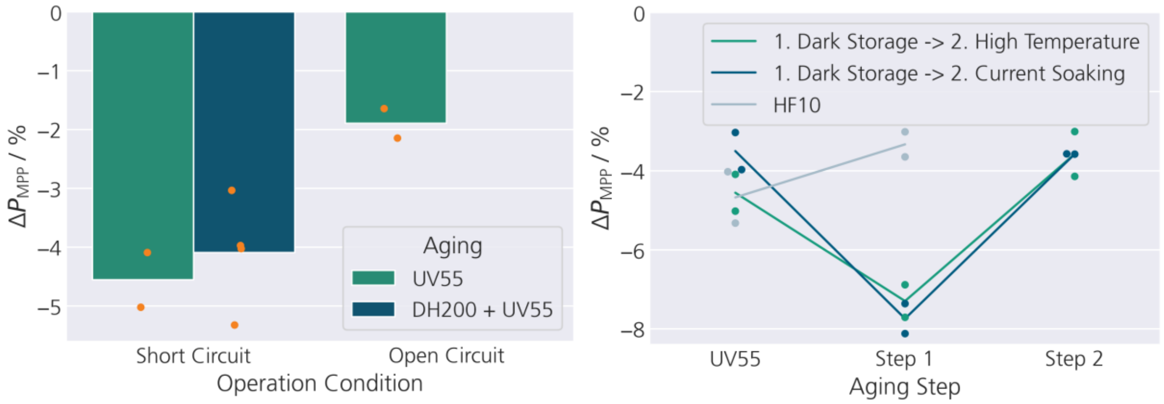

Figure 12: Change in performance after UV degradation relative to initial (PMPP): Dependence on the load condition and previous damp heat test (left); Effect of recovery and stabilization trials after UV degradation (right).

damp heat step, the modules show the same extent of degradation after UV aging, which leads to the conclusion that the initial damp heat treatment has no significant effect. Consequently, this treatment was discarded from the following experiments on UV degradation and recovery.

In contrast, changing the operating condition from short circuit (the situation for most tests) to open circuit, the observed power loss dropped from -4.2 to only -1.9 % in P_{MPP}. This corresponds well with the findings of the outdoor results (Figure 10). Here, the degradation is not very pronounced in general due to the low UV dose between January and June in Freiburg, but the degradation is only observed for the module in short circuit. In contrast to the lab tests, the outdoor operation degrades not only V_{OC}, but also I_{SC} parameters, which also has been observed by another currently running outdoor experiment [20]. The reasons for this phenomenon are currently not clear; Influences of temperature on the encapsulant degradation could be a contribution, but more outdoor data is needed to understand this behavior. The minor increase in *FF* confirms the absence of corrosion effects, which increases the probability that the UVID is indeed responsible for the observed degradation.

After UVID, the modules were treated in different potential stabilization procedures to further investigate the observed recovery behavior (Figure 12, right). As expected, the HF10 test led to partial recovery of two modules. In contrast, a dark storage for the same duration led to an additional degradation of almost -4 %. This unexpected behavior could subsequently be reversed by high temperature treatment (85 °C) in the dark with or without additional current injection of 2 x (I_{SC}-I_{MPP}). This leads to the conclusion that the high temperature during the thermal cycles in HF is responsible for the recovery. Additionally, the performance level after that last recovery step was very similar to the level after HF, suggesting that further treatment would not increase module performance further. In contrast, shorter times may also be sufficient to obtain the same results. The fact that the conditions at high temperature and current injection led to partial recovery suggests that similar behavior can also be expected for light soaking, which can already be used in standard test approaches, i.e. as stabilization procedure after aging tests. A similar approach could potentially be useful in the case of UVID, but requires further validation with different module types. Furthermore, the stability of the modules after these tests is not yet proven, so investigations in the behavior of repeated cycles of UVID dark storage and regeneration are the next steps to understand the degradation behavior and design a sensible test that can provide useful information about the expected outdoor degradation.

In conclusion, it is crucial to acknowledge that the real-life implications of the lab-observed UVID still remain unclear at this stage: As the investigations show, the in-field yield loss due to UVID would be strongly affected by multiple factors such as the mode of operation, e.g. MPP-tracking and local influence of light and temperature over time. The diverse conditions that led to recovery in the indoor tests suggest that the outdoor conditions for partial recovery would be met at least during some parts of a typical day. Furthermore, the state of the modules between construction and commissioning of the power plant should be considered because it could influence UVID and the later-observed yield loss.

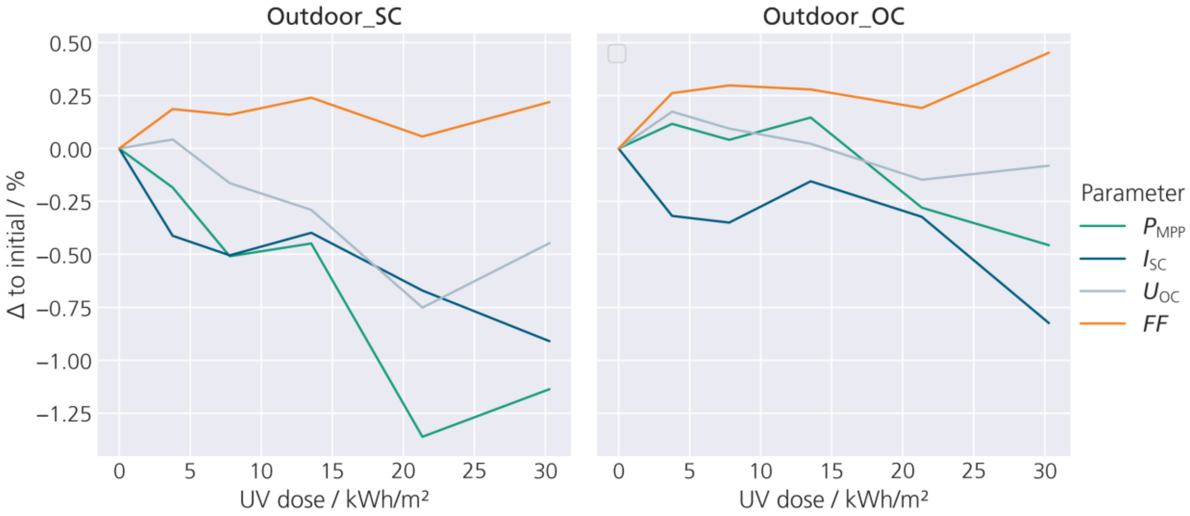

Figure 13: Results of the outdoor exposure of two modules of type 16 during the period between January 3 and July 8 2024.

V. CONCLUSIONS

This study utilized electrical characterization and accelerated aging tests to assess various PV module types based on the TOPCon cell technology from a wide range of different manufacturers.

The evaluation confirmed the superior performance and projected yield of modern PV modules based on TOPCon cell technology, as evidenced by electrical characterization and energy rating calculations. The TOPCon modules demonstrated higher efficiency, bifaciality, and better temperature coefficients compared to typical PERC modules. Similar to recent PERC generations, the TOPCon modules did not show increased sensitivity towards LID, LeTID, or PID.

However, the study also uncovered critical degradation effects related to moisture ingress and UV irradiation in accelerated aging, which are in stark contrast to the ambitious warranty conditions provided by manufacturers. In case of moisture-related degradation, the underlying issues such as the sensitivity of current front metallization pastes, is a known problem that may be mitigated in future module generations [21].

The combined UV/HF test sequence revealed a 'W-pattern' of significant degradation followed by partial recovery. As subsequent investigations showed, the degradation was influenced by the mode of operation (i.e. short- or open circuit), while the recovery was influenced by temperature, current injection and therefore most likely also light soaking (currently under test). Further outdoor exposure of UV-aged and unaged modules in MPP-tracking are currently carried out to investigate further a) which test conditions in the lab are more representative for the in-field degradation and b) if the conditions for recovery are met in realistic outdoor scenarios.

While this and similar studies have provided valuable insights, there is room for refinement in future test sequences. For example, we would put focus less on LeTID and LID. Instead, we recommend conducting focused tests on specific module types (tailored to the BOM if possible), emphasizing damp heat, PID, UV, and mechanical load, before purchasing substantial quantities of TOPCon modules from the current market. Due to the relative recent appearance TOPCon based modules on the market, we expect the reliability characteristics to change and improve during the next months, which could also change the best practice for qualification testing.

VI. ACKNOWLEDGEMENT

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