Degradation and Failure Modes in New Photovoltaic Cell and Module Technologies

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Main Authors:
M. Köntges, ISFH, Germany; J. Lin, PV Guider; A. Virtuani, CSEM, Switzerland; G. C. Eder, OFI, Austria; G. Oreski, PCCL, Austria; P. Hacke, National Renewable Energy Laboratory, USA; J. S. Stein, Sandia National Laboratories, USA; L. Bruckman, CWRU, USA; P. Gebhardt, Fraunhofer ISE, Germany; D. Barrit, Total Energies, France; M. Rasmussen, CWRU, USA; I. Martin, CWRU, USA; K. O. Davis, UCF, USA; G. Cattaneo, CSEM, Switzerland; B. Hoex, UNSW, Australia; Z. Hameiri, UNSW, Australia; E. Özkala, SUPSI, Switzerland.

Editors:
M. Köntges, ISFH, Germany; J. Lin, PV Guider; U. Jahn, Fraunhofer CSP, Germany.

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Executive Summary

The levelized cost of electricity (LCOE) of photovoltaic applications depends on, among other things, the performance, price and durability of the photovoltaic (PV) module. Performance and price can be determined with little effort. Durability is the least known of these three factors. In this report, we evaluate the impact of degradation/failure modes of innovations in the market.

The reliability situation of Tunnel Oxide Passivated Contact (TOPCon) and Silicon Hetero-Junction (SHJ) is shown in Figure 1 for selected degradation and failure modes. Especially semiconductor-related degradation modes show degradation and recovery paths: light (and elevated temperature)-induced degradation (LeTID/LID), UV-induced degradation (UVID), and potential-induced degradation (PID). Their impact can only be assessed if the degradation and recovery paths are understood, and a test method is available. Common degradation modes or failures related to embedment, glass and junction box are shown in Figure 1 on the right. Current standard tests, especially of the IEC 61215 standard, cannot reveal these degradation or failure modes. As these modes are safety relevant, it is important to understand the causes and develop standardized tests to identify these reliability problems.

In the following we go through degradation modes which changed with new innovation. We find that the impact of cell cracking has been mostly overcome by the innovation of multi-wire technology. Also, LID/LeTID has been well understood and solved by switching from Boron to Gallium as a dopant for Si-wafers, by using adjusted processes in the cell production together with the use of thin wafers, and lowering the number of impurities in the wafer production. Furthermore, standard test procedures are available, so that the LID/LeTID impact on long-term performance can be tested even for innovation. The degradation mechanisms which lay behind PID can be triggered and mitigated at cell, module and system level. These degradation mechanisms are caused by high system voltage and may be influenced by light, in particular UV irradiation. PID tests for modules with Passivated Emitter and Rear Totally diffused (PERT) cells have shown that additional light during a PID test can effectively prevent degradation. It has been shown in one case that an UV irradiance equivalent to the UV content in the standard AM1.5 spectrum at 1000 Wm^{-2} can reduce the PID effect for a module with TOPCon cells to below 3%. In contrast, in this case no UV irradiation during the PID test leads to a degradation of 28%. For PV modules with SHJ cells a new potential PID degradation mechanism is identified. However, no PID affected modules are found in the field corresponding to this mode, yet. To assess the irradiation

impact on real installations, the upcoming PID standard IEC TS 62804-1 (2025) offers a combined potential and light test procedure.

In some solar modules with TOPCon and SHJ cells, UVID is pronounced after accelerated aging tests. It is still unclear whether the degradation can be reversed by outdoor exposure and how the test can be transferred from laboratory to field, since many interacting mechanisms influence UV degradation and recovery. It must be emphasized that the UVID is a solvable problem, since some modules in accelerated tests are UV-stable. The reflection or absorption of UV radiation before it reaches the c-Si/passivation interfaces (e.g. by the encapsulation material) can mitigate the UVID.

For encapsulant materials standardized PV module tests (e.g., of the IEC 61215 series or other PV safety standards) often do not reveal relevant degradation paths as their focus is on the electrical performance of the PV modules and not on the polymer materials stability. Therefore, many PV modules are found in the field with damaged lamination material. Combined stresses with e.g. temperature change, humidity and UV radiation can reveal these polymer-related degradation paths. Especially for these degradation modes, new combined aging tests are required as discussed in detail in the IEA PVPS TASK 13 sister report “Accelerated testing - combined stress vs. sequential stress testing methods and inclusion of specific load situations”. As degradation of encapsulation material is not recoverable and often leads to safety issues, these additional tests are recommended for new encapsulant materials.

In practice, thin glass (thickness ≤ 2 mm) used in new glass/glass modules sometimes results in unpredictable high glass breakage rates. In documented cases 5% to 10% of the module rear glasses broke in the first two years after installation. The mechanical load test in IEC 61215 cannot reveal this vulnerability, as it would need parallel tests on tens of modules, instead of only one, to assess the failure rate. Currently, only a high number of tests in the final mounting position can reveal the stability of thin glass modules.

More frequently than before, it happens that electrical contacts in the junction boxes are not soldered correctly. This may mean that the bypass diodes (BPDs) are not properly contacted. Faults in the junction box can lead to fires and power losses in entire module strings. However, unconnected BPDs are difficult to detect in PV systems that have already been installed. It is therefore recommended to check the function of 100% of the BPDs during production. A PV system installation should be 100% tested if there are indications that this type of failure is occurring in the selected modules.

This report also includes a concise summary on the reliability of metal halide perovskite (MHP)-based PV modules according to the current scientific literature. There are many known degradation paths for which remedies exist at the conceptual or laboratory level. For example, protective encapsulation against UV radiation, moisture and oxygen basically helps to stabilize the perovskite solar cells (PSCs). However, besides others, two prominent challenges are the temperature and the ion migration stability. The limited temperature stability and the high ion mobility lead to unsolved degradation paths under normal operation conditions like shading and high system voltage. There are new degradation modes in tandem solar cells with MHPs. For example, the reverse voltage states occurring in the top and bottom cells during shaded conditions depend on the irradiation spectrum and cannot yet be reproduced by standard qualification tests. New tests addressing this shading condition are important to evaluate new degradation pathways that do not occur in single junction PV modules.

To produce reliable PV modules, all degradation pathways must be understood and mitigated in one solution. There are currently no comprehensive solutions in the literature to address the multiple reliability issues of perovskite solar cells.

Along with this report Photovoltaic Failure Fact Sheets (PVFS) 2025 are delivered to provide praxis and field-oriented information for PV planners, installers, investors, inspectors, consultant and insurance companies.

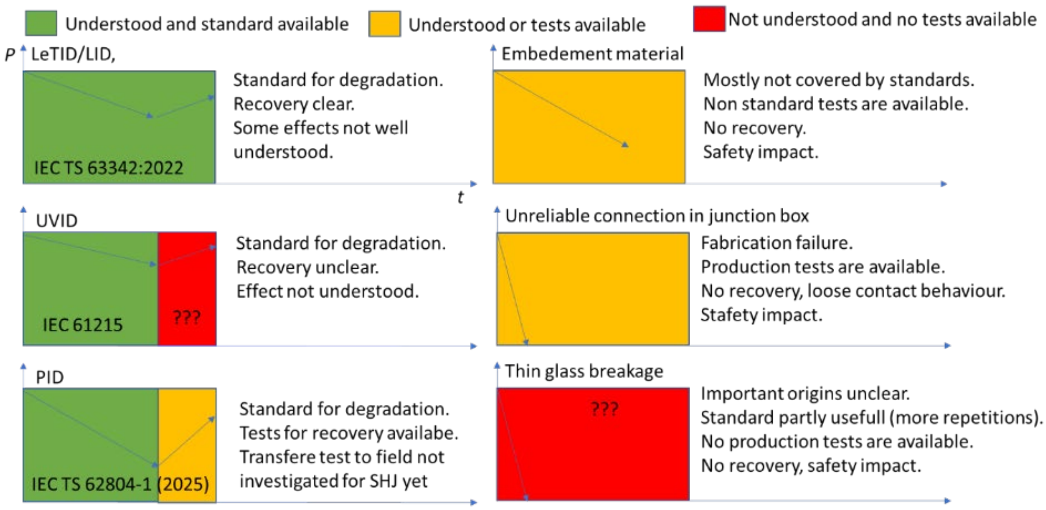

Figure 1: Overview of test availability and impact of currently relevant degradation modes of TOPCon and SHJ module designs.

Key Takeaways

1. **Innovation Impact on Degradation**: Cell cracking issues are mitigated by multi-wire technology, while light and temperature-induced degradation (LID/LeTID) is addressed by using gallium-doped wafers and improved manufacturing processes.
2. **Potential-Induced Degradation (PID)**: PID mechanisms can be reduced through targeted tests and adjustments at cell, module, and system levels. UV irradiation during testing shows promise in minimizing degradation in specific cell types like TOPCon.
3. **UV-Induced Degradation (UVID)**: This occurs in some PV modules but is manageable by using UV-stable designs and encapsulation materials. However, more research is needed to fully replicate laboratory tests to field conditions.
4. **Encapsulation Material Challenges**: Degradation in polymer encapsulation materials remains a major issue, requiring new testing standards that combine stresses like UV radiation, humidity, and temperature.
5. **Thin Glass Durability**: Thin glass in modern modules has shown higher breakage rates, necessitating multiple-module testing under real installation conditions.
6. **Junction Box Reliability**: Faulty bypass diode connections pose safety and performance risks. It is recommended to implement 100% testing during production and in affected installations.
7. **Perovskite based PV modules:** There are still plenty of reliability issues for perovskite-based PV module technologies in literature. There are many possible solutions, but they have not yet been evaluated in literature when combined in a single process solving all challenges at once.

These findings emphasize the need for enhanced testing standards to address emerging reliability challenges in photovoltaic modules.