UV-induced degradation of n-TOPCon and other PV cell technologies

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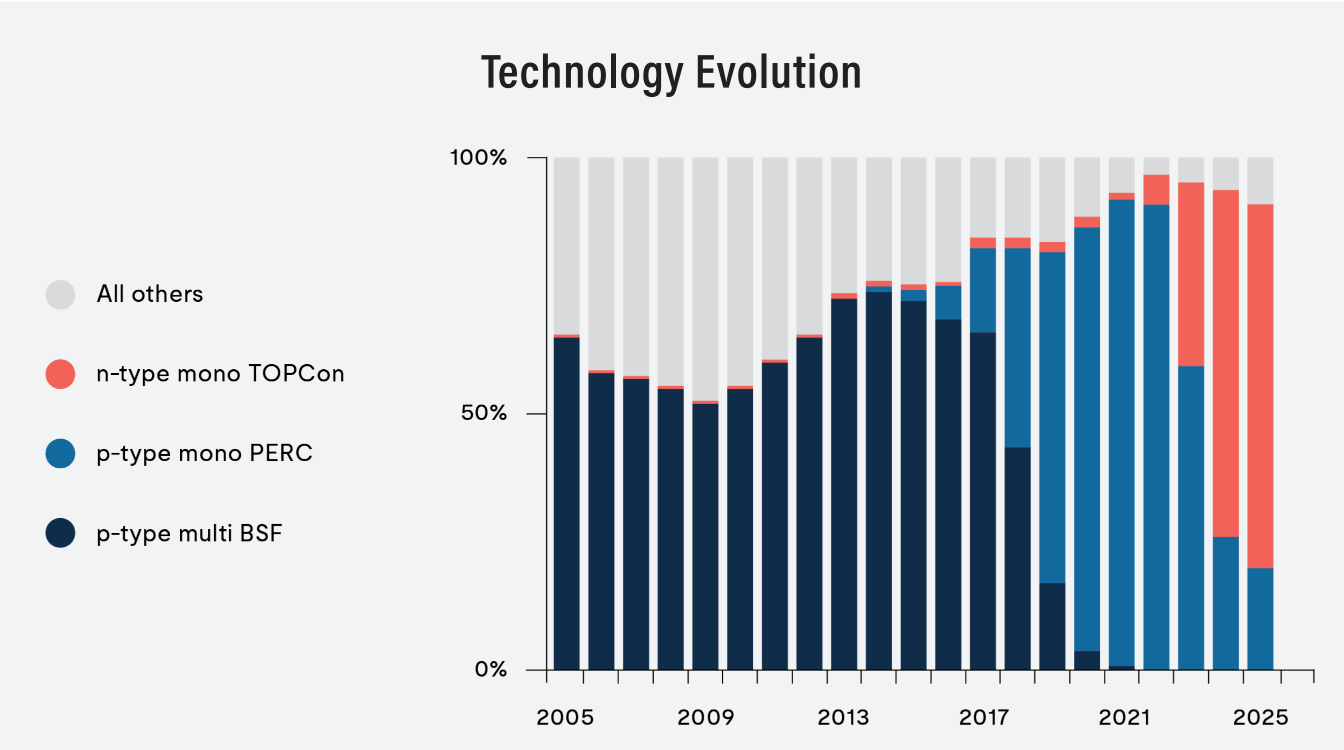
As n-type tunnel oxide passivated contact (n-TOPCon) photovoltaic (PV) cell technologies gain widespread adoption due to their high initial efficiencies, a critical reliability concern is emerging: ultraviolet (UV)-induced degradation (UVID). This article offers a clear assessment of UVID, its impact on n-TOPCon and other advanced PV cell architectures, and the associated technical and financial risks facing manufacturers, developers, and investors. Drawing on field data, peer-reviewed research, and technical insights from UL Solutions, it outlines current mitigation strategies, recommended UV testing practices, and key factors influencing long-term PV system performance.



Source: See Ref. [1]

As UVID remains a relatively new and actively evolving area of research, this article will be regularly updated by UL Solutions to reflect the latest scientific developments. Readers are encouraged to revisit our website periodically for the most up-to-date information on this important industry challenge.

In recent years, n-type PV technologies have gone from 0% market share to an astonishing nearly 70%, as p-type passivated-emitter rear contact (p-PERC) PV cell manufacturing lines continue to transition to produce mostly n-TOPCon PV cells. As always, with new PV technologies, new challenges and risks arise.

The value of a PV module is directly related to its initial power rating. Modules with high initial efficiency benefit the PV module manufacturers; however, it is only a benefit to consumers if the degradation of the module efficiency over time is predictable and as small as possible. While n-TOPCon clearly demonstrates high initial efficiency, the question remains: how durable is the performance of n-TOPCon modules over time in outdoor operation?

Background on UVID

Scientific literature and test results, e.g., from the University of New South Wales (UNSW), Yingli Solar, and other research and testing institutions indicate that n-TOPCon comes with certain risks, including damp heat (DH), potential-induced degradation (PID), and, perhaps most significantly, UV-induced degradation (UVID).

First coined by ECN/Yingli in 2016 [2], UVID is presently understood as the irreversible breakdown of the 'tunnel oxide' dielectric passivation and anti-reflective (AR) coatings on the top and, if applicable, bottom sides of the PV cells by UV light, damaging atomic bonds (e.g., hydrogen bonds) and resulting in recombination centers that lead to unwanted electron-hole pairing at the PV cell surface(s), in turn leading to localized heating and reduced efficiency.

What is UVID and what are the risks?

UVID occurs when UV light exposure damages the deposited 'tunnel oxide' dielectric passivation and anti-reflective coating (ARC) layers on the front and/or rear sides of a PV cell. When UV, electrons and holes damage these layers start recombining at the front and rear surfaces of the PV cell at these atomic damage sites, leading to heat generation instead of electricity collection and thereby lowering PV cell efficiency.

This permanent effect can lead to ~1%-17% power degradation (relative) [3,4,5] in the equivalent of the first few years of outdoor operation. UVID (and DH and PID) remain significant issues of concern for n-TOPCon and other advanced PV cell technologies, and many manufacturers have not yet solved UVID, so it is hypothesized that many PV modules that are being deployed will have high initial rates of degradation and thus reduced conversion efficiencies.

While manufacturers raced to adopt n-TOPCon for the competitive initial efficiency advantage, it turns out this product, depending on the PV cell manufacturing process, can be susceptible to this field degradation effect that can eliminate some or all of that initial efficiency advantage. Because manufacturers are compensated on the initial flash test data, UVID has primarily introduced a risk to buyers.

Which PV cell technologies are susceptible to UVID?

Many types of PV cell technologies have dielectric passivation layers, such as SiO2 or Al2O3, combined with ARC layers such as SiNx or TiO2 on the front or rear PV cell surface(s). Any cell technology with these characteristics introduces a risk of UVID.

Vulnerable technologies can include certain p-PERC, n-TOPCon, n-type heterojunction with intrinsic thin-layer (n-HJT or n-HIT), n-type interdigitated back contact (n-IBC), and several other, less common n-type PV cells, e.g., n-type passivated on all sides H-pattern (n-PASHA), n-type passivated emitter rear totally diffused (n-PERT), and n-type passivated emitter with rear locally diffused (n-PERL). n-TOPCon currently dominates the market and is the main concern and focus of this article.

How can n-TOPCon UVID risks be mitigated, and which mitigation approach(es) is UL Solutions looking for as an independent engineering (IE) advisor to financiers of PV projects and technologies?

- We would first want to know what strategies the PV module supplier has implemented to mitigate UVID risks on the PV cell and PV module levels.
- We want to see UVID test results on a statistically significant sample size of PV modules (and/or results for an even larger sample size of mini-modules/coupons). UL Solutions has expert staff who work and collaborate with PV testing laboratories in Asia, India, Europe, North America and Saudi Arabia that can witness production and sampling, and UL Solutions can perform state-of-the-art testing to evaluate module susceptibility to UVID.
- Random sampling and independent testing, such as offered by UL Solutions experts, are ideally implemented on samples going to the project under our independent engineering (IE) review.
- Finally, UL Solutions, the customer, and the original equipment manufacturer (OEM) must work together to determine if any adjustments are warranted in the energy production estimates, including contractual pro forma models, and overall project economics, including operations and maintenance (O&M) costs and levelized cost of electricity (LCOE).

While it is prudent for buyers to confirm that the PV module warranty covers excessive degradation effects during operation, most warranty terms do not cover labor costs required to identify and pursue a warranty claim, uninstallation or reinstallation costs, or lost energy production due to downtime – all factors which can hinder the use and reduce the effectiveness of said warranties. Predictions of UVID susceptibility is therefore critically important to reduce the financial risk to consumers.

UVID testing best practices

UL Solutions is actively engaged in developing a UVID test standard, IEC TS 63624-1, and offers testing according to the latest international guidance or custom test procedures. Manufacturers and stakeholders can also mitigate the risk of UVID by following the guidelines below:

Favor larger sample sizes

Evaluation of a technology based on a small number of samples yields limited confidence in the results. Confidence in the diligence evaluation increases with more samples tested.

Include more incremental power measurements throughout the UV exposure testing

Degradation from UVID is non-linear and demonstrates an asymptotic effect. An accurate characterization requires power measurements at multiple points through the UVID stress testing as opposed to a single initial power measurement prior to UV exposure, followed by a final power measurement at the end of the test.

With only two measurements, it will not be known if the UV exposure dose was sufficient for the degradation to stabilize. UL Solutions recommends collecting more incremental data points in order to characterize this asymptotic degradation curve. This way, technical due diligence stakeholders can directly observe that the sample has stabilized and the degradation from UVID has reached its maximum value and is complete.

Favor longer UV exposure times

There is currently no consensus standard for UVID test procedures, so test methodologies can vary between laboratories. The required UV dose is still a subject of discussion and debate among industry experts. Most laboratories use 120 to 220 kWh/m2. Longer exposure times provide better assurance that UVID susceptibility is identified; however, it increases testing cost and time.

More data is needed to settle on an appropriate UV exposure dose for a product qualification acceptance criterion. Until a data-based consensus is reached, UL Solutions recommends a UV test duration that is sufficient to demonstrate that any observed power degradation has stabilized.

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Highly accelerated coupon-level testing in a UV weatherometer is a way to test longer UV exposures more efficiently, and UL Solutions considers such approaches to be effective. Note, however, that if coupon or mini-modules are tested, a much larger sample size is needed. Adhere to UV light source specifications defined in PV-specific IEC and UL Standards.

The UV light source must adhere to the specifications defined in PV-specific IEC and UL Standards, namely, IEC and UL 61215, the Series of Standards for Terrestrial Photovoltaic (PV) Modules [6,7], and IEC 62788-7-2 for PV coupons, mini-modules, and materials [8]. Test modules under load at their maximum peak power point.

The ideal test condition is with the module under load, with the sample's current-voltage (I-V) characteristic curve held at or close to its maximum power point (MPP) condition, either via MPP tracking or using a fixed load resistor

If MPP tracking is not possible, UL Solutions recommends testing in short-circuit conditions (at Isc), with care taken to avoid hotspots. Avoid testing in open-circuit voltage conditions, as it will not produce the extent of degradation at the rate that would be expected in the field. If open-circuit testing is necessary, UL Solutions recommends longer UVID testing exposure times in order to compensate for the lower stress as compared to the operational MPP tracking conditions.

Conduct electroluminescence (EL) imaging before and after UV exposure

PV modules will appear to have a patchwork, quilting or checkerboarding pattern of mixed light and dark cells after UVID testing, if susceptible to UVID. The checkerboarding effect is greater at low currents.

Conduct I-V curves before, during and after UV exposure

Generally, the signature degradation characteristic of UVID for n-TOPCon is an equal decrease in both Isc and Voc, with no change in fill factor (FF).

If Isc degrades while Voc remains the same, then the root cause is likely to be UV-driven discoloration (a different problem) and not UVID.

Note that I-V curve effects may not always be the same within or across PV cell technologies. For example, some manufacturers and labs have reported a decrease in FF for n-HJT.

Consider acceptable power degradation after UV exposure tests

In general, power degradation of less than 3% represents minimal risk, provided that the testing is conducted until degradation stabilizes. This level of performance is within the acceptable uncertainty range for the industry-standard flash testers and is well within the typical intra-lab repeatability on the same flash tester and calibration reference.

Consider post-UVID light soak

Certain PV cell technologies may exhibit metastability effects which cause increased degradation following UVID, especially if PV modules are stored under no illumination and in open- or short-circuit condition following UVID testing. To reduce metastability effects on UVID testing results, a post-UVID light soak step following UVID testing is encouraged for metastable PV cell technology types.

This involves light soaking under full spectrum irradiation at 300 – 1,000 W/m2 intensity for a total dose of 1 kWh/m2 (or more) under MPPT conditions while keeping the PV module temperature at or below 60 °C. The exact testing details and requirements of the post-UVID light soak are described in the draft version of standard IEC TS 63624-1 on PV module UVID testing, which remains under development.

How long would it take to see UVID in outdoor operation?

Significant indoor module performance degradation with as little as 90 kWh/m2 of UV light soak has been reported in industry literature [3]. This indoor UV dosage equates to an outdoor, full-spectrum sunlight exposure time of approximately 1.2 years.

How can UVID be solved on the PV cell level?

UVID is solvable at the PV cell level through a diligent PV cell manufacturing process optimization. This requires an analysis of the sensitivity to UVID to process variability in the PV cell manufacturing line relating to deposited nanolayer chemistries, thicknesses, densities, refractive indices, and more.

This approach is complex and difficult to achieve on one PV cell manufacturing line for one PV cell batch, and even more difficult to achieve consistently across PV cell batches and across PV cell manufacturing lines. Some of the top PV suppliers may have several PV cell lines in each of several PV factories located in several countries. In such cases, diligent UVID solutions and the associated quality assurance / quality control (QA/QC) requirements to keep the solution in check present an extreme challenge.

Bottom line: Solving UVID on the PV cell level is very technically challenging, and it is even harder to maintain a solution from a QA/QC perspective. Much oversight and diligence are needed.

How can UVID be solved on the PV module level?

Certain manufacturers are implementing PV module-level solutions to mitigate UVID, namely, the incorporation of UV light down-converting layers. Such polymers are added in front of the PV cell surface(s) and are intended to convert the short wavelength UV light which causes UVID into longer light wavelengths which will not cause UVID. UL Solutions notes that whenever new materials are added into the bill of materials (BOM) stack of a PV module, testing must be repeated.

Retesting is required for safety and qualification testing according to IEC TS/UL 62915, and the IEC/UL 61730 and 61215 series. Extended durability testing is highly recommended according to IEC TS 63209-1, as well as repeating the UVID susceptibility testing. Extended outdoor exposure of modules operating at MPP is of course always beneficial in order to further mitigate the risk of new materials contributing to premature and unexpected degradation of PV performance.

Bottom line: Solving UVID on the PV module level may be simpler than on the PV cell level via the use of added UV down-converting polymer layers, however, any added materials in the PV module BOM stack requires extensive durability testing in order to ensure the durability of stack is maintained.

Mitigating known UVID risks in case the PV manufacturer has not confidently solved UVID at the PV cell or module level

If the OEM has not confidently solved UVID at the PV cell or module level, as is often the case today [3,4,5], one approach is for n-TOPCon suppliers to derate their power ratings to reflect anticipated UVID effects. This is similar to how cadmium telluride (CdTe) suppliers derate their power ratings for the well-known, rapid wear-in degradation that occurs during initial outdoor operation under sunlight exposure.

Is UVID recoverable?

Some researchers claim UVID may be partly recoverable. At this time, UL Solutions understands that UVID is a destructive phenomenon and that any recoveries that may have been observed and reported relate to another known phenomenon of these same products, called metastability.

How does indoor UV(ID) testing translate into outdoor exposure time?

Only the UV portion of the solar irradiance spectrum is relevant to UVID. The UV portion of the spectrum is a small fraction of the standard solar spectrum (AM1.5G). AM1.5G is used in laboratory performance ratings ('flash tests') of PV modules, because it is representative of typical sunlight at the Earth's surface under clear sky conditions. Conversely, light sources that are used in UV test chambers deviate from AM1.5G by design, to accelerate degradation known to be triggered by the UV portion of the solar irradiance spectrum.

Therefore, a transfer function is required to approximate how the UV dose in a UV test chamber will equate to an exposure duration outdoors under more field-representative spectral irradiance distributions close to AM1.5G (with some variance, given some red- and blue-shifting away from AM1.5G occurring during the day and seasonally).

A few of the papers cited [9,10,11] propose such a transfer function to show that the UV pre-conditioning irradiation dose of 15 kWh/m2 specified in the UL/IEC 61215-2 preconditioning tests roughly equates to 70-77 days of outdoor, full-spectrum sunlight exposure. Extrapolating on this transfer function, and assuming linearity from a UV irradiation dosage of 15 kWh/m2 to the UV irradiation dosage of 90-220 kWh/m2 that is applied in typical, commercial UVID testing of full-sized PV modules, yields an equivalent outdoor, full-spectrum sunlight exposure time of approximately 1.2-2.8 years.

Therefore, we would expect that whatever degradation seen in such typical UVID tests would approximate 1.2-2.8 years of outdoor exposure under full-spectrum solar irradiation spectra. Note that this transfer function is meant to be an average use case for making generalized approximations; different PV system orientations and different geographical locations will have different UV exposure.

Are indoor UVID results relevant to what will occur under outdoor exposure?

Indoor UV testing, subject to the limits outlined in the UL/IEC 61215 series and IEC 62788-7-2 standard [8] can help ensure that indoor UVID testing yields results that would be expected to occur outdoors, albeit over longer timescales, given the difference between the dominant UV light spectra of indoor testing vs. full-spectrum sunlight of outdoor exposure.

These indoor UV testing limits in the aforementioned IEC and UL Standards for PV relate to:

A. The intensity of UV light, to avoid subjecting PV modules to unrealistic, non-field representative UV light intensities;

B. Sample temperature during UV testing, to help ensure reasonable, field-representative sample temperatures during test;

C. UV light spectra, to help ensure a representative spectral distribution of UV light relative to the spectral distribution of the UV portion of the solar spectra of AM1.5G; and

D. UV irradiation dosage that will likely never be enough to reach a field-equivalence of 25 years of outdoor exposure.

Therefore, given these carefully considered/designed UV testing limits in the relevant IEC and UL Standards for PV listed above, indoor UV testing of PV modules in accordance with applicable PV-specific guidelines and standards can help ensure field-relevant UVID results.

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