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A case study on accelerated light- and elevated temperature-induced degradation testing of commercial multi-crystalline silicon passivated emitter and rear cell modules

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Abstract

Light- and elevated temperature-induced degradation (LeTID) can have significant and long-lasting effects on silicon photovoltaic modules. Its behaviour is complex, showing highly variable degradation under different conditions or due to minor changes in device fabrication. Here, we show the large difference in LeTID kinetics and extents in multi-crystalline passivated emitter and rear cell (multi-PERC) modules from four different manufacturers. Varied accelerated testing conditions are found to impact the maximum extent of degradation in different ways for different manufacturers complicating the ability to develop a universal predictive model for field degradation. Relative changes in the open-circuit voltage (V_{OC}) have previously been used to assess extents of LeTID; however, due to the greater impact of the defect at lower injection, the V_{OC} is shown to degrade less than half as much as the voltage at maximum power point (V_{MPP}). The MPP current (I_{MPP}) and fill factor (FF) also degrade significantly, having an even larger overall impact on the power output. These observations imply that currently employed methodologies for testing LeTID are inadequate, which limits the reliability of future predictive models. In light of this, the field must develop a more holistic approach to analysing LeTID-impacted modules, which incorporates information about changes under MPP conditions. This will allow for a much clearer understanding of LeTID in the field, which will assist the performance of future PV systems.

KEYWORDS

degradation, LeTID, light- and elevated temperature-induced degradation, multi-PERC, PV modules, silicon solar cells

1 | INTRODUCTION

Since 2012,[1] the photovoltaic (PV) industry has been aware of a new type of degradation affecting multi-crystalline silicon passivated emitter and rear cells (multi-PERC) under typical operating conditions. It was subsequently termed light- and elevated temperature-induced degradation (LeTID)[2] due to the conditions under which it was identified and typically tested for at this time. We now know the same degradation can form in the dark with or without current injection,[2–4] and also affects all silicon wafers, including Czochralski,[4] *n*-type,[5] gallium doped[6,7] and float-zone.[8–13] The exact defect causing the degradation is not yet known; however, there is a growing consensus that hydrogen is involved, due to the strong correlation with the hydrogen concentration.[14] The degradation can lead to >10% relative efficiency loss if untreated and take decades to degrade and recover in the field.[15]

LeTID has a complex behaviour showing varied degradation and recovery behaviours based on wafer type, testing conditions, device structure[16] and even minor differences in prior thermal history.[17,18] In addition, module operating temperatures vary widely depending on location and type of installation. A roof-mounted module in Sydney can reach almost 100°C and a BIPV module in Tucson can spend over 1600 h above 50°C every year, while a field rack-mounted array in Hamburg does not even reach 60°C and spends only 17 h over 50°C in a year.[19] As a result, despite several years of investigation, the impact on commercial modules is not well understood.

A study by Kersten et al has shown much slower degradation of LeTID sensitive modules installed in a cool German climate when compared with a warm, sunny Greek climate.[20] Fokuhl et al[16] have shown that modules consisting of different cell structures show different degradation and regeneration behaviour and different responses to accelerated testing conditions. Relative to multi-PERC modules, in monocrystalline silicon PERC modules, the recovery process appeared to accelerate far more significantly than the degradation process, leading to a reduced extent of degradation. This was even more the case for silicon heterojunction (SHJ) modules, which only showed improvement under the further accelerated conditions. Deceglie et al have shown that even modules of the same type from the same manufacturer can degrade differently in the field, possibly attributed to different rear contacts.[21] Dupuis et al used comprehensive experimental data of bifacial module degradation combined with predictive modelling to highlight the challenges accounting for the large variability between cells in a module as well as other uncertainties including activation energies.[22]

All of this complexity and uncertainty can be disastrous for warranty claims, investors and consumers relying on accurate projections and costing of future output, designers sizing systems and so forth. If left untreated, the highly variable degradation could cause havoc for IEC qualification and reliability testing.[23] Due to the long timescales of the degradation, suitable accelerated tests are essential for quickly identifying LeTID susceptibility and predicting future output. The existing prior studies have begun to understand the varied LeTID response of modules in the field by either studying different module types under the same conditions or studying modules from the same manufacturer under varied testing conditions. However, an analysis of modules from different manufacturers tested under a variety of LeTID testing conditions is crucially missing from literature. In particular, it is important to assess the impact of the wide range of temperatures that could be experienced by a module in the field.

This work investigates LeTID degradation of multi-PERC modules from four different manufacturers and how the degradation of each varies under different lab acceleration test conditions. To do so, we applied a new approach of deliberately allowing a temperature gradient to form across the module during testing due to the non-uniform illumination from the light source with no diffuser. This approach allowed for deeper insights into how multi-PERC cells from different manufacturers degrade under different operating conditions.

2 | METHOD

Multi-PERC modules from four different manufacturers were acquired from the market between 2016 and 2018:

- Manufacturer A: 285-W 60-cell module acquired November 2018, no mention of LeTID solution.
- Manufacturer B: 280-W 60-cell module acquired November 2016, claimed LeTID solution and linear degradation warranty.
- Manufacturer C: 335-W 72-cell module acquired December 2016, no mention of LeTID solution.
- Manufacturer D: 285-W 120 half-cut cells acquired November 2016, claimed LeTID solution and linear degradation warranty.

Modules were light soaked in open-circuit conditions under an array of 12 × 500 W halogen tube lights, as shown in Figure 1A. To enable a wide variation of accelerated testing conditions to be tested on a single module, the temperature was allowed to naturally rise due to the illumination with no diffuser, thereby causing varied illumination and temperatures across the module. The array was constructed separately for each module resulting in slight variations in angles and positioning for each, thereby causing differences in illumination intensity and temperature across each module. To enable meaningful results, the temperature and irradiance were measured at the centre of each cell of each module; temperature was measured using both an infrared gun on the front and a type K thermocouple (on the front and rear, showing typically 1°C–2°C higher on the illuminated front side) to gain confidence in the measurements; the irradiance was measured with a Thorlabs 40-W thermal detector. To demonstrate the non-uniformities, Figure 1B,C shows the illumination intensity and temperature maps, respectively, for the 120 half-cell module from manufacturer D. Temperatures ranged from ∼50°C to ∼115°C. Illumination varied from ∼0.5 to 2 kW/m^2 in a similar distribution. Since the temperature rise was due only to illumination, the two were linked (see Figure 1D), as would occur similarly in field conditions. A solid line shows a linear trend of all data points from all manufacturers. Some spread can be expected due to thermal conductivity between adjacent cells and increased thermal radiation from module edges. LeTID kinetics is dependent on both temperature and the excess carrier density.[15,24] However, due to the logarithmic dependence of the excess carrier density on the illumination intensity, increasing the illumination intensity around this range has been shown to have minimal effect on the degradation kinetics,[25] as also confirmed in our data (not shown). In light of this and for simplicity, results in this paper will be reported according to the temperature variations.

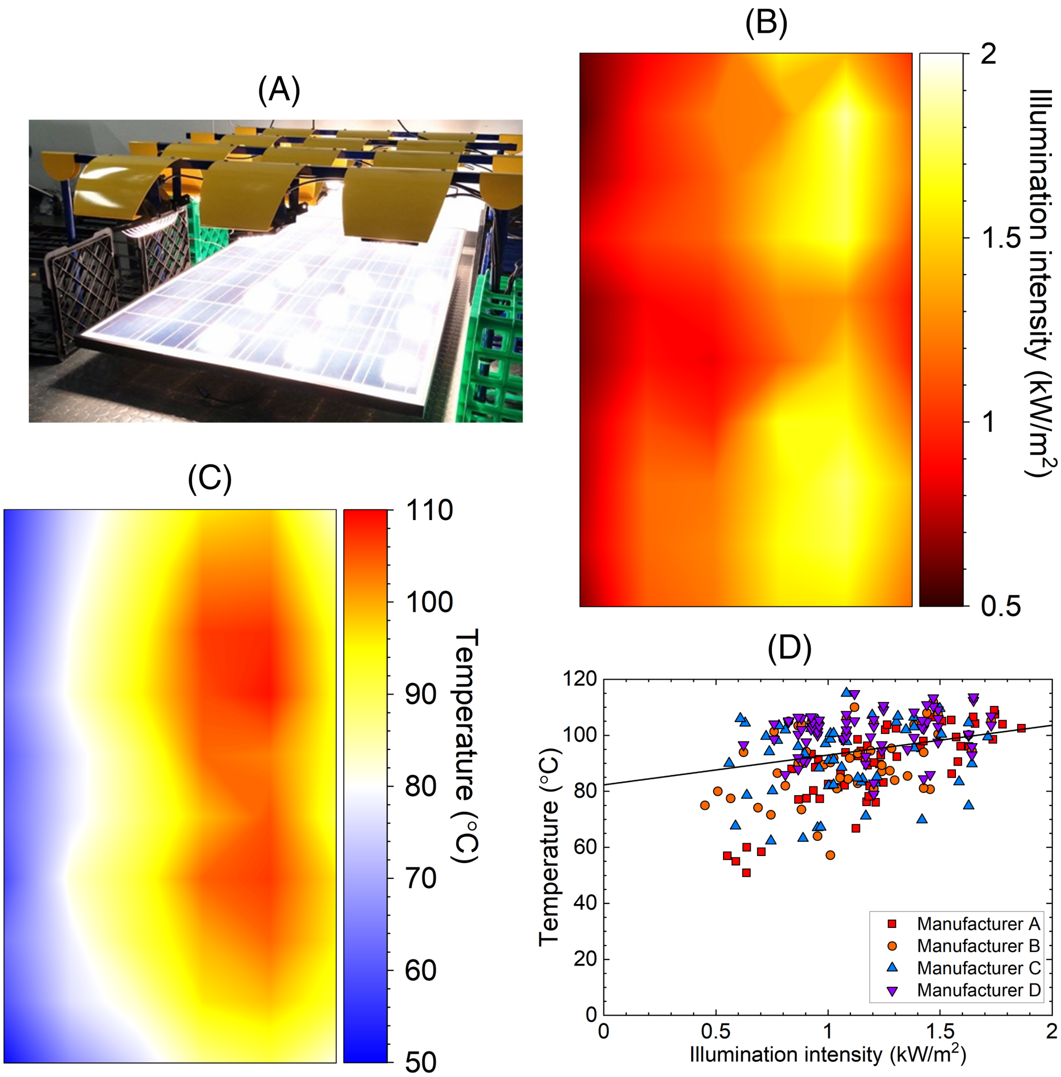

FIGURE 1 (A) LeTID light soak testing under an array of 12 × 500 W halogen lights; (B) illumination intensity map and (C) temperature map across the module from manufacturer A during light soaking; measured at the centre of each half-cut cell (120 points); (D) illumination intensity versus the temperature as measured at the centre of each cell of each module

All modules were photoluminescence imaged in open-circuit conditions using a custom-built module line-scanning tool (PL_LS)[26] in the as-received state, and at successive increasing increments during light soaking: after 60, 120, 240, 480, 960, 2000, 5000 and 10,000 min (a total duration of 166.66 h, or ~1 week). The module from manufacturer A was also electroluminescence (EL_LS) imaged using a forward current of 0.95 A to create operating conditions similar to those at maximum power point (MPP) under 1000 W/m^2 AM1.5G illumination.[27] The average PL_LS or EL_LS counts of each cell in each module was measured at each point. The change in V_{OC}/V_{MPP} for each cell in each module was then calculated according to the following equation[28]:

$$\Delta V_{OC}(V) = \frac{kT}{q} \cdot \ln\left(\frac{\mathrm{PL\_LS_{new}}}{\mathrm{PL\_LS_{initial}}}\right)$$

A sister module (same batch) from manufacturer A was also sent to DNV-GL (now PV Evolution Labs, known as PVEL) and tested similarly using a highly uniform Class A + A + A + Pasan SunSim 3b solar simulator. Periodic IV measurements and EL images were taken over 250 h; the module temperature naturally rose to ~100°C ± 4°C.

After the 10,000 min of LeTID testing, the module from manufacturer C was dark annealed in a laminator for 10 h at 150°C. The purpose of this was to destabilise the regenerated defect in a manner similar to that shown by Fung et al who used 8 min at 232°C.[29] Since the laminated module could only be taken to 150°C without risking permanent damage, the anneal was performed for 10 h to account for the exponentially slower reactions at the lower temperature. The module was then LeTID tested again for 10,000 min.

A depiction of the various experimental conditions and process flow is shown in Figure 2.

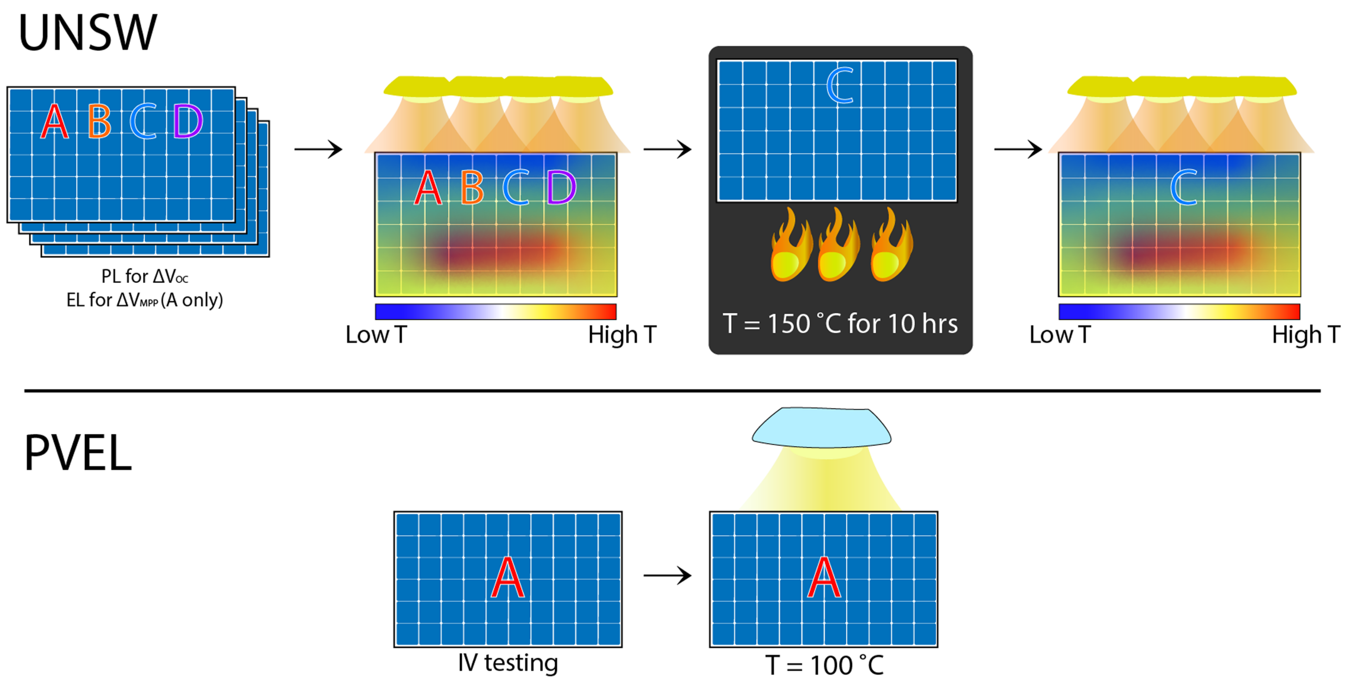

FIGURE 2 Process flow depicting the test and characterisation conditions of the different manufacturers' modules at the different test facilities

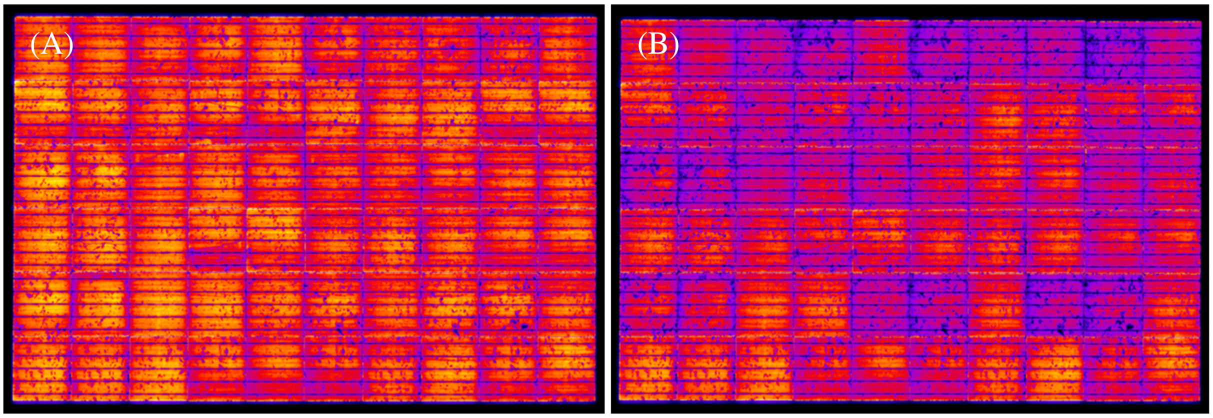

FIGURE 3 Module line-scanning PL_LS images shown using fire colour scale of manufacturer A module (A) as received and (B) after 2000 min of LeTID testing

3 | RESULTS

3.1 | LeTID with varied temperature

Example PL_LS images taken using the custom-built-line-scanning module PL tool are shown in Figure 3. These images were taken of the manufacturer A module as received and after 2000 min of LeTID testing. The differences in degradation due to the non-uniform illumination and temperature can be seen, as well as general variations due to differences between cells. This is to be expected for the reasons mentioned prior, and the fact that even cells manufactured on the same line do not degrade the same under the same conditions, as seen by the checkerboard variation in EL images of degraded modules such as that shown in,[15] and later in Figure 8B.

Figure 4A–D shows the calculated ΔV_{OC} per cell as a result of LeTID testing according to temperature for manufacturers A–D, respectively. Cell data are grouped in 10°C temperature increments. The temperature curves are recorded using the average of all cells within each 10°C range, which varied between modules for the reasons mentioned above.

The typical degradation and recovery behaviour as a result of LeTID is clearly observed for manufacturers A, C and D. However, there is a widely varied appearance of LeTID between all four

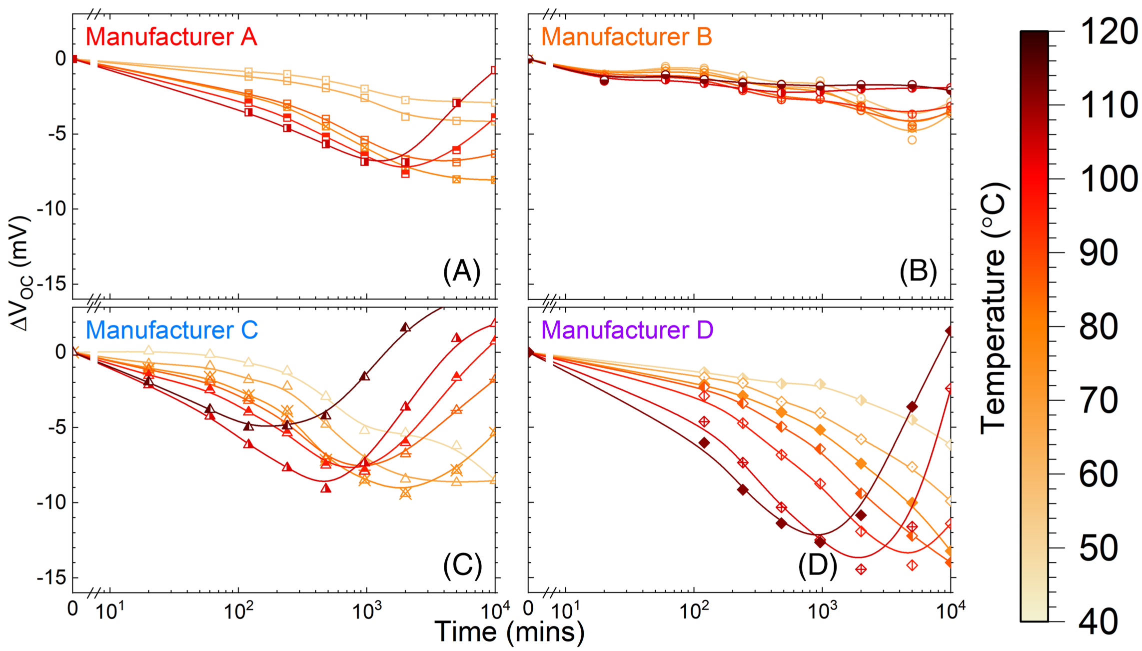

FIGURE 4 (A–D) Modules from manufacturers A–D, respectively, showing the ΔV_{OC} in mV per cell as a result of LeTID testing under spatially non-uniform halogen array illumination. Each temperature curve represents an average of all cells in a module grouped into 10°C increments

manufacturers. Of these four, only manufacturer B appears to be stable, which is likely due to an effective LeTID mitigation strategy as claimed by this particular manufacturer. Degradation in open-circuit conditions occurs an order of magnitude faster compared to MPP conditions.[15] Roughly 300 h at 75°C in MPP is equivalent to ~1 year in Greece.[20] The ~75°C curve in each plot would therefore correspond to ~5.5 years installed in Greece. These long timescales are concerning, as even in a warm sunny climate, with the exception of manufacturer C, the full extent of degradation is not realised within this timeframe, let alone the slower recovery process. The impact of this degradation is therefore likely to impact power output for most or all of a module's working life, even with the increasingly longer warranties.[30] Over this period, manufacturers A and C show roughly a 2% drop in V_{OC}, negligible degradation for manufacturer B, and 2.5% for manufacturer D. This may not seem significant; however, V_{OC} is only one indicator of LeTID and alone does not show the full impact of the degradation on performance (as we will show). In addition, the averaging over multiple cells means that the true maximum extent is not realised due to variations between individual cells degrading and recovering at different times. Interestingly, manufacturers B and D were the two that claimed to have LeTID stability solutions at the time these modules were acquired (not necessarily manufactured). While manufacturer B clearly has effective solutions, manufacturer D suffered the largest degradation in V_{OC}. Although manufacturer B shows negligible degradation, the significant degradation seen in the module from manufacturer C followed by a large recovery to higher than starting values may be preferable in some cases. For example, in a warm climate where the relatively fast regeneration can take place in the first decade of the module's life, the LeTID regeneration can ensure higher output over the long lifespan of the module.

3.2 | Temperature dependence of LeTID extent

Increasing the accelerated testing temperature is reported to cause a decrease in the maximum extent of LeTID observed.[15,16,25] With independent and competing degradation and recovery processes, increased acceleration is generally seen to increase the recovery process more significantly, thereby causing it to dominate earlier and reduce the maximum extent of degradation. However, we also know that even minor differences in prior thermal history, doping and wafer position can drastically change the kinetics of the degradation. Figure 5A–D plots the maximum extent of degradation seen in each cell of each module (manufacturers A–D, respectively) against its respective temperature.

Data for any cells that were not showing recovery by 10,000 min have been included as open data points. These data have not been included in fittings so as not to confuse trends since the maximum extent may not have yet been reached due to the slower reaction rates at lower temperatures. This is very evident in the open data points of manufacturers A and D, showing increasingly less (more incomplete) degradation with decreasing temperature. The dashed line in each figure shows the linear correlation of maximum degradation extent for cells that have progressed passed the minima; the highlighted region shows 95% confidence interval. Some variability even for cells under similar conditions is to be expected for the reasons mentioned above. However, we can clearly see the expected

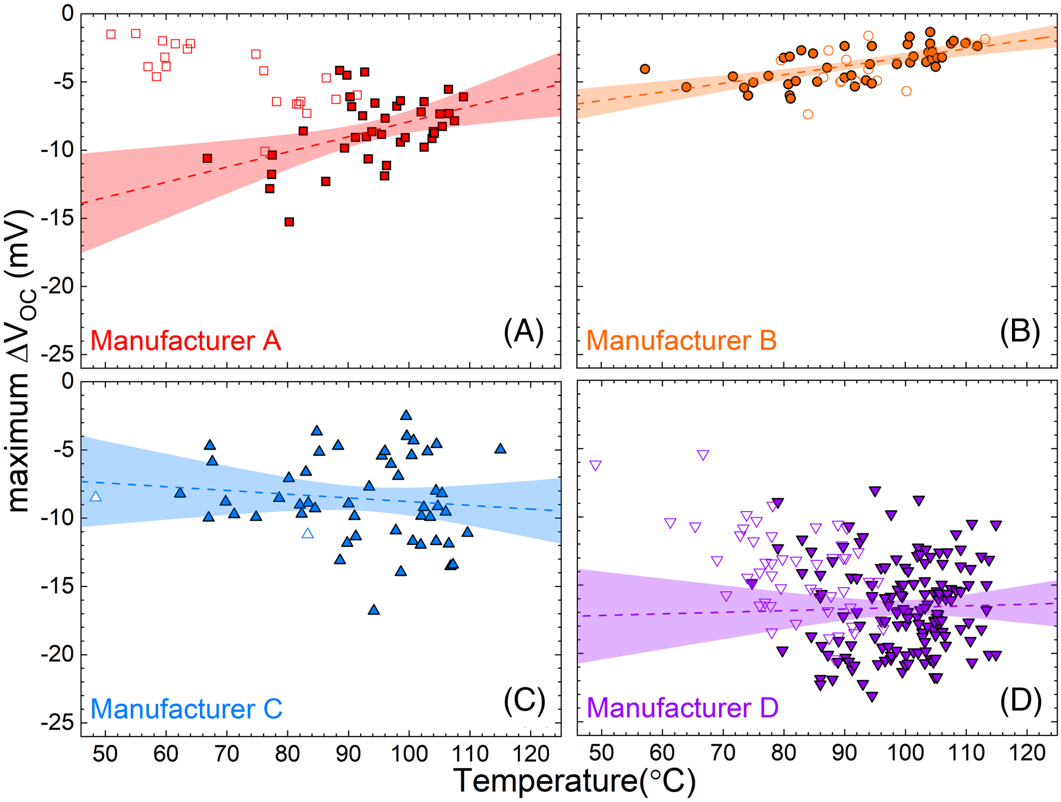

FIGURE 5 (A–D) Maximum LeTID degradation extent vs. temperature for modules from manufacturers A–D, respectively; solid data points are cells showing recovery before ceasing LeTID testing. The dashed lines are a linear fit, and the highlighted region indicates 95% confidence interval. Open data points are cells not showing recovery at 10,000 min and as such may not be the maximum extent

trend of decreased extent with increased temperature for manufacturers A and B. This trend does not appear to apply to manufacturer C or D. The variability of the trends observed make assumptions of expected behaviour at increased temperature unreliable for predicting how any given module will perform in any given climate. The maximum degradation data for the cells that had fully degraded (coloured markers) is also tabulated in Table 1, averaged in 10°C increments for each manufacturer.

3.3 | LeTID temperature dependence following destabilisation

The 10-h dark anneal at 150°C was successful in destabilising the defect allowing a second LeTID cycle to be observed in the module from manufacturer C. The maximum degradation extent plotted with respect to temperature for the second LeTID testing cycle is shown in Figure 6.

Unlike the trend (or lack of) seen in the first LeTID cycle (Figure 5C), there is now a clear trend showing the expected decreased extent with increased temperature, that resembles that of manufacturer B in Figure 5B. This is the exact same module having simply undergone some thermal annealing processes (illuminated LeTID testing at 50°C–115°C, and dark annealing at 150°C) and showing different trends with increased temperature. This can explain why each of the different manufacturers' multi-PERC modules might show different trends with increased temperature despite being the same cell structure; the thermal processes during manufacture are unlikely to be identical, especially if LeTID treatments are performed or other thermal treatments such as hydrogenation are included in the process flow.[31]

3.4 | Impact on overall module performance

Changes in open-circuit voltage measured using PL are a good-representation of changing recombination within the silicon devices,[32] and the results are commonly used for monitoring LeTID. However, V_{OC} is only part of the performance and is therefore only partly representative of losses due to LeTID. To determine the impact on overall module performance, a sister module of manufacturer A was sent to DNV-GL (now PVEL) where it was degraded under a highly uniform Class A + A + A + light source. The resulting module performance at various stages of LeTID testing is shown in Figure 7A–F, and key performance data in Table 2. The module performance as received deviated from the nameplate values (in brackets); measuring 279 W (285–0/+5 W), 38.59 V V_{OC} (38.92 V), 9.41 A I_{SC} (9.57 A), 31.44 V V_{MPP} (31.30 V), 8.88 A I_{MPP} (9.11 A).

TABLE 1 Maximum change in V_{OC} averaged for all cells that had reached maximum degradation within 10,000 min, averaged in 10°C increments

	Manufacturer A			Manufacturer B		Manufacturer C		Manufacturer D	
Temp (°C)	No. data points	Avg. max ΔV_{OC} (mV)	Avg. max ΔV_{MPP} (mV)	No. data points	Avg. max ΔV_{OC} (mV)	No. data points	Avg. max ΔV_{OC} (mV)	No. data points	Avg. max ΔV_{OC} (mV)
50–60	0	–	–	1	−4.1	0	–	0	–
60–70	1	−10.6	−15.1	1	−5.4	5	−7.5	0	–
70–80	3	−11.65	−16.8	6	−4.8	3	−9.4	1	−8.9
80–90	6	−9.1	−14.8	11	−4.4	11	−8.1	8	−13.2
90–100	17	−8.2	−14.2	10	−3.8	13	−8.4	21	−14.2
100–110	12	−7.7	−14.7	17	−2.7	18	−9.4	33	−14.8
110–120	0	–	–	3	−2.1	1	−5.0	7	−13.0

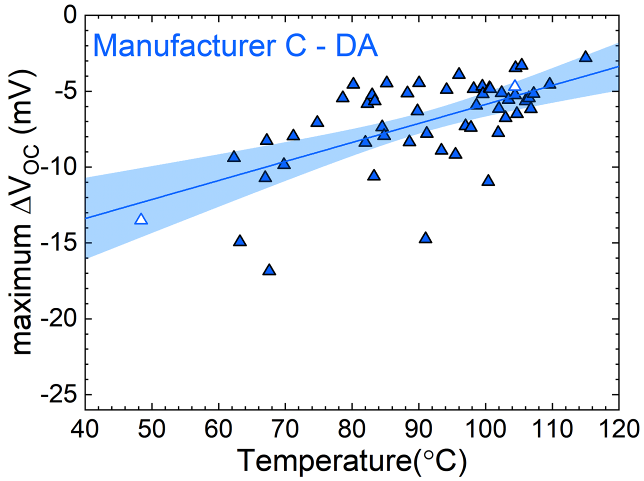

FIGURE 6 Maximum extent of LeTID versus temperature for manufacturer C after destabilisation by dark annealing at 150°C for 10 h (DA). The line is a linear fit, and the highlighted region indicates 95% confidence interval. Open data points are cells not showing recovery at 10,000 min and as such may not be the maximum extent

Firstly, it is interesting to note that the maximum drop in V_{OC} is only measured to be 1.13%. At the equivalent temperature ~100°C, we saw ~1.5% drop measured at UNSW (less than the ~2% drop measured at 75°C due to the decreasing extent seen at higher temperatures). The additional difference may be explained by the variability between individual cell degradation; EL images (Figure 8) taken as received and after 20 h of LeTID testing under highly uniform illumination at 100°C show the checkerboard appearance—different cells degrading different amounts at different times. The overall module performance represents the average of all 60 cells, and as a result will not capture the maximum loss of each cell; instead, the losses will appear reduced in maximum extent but likely drawn out over a longer time frame.

However, more concerning for the field performance is the impact on the power output. Here, we see a 4.81% drop in output power, made up of 2.54% drop in V_{MPP}, 2.22% drop in I_{MPP}, and 1.12%$_{rel.}$ drop in FF. This may seem acceptable based on the 5% degradation pass/fail criteria in the new IEC 61215-2 standards; however, this is significant degradation to impact a module over the majority of its working life and also likely less than what would be seen in the cooler field conditions where manufacturer A sees increased degradation extent (refer back to Figure 5A).

It is not uncommon for V_{OC} to be used as a metric for assessing LeTID due to the relationship between V_{OC} and device recombination.[18,25,33,34] It is therefore interesting to note that the V_{MPP} degrades 2.54%; more than twice as much as the relative drop in V_{OC}. This can be explained by the injection level dependence of the LeTID defect, having a more pronounced effect and increased recombination at lower injection levels/voltages.[4] In a similar way, the I_{SC} is also observed to degrade more relatively than the V_{OC}. Measuring at V_{OC} is therefore not able to capture the full impact of the degradation. Figure 9 shows the ΔV_{MPP} (A) with time and (B) maximum extent versus temperature of the manufacturer A sister module that was degraded at UNSW and ΔV_{MPP} was calculated from EL_LS images taken with low current injection (= 0.95 A).[27,35] In hindsight, the injection current could have been modified to more accurately represent MPP conditions as a result of the changes due to degradation. Fortunately, due to the log dependency, the constant current used to create MPP conditions is a reasonable approximation.[36] In fact, the slightly larger current places the degraded cells at a slightly higher injection level than MPP and therefore a higher V_{MPP} is measured. This therefore slightly underestimates the ΔV_{MPP} meaning that the true impact would be even more pronounced than that shown. Comparing with Figures 4A and 5A, it can be seen that here V_{MPP} also degrades roughly twice as much as V_{OC}. These data are included in the maximum degradation data of Table 1. It is also interesting that even though the V_{OC} shows a strong trend of reducing degradation extent at higher testing temperatures, the V_{MPP} does not show quite as strong trend. As such, although still limited to only one aspect of module performance, the V_{MPP} is a better representation of LeTID on cell or module performance than the V_{OC}.

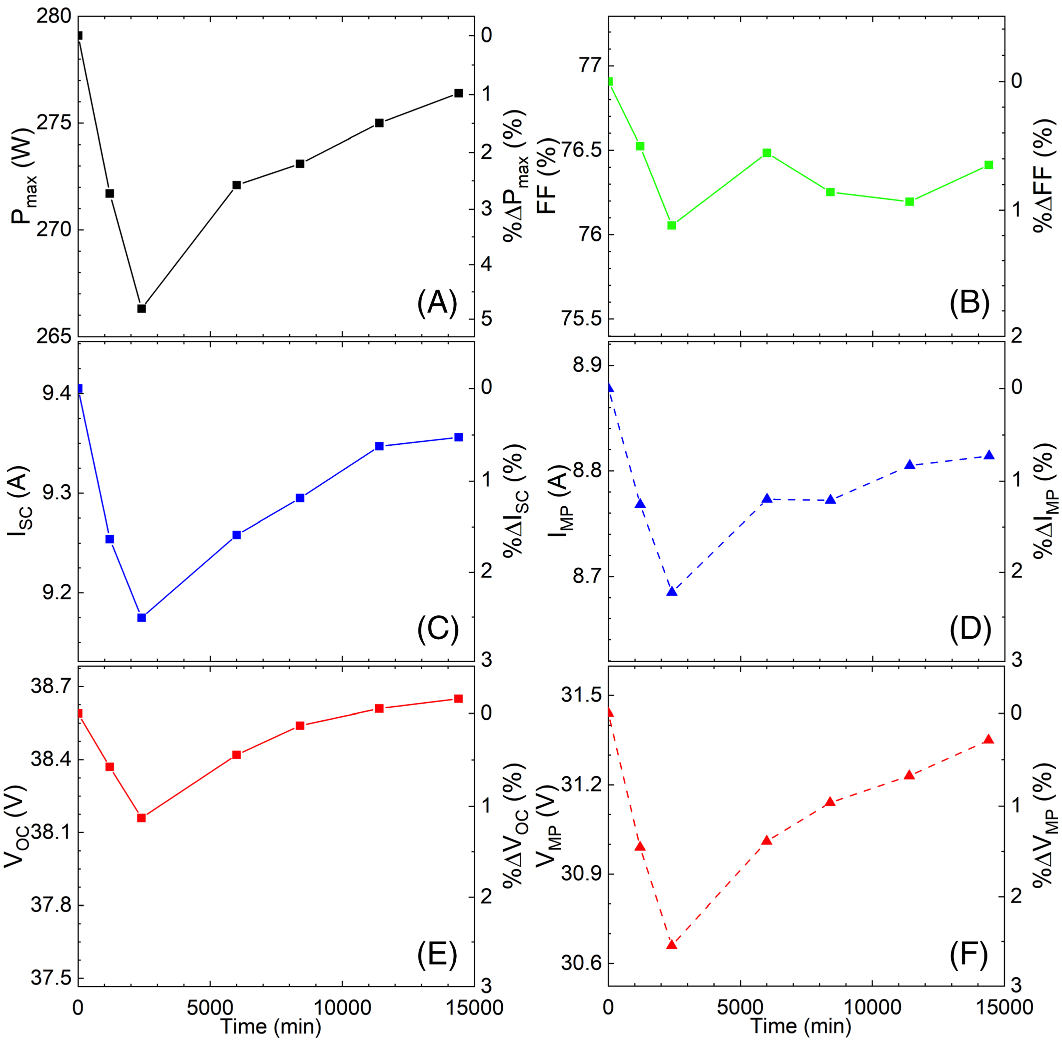

FIGURE 7 Manufacturer A module IV performance: (A) P_{max}; (B) FF; (C) I_{SC}; (D) I_{MPP}; (E) V_{OC}; (F) V_{MPP}; due to LeTID testing at ~100°C on a Class A + A + A+ solar simulator for 240 h (almost 15,000 min)

TABLE 2 Key performance data for manufacturer A's module degraded at ~100°C on a Class A + A + A+ solar simulator

	Start	Maximum degradation			Almost recovered		
			Difference			Difference	
	0 h	40 h	Absolute	Relative (%)	240 h	Absolute	Relative (%)
P_{max} (W)	279.1	266.3	−12.8	−4.81	276.4	−2.7	−0.98
V_{OC} (V)	38.59	38.16	−0.43	−1.13	38.65	0.06	0.16
V_{MPP} (V)	31.44	30.66	−0.78	−2.54	31.35	−0.09	−0.29
I_{SC} (A)	9.405	9.175	−0.23	−2.51	9.356	−0.049	−0.52
I_{MPP} (A)	8.878	8.685	−0.19	−2.22	8.814	−0.064	−0.73
FF (%)	76.9	76.1	−0.8	−1.12	76.4	−0.5	−0.65

It is unclear what exactly causes the reduced extents with increased temperatures in some modules and not others. It is likely to be due to a difference in the balance of the competing degradation and recovery reactions. One possibility is that the recovery reaction rates show greater temperature dependence in some modules, thereby dominating over the degradation process earlier and reducing the maximum extent, as similarly seen in Fokuhl et al.[16] If the recovery is largely due to dispersion of problematic hydrogen, factors such as passivation layers,[14,37,38] wafer thickness[39] emitter doping,[40] metal contact area,[41] or bulk lifetime and traps are expected to play a role.[42] Another possibility is differing concentrations of defect precursor states that are released differently under different conditions; for

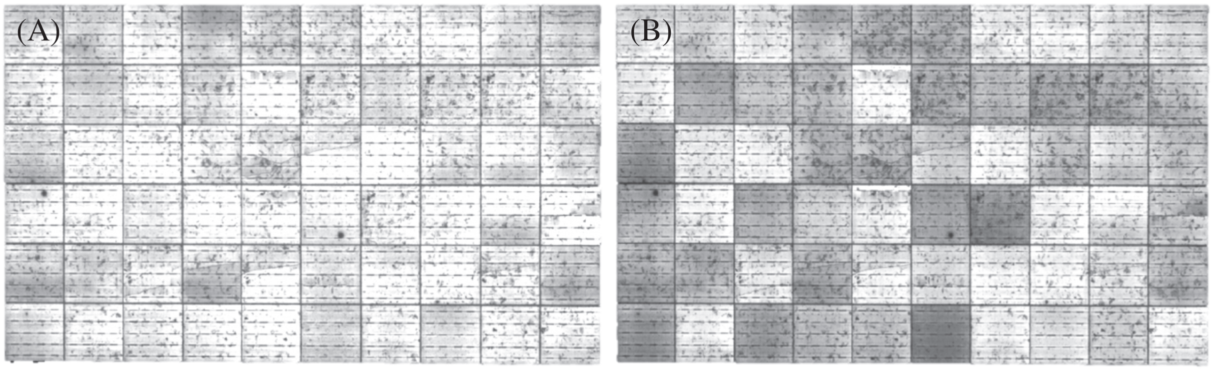

FIGURE 8 EL images (A) as received and (B) after 20 h of LeTID testing under highly uniform illumination (Class A + A + A+ solar simulator) at 100 ± 4°C module temperature

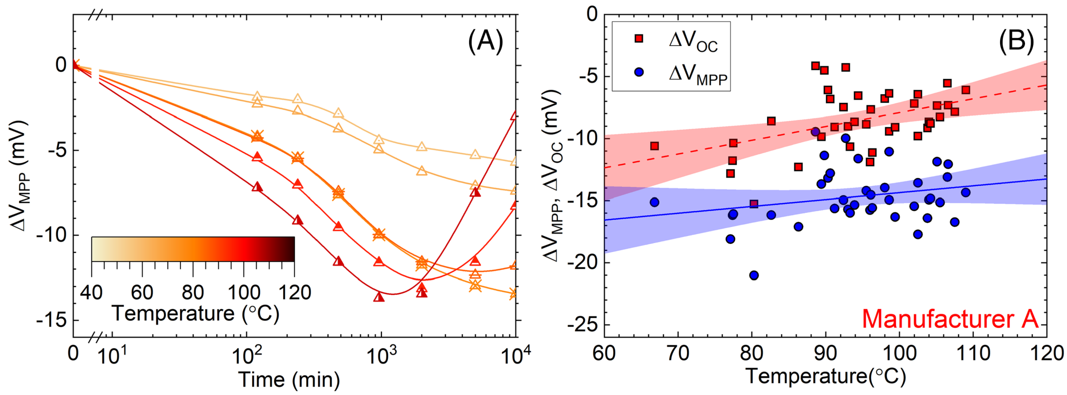

FIGURE 9 ΔV_{MPP} of manufacturer A due to LeTID testing at different temperatures (A) over time with cells grouped in 10°C increments, and (B) maximum ΔV_{MPP} versus temperature. The trend lines are a linear fit, and the highlighted region indicates 95% confidence interval

example, hydrogen bound to dopants, traps or in molecules.[29] This latter point may help explain the different behaviour seen after a module is dark annealed, as the dark anneal is known to alter concentrations of such states.[29] In any case, each of these possibilities mean that not only is the maximum extent of degradation under accelerated conditions not predictable from one manufacturer to another but also the longer term impact of degradation during the recovery phase is also unpredictable without more extensive testing data. We saw earlier (Figure 4) that some modules recover quicker and to a higher value than their starting point, while others recover slower under the same conditions. This is not surprising when considering the hugely varying degradation and recovery 'modes' seen in Chan et al[17] after only minor differences in thermal treatments. Currently, proposed testing IEC 61215-2 ED2 *(Terrestrial photovoltaic (PV) modules—Design qualification and type approval—Part 2: Test procedures)* only monitors the degradation until the slope is less than 1% power loss over 162 h under current injection to simulate ~MPP ($I_{SC} - I_{MPP}$) at 75°C (equivalent to ~2/3 years in Greece).[20] The test may therefore halt too early for any modules that degrade slower than this rate and not accurately predict the maximum extent. It also does not observe the recovery phase for any module and therefore cannot determine the much longer term impact on system output. As a result, current testing procedures are inadequate for accurately identifying and predicting the impact of LeTID on commercial modules. Thus, the large variability across different manufacturers displayed in this paper indicates that a paradigm shift in thinking regarding the accepted testing methodology for assessing LeTID in the field may be required, to more accurately describe the associated losses.

4 | CONCLUSIONS

In this report, we compared the LeTID behaviour of multi-PERC modules from four different leading manufacturers, obtained in the time spanning 2016–2018. To do so, we used a new approach that purposefully created a temperature gradient across the module during testing. The wide range of temperatures the individual cells experienced provided us with a deeper insight into the impact of temperature variations on the LeTID kinetics of cells in the same module. Variations in V_{OC} at the cell level were determined from line scanned photoluminescence images (PL_LS) of the modules. First, we showed that the LeTID response for modules from different manufacturers was vastly different. Both the extent and rate of degradation/recovery varied widely across modules from different manufacturers. Only one manufacturer appeared to have an effective solution to suppress LeTID. Two manufacturers' modules showed a reduced extent of degradation with increased temperature, while the other two did not show such a trend. One of the latter cases also exhibited a stronger recovery period with cells degraded under higher temperatures increasing to beyond their starting performance. This surprisingly varied response highlights the difficulty in developing predictive models to estimate the behaviour of multi-PERC modules in the field. It also raises the possibility of selecting specific modules for certain climates based on their performance under different conditions if known. To supplement our in-house measurements, modules were also sent for external measurement at PVEL. This showed that during LeTID testing, a larger impact was seen in the V_{MPP}, rather than the commonly used metric of V_{OC}, which was confirmed on the non-uniformly degraded sister module using EL_LS at ~MPP conditions. Changes in I_{MPP} and FF were also observed to contribute to reduced power output during LeTID conditions. These results combined indicate that current existing methodologies used to assess LeTID are inadequate. The vast variability in the degradation behaviour between manufacturers and the seemingly narrow view provided by only assessing V_{OC} conditions or only testing the degradation phase indicates that future testing regimes should be expanded to accurately describe LeTID. A better understanding of this degradation in the field will have a profound impact on costing, system design and warranties.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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