Received: 11 April 2022 | Revised: 29 June 2022 | Accepted: 12 July 2022
DOI: 10.1002/pip.3615

RESEARCH ARTICLE

PROGRESS IN PHOTOVOLTAICS WILEY

Onymous early-life performance degradation analysis of recent photovoltaic module technologies

Marios Theristis[1] | Joshua S. Stein[1] | Chris Deline[2] | Dirk Jordan[2] | Charles Robinson[1] | William Sekulic[2] | Allan Anderberg[2] | Dylan J. Colvin[3] | Joseph Walters[3] | Hubert Seigneur[3] | Bruce H. King[1]

[1]Sandia National Laboratories, Albuquerque, New Mexico, USA

[2]National Renewable Energy Laboratory, Golden, Colorado, USA

[3]University of Central Florida – FSEC Energy Research Center, Cocoa, Florida, USA

Correspondence
Marios Theristis, Sandia National Laboratories, Albuquerque, NM 87185, USA.
Email: mtheris@sandia.gov

Funding information
U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), Grant/Award Numbers: 38268, 38535

Abstract

The cost of photovoltaic (PV) modules has declined by 85% since 2010. To achieve this reduction, manufacturers altered module designs and bill of materials; changes that could affect module durability and reliability. To determine if these changes have affected module durability, we measured the performance degradation of 834 fielded PV modules representing 13 module types from 7 manufacturers in 3 climates over 5 years. Degradation rates (*Rd*) are highly nonlinear over time, and seasonal variations are present in some module types. Mean and median degradation rate values of −0.62%/year and −0.58%/year, respectively, are consistent with rates measured for older modules. Of the 23 systems studied, 6 have degradation rates that will exceed the warranty limits in the future, whereas 13 systems demonstrate the potential of achieving lifetimes beyond 30 years, assuming *Rd* trends have stabilized.

1 | INTRODUCTION

Photovoltaic (PV) energy systems are one of the least expensive and fastest growing sources of electrical generation in many parts of the world.[1] This major technology shift is largely because of the 85% decrease in the cost of solar modules since 2010.[2] Economies of scale; use of new, higher efficiency cell designs; automation of production lines; larger modules; and changes to the bill-of-materials (BOM) (thinner glass and frames, new encapsulants, backsheets, etc.) have contributed to cost reductions. The levelized cost of electricity (LCOE) is sensitive to the power degradation rate (*Rd*); as it increases, LCOE rises, and system lifetime falls. As a note, there is no consensus on PV lifetime definition; this study arbitrarily defines lifetime as the period of time until PV performance drops to 80% of initial. However, this does not mean that a PV power plant should retire once it reaches this state.[3]

Since many of the degradation processes originate from how modules and their materials interact with the environment, there is concern that cost cutting design and materials changes may result in higher degradation rates, which could cancel out many of the positive results of lower module costs. Studies on modules manufactured between ∼1979 and ∼2014 conducted by Jordan et al[4,5] found module *Rd* values between −0.8%/year and −0.9%/year with the median between −0.5%/year and −0.6%/year. These studies were based on several thousand modules; however, many of the *Rd* values were calculated as changes from nameplate power rating based on a single flash test measurement taken after field exposure rather than measuring the modules at the time of installation and retesting over the years. This approach based on only two points in time provides a linear estimate of degradation but may be biased if the nameplate rating does not match the initial performance. Is the average degradation rate for newer modules significantly different because of recent changes to module design and materials?

The PV market is continuously changing, recently transitioning from conventional aluminum back surface field (Al-BSF) designs, which dominated (by up to 90%) the global solar cell production until 2018, to other high-efficiency cell concepts including passivated emitter and rear cell (PERC), passivated emitter with rear locally diffused cell (PERL), passivated emitter rear totally diffused cell (PERT), silicon heterojunction (SHJ), and tunnel oxide passivated contact (TOPCon) designs.[6] According to the International Technology Roadmap for Photovoltaics,[7] the market share in 2020 was around 15% for Al-BSF and around 80% for high-efficiency cell concepts, mainly dominated by PERC. There is a lack of long-term field data for these new cell and module technologies.[8,9] High-efficiency modules can exhibit open-circuit voltage (*Voc*) degradation as opposed to the short-circuit current (*Isc*) or fill factor (*FF*) degradation common in Al-BSF modules.[8] Nonlinear degradation modes such as light induced degradation (LID)[10] or light and elevated temperature induced degradation (LeTID)[11] are more common in high efficiency modules and can impact project cash flows[5,12,13] and increase uncertainty in lifetime energy yields.

The market is also seeing increases to module size, use of new materials (e.g., anti-reflection and anti-soiling coatings, thinner glass, new encapsulants, and backsheets), or other concepts such as split cells, dense interconnection designs (shingling), or increased number and topology of busbars or wires. Such concepts may increase module efficiency and reduce balance of system (BOS) costs, but it remains unknown how these changes affect degradation rates and long-term reliability.

To investigate this question, our team purchased and fielded 834 modules from the open market representing 13 different module types from 7 manufacturers and deployed them in the field at 3 locations (New Mexico [NM], Colorado [CO], and Florida [FL]) representing a range of climates. We measured performance under Standard Test Conditions (STC) at the start of the study, examined initial power stabilization, and periodically retested the modules over the following 5 years to monitor degradation rates over time.

The Sandia National Laboratories (Sandia), the National Renewable Energy Laboratory (NREL), and the University of Central Florida's Florida Solar Energy Center (FSEC) partnered for this project in 2016.[14] The objective was to measure PV degradation rates over time for technologies with significant US market share and release onymous (not anonymous) results publicly to inform relevant stakeholders and inform best practices. More than 2000 separate flash tests were analyzed in this study.

2 | DESCRIPTION OF FLASH TEST CAMPAIGNS

2.1 | Module selection

The PV modules included in this study were carefully selected to represent the make and models that were being installed in the US market (since ∼2015) while at the same time maintaining a diversified selection to include different cell technologies and significant emerging trends in module construction.

Market research from a solar industry analysis firm (Wood Mackenzie) informed the module selection based on statistics from US market share for residential and commercial installations. The utility-scale market shared some commonality with these and also included many custom or difficult to source module types. According to this analysis,[15] this study (see modules under test in Table 1) represents 55% of the 2020 market measured in terms of number of companies represented. To avoid all modules originating from one batch or production run, modules with the same model number were sourced from two or more vendors, when available.

2.2 | Module stabilization and testing protocols

Upon arrival at Sandia, NREL, and FSEC, at least 25% of the modules were sampled for flash testing prior to any light exposure. Before flash testing at STC, Jinko260, Jinko265, Trina255, and Trina260 modules were light soaked for at least 4.3 kWh/m^2 in 2016, whereas the remaining modules (post-2016) were light soaked for at least 20 kWh/m^2, consistent with an update to IEC61215-1:2016.[16] The modules were then installed in the field, connected to inverters and the grid. A sub-sample of modules (25%) was retested annually, and light-soaked control modules were stored in climate-controlled dark rooms and tested with each batch of fielded modules to help distinguish between field-related degradation and non-field-related material degradation. Additional process control modules (different types) were tested before each flash test session at all laboratories to monitor the long-term stability of the flash simulators. It should be noted that the FSEC modules were purchased by Sandia but directly shipped to Florida by the vendor. As such, Sandia and FSEC modules were sourced from the same batch and might differ in BOM with the respective modules at NREL. A flowchart describing the module testing protocol is shown in Figure 1.

2.3 | Indoor flash testing and stability

Sandia, NREL, and FSEC harmonized the flash testing procedures for this project. All laboratories included control modules for each module technology under test, which were stored indoors, in the dark, in a climate-controlled room. All modules were light soaked at the beginning of the project before baseline flash testing, whereas a subsample (typically 50%) was flashed before light soaking to assess initial power stabilization. For all flash testing, the modules were placed at the same location on the simulator test planes to reduce uncertainties because of light non-uniformity. For each test campaign, all modules retrieved from the field were brought indoors the night before flash testing and allowed to thermally equilibrate. However, there are some differences between the methods used at each facility because of different site constraints; these are listed in Table 2.

With respect to temperature corrections, *Isc*, *Voc*, and power at maximum power (*Pmp*) are corrected for temperature using the temperature coefficients from the specification sheets. Quantifying the

TABLE 1 Modules under test in Albuquerque, NM, Golden, CO, and Cocoa, FL

Company	Model and power rating	Type	Abbreviation	Features	Date deployed	Number in NM	Number in CO	Number in FL
Jinko Solar	JKM260P 260 W	Poly-Al-BSF	Jinko260	4 busbars	06/2016 (NM) 09/2016 (CO) 09/2017 (FL)	56* (28 × 260, 28 × 265)	28	56* (28 × 260, 28 × 265)
Jinko Solar	JKM265P 265 W	Poly-Al-BSF	Jinko265	4 busbars	10/2016		28	
Trina Solar	TSM-PD05.05255 W	Poly-Al-BSF	Trina255	4 busbars	10/2016	-	28	-
Trina Solar	TSM-PD05.08260 W	Poly-Al-BSF	Trina260	4 busbars	06/2016 (NM) 09/2016 (CO) 09/2017 (FL)	56	28	56
Canadian Solar	CS6K-270P 270 W	Poly-Al-BSF	CSpoly270	4 busbars	10/2017	48	-	-
Canadian Solar	CS6K-275 M Quartech 275 W	Mono-Al-BSF	CSmono275	4 busbars	10/2017	48	-	-
Canadian Solar	CS6K-300MS Quintech 300 W	Mono-PERC	CSmono300	5 busbars	08/2018	-	28	-
Hanwha Q-Cells	Q.Plus BFR-G4.1 280 W	Poly-PERC	Qpoly280	4 busbars	10/2017	48	28	-
Hanwha Q-Cells	Q.Peak BLK G4.1 290 W (NREL) and 300 W (Sandia)	Mono-PERC	Qmono290 Qmono300	4 busbars	10/2017	48	28	-
LG	LG320N1K-A5 320W	N-type Mono-PERT	LG320	Bifacial, 12 multi wire busbars	06/2018	48	28	-
Panasonic	N325SA16 325 W	N-type Mono-SHJ	Panasonic325	Bifacial, 4 busbars	06/2018	48	30	-
Mission Solar	MSE300SQ5T 300 W	P-type Mono-PERC	Mission300	4 busbars	05/2019	48	-	-
Mission Solar	MSE360SQ6S 360 W	P-type Mono-PERC	Mission360	4 busbars	12/2018	-	20	
Site Totals						**448**	**274**	**112**
Program Total						**834 modules**		

*Installed as one system, two strings of each.

stability and repeatability of solar simulators at each site is important because degradation studies require monitoring small changes in module power ratings over long periods of time (up to 10 years or more). All laboratories have identified a set of performance monitoring modules that were carefully stored indoors and flash tested regularly to monitor the stability of the simulator. Figure 2 shows the repeatability in normalized *Pmp* for 10 of these modules at Sandia and 11 modules at FSEC since mid-2017 and 15 since mid-2018; NREL's repeatability has been published elsewhere (±0.1% around 2 sigma[19] based on the module self-reference method[20]), and it will not be repeated here. The dashed red, green, and blue lines represent ±3%, ±1% and ±0.5% around the median, respectively. Most of the data (9 out of 10 modules at Sandia and 11 out of 15 modules at FSEC) fall within this uncertainty bound, which verifies the current repeatability of the measurements made at Sandia, FSEC, and NREL (for additional information on NREL's repeatability/uncertainty, see Ndione et al.[19]). Changes to FSEC's system introduced short-term spread on the stability plot because of the removal of the lamp filter, improvements made

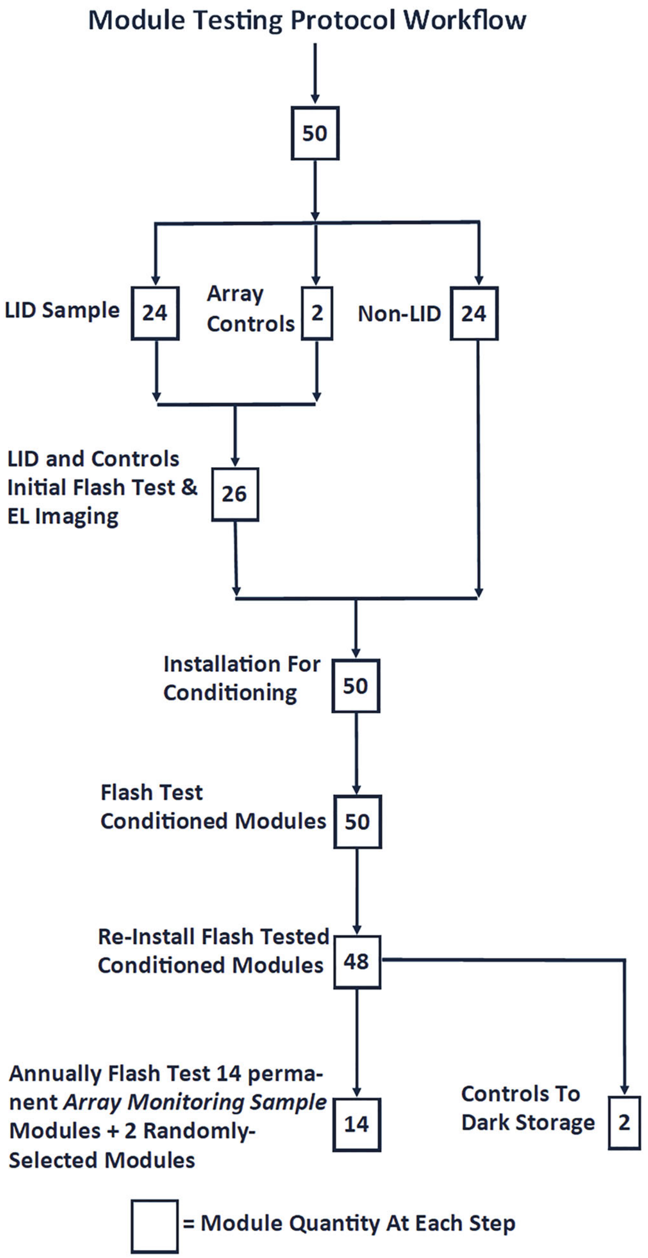

FIGURE 1 Exemplary module testing protocol workflow at Sandia, NREL, and FSEC. The numeric values will vary by module type and laboratory

in non-uniformity, and a change in calibration procedure. Overall, uncertainties of relative power changes over time (±0.5%) are much lower than the absolute power accuracy.[14]

3 | INITIAL PERFORMANCE AND POWER STABILIZATION

Selected modules were flashed before any outdoor light exposure, and deviation from the nameplate power rating is shown in Figure 3. Median percentage differences ranged from around −3.6% to +4%. However, the uncertainty in measured power is approximately ±2.3%, based on interlaboratory comparisons. Because all module manufacturers claim positive bin tolerances (up to +10% for Panasonic, +5 W for Canadian Solar, and +3% for the remaining manufacturers), most modules appear to be 'under-rated' (i.e., measured power > nameplate), whereas others are near or even below nameplate. This is important because degradation in the context of a warranty is relative to the nameplate power. Modules that are 'under-rated' can degrade further before a warranty claim can be made.

LID can cause initial degradation in poly-crystalline (or multi-crystalline) and mono-crystalline silicon modules within the first 10 kWh/m^2 of light exposure through formation of boron-oxygen defects.[21] Examples of the temperature-corrected power stabilization process are shown in Figure 4 for four representative modules. The largest initial power loss of −3.3% was for the mono-silicon module-type CSmono275 compared with a similar poly-Al-BSF (CSpoly270) from the same vendor that saw only −1.5% power loss. This is to be expected since LID is known to more strongly affect mono-Al-BSF. Two PERC module types had comparable performance loss of −1.2% (Qmono290 and Qpoly280). The observed stabilization of the PERC modules is similar to a recent study by Chen et al.[22]

Initial power stabilization deviations for the other module types are given in Table 3. It is worth noting that the initial power improvement of the Panasonic325 at NREL is in agreement with a study by Kobayashi et al.[23] where silicon heterojunction solar cells demonstrated a light-induced performance gain prior to long-term degradation. Kobayashi et al.[23] attributed this improvement to an increase in surface passivation.

TABLE 2 Summary of characterization differences among the laboratories

Laboratory	Temperature control	Method*	Repeatability	Mean 2 standard deviations**	Flash tester
Sandia	±0.5 °C	Isc to Voc	±0.5% on normalized Pmp	±1.2% on normalized *Pmp* ±1.1% on normalized *Isc* ±0.2% on normalized *Voc*	Spire 4600 SP
NREL	±0.5 °C	Voc to Isc	±0.1% on Pmp	1.3792 W 0.0122 A 0.0783 V	Spire 5600
FSEC	±1 °C	Isc to Voc	±1% on normalized Pmp	±1.55% on normalized *Pmp* ±1.5% on normalized *Isc* ±0.3% on normalized *Voc*	Sinton Instruments FMT-350

*Although the absolute measured values differ from one sweep direction to another,[17,18] this study reports on relative changes over time. As such, the IV curve sweep direction should have a negligible effect as long as each laboratory is consistent over time.
**Standard deviation values for NREL were taken from Ndione et al.[19]

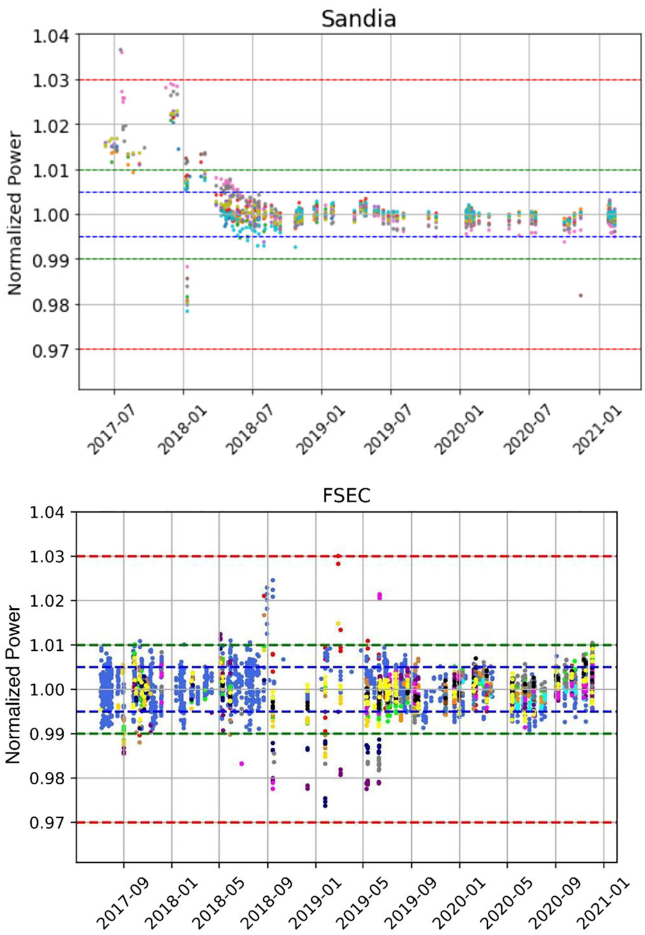

FIGURE 2 Normalized power of performance library modules at Sandia (top) and FSEC (bottom). Dashed red, green, and blue lines represent ±3%, ±1%, and ±0.5%, respectively. Mean 2 standard deviation values for normalized Pmp, Isc, and Voc are, respectively, ±1.2% (Sandia), ±1.55% (FSEC), ±1.1% (Sandia), ±1.5% (FSEC), and ±0.2% (Sandia), ±0.3% (FSEC). NREL repeatability and uncertainty has been reported by Ndione et al.[19]

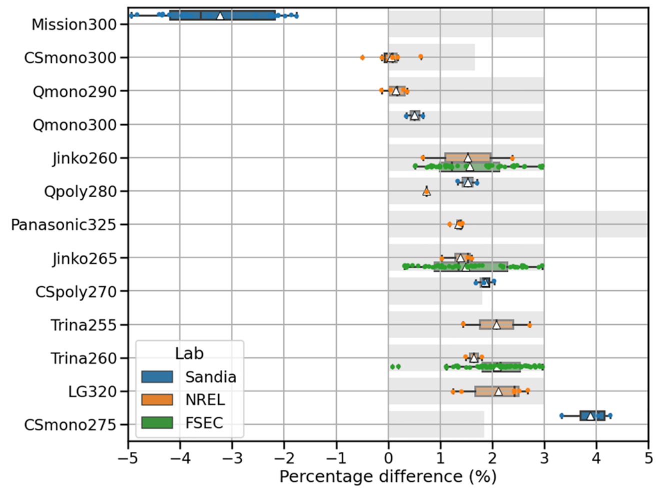

FIGURE 3 Boxplots with percentage differences of nameplate power ratings compared to the out-of-box flash tests at Sandia, NREL, and FSEC. Black vertical lines represent median values, and white triangles indicate the mean values. The light-colored dots are the individual measurements, and the bars in light gray color represent the spec sheet tolerances for a reference. Tolerance for Panasonic325 is +10%, but the positive x axis limit was shortened for clarity.

4 | OBSERVED DEGRADATION PATTERNS

Studying performance degradation patterns on a large group of diverse modules in a well-controlled lab environment allows us to observe both general trends and variations in behavior indicative of modules being produced on different production lines including typical variations in the bill of materials due to complex supply chains. A systematic analysis of all the module results is presented in supporting information sections A and B. The most interesting highlights are summarized below.

LeTID-like behavior was observed on certain PERC and Al-BSF modules in this study. Jinko260 (Figure 5) and Jinko265 (see supporting information section A1) modules exhibited a steep drop in performance followed by unstable behavior indicative of LeTID. These modules measured at NREL every 6 months showed that performance was lower in the summer and increased in the winter, consistent with this degradation process. LeTID in Jinko260 modules was split between current and voltage loss, which can be seen in the Isc and Voc curves in Figure 5B and C. Although typically associated with PERC cells, LeTID has been identified in some Al-BSF multi-crystalline cells,[24] and these modules were shown to be LeTID susceptible in IEC 61215 module quality tests 23.[25] In this case, LeTID was also verified through another study where a sample of the same Jinko260 modules was used to compare LeTID progression against an LeTID prediction model.[26] Furthermore, one outlier Trina260 module at NREL also appears to exhibit LeTID-like performance.

Some modules showed differing patterns over time at different sites. Trina260 modules at Sandia showed a modest drop in *Pmp*, *Isc*, and *Voc* in the first year, but these values remained relatively unchanged thereafter (see Figure 6). In contrast, these same modules at NREL showed continual drops in *Pmp*, *Voc*, and *FF* from 2016 to 2020 followed by an increase in 2021. Furthermore, the outlying Trina260 module at NREL (see purple color in Figure 6) points out that even when the same module is purchased from the same vendor, there is a possibility of ending up with different BOM and thus, a potential different behavior.

LG320 modules displayed moderate overall power degradation at Sandia (−0.69%), whereas at NREL, these modules on average remained relatively stable in performance over time (−0.06%); however there was significant variation in individual modules, with some increasing and others decreasing (see supporting information section A3). One explanation for why some results varied between sites could be because of differences in duration of the initial light soaking at each site. LG320 modules were exposed for 20 kWh/m^2 at NREL and 356.8 kWh/m^2 at Sandia. It is possible that the performance of the Sandia modules improved during this extended light

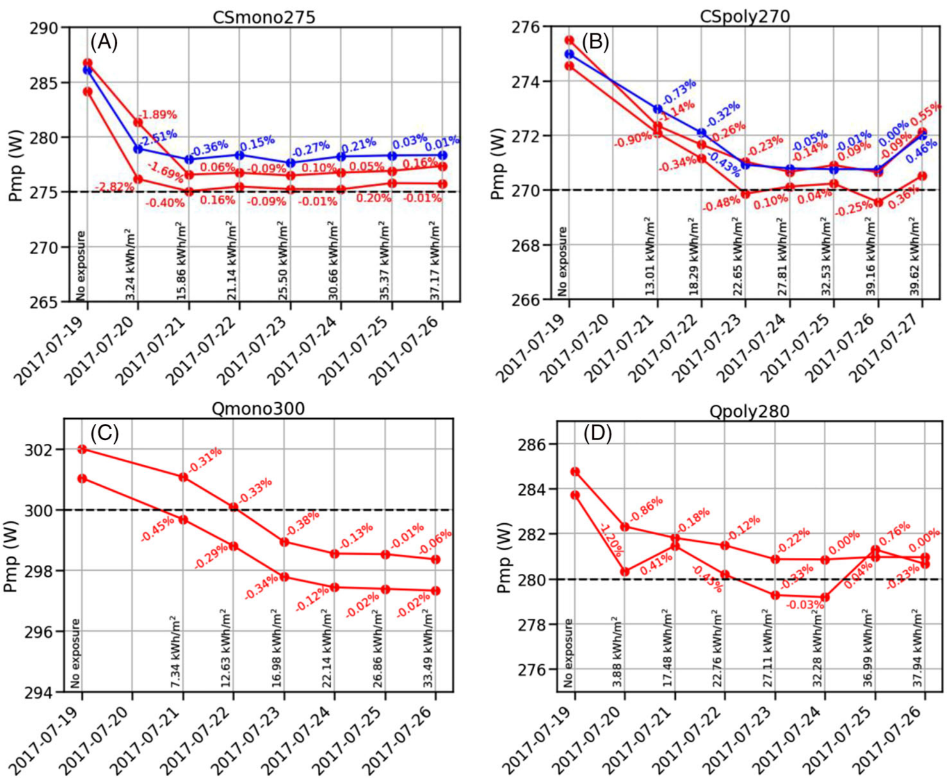

FIGURE 4 Examples of stabilization process for (A) CSmono275, (B) CSpoly270, (C) Qmono300, and (D) Qpoly280 modules at Sandia. Red and blue colors indicate control and field modules, respectively. Percentage differences from one datapoint to the next one and light exposure values are also shown. Black dashed line indicates the rated power.

TABLE 3 Deviations during initial power stabilization of PV modules that were out-of-box tested (i.e., at 0 kWh/m^2) along with outdoor exposure values. Modules without out-of-box measurements or adequate exposure records are not included

Module	Exposure (kWh/m^2)	Deviation (%)
Jinko260 [FSEC]	21	−1.9
Jinko265 [NREL]	13–14.4	−1.8
Jinko265 [FSEC]	19.3–22.9	−0.3
Trina255 [NREL]	20	−0.9
Trina260 [NREL]	10.25–10.85	−0.5
Trina260 [FSEC]	22.3–26.1	−1.1
CSpoly270 [Sandia]	22.7	−1.5
CSmono275 [Sandia]	21.1	−3.3
CSmono300 [NREL]	20	−0.7
Qpoly280 [Sandia]	22.8	−1.2
Qpoly280 [NREL]	21–24	−1.1
Qmono290 [Sandia]	22.1	−1.2
Qmono290 [NREL]	20.7–26.4	−1.1
LG320 [NREL]	20	−0.5
Panasonic325 [NREL]	20	+0.6

soak period, whereas the NREL modules did not have sufficient time to do so. Also, the control modules at the two laboratories also showed contradicting performance with −0.32% and +0.43% power change at Sandia and NREL, respectively. This might suggest that the BOMs may also be different.

The power loss of the Panasonic325 modules (−1.87% at Sandia and −0.68% at NREL; see supporting information section A4) was large because of decreases in voltage, and, in fact, *Isc* increased over time for these modules at both sites, overall changes in *Isc* (i.e., *ΔIsc*) of +0.24% and +0.57% and *ΔVoc* of −1.48% and −1.03% for Sandia and NREL, respectively.

5 | DISCUSSION

Module *Rd* is calculated using two methods that differ in how the initial power rating of the module is defined. The first uses nameplate rating as the starting point and the second uses the first post-stabilization flash test. Figures 7 and 8, show the evolution of *Rd* for all module types across the different laboratories based on these two methods. In Figure 7, because the first flash test is at 'time zero' (i.e., there is no time information between the first flash and nameplate), it is only possible to calculate a *ΔPmp* in percent and not an *Rd* in percent/year. For this reason, first measurements are excluded from Figure 7. A summary of the reported degradation rates and differences among the two methods are summarized in Table SB13.

Nameplate-based *Rd* values ranged from −2.79%/year to 0.72%/year, whereas first flash-based *Rd* values ranged from −1.94%/year to 0.33%/year. Trina260 and CSmono275 exhibited positive nameplate-based *Rd* values at Sandia (+0.29%/year, +0.72%/year), whereas the *Rd* of Panasonic325 and LG were +0.30%/year and +0.60%/year at NREL. However, first flash-based *Rd* values were positive only for CSmono275 at Sandia (+0.33%/year); this module exhibited the

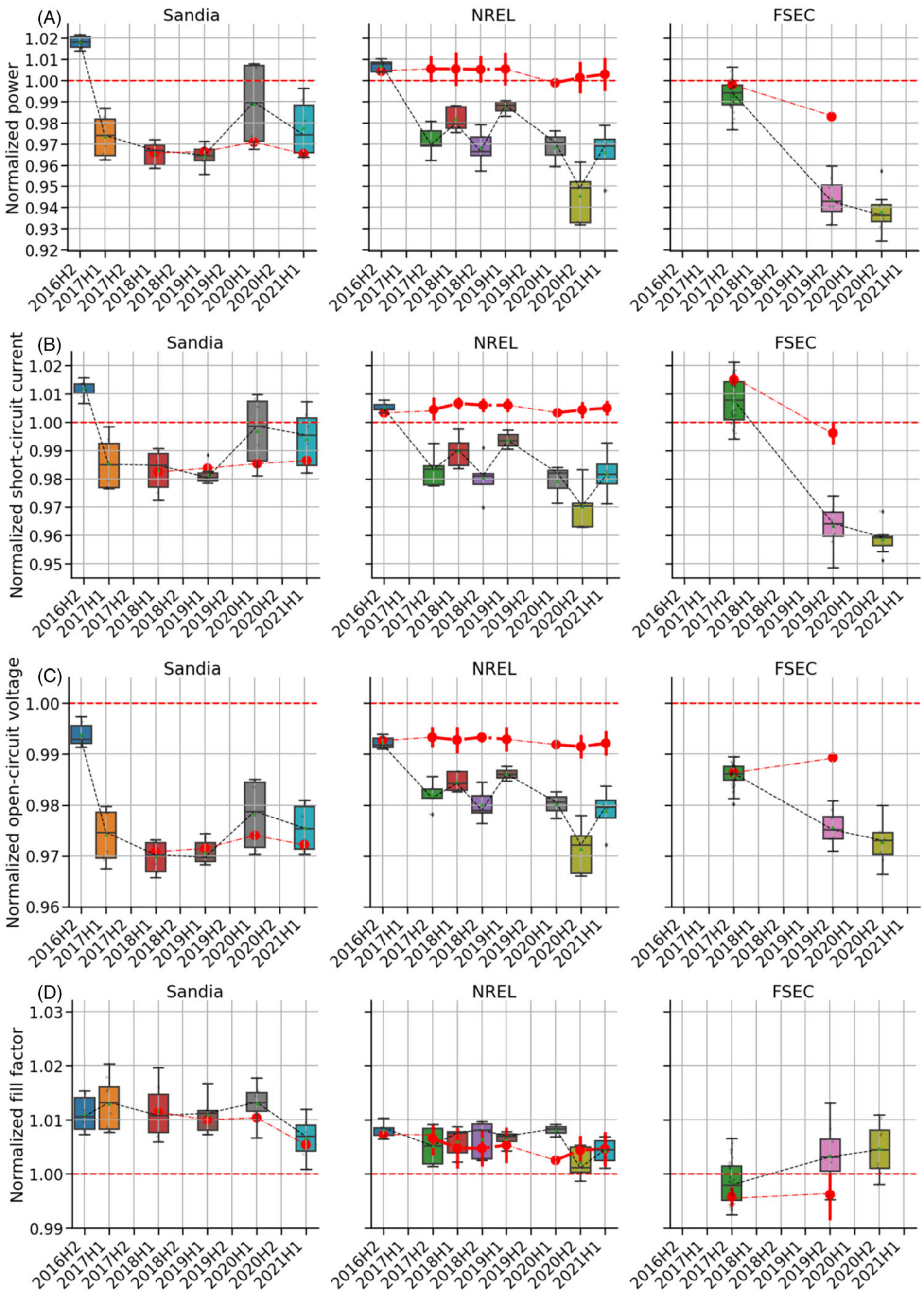

FIGURE 5 Normalized (A) power, (B) short-circuit current, (C) open-circuit voltage, and (D) fill factor of Jinko260 modules over the flash test dates classified as first and second half of the corresponding year (i.e., H1 and H2). Black dashed lines represent the trends by connecting the median values, whereas the red lines correspond to the control modules. Light colored black dots are the measurements.

greatest initial power deviations. Therefore, most positive nameplate-based *Rd* values could be because of initial measured power > nameplate (i.e., under-rating) and not necessarily because of module performance gains. The overall mean and median *Rd* values were found to be −0.61%/year and −0.58%/year, respectively.

The following observations can be made from the results of this study:

1. *Nameplate-based Rd versus Rd based on the first post-stabilization flash test*: How *Rd* is defined, whether relative to nameplate or initial flash, can influence the resulting rate. *Rd* varied by up to 2.39%/year for newer Mission300 modules, although this high difference was largely because of those modules being initially over-rated (i.e., initial measured power < nameplate). Even older modules such as Trina260 exhibited high differences of up to 0.69%/year (see Table SB13). These results suggest that different module manufacturers may follow different strategies for rating their modules and are willing to accept more or less rating uncertainty. Vendors that sell under-rated modules may incur some financial loss in exchange for a safety margin in the case that degradation rates are greater than expected. However, if modules are over-rated and the expectation is the opposite, then the vendors may realize more profit at the time of sale but run a higher risk of warranty returns. Moreover, the intended market for the modules may also influence how a manufacturer chooses to rate their modules. It is common for large utility-scale module procurement contracts to include

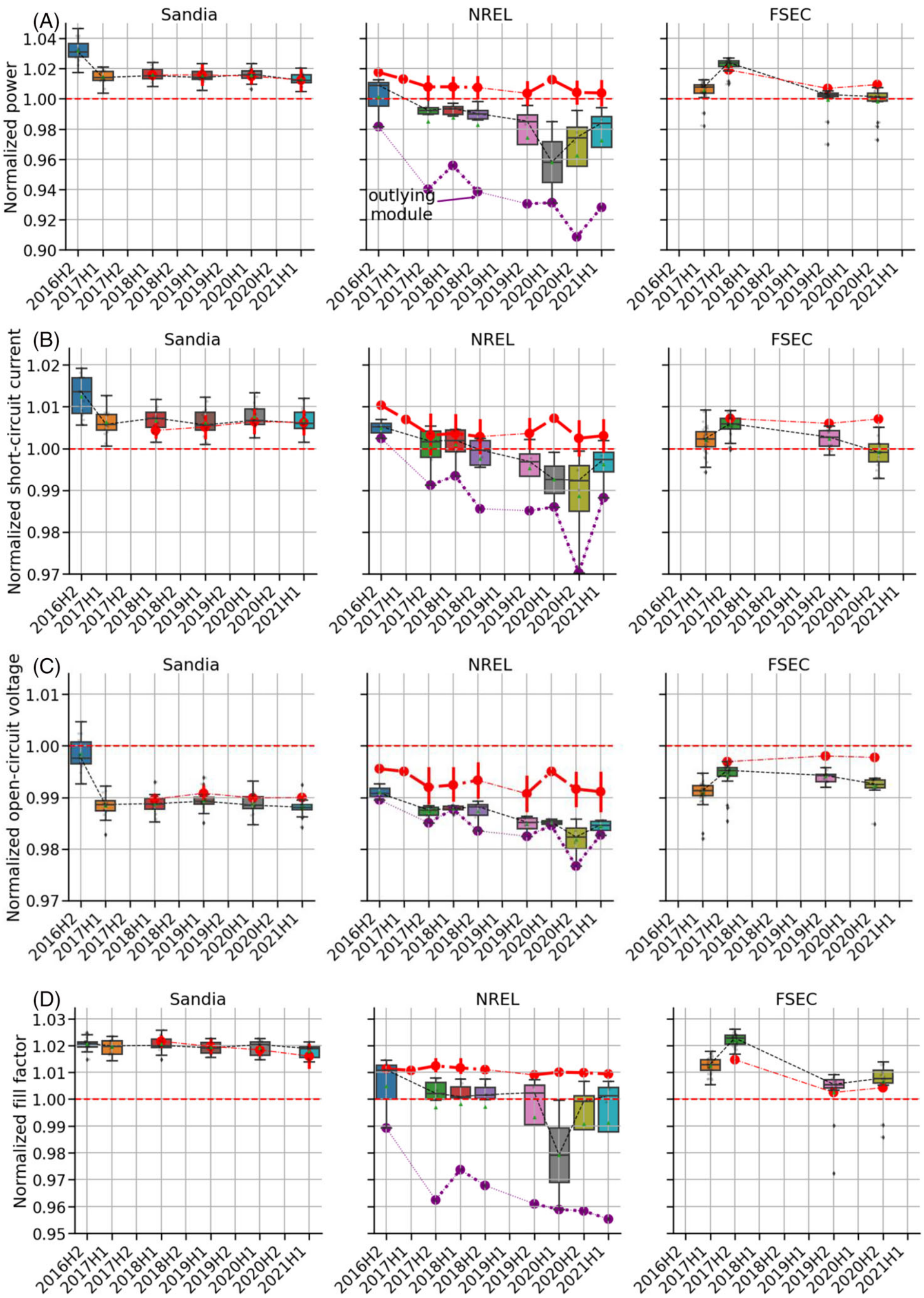

FIGURE 6 Normalized (A) power, (B) short-circuit current, (C) open-circuit voltage, and (D) fill factor of Trina260 modules over the flash test dates classified as first and second half of the corresponding year (i.e., H1 and H2). Black dashed lines represent the trends by connecting the median values, whereas the red lines correspond to the control modules. Light colored black dots are the measurements. An outlying module is displayed separately in the NREL normalized power plot with purple color.

provisions for adjusting the rating after modules are delivered following tests by an independent laboratory. If the modules are found to be over-rated, refunds are issued. In contrast, modules aimed at the residential or even some commercial/industrial markets rarely will be tested by independent laboratories and may thus be more at risk of being over-rated. If so, this introduces a bias in the pro-forma estimates and sets up the PV system for underperformance relative to nominal expectations, even if the modules are not subject to warranty claims until much later. This could be sooner than an insurer would expect and, therefore, lead to higher insurer losses. Therefore, post-stabilization flash tests are needed: to ensure that even after initial field exposure, the module performs according to the expectations set by the nameplate rating and the assumption of a positive tolerance. This harmonization is also required for energy yield estimates. For example, consider a 30-year project with a 100 MWp plant, 0.05 $/kWh electricity price, and 1700 kWh/kWp/year specific yield. Assume also Jinko260 (Sandia) modules with nameplate-based *Rd* of −0.52%/year and first flash-based *Rd* of −0.93%/year. The difference in the 30-year energy yield and revenue estimates would be 7.4% and $16.2 million, respectively. Thus, these apparently small differences in *Rd* add up to significant energy and financial performance over the life of a plant.

2. *Impact of PV module cost reductions on degradation*: Considering first flash-based *Rd* estimates only, mean and median values were −0.62%/year and −0.58%/year, respectively. Therefore, despite

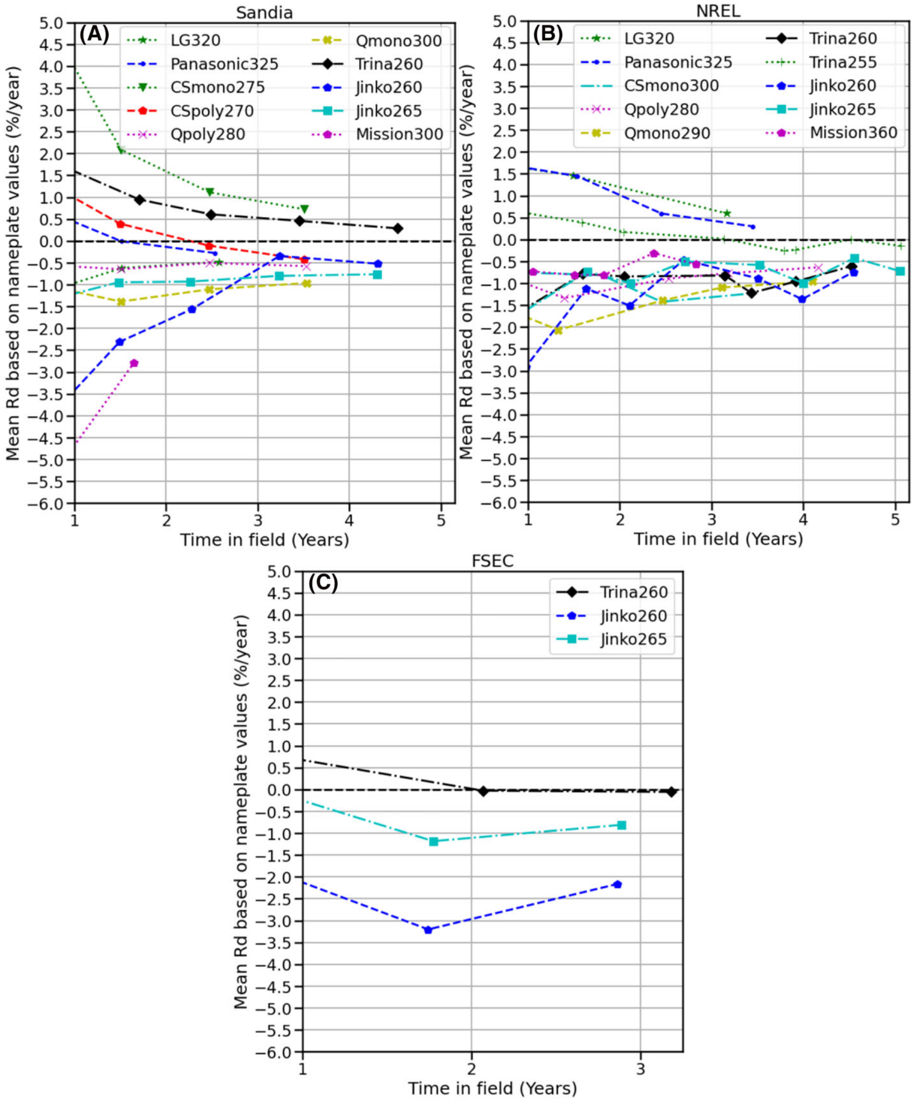

FIGURE 7 Interlaboratory ((A) Sandia, (B). NREL, and (C) FSEC) evolution of average degradation rates (%/year) for all PV module technologies based on nameplate values

the 85% cost reductions in PV module costs between 2010 and 2020,[2] *Rd* did not increase in absolute value when compared to the rates reported by Jordan et al.,[4,5] which is an encouraging result. However, there are still opportunities to reduce *Rd* to levels that enable longer PV module lifetimes.[27] For example, for 35- and 50-year lifetimes, PV modules should operate at *Rd* values ≥ -0.55%/year and -0.4%/year, respectively. Although more time is required, the analysis so far shows that, assuming that *Rd* ceases to change, 6 out of 23 systems are projected to exceed the warranty limits (i.e., $Rd < -0.8$%/year) and qualify for module replacements, whereas 13 out of 23 systems demonstrated the potential of achieving lifetimes beyond 30 years (i.e., $Rd \geq -0.65$%/year).

3. *Nonlinear behavior*: Overall, most modules exhibit nonlinear degradation with higher *Rd* values in the first 1–3 years. *Rd* values tend to converge within ±1%/year after ∼3–4 years of outdoor exposure. Such nonlinearities raise a concern on the statistical approaches usually used on outdoor field data assuming linearity. Applying methodologies that consider nonlinear *Rd* behavior may improve accuracies: e.g.,[13,28–30]. From a warranty perspective, if degradation modes such as LeTID cause significant early performance loss, there may be a risk of triggering warranty claims before regeneration occurs. Furthermore, if the performance expectations of asset owners differ in any given year because of nonlinear performance loss, then false and unnecessary operation and maintenance alerts might be triggered. Plant operators should understand that early nonlinear changes in performance and associated *Rd* are not uncommon in the first 3–4 years. However, further investigations are required to verify whether such behavior remains constant or tends to change during a PV module's lifetime, especially when approaching the 'wear-out' phase.

6 | SUMMARY AND CONCLUSIONS

Our team purchased over 834 modules representing 13 different technologies from 7 manufacturers and deployed them in the field at 3 different locations representing a range of climates. We measured performance indoors under standard test conditions at the start of the study, examined initial power stabilization, and periodically

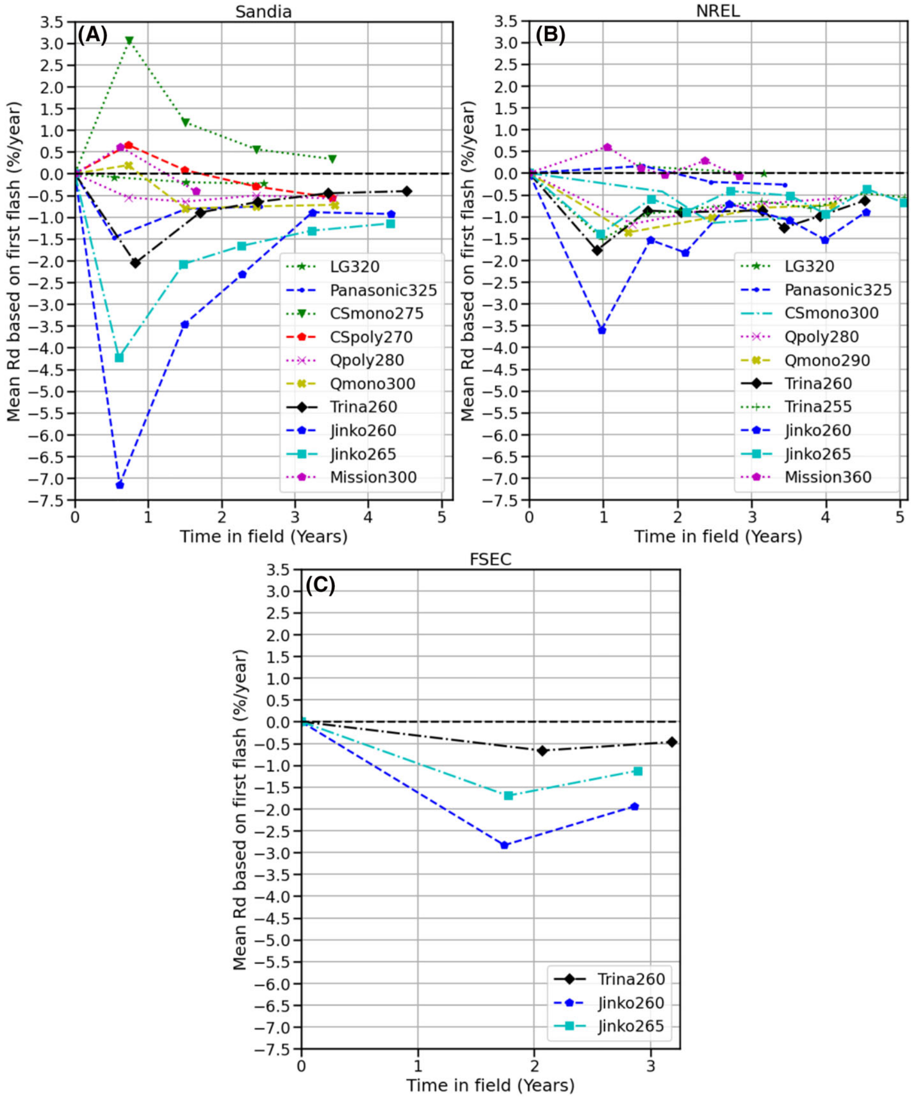

FIGURE 8 Interlaboratory ((A) Sandia, (B) NREL, and (C) FSEC) evolution of average degradation rates (%/year) for all PV module technologies based on average values of first post-stabilization flash measurements

recharacterized the modules over the following 4 years to monitor degradation rates over time.

Nameplate power rating differences ranged from around −3.6% to 4% with initial power stabilization varying from −3.3% to +0.6%. Flash-over-flash measurements showed variable performance with seasonality amplifying the variations. Furthermore, the module power loss for higher efficiency technologies (e.g., SHJ and PERC) was driven by *Voc* degradation indicating that the cells are still changing, whereas LeTID was observed in PERC and Al-BSF modules confirming previous studies. It was also observed that the BOM makes a big difference in field performance even when the modules were purchased from the same vendor.

The *Rd* values were evaluated based on nameplate values and first post-stabilization flash power ratings and showed differences of up to −2.39%/year depending on the reference used. We found that post-stabilization flash measurements help to ensure that a module performs according to expectations and avoids energy yield and financial bias. Furthermore, we observed that the *Rd* 'stabilizes' after ∼3–4 years.

The analysis found mean and median *Rd* of −0.62%/year and −0.58%/year, respectively, with some modules exhibiting improvements over the test period. Even though the median *Rd* values at Sandia (New Mexico; hot climate) and NREL (Colorado; cooler climate) were very close (−0.56%/year and −0.61%/year), this was not the case for the systems at the hot and humid subtropical climate of Florida (FSEC) exhibiting twice the median *Rd* value of −1.12%/year. However, more samples are required to verify such weather dependent findings.

Overall, the degradation rates found in this work are within the values observed in the past (from ∼1979 to ∼2014 module technologies) for more expensive (by up to 85%) conventional PV technologies. Therefore, although the costs declined sharply in the last decade, module degradation rates do not seem to be affected, at least for the sample investigated in this work. This is a very encouraging result, but more opportunities exist to reduce *Rd* to levels that enable longer PV module lifetimes. Finally, with respect to module warranties, the analysis so far showed that 26.1% of the systems are exceeding the warranty limits, whereas 56.5% of the systems demonstrated the potential of achieving lifetimes beyond 30 years assuming that *Rd* trends are stabilized.

ACKNOWLEDGEMENTS

The authors would like to thank the PV team at the Solar Energy Technologies Office for the critical review. Sandia acknowledges the technical work of Douglas M. Robb and William Snyder. NREL acknowledges the work of personnel in the NREL Measurement and Characterization group including Steve Rummel and Paul Ndione, as well as Byron McDanold and Josh Parker. This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Numbers 38268 and 38535. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This work was co-authored by Alliance for Sustainable Energy, LLC, the manager and operator of the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

CONFLICT OF INTEREST

All PV modules used in this study were purchased by the Sandia National Laboratories and National Renewable Energy Laboratory from independent vendors with the financial support of the US Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office. As such, the results are reported in an onymous (not anonymous) manner. The authors declare no competing interests.

AUTHOR CONTRIBUTIONS

Conceptualization: MT and JSS; Data curation: MT; Formal analysis: MT; Funding acquisition: BHK and CD; Investigation: CR, WS, AA, and DJC; Methodology: MT and JSS; Project administration: BHK, CD, JW, and HS; Software: MT and JSS; Supervision: JSS, BHK and CD; Validation: MT, JSS and CD; Visualization: MT and JSS; Writing – original draft: MT and JSS; Writing – review and editing: MT, JSS, CD, DJ, CR, WS, DJC, and HS. All authors read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

All flash test data collected at Sandia, NREL, and FSEC will be available in DuraMAT DataHUB.

ORCID

Marios Theristis https://orcid.org/0000-0002-7265-4922
Joshua S. Stein https://orcid.org/0000-0002-9422-1976
Chris Deline https://orcid.org/0000-0002-9867-8930
Dirk Jordan https://orcid.org/0000-0002-2183-7489
Hubert Seigneur https://orcid.org/0000-0002-5047-4541

REFERENCES

1. International Energy Agency (IEA), "*World Energy Outlook 2021*," IEA, Paris. https://www.iea.org/reports/world-energy-outlook-2021
2. Feldman D, Ramasamy V, Fu R, Ramdas A, Desai J, Margolis R. US solar photovoltaic system and energy storage cost benchmark: Q1 2020. National Renewable Energy lab.(NREL), Golden, CO (United States). NREL/TP-6A20-77324. 2021.
3. Peters IM, Hauch J, Brabec C, Sinha P. The value of stability in photovoltaics. *Joule*. 2021;5(12):3137-3153. doi:10.1016/j.joule.2021.10.019
4. Jordan DC, Kurtz SR. Photovoltaic degradation rates—an analytical review. *Prog Photovolt: Res Appl*. 2013;21(1):12-29. doi:10.1002/pip.1182
5. Jordan DC, Kurtz SR, VanSant K, Newmiller J. Compendium of photovoltaic degradation rates. *Prog Photovolt: Res Appl*. 2016;24(7):978-989. doi:10.1002/pip.2744
6. Blakers A. Development of the PERC solar cell. *Ieee J Photovolt*. 2019;9(3):629-635. doi:10.1109/jphotov.2019.2899460
7. ITRPV. *International Technology Roadmap for Photovoltaic (ITRPV)*. Vol. 2021. 12th Ed, November; 2021.
8. Jordan D, Kern D, Johnston S, et al. High efficiency silicon module degradation - from atoms to systems. In 37th European photovoltaic solar energy conference and exhibition (EU PVSEC 2020); 2020.
9. Ishii T, Masuda A. Annual degradation rates of recent crystalline silicon photovoltaic modules. *Prog Photovolt: Res Appl*. 2017;25(12):953-967. doi:10.1002/pip.2903
10. Sopori B, Basnyat P, Devayajanam S, et al. Understanding light-induced degradation of c-Si solar cells. in 38th IEEE Photovoltaic Specialists Conference (PVSC); 2012:1115-1120.
11. Kersten F, Engelhart P, Ploigt H, et al. A new mc-Si degradation effect called LeTID. in 42nd IEEE Photovoltaic Specialist Conference (PVSC); 2015:1-5.
12. Jordan DC, Silverman TJ, Sekulic B, Kurtz SR. PV degradation curves: non-linearities and failure modes. *Prog Photovolt: Res Appl*. 2017;25(7):583-591. doi:10.1002/pip.2835
13. Theristis M, Livera A, Jones CB, Makrides G, Georghiou GE, Stein JS. Nonlinear photovoltaic degradation rates: modeling and comparison against conventional methods. *Ieee J Photovolt*. 2020;10(4):1112-1118. doi:10.1109/jphotov.2020.2992432
14. Stein JS, Robinson C, King B, Deline C, Rummel S, Sekulic B. PV lifetime project: measuring pv module performance degradation: 2018 indoor flash testing results. in 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC); 2018:771-777.
15. Wood Mackenzie, U.S. PV Leaderboard, 2019 [Online]. Available: https://www.woodmac.com/our-expertise/focus/Power–Renewables/U.S.-PV-Leaderboard/
16. Standard IEC 61215, "crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval. 2016.
17. Gao Q, Zhang Y, Yu Y, Meng F, Liu Z. Effects of I–V measurement parameters on the hysteresis effect and optimization in high-capacitance PV module testing. *Ieee J Photovolt*. 2018;8:710-718. doi:10.1109/jphotov.2018.2810852
18. Pravettoni M, Poh D, Prakash Singh J, Wei Ho J, Nakayashiki K. The effect of capacitance on high-efficiency photovoltaic modules: a review of testing methods and related uncertainties. *J Phys D Appl Phys*. 2021;54(19):193001. doi:10.1088/1361-6463/abe574
19. Ndione PF, Osterwald CR, Ottoson L, et al. Combining indoor and outdoor measurements to lower uncertainty in PV modules performance. in 2020 47th IEEE Photovoltaic Specialists Conference (PVSC); 2020:2185-2187.

20. Levi DH, Osterwald CR, Rummel S, Ottoson L, Anderberg A. Self-reference procedure to reduce uncertainty in module calibration. in 44th IEEE Photovoltaic Specialist Conference (PVSC); 2017: 467–471.
21. Lindroos J, Savin H. Review of light-induced degradation in crystalline silicon solar cells. *Sol Energ Mat sol C*. 2016;147:115-126. doi:10.1016/j.solmat.2015.11.047
22. Chen C, Wang H, Wang J, Lv J, Yang H. Performance degradation of commercial Ga-doped passivated emitter and rear cell solar modules in the field. *Prog Photovolt: Res Appl*. 30(3):300-309. doi:10.1002/pip.3512
23. Kobayashi E, Wolf SD, Levrat J, et al. Light-induced performance increase of silicon heterojunction solar cells. *Appl Phys Lett*. 2016; 109(15):153503. doi:10.1063/1.4964835
24. Ramspeck K, Zimmermann S, Nagel H, et al. Light induced degradation of rear passivated mc-Si solar cells. in 27th European Photovoltaic Solar Energy Conference and Exhibition; 2012:861–865.
25. Repins IL, Kersten F, Hallam B, VanSant K, Koentopp MB. Stabilization of light-induced effects in Si modules for IEC 61215 design qualification. *Sol Energy*. 2020;208:894-904. doi:10.1016/j.solener.2020.08.025
26. Repins IL, Jordan DC, Woodhouse M, et al. Long-term impact of light and elevated temperature induced degradation on photovoltaic arrays. (under review). 2022.
27. Stein JS. Technical opportunities for improving PV modules and systems? The path to a 50 yr module. Sandia report no. SAND2019-14779C.2019.
28. Theristis M, Livera A, Micheli L, et al. Comparative analysis of change-point techniques for nonlinear photovoltaic performance degradation rate estimations. *Ieee J Photovolt*. 2021;11(6):1511-1518. doi:10.1109/jphotov.2021.3112037
29. Theristis M, Livera A, Micheli L, Jones CB, Makrides G, Georghiou GE, Stein JS. Modeling nonlinear photovoltaic degradation rates. in 47th IEEE Photovoltaic Specialists Conference (PVSC); 2020.
30. Lindig S, Louwen A, Moser D, Topic M. New PV performance loss methodology applying a self-regulated multistep algorithm. *IEEE J Photovolt*. 2021;11(4):1087-1096. doi:10.1109/jphotov.2021.3078075

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Theristis M, Stein JS, Deline C, et al. Onymous early-life performance degradation analysis of recent photovoltaic module technologies. *Prog Photovolt Res Appl*. 2023;31(2):149-160. doi:10.1002/pip.3615