PV Lifetime Project: Measuring PV Module Performance Degradation: 2018 Indoor Flash Testing Results

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***Abstract* — Photovoltaic (PV) module and system performance degradation is being measured by periodic flash testing of fielded PV modules at three sites. As of early 2018, results from modules fielded in New Mexico and Colorado are now available. These data indicate that module degradation varies significantly between module types and can also vary between modules of the same model. In addition, degradation rates for some module types appear to vary over time. Great care is made to control for stability and repeatability in the measurements over time, but there is still a +/-0.5% uncertainty in flash test stability. Therefore, it will take several more years for degradation rate results to be known with higher confidence.**

***Index Terms* —Photovoltaic cells, solar energy, degradation, lifetime estimation.**

I. Introduction

Rapid growth and cost pressure on PV manufacturing have produced complex supply chains that may create a wide (and obscured) range of service lifetimes. Despite this potential for differentiation, PV modules are often assumed to be an interchangeable commodity with respect to the degradation rates and service lifetimes. Due to the typically slow pace of PV module degradation in operation, often less than 1% per year [1], as well as variations in the operating and test conditions, any resulting differences in degradation rate are difficult both to measure and compare.

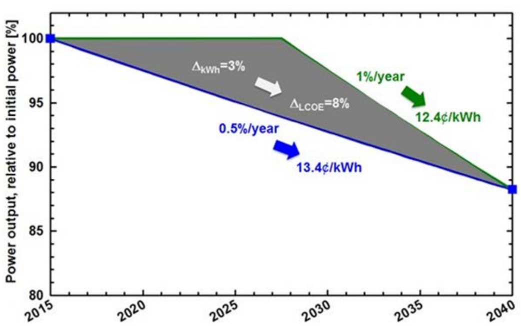


Fig. 1. Example of how non-linear degradation rate can affect LCOE.

The PV Lifetime project expands the data set related to the lifetime of PV hardware that is available to the public, with measurements taken over shorter intervals than has been common in the field and using repeatable test methods. The focus is on the PV module, as well as other hardware components (junction boxes, bypass diodes, module-level electronics) attached to it. For each module type, a “hardware set” is defined that includes the ancillary components (such as module-level electronics) to be studied in parallel. The data will enable an increase in the accuracy and precision of degradation profiles calculated for representative PV hardware installed in the U.S., which should impact PV project LCOE calculations and financing rates (e.g., Fig. 1).

The objective of the PV Lifetime Project is to determine & communicate module degradation profiles over time, including the uncertainty and any differentiation between module types. This will be done by:

- Annual flash testing of PV modules operated in the field in a variety of locations and climates.
- Analysis of timeseries production and string IV data to detect system degradation rates and causes.
- Sharing of reviewed results and data publicly.

This paper summarizes the results of the annual flash testing for systems in New Mexico and Colorado as of 2018. Analysis of the field IV curves and timeseries production data will be covered in later publications.

II. Modules Under Evaluation

Modules that are included in the study are carefully chosen to represent the make and models that are being installed in the US market as well as span cell technologies that are the most promising and popular today. We examined market research from solar market analysis firms and chose the following modules to begin our study. Additional modules from other companies will be added in the future.

- Jinko Solar — #1 Module Supplier in 2017
- Trina Solar — #2 Module supplier in 2017
- Canadian Solar — #3 Module supplier in 2017
- Hanwha Q-Cells — #5 Module supplier in 2017
- SolarWorld — Module and cell production in US
- LG — N-type mono, high efficiency
- Panasonic — HIT bifacial cell, high efficiency

In order to avoid all modules originating from one batch or production run, we sourced modules from two or more vendors. Upon arrival at the lab, we sample about 25% for flash testing out of the box prior to any light exposure. Then all modules are stabilized by light soaking for at least 20kWh/m^2. Then all modules are flash tested at STC and then are installed in the field and grid connected. A sub-sample of modules is retested approximately every year. Light-soaked control modules are stored in a climate controlled dark room and tested with each batch of fielded modules to help monitor and correct for any drift in the flash simulator over time. Additional performance monitoring modules (different types) are tested approx. weekly in NM to assess stability over shorter time periods.

A. New Mexico Systems

Most of the modules under test are located at Sandia National Laboratories in Albuquerque, New Mexico. Table I lists the model number, cell type and quantity of modules under test at this site. Fig. 2 shows one of the systems installed in NM.

TABLE I. MODULE UNDER TEST IN NEW MEXICO

Company	***Model***	***Type***	***Number***
Jinko Solar	JKM260, JKM265	multi	28/28
Trina Solar	TSM-PD05.08 260W	multi	56
Canadian Solar	CS6K-270P 270W	multi	48
Canadian Solar	CS6K-275M 275W	mono	48
Hanwha Q-Cells	Q.Plus BFR-G4.1 280	PERC	48
Hanwha Q-Cells	Q.Peak BLK G4.1 290	mono-PERC	48
Solar World	SW 245W Mono	mono	21
LG	LG320N1K-A5 320W	N-Si	48
Panasonic	N325SA16 325W	HIT	48

Fig. 2. Canadian Solar Modules at Sandia National Laboratories in New Mexico.

B. Colorado Systems

Modules under test in Colorado are located at the National Renewable Energy Laboratory in Golden, CO (Fig. 3). Table II lists the installed modules at this site. Two additional systems are planned to be installed in 2018.

TABLE II. MODULES UNDER TEST IN COLORADO

Company	***Model***	***Type***	***Number***
Jinko Solar	JKM260, JKM265	multi	28/28
Trina Solar	TSM-PD05.08 260W	multi	28
Trina Solar	TSM-PD05.05 255W	multi	28
Hanwha Q-Cells	Q.Plus BFR-G4.1 280	PERC	28
Hanwha Q-Cells	Q.Peak BLK G4.1 290	mono-PERC	28
Canadian Solar	CS6K-300MS 300W	PERC	28
Panasonic	N325SA16 325W	HIT	30
LG	LG320N1K-A5 320W	N-Si	28

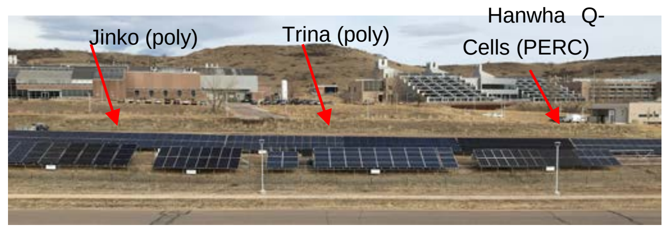


Fig. 3. PV Lifetime systems in Colorado at NREL.

III. MEASUREMENT METHODS

Both Sandia and NREL are working to harmonize our flash testing procedures for this project. We both include control modules for each module technology under test. These modules are stored indoors in the dark in a climate controlled room. We both light soak a subsample of modules at the start of the field test to monitor any initial light induced degradation. We both place the modules on the test plane at the same location for each test and between tests to reduce uncertainties due to light nonuniformity.

However, there are some differences between the methods used at each facility due to different site constraints. For example, Sandia performs temperature corrections to its flash test results because its laboratory temperature control is not as stable as it is at NREL, which can keep its lab at 25 °C (+/-0.5°C). Sandia can have larger temperature fluctuations in the lab of +/-1°C normally and even larger at limited times. We correct measured Imax for temperature using the spec sheet Isc temperature coefficient. We correct Vmax similarly using the Voc temperature coefficient. We then calculate a corrected Pmp value, which is reported. We have demonstrated that this method significantly lowers the uncertainty in our repeatability over time at Sandia.

A. Solar Simulator Stability

Because we are interested in measuring small changes in module power rating over long periods of time (up to 10 years or more), it is very important we know and measure the stability and repeatability the solar simulators at each site (SPIRE 4600 SP in NM and Spire 5600 in Colorado). Both labs have identified a set of performance monitoring modules that are carefully stored indoors and flash tested regularly to monitor the stability of the simulator.

At Sandia, three of these modules match the module models being examined by the PV Lifetime project. Fig 4 shows the repeatability in Pmp for these modules at Sandia since late

2017. The green line shows the mean of the measurements and the red lines show +/- 0.5% deviation. Most of the data fall within this uncertainty bound. We consider this bound a good estimate of the current repeatability of the measurements made at Sandia and NREL.

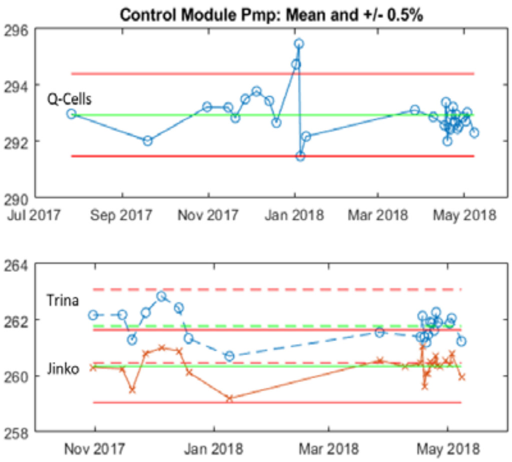


Fig. 4. Pmp results from three "control" modules from Sandia. Green horizontal lines represent means. Red lines represent +/- 0.5% variation. Dashed lines in lower plot are for Trina.

At NREL, control modules are maintained indoors to identify simulator variability. In one measurement case, an incorrect low simulator light level was used, requiring results to be corrected by + 1.5% - specifically for initial 2016 Jinko measurements. Subsequently and for other module types, a correct higher simulator setting was used.

IV. Results

A. *Initial Light-Induced Degradation (LID)*

LID can cause initial degradation in multi-crystalline and mono-crystalline silicon modules within the first 10 kWh/m^2 of light exposure through formation of boron-oxygen defects [2]. A selected number of modules from Canadian Solar and Q-Cells were monitored in NM and Colorado for degradation in the first few days of light exposure. The standard aluminum back-surface field (Al-BSF) Canadian Solar modules deployed in NM (Figure 5) show a larger initial loss of about -3.3% for the monocrystalline technology, compared with -1.5% for multi-crystalline. This difference is to be expected, with LID known to more strongly affect mono Al-BSF vs multi-crystalline cells [3]. LID was also monitored in four additional multi-crystalline Al-BSF module types in Colorado, showing initial loss of -0.4% for Trina TSM255 and TSM260 module types, and -0.5% — -1.5% loss in Jinko JKM260 and JKM265 types, respectively (not shown).

Two types of Q-Cells passivated emitter rear contact (PERC) modules, and one type of Canadian Solar PERC module were also evaluated for initial LID. Although high initial degradation of PERC cells greater than -7% has been reported in the literature [4], the initial LID losses of these modules are modest. Both Q-Cells mono-PERC and multi-PERC modules decreased by -1% — -1.5% in the measurements taken by Sandia in NM (Fig. 6a) and by NREL in Colorado (Fig. 6b). Canadian Solar multi-PERC modules showed an initial LID of -0.5% (Fig. 6c).

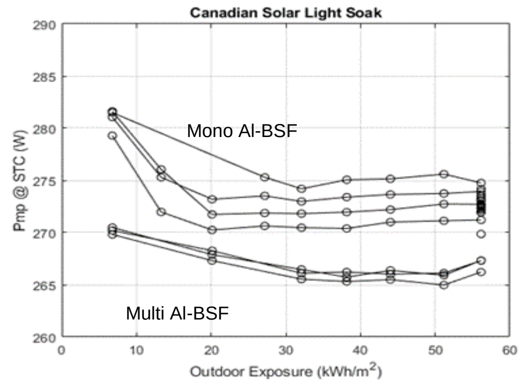
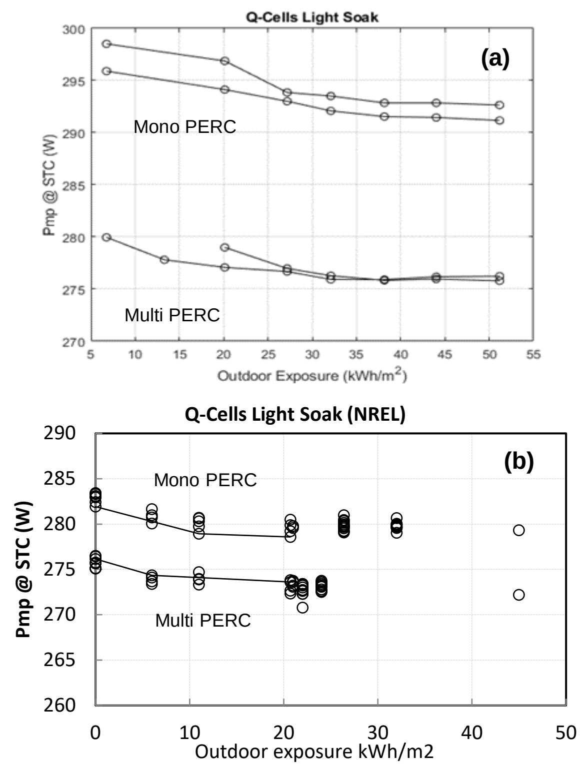


Fig. 5. Initial LID degradation of the non-PERC modules observed in NM in the first few days of exposure. Mono: -3.3%. Multi: -0.7%.



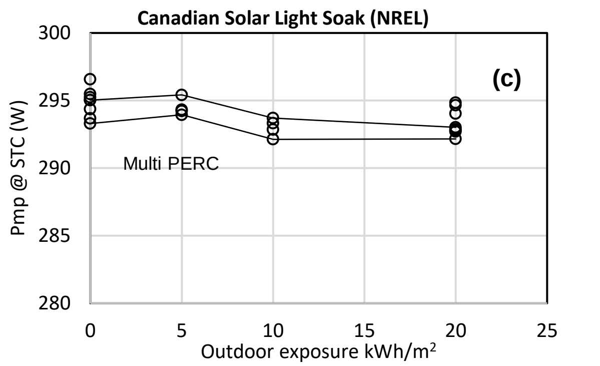


Fig. 6. Initial LID degradation of Q-Cells PERC modules observed in NM (a) and CO (b) ranged from -1% to -1.5% . Canadian Solar multi-PERC in CO had initial LID of -0.5% after 20 kWh/m2 (c).

B. Field Aged Modules – Jinko Solar and Trina Solar

Jinko Solar and Trina Solar modules were deployed in the fall of 2016 following 20kWh/m^2 light soak and characterization. A subset of modules were brought back indoors for IV curves in the summer of 2017 and 2018 as part of what has become an annual campaign.

Fig 7 shows results from Jinko Solar in NM after nearly 2 years of field exposure. Red dashed lines are un-exposed control modules showing the stability of the simulator. Two module types are considered, each displaying different degradation characteristics. Following two years in the field, both JKM265 and JKM260 modules have stabilized at a value that is -3.4% and -5% below initial light-soaked measurement, respectively.

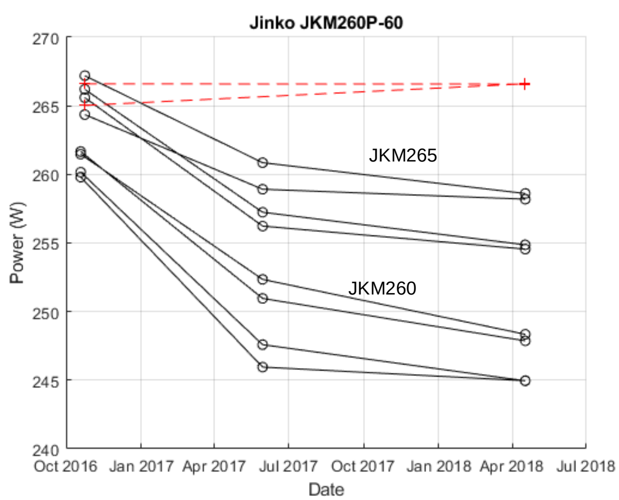


Fig. 7. Module Pmp measurements from Jinko Solar in NM after ~2 yr of field exposure. Initial LID has been considered, but not shown here.

Similar results are shown in Fig. 8 for JKM260 and JKM265 modules deployed in Colorado. Both module types displayed additional loss beyond the initial 20 kWh/m^2 LID exposure, on the order of -3.2% after year 1 for JKM260, and -1.5% after year 1 for JKM265. Compared with the values shown in Fig. 7 for NM, this is roughly half the overall degradation. But similar trends are visible where JKM260 modules degraded more than JKM265 modules.

Follow-up measurements in CO in 2018 showed a slight performance recovery for both JKM260 and JKM265 modules. This was within measurement uncertainty for JKM265, but outside the measurement uncertainty for JKM260. This possibly indicates post-LID regeneration of whatever effect (possibly LeTID [5]) is responsible for additional performance loss during years 1 and 2. Continuous monitoring of the NM modules will identify whether this recovery effect becomes visible at both sites.

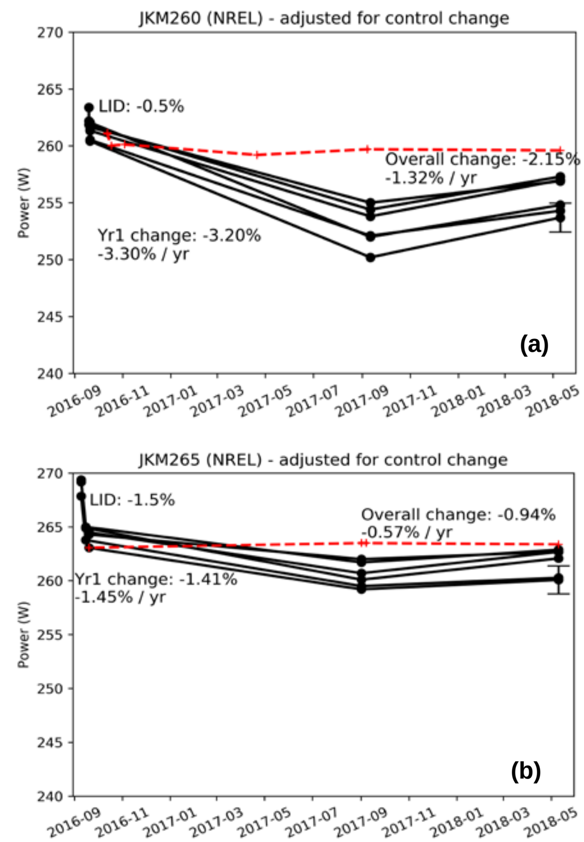


Fig. 8. Module Pmp for JKM260 (a) and JKM265 (b) in Colorado after ~2 yr of field exposure. Year 1 loss: JKM260 -3.2%, JKM265 -1.5%. A possible recovery is visible in year 2. Red dashed lines indicate indoor control module.

Trina Solar modules were also deployed and re-measured on a similar timeline as the Jinko Solar modules. Performance loss values are considerably smaller, and show less variability at the NM site (Fig. 9). Average loss values around -1.5% are measured after year 1. Similar to Fig.8, a slight performance recovery is visible by the second year.

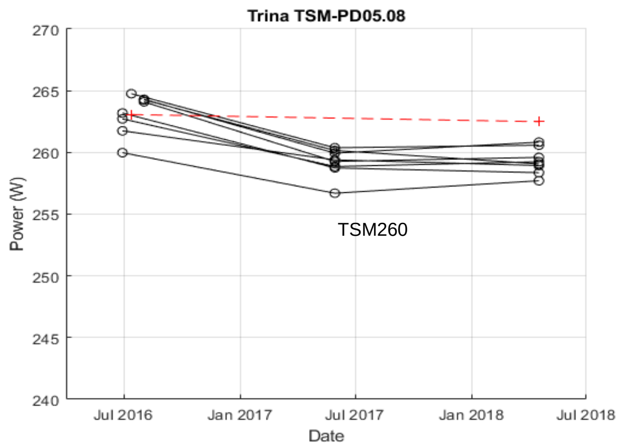
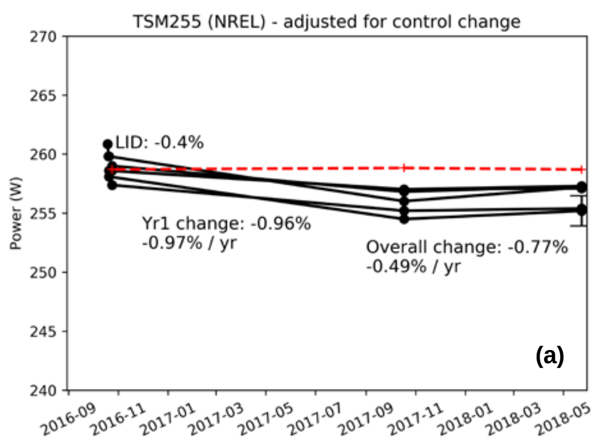


Fig. 9. Module Pmp for Trina Solar in NM after ~2 yr of field exposure. Year 1 loss: -1.5% followed by a slight year 2 recovery.

Trina Solar modules in CO show performance comparable to NM with one notable exception. The majority of TSM255 (Fig. 10a) and TSM260 (Fig. 10b) modules show first year performance loss of between -1% and -1.5%. However, one TSM260 module was found with an initially low STC performance, followed by greater than average year 1 performance loss (-3.9%) and larger magnitude recovery (+1.6%) by year 2. The characteristic follows closely the behavior shown by JKM260 modules in Fig. 8, and may indicate a Trina module made from a different cell batch, possibly from a contract manufacturer.



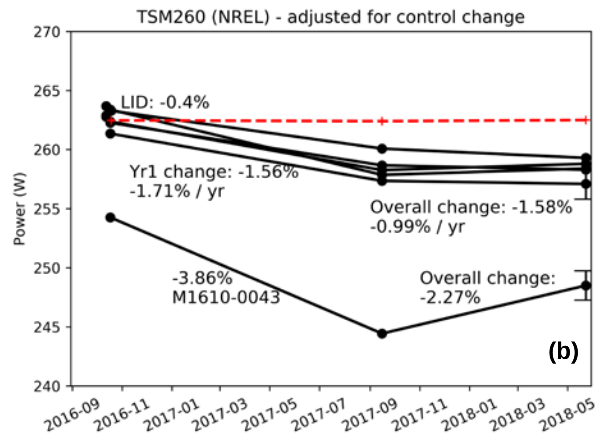


Fig 10. Module Pmp measurements from Trina Solar systems in Colorado after about two years of field exposure. Red dashed lines indicate indoor control modules. Error bars indicate 0.5% measurement uncertainty.

Year 1 follow-up measurements for other modules listed in Table I have also been made. The most notable change is with Canadian Solar, which showed an increase with time, mainly in the mono Al-BSF module type. The 3% performance recovery brings these modules back to their pre-LID state, shown in Fig. 5. The multi-Si modules showed a slight 0.7% recovery as well.

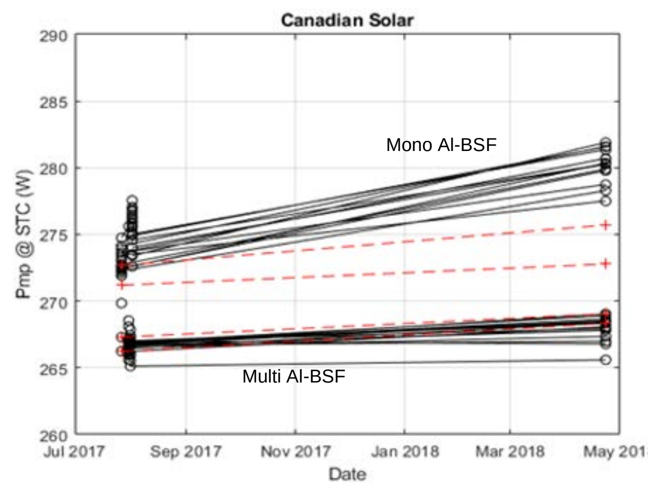


Fig. 9. Module Pmp measurements from Canadian Solar after ~9 months of field exposure. Both module types have recovered near their pre-LID state shown in Fig. 5.

VI. Discussion And Conclusions

The PV Lifetime project aims to measure the detailed progression of PV module performance degradation over time at two field sites. The total number of modules per system varies but is typically near 60 modules in NM and 30 modules in CO. At the start, all modules are characterized on an indoor solar flash simulator at each site. Periodically (roughly annually) a sample of modules are brought indoors and IV curves at STC are measured on a flash simulator at each site. The remaining modules are left untouched outdoors to ensure that some of the modules are not handled and damaged. Initial light induced degradation is measured on a small selection of modules by measuring their performance daily over a series of days during which the modules are exposed to sunlight in the field. Light-soaked control modules are stored indoors and flashed along with the fielded modules to track whether the flash simulator is drifting over time. In addition, a set of performance monitoring modules are stored inside and flash tested approximately weekly to help define the uncertainty in the repeatability of the measurements.

The first results from this project are now available and reported in this paper. Analysis of the performance monitoring library modules indicate that both Sandia and NREL can achieve about a +/- 0.5% uncertainty on the repeatability of flash measurements of Pmp. At present, the source of this uncertainty is likely a combination of uncertainty in measuring current and voltage, temperature, spatial uniformity, and spectral stability. We will continue to investigate these uncertainties and work to improve our measurements in the future.

Degradation results as of the spring of 2018 indicate that there are considerable differences in the degradation behavior between different module types and possible variations between modules in the same population. Below we summarize some of the most important results:

- There is significant variation in the initial unexposed power rating of modules compared with their nameplate, however the uncertainty in the absolute power is considerably higher (approx. +/-2% or higher) than for the repeatability (+/-0.5%). Some modules in our test appear to be "under-rated" (measured power > nameplate) while others are near or over nameplate. This is important since degradation in the context of a warranty is relative to the nameplate power. Module that are "under-rated" can degrade further before a warranty claim can be made. The reported degradation rates here are relative to the initial flash test after light soaking stabilization.
- Initial LID of modules was measured a sample of modules. In NM, Q-Cells and Canadian Solar modules showed about 1.5% and 2% LID, respectively (+/- 0.5% uncertainty). In CO, Q-Cells and Canadian Solar showed about 1-1.5% decrease. The two different power bins of Jinko in CO showed very different LID with the 260W modules experiencing a 0.5% decrease and the 265W modules experiencing a 1.5% decrease.
- Degradation in Pmp measured during the first year of field exposure varied significantly. This is possibly because of LeTID, whose effects can be mitigated by careful treatment of cells, but otherwise can cause degradation in the first ~1000 hours of system operation [5]. While typically associated with PERC cells, LeTID has been identified in standard Al-BSF multi-crystalline cells as well [6]. Other characteristics of LeTID include a temperature dependence in both the speed of degradation, and the final degradation amount, which might help explain some differences seen between CO (cooler climate) and NM (hot climate). LeTID is also recoverable, on timescales from days to years, depending on the temperature and kinetics of the defect [5]. This can help explain some of the recovery in power seen in NM and CO for multiple module types.
- For the systems for which we have data from the second year of field exposure, degradation rates appear to have slowed down. In NM, Trina Solar modules have no measurable degradation. Jinko Solar modules degraded by a mean of 1% in year 2. In CO, Jinko Solar 260W modules appear to have increased in year 2 for both power bins, but these increases are near the measurement uncertainty.

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