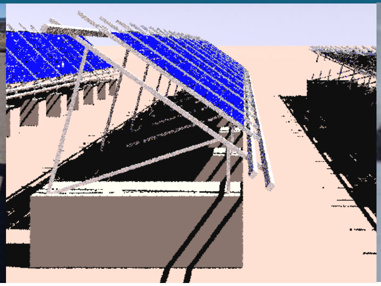
SAND2022-3557C

Early-life module degradation results from the PV system long-term exposure (SLTE) project



PRESENTED BY

Marios Theristis

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PVPG/SLTE Team

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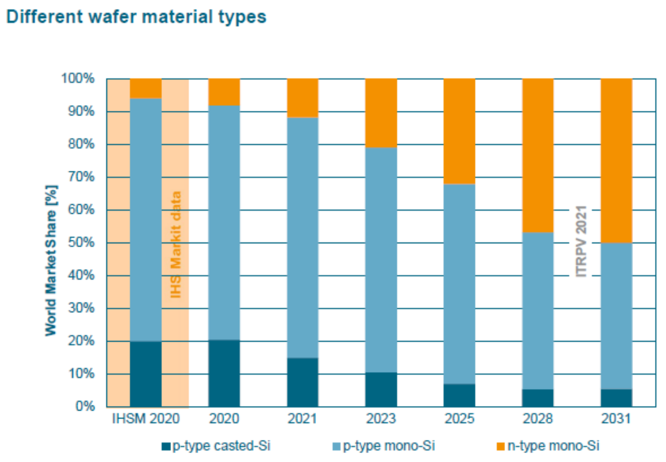
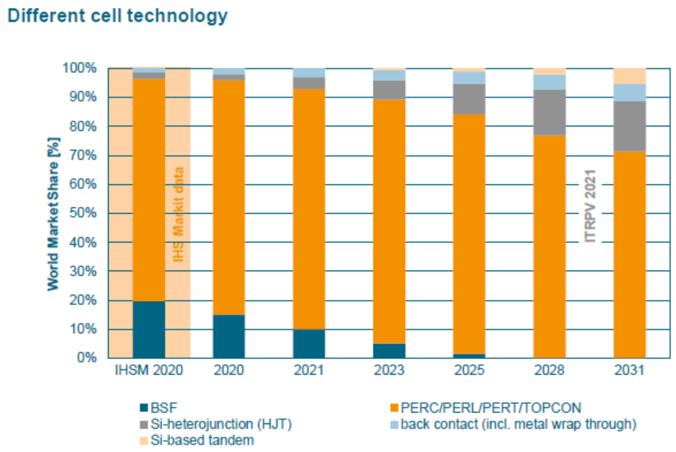
Introduction

- Cost of PV modules has declined by up to 85% since 2010 [1]
- Module designs and BOM have been altered to achieve these cost reductions
- PV module market is changing, costs are dropping
- Common practices assume degradation rates of -0.5%/year to -0.6%/year based on Jordan et al. [2], [3] (~1979 and ~2014)

→ Are **module** degradation rates changing?





Figures obtained from ITRPV 2021 [4]

[1] D. Feldman, et al., "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.
[2] D. C. Jordan and S. R. Kurtz, "Photovoltaic Degradation Rates—an Analytical Review," *Progress in Photovoltaics: Research and Applications,* vol. 21, pp. 12-29, 2013.
[3] D. C. Jordan, *et al.*, "Compendium of photovoltaic degradation rates," *Progress in Photovoltaics: Research and Applications,* vol. 24, pp. 978-989, 2016.
[4] ITRPV 2021, "International Technology Roadmap for Photovoltaic (ITRPV)," 12th Edition, November 2021.

Approach

- We purchased and fielded 834 modules
 [13 different module types, 7 manufacturers]

- The systems are deployed in the field at 3 locations
- Continuous and discreet IV and MPP measurements
- We report on early-life module degradation (< 5 years) based on > 2000 IV curves at STC
- **Onymous** analysis not anonymous

Module selection

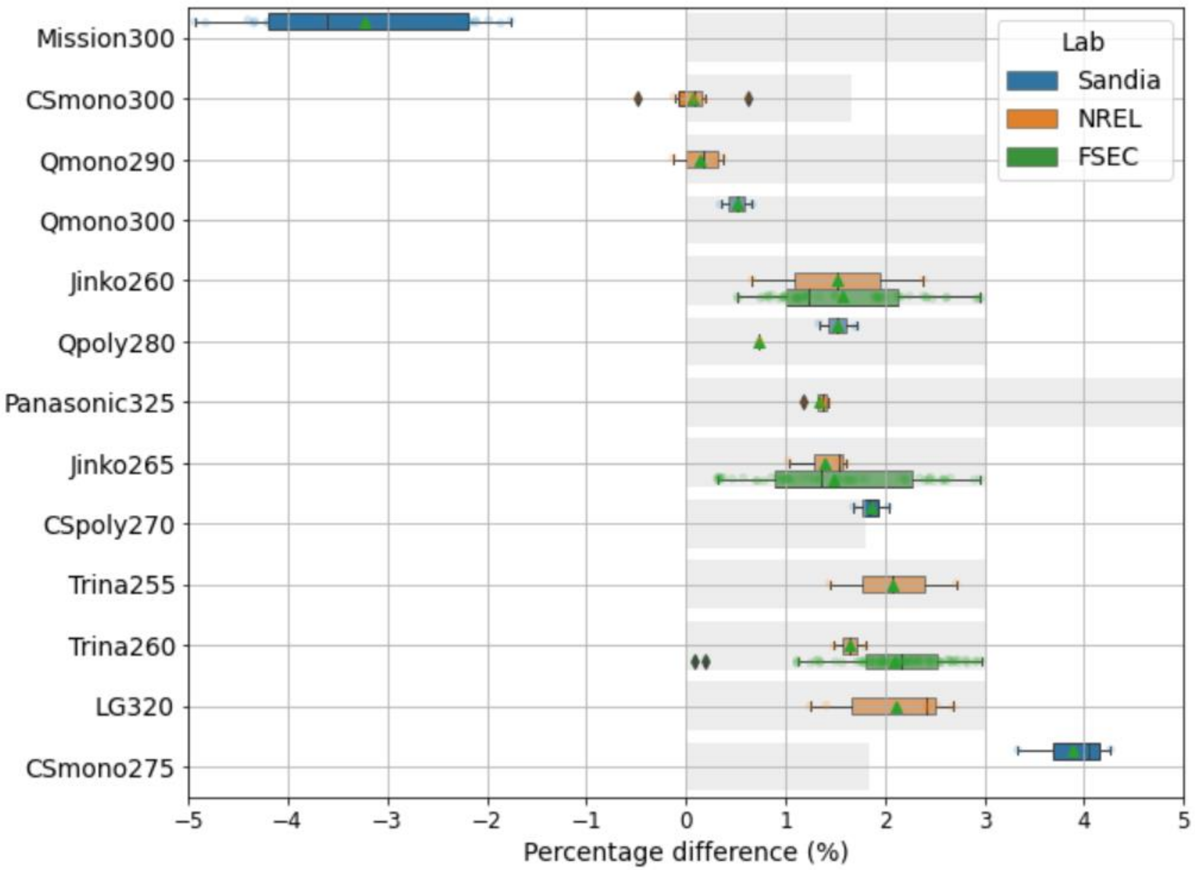
- SLTE represents 55% of the 2020 US market
- Attempted to maintain diversified selection to include different technologies
- Modules with the same model number were sourced from two or more vendors
- Modules are continuously being installed since 2016:

https://pvpmc.sandia.gov/pv-research/pv-lifetime-project/pv-lifetime-modules/

Company	Model and power rating	Type	Features	Date deployed	Number in NM	Number in CO	Number in FL
Jinko Solar	JKM260P 260W	Poly-Al-BSF	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 265W	Poly-Al-BSF	4 busbars	10/2016		28	
Trina Solar	TSM-PD05.05 255W	Poly-Al-BSF	4 busbars	10/2016	-	28	-
Trina Solar	TSM-PD05.08 260W	Poly-Al-BSF	4 busbars	06/2016 (NM) 09/2016 (CO) 09/2017 (FL)	56	28	56
Canadian Solar	CS6K-270P 270W	Poly-Al-BSF	4 busbars	10/2017	48	-	-
Canadian Solar	CS6K-275M Quartech 275W	Mono-Al-BSF	4 busbars	10/2017	48	-	-
Canadian Solar	CS6K-300MS Quintech 300W	Mono-PERC	5 busbars	08/2018	-	28	-
Hanwha Q-Cells	Q.Plus BFR-G4.1 280W	Poly-PERC	4 busbars	10/2017	48	28	-
Hanwha Q-Cells	Q.Peak BLK G4.1 290W (NREL) and 300 W (Sandia)	Mono-PERC	4 busbars	10/2017	48	28	-
LG	LG320N1K-A5 320W	N-type Mono-PERT	Bifacial, 12 multi wire busbars	06/2018	48	28	-
Panasonic	N325SA16 325W	N-type Mono-HIT	Bifacial, 4 busbars	06/2018	48	30	-
Mission Solar	MSE300SQ5T 300W	P-type Mono-PERC	4 busbars	05/2019	48	-	-
Mission Solar	MSE360SQ6S 360W	P-type Mono-PERC	4 busbars	12/2018	-	20	
Site Totals					448	274	112
Program Total					834 modules		

Initial performance

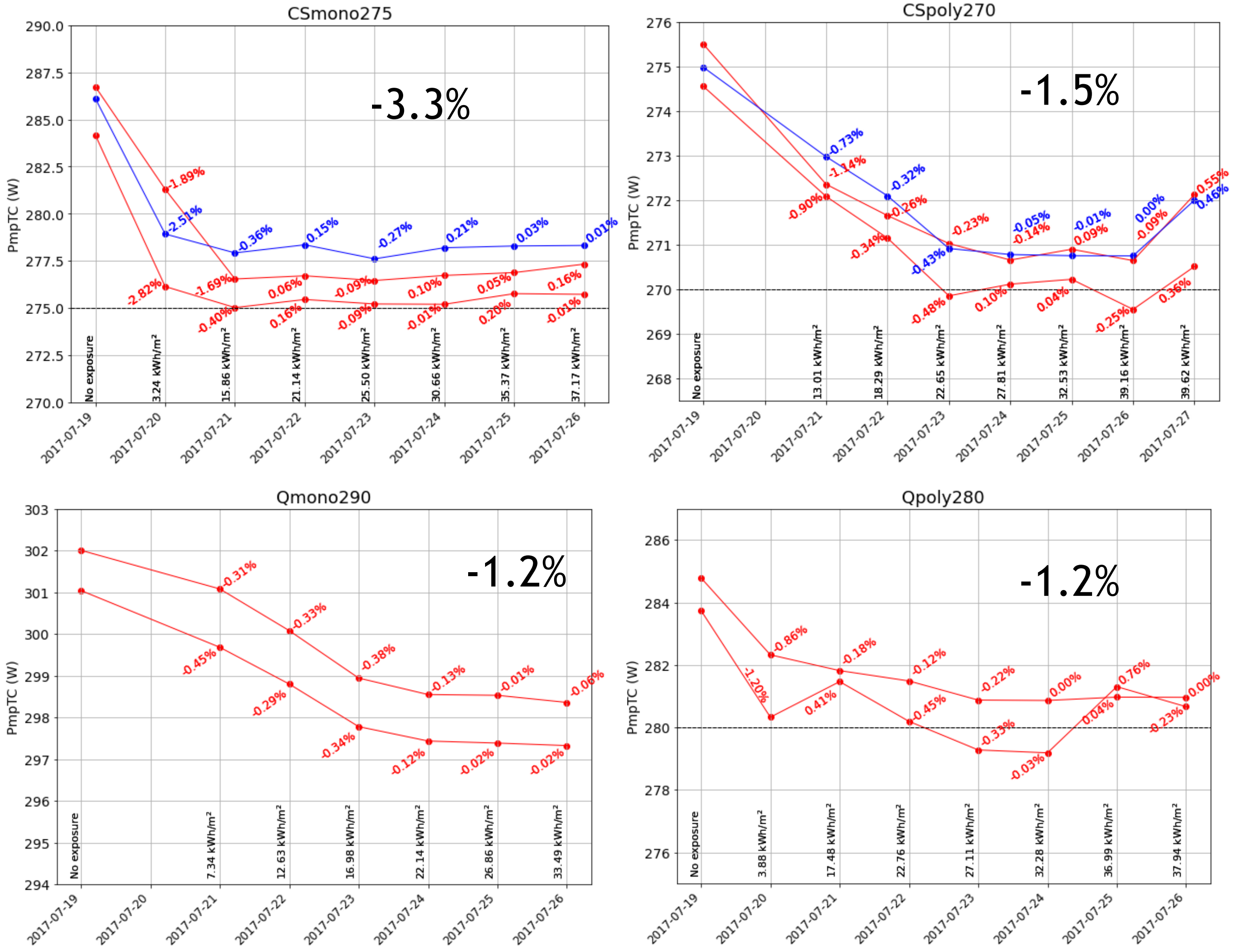
- Percentage differences of nameplate power ratings against out-of-box measurements
- This is important since Rd in the context of a warranty is relative to the nameplate power
- Median differences from -3.6% to 4%
- Positive bin tolerances; most modules are under-rated (measured power > nameplate)



Light induced degradation

- Examples of modules that were characterized daily
- Expected larger difference between CSmono275 and CSpoly270
- PERC behavior qualitatively similar to Chen et al. [1]
- LID range from -3.3% to +0.6%
- "Positive LID" of Panasonic325 at NREL in agreement with a study by Kobayashi et al. [2]

Module	Exposure (kWh/m²)	LID (%)
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



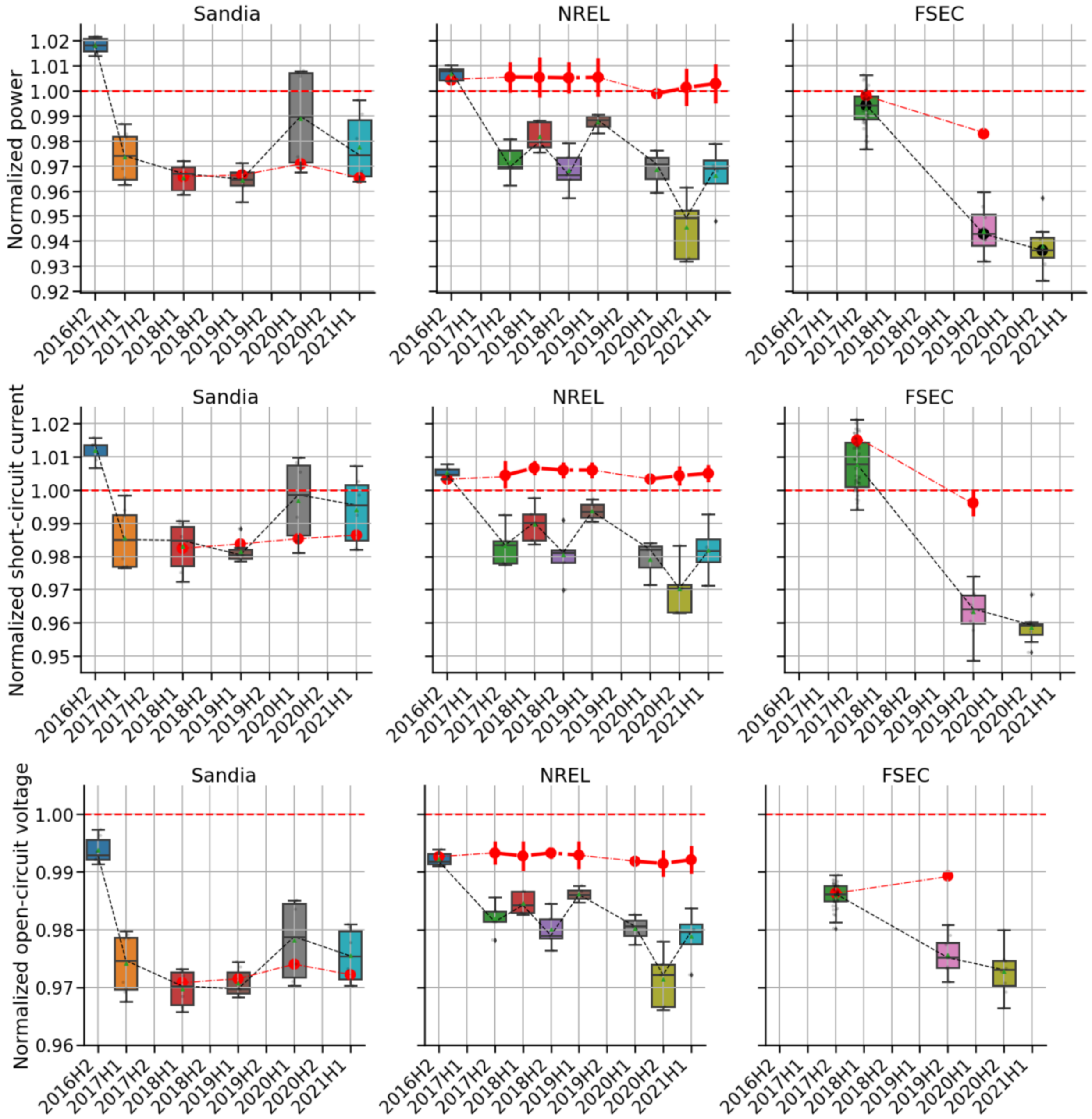
Examples of stabilization process for a) CSmono275, b) CSpoly270, c) Qmono290, d) Qpoly280 modules at Sandia. Red and blue colors indicate control and field modules, respectively. Percentage differences and light exposure values are also shown.

[1] C. Chen, *et al.*, "Performance degradation of commercial Ga-doped passivated emitter and rear cell solar modules in the field," *Progress in Photovoltaics: Research and Applications, 2021*.
[2] E. Kobayashi, *et al.*, "Light-induced performance increase of silicon heterojunction solar cells," *Applied Physics Letters*, vol. 109, p. 153503, 2016.

Flash test results from selected modules

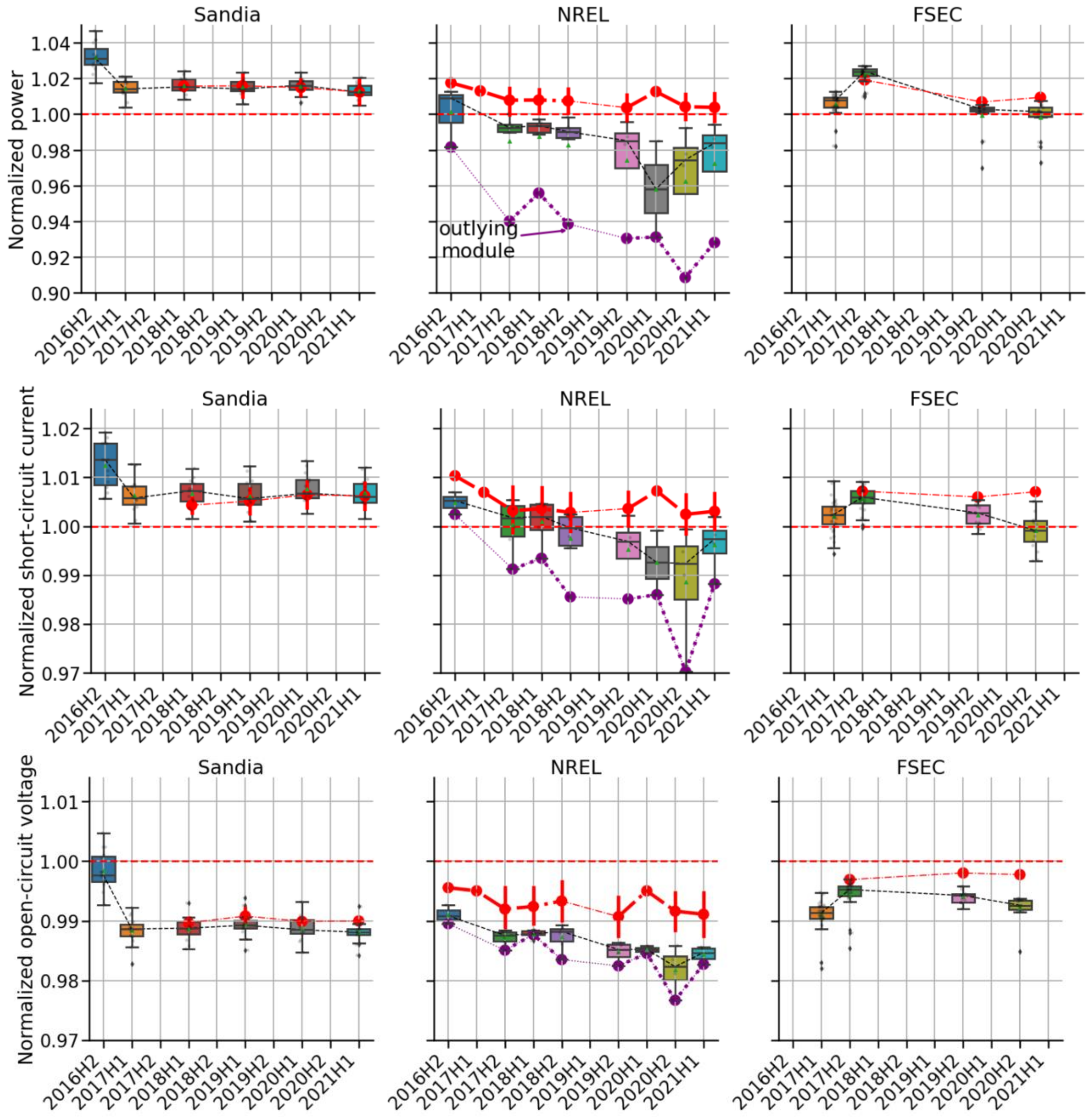
Jinko Solar 260

- Steep drop in Y1 followed by a relatively unstable behavior with a trend indicating LeTID in Al-BSF
- Seasonality effects evident in NREL flash tests
- NREL and FSEC indicate that degradation is greater in Isc



Trina Solar 260

- Modest power degradation with one exception
- Outlying module demonstrated an LeTID-like behavior
- Even when a same module is purchased, there is a possibility of ending up with different BOM and thus, a potential different behavior
- Overall power change ranged from -2.5% to -0.6% whereas the outlying module exhibited -5.3%

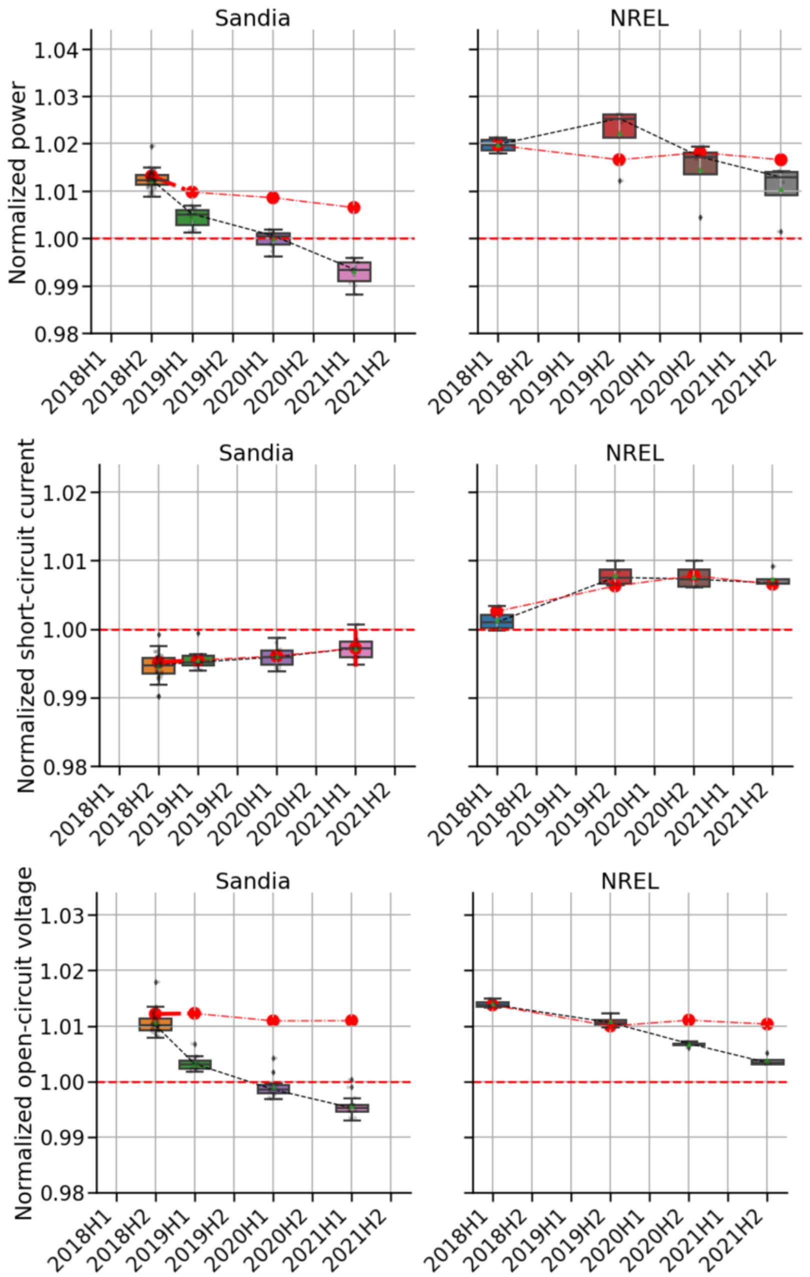


Panasonic 325

- Exposed for 370 kWh/m^2 (Sandia) and 20 kWh/m^2 (NREL)

- Modest power degradation with increasing Isc

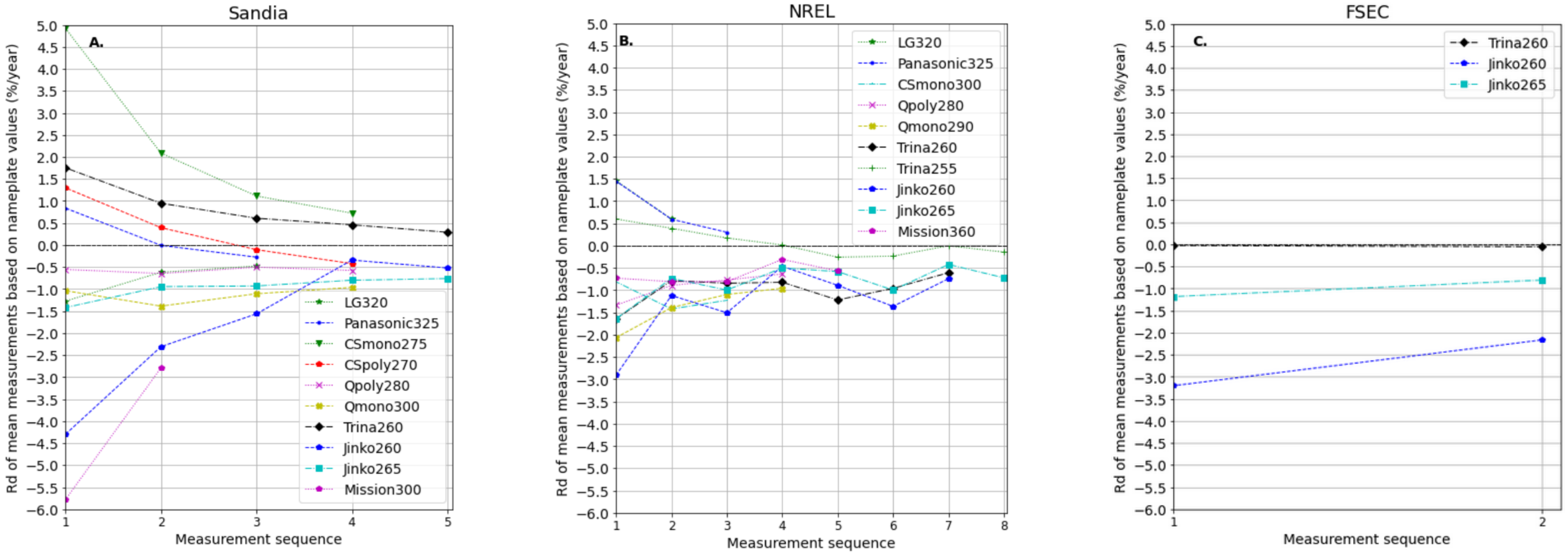
- Degradation is voltage driven (-1% to -1.5%) indicating that cells are still changing



Degradation rates

Module degradation rates based on two methods

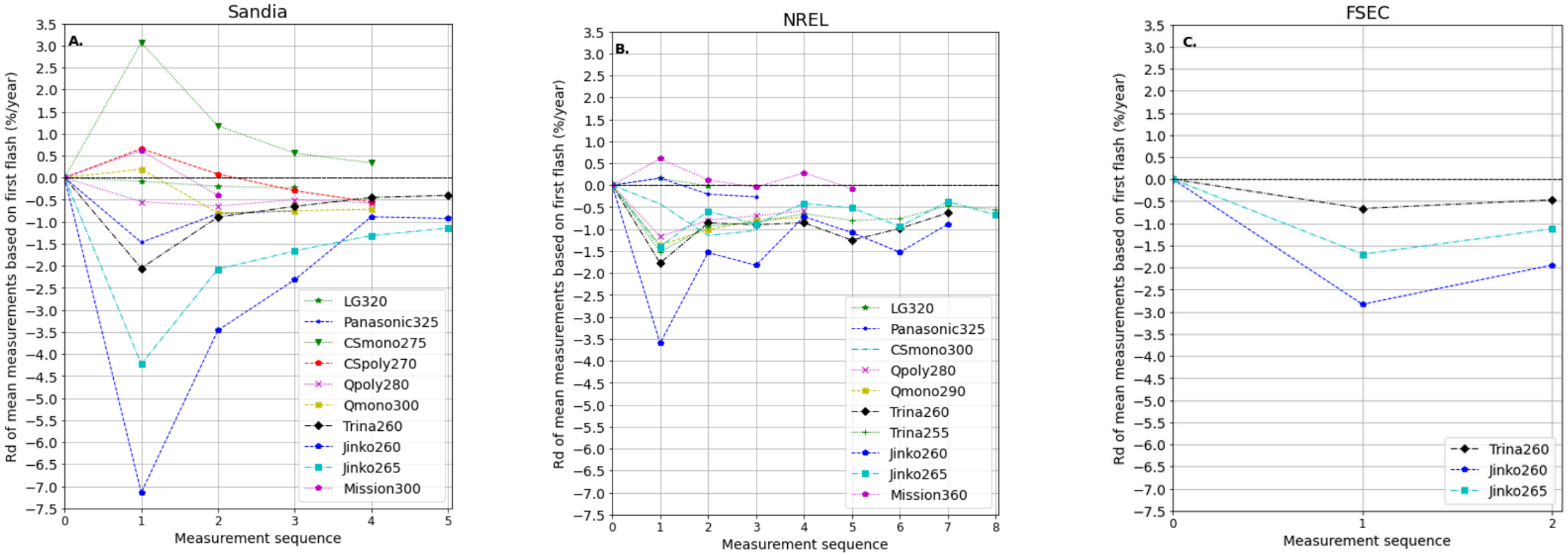
Based on nameplate values



Range:
-2.8%/year (Mis300) to
+0.7%/year (CSmono275)

Positive Rd:
Trina260
CSmono275
LG
Panasonic

Based on first post-LID flash values



Range:
-1.9%/year (Jinko260) to
+0.3%/year (CSmono275)

Positive Rd:
CSmono275

Mean and median values around -0.6%/year

Few points for discussion and future work

Discussion point #1

Nameplate-based Rd vs. Rd based on the first post-LID flash test

- It can influence the resulting degradation rate, and energy yield projections

- Vendors may sell under-/over-rated modules
  - Under-rated = some financial loss when selling, but "safety" in case Rd is higher than expected
  - Over-rated = more profit when selling, but high risk of warranty returns (could be sooner than an insurer would expect)
  - This depends on the intended market; might not be the case in utility-scale module procurement contracts

- Post-LID flash tests should be performed to ensure that even after LID, the module performs according to expectations

Discussion point #2

How are we doing with respect to the absolute values of Rd and warranties?

- Costs dropped, technology evolved, but Rd values do not seem to be affected, which is an encouraging outcome
- There are still opportunities to reduce Rd to levels that enable longer PV module lifetimes
- Assuming SLTE Rd values cease to change:
  - 6 out of 23 (or 26.1%) systems are projected to exceed the warranty limits (i.e., Rd < -0.8%/year) and qualify for module replacements
  - 12 out of 23 (or 52.2%) systems demonstrated the potential of achieving lifetimes beyond 30 years (i.e., Rd > -0.6%/year)

Discussion point #3

Highly nonlinear degradation behavior

- Unnecessary O&M alerts might be triggered when expectations differ in any year

- Understanding that such nonlinearities are not uncommon in the first years; tend to converge after ~4 years

- Applying statistical approaches that consider nonlinearities might help; here are some examples:

1112 IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 10, NO. 4, JULY 2020

Nonlinear Photovoltaic Degradation Rates: Modeling and Comparison Against Conventional Methods

Marios Theristis, Andreas Livera, C. Birk Jones, George Makrides, George E. Georghiou, and Joshua S. Stein

IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 11, NO. 4, JULY 2021 1087

New PV Performance Loss Methodology Applying a Self-Regulated Multistep Algorithm

Sascha Lindig, Atse Louwen, David Moser, and Marko Topic

IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 11, NO. 6, NOVEMBER 2021 1511

Comparative Analysis of Change-Point Techniques for Nonlinear Photovoltaic Performance Degradation Rate Estimations

Marios Theristis, Andreas Livera, Leonardo Micheli, Julián Ascencio-Vásquez, George Makrides, George E. Georghiou, and Joshua S. Stein

Future work

- Article and data will be published this year
- We will continue deploying new systems and publishing **onymous** data during all lifetime stages for informing and/or reassuring current assumptions on stability and reliability
- Follow-up work will include EL imaging coupled to the outdoor continuous monitoring data

Thank you!

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