NREL
NATIONAL RENEWABLE ENERGY LABORATORY

PV Reliability Workshop – Lakewood, CO

February 26, 2020

Welcome to the 2020 Photovoltaic Reliability Workshop! This year's PVRW continues in the tradition of attendee participation. Attendees (and one guest) should present on the reliability of PV, either giving an oral or poster presentation. The workshop provides a unique opportunity for learning, discussion, and leadership relative to the present issues in PV-module and -system reliability.

Topics of interest during the PVRW include failure modes and degradation rates of fielded systems, module degradation modes (for materials and components), modeling of degradation, extreme weather events, collaborative research, PV standards and accelerated testing, extending system life, power electronics, trackers, and fires.

Chair:

David MILLER

Committee:

Teresa BARNES
Mike BOLEN
Dan BRAKE
Evelyn BUTLER
Chris DELINE
James ELSWORTH
Jack FLICKER
Tassos GOLNAS
Margaret GORDON
Greg KIMBALL
Inna KOZINSKY
Sarah KURTZ
Sumanth LOKANATH
Jenya MEYDBRAY
Matt MULLER
Dana OLSON
Nancy PHILLIPS
Jon PREVITALI
Ingrid REPINS
Laura SCHELHAS
Tim SILVERMAN
Josh STEIN
Scott STEPHENS
Mani G. TAMIZHMANI
Andy WALKER
Kent WHITFIELD

AGENDA – Wednesday, 26 February 2020

7:30 - 8:00	**Continental Breakfast**
8:00 - 9:50	**Session F: PV and extreme weather events** *Session Chairs: Nick DeVRIES (Silicon Ranch) and Narendra SHIRADKAR (IIT-Bombay)* **8:00** – Multi-site assessment of extreme weather impacts on PV plant performance and reliability – Nicole JACKSON (SNL) **8:20** – Storms and other events - experiences with cell cracks – Will HOBBS (Southern Company) **8:40** – Bankable independent engineering review for extreme weather conditions: structural loads, hydrological and geotechnical hazards – Dan BERGER (DNV GL) **9:00** – Hail damage – laboratory and field studies – James RAND (Energy Works LLC) **9:20** – Questions/Discussion – led by Session Chairs and Slido Team
9:50 - 10:10	**Coffee Break**
10:10 - 11:40	**Session G: PVQAT and other collaborative efforts** *Session Chairs: Peter HACKE (NREL) and Ingrid REPINS (NREL)* **10:10** – PVQAT: Overview – Tadanori TANAHASHI (AIST) **10:30** – Update on the newly formed PVQAT - India – Narendra SHIRADKAR (IIT-Bombay) **10:50** – The developments and research of PVQAT TG13 [PV cells] – Qi WANG (Jinko Solar) **11:10** – Questions/Discussion – led by Session Chairs and Slido Team
11:40 - 12:40	**Lunch** (poster viewing/discussion encouraged)
12:40 - 14:10	**Poster Session H -** posters associated with Sessions F, G, I, and J
14:10 - 15:40	**Session I: PV system performance and degradation** *Session Chairs: Evelyn BUTLER (SEIA) and Bruce KING (SNL)* **14:10** – PV reliability of 100,000 systems– Dirk JORDAN (NREL) **14:30** – Data analytics to predict onset of failure – Alex AU (NEXTracker) **14:50** – Degradation case studies: from the field to the lab – Michael DECEGLIE (NREL) **15:10** – Questions/Discussion – led by Session Chairs and Slido Team
15:40 - 16:00	**Coffee Break**
16:00 - 17:35	**Session J: PV standards and accelerated testing** *Session Chairs: Keiichiro SAKURAI (AIST) and John WOHLGEMUTH (Powermark Corp)* **16:00** – IEC standards and PV system certification – George KELLY (Sunset Technology) **16:20** – Revised static load requirements for PV modules – Sumanth LOKANATH (First Solar) **16:40** – IECRE PV system certification on quality system of manufacturers and service providers – Masaaki YAMAMICHI (RTS) **17:00** – Questions/Discussion – led by Session Chairs and Slido Team **17:30** – Today's Poster Awards – Xiaohong GU (NIST) and David MILLER (NREL)
17:35	**Adjourn from Workshop**
	BONUS NETWORKING & POSTER TIME: Attendees are welcome to view posters Wed evening. A cash bar and hors d'ouerves are available near the City Lights Ballroom.
17:35	**Adjunct Meetings**
	Hail Damage & PV meeting – Sumanth LOKANATH – Lakewood Ballroom • How PVEL is addressing cell cracking in the lab and in the field – Tristan ERION-LORICO (PVEL) • Hail impacts overview – Rob ANDREWS (Heliolytics) IECRE – Masaaki YAMAMICHI – Jefferson Boardroom

POSTER SESSION H: Wednesday, 26 February 2020

*Session H posters are associated with Sessions **F**, **G**, **I**, or **J***

1. *B. Aissa, R.J. Isaifan, V.E. Madhavan, N.H. Al-Jufairi, A.A. Abdallah,*
"Structural and physical properties of the dust particles in Qatar and their influence on the PV panel performance"

6. *K. Anderson, K. Perry,*
"Estimating subhourly inverter clipping loss from satellite-derived irradiance data"

8. *S. Toth, M. Hannigan, M. Vance, M. Deceglie,*
"Predicting photovoltaic soiling from air quality measurements"

10. *D. Fregosi, N. Paudyal, S. Hackett, M. Bolen,*
"Benchmarking performance and loss rate of PV plants"

14. *P. Bostock, B. Littmann,*
"A framework for estimating PV energy production and probabilities of exceedance"

16. *N. Brunner,*
"A case study in year-on-year trending of photovoltaic performance ratio"

18. *L. Burnham, C. Stark, S. Dittmann, R. Gottshalg, A. Benlarabi, T. Betts, J-H Choi, B. Figgis, S-Y Oh, T. Reindl, R. Ruther,*
"A global cross-climate platform for high-quality data sharing"

19. *E. Ortega, G. Aranguren, J.C. Jimeno*,
"New monitoring method to self-characterize individual modules in large photovoltaic systems"

20. *V. Chawla, T. Tolliver, M. Reusser, H. Larson,*
"Evaluation of system degradation and useful life for solar project finance"

22. *D. Cormode, R. Hamilton, N. Croft,*
"Improving predictive value of capacity tests via parameter adjustment"

23. *J. Chard, M. Dooraghi, C. Hunter, J. Robinson, K. Morley,*
"A comparison of ground-based PV module soiling measurements systems at a semi-arid site in northern Utah"

26. *N. de Vries, D. Sontag, C. Helms, E. Spraggins,*
"Identifying failing inverters using normalized IGBT temperature"

27. *J. Forbess, T. Reed,*
"Daily soiling rates correlated with air quality and other meteorological data in Oakland CA"

28. *J. Elsworth, O. Van Geet,*
"PV storm hardening costs"

30. *M. Gostein, B. Marion, B. Stueve,*
"Spectral mismatch in albedo measurements"

32. *A. De Mendoza, Z. Hammond,*
"The effect of polar vortices on fixed-tilt solar PV systems"

34. *L. Ji, S. Jezwinski, C. O'Brien, K. Boyce,*
"UL and IEC standard updates on PV connectors ñ field assembly and incompatibility"

38. *B. Kim, A. Vilanova Cortezon, C. Ki Kim, Y-H Kang, H-G Kim,*
"Non-linear regression model between solar irradiation and PV generation output"

39. *A. Habte, M. Sengupta,*
"Modeling of ultraviolet irradiance from total irradiance: a simplified approach"

40. *C.K. Kim, H. Kim, Y-H Kang, B-Y Kim, C-Y Yun,*
"Examination of performance ratios for solar power plants based on satellite-derived solar irradiance in the Korean Peninsula"

42. *B. Marion,*
"Albedo data for bifacial PV systems update"

44. *B. Meyers, L. Schelhas,*
"Solar data tools: automatic solar data processing pipeline"

46. *H. Seigneur, E. Schneller, D. Colvin, R. Janoch, A. Anselmo, A. Gabor,*
"The influence on cracked solar cell degradation from Hurricane Dorian wind-loading events and the influence of RailPad bracing elements"

52. *O. VanGeet, J. van Dam, S. Dana, J. Elsworth, G. Robinson,* "PV high wind user test facility"

54. *M. Owen-Bellini, P. Hacke, S. Spataru, D. Sulas, H. North, D.C. Miller, M.D. Kempe,*
"Combined-Accelerated Stress Testing for Advanced Reliability Assessment of Photovoltaic Modules"

58. *E. Kam-Lum, D. Cosme, M. Sakhuja, J. Chapon, M. Sander, S. Aid,*
"Determination of outdoor soiling rates in desert environments by comparing daily Impp current of soiled and cleaned photovoltaic strings"

60. *P. Hacke, K. Terwilliger, A. Walker, V. Guthrie,*
"Analysis of Hail Damage in PV Modules with Respect to Mounting Angle and Direction"

68. *C. Schmid, C. Honeker, A. Watts, A. Lloyd, K. Lee, J. Richards, D. McDougall, J. Miller, W. MacDonald,*
"Reliability aspects of adhesive mounting of conventional PV solar modules"

71. *M. Köentopp, F. Kersten, E. Herzog,*
"Towards an IEC LETID test standard. procedures, kinetics and separation of B-O degradation from LETID"

76. *M.M. Kivambe, A.A. Abdallah, B. Aissa, B. Figgis, C.A. Broussillou,*
"Performance comparison of bifacial PV modules due to soiling in desert climates"

84. *J. Wohlgemuth,*
"PV standards activities of IEC"

86. *D. Celvi, R. Tirawat, C. Schreiber, G. Zhu,*
"Development of an accelerated aging test procedure for solar mirrors"

*Session H posters are associated with Sessions **F, G, I, or J***

89. *S. Nalin Venkat, J. Liu, N.S. Bosco, J. Dai, W.J. Gambogi, B. Brownell, Y. Gu, J. Carter, L.S. Bruckman, J-N Jaubert, J.L. Braid, R.H. French,*
"Towards 50 year module lifetimes: impact of module architecture and packaging materials"

90. *K. Lee, J. Nagyvary, J. Sharp, L. Creasy,*
"Testing for risk of hot spots and bypass diode activations in bifacial arrays on single-axis trackers"

94. *A. Richter,*
"PV mounting: often underestimated for reliability of solar systems"

98. *W. Shan, H. Zhou,*
"Effective efficiency of energy generation by field-deployed PV modules as a long-term performance indicator"

102. *A. Barriga, A. Shinn,*
"Deciphering degradation: machine learning on real-world performance data"

106. *L.J. Simpson, J.M. Newkirk, C. Lanaghan, A. Einhorn, R. Huntamer, A. Bergeson-Keller, L.T. Schelhas, C. Engtrakul, M. Muller, D. Holsapple, J. Morse, B. To, P.F. Ndione, H.R. Moutinho, A. Alnuaimi, J.J. John, B. To, B. MacDanold, D.C. Miller,*
"IEC 62788-7-3 Standard: PV abrasion development update"

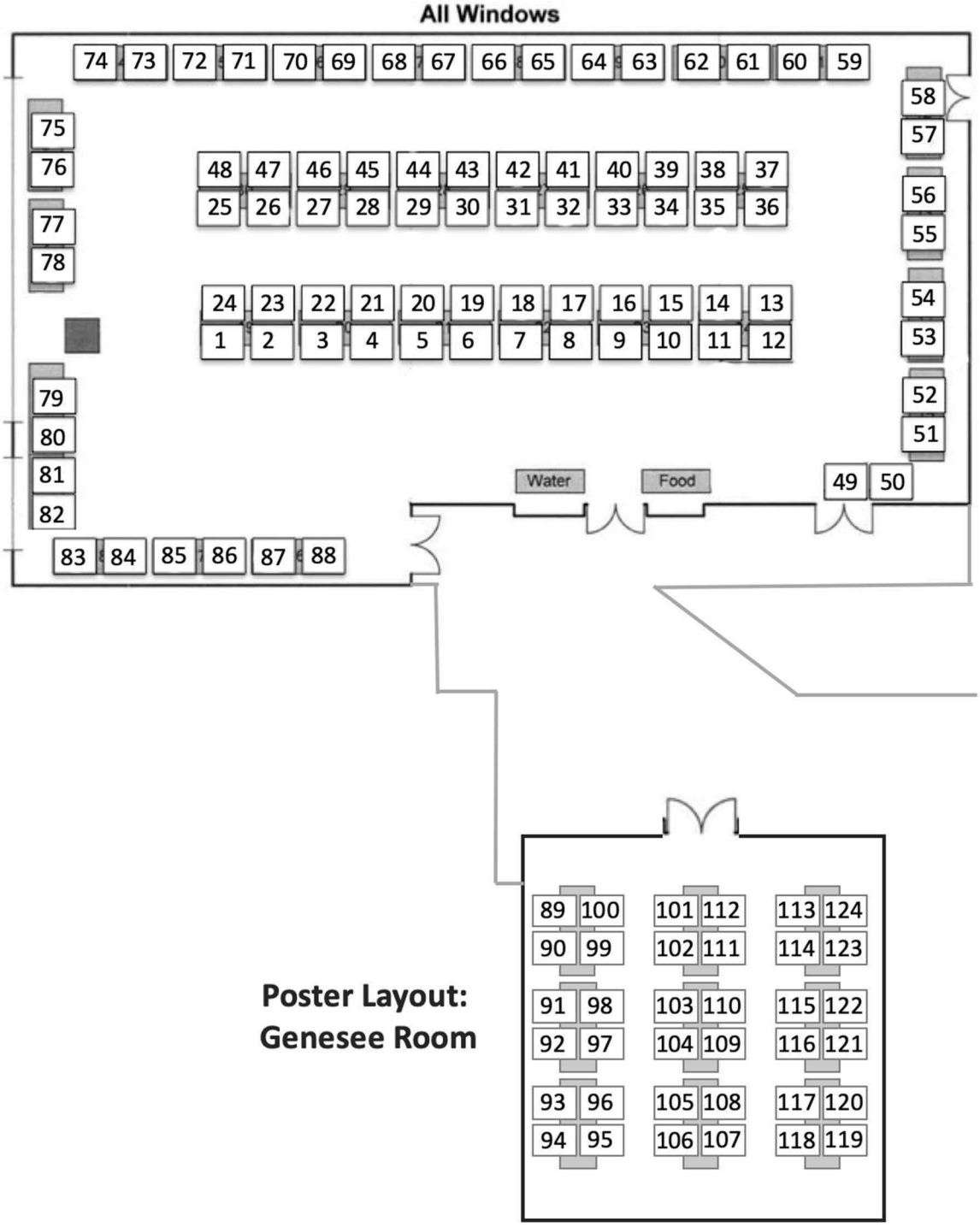
108. *C. Wolfrom, S. MacAlpine,*
"Empirical method for determining heat transfer coefficients"

110. *A. Livera, M. Theristis, E. Koumpli, G. Makrides, J. Sutterlueti, J.S. Stein, G.E. Georghiou,*
"Guidelines for ensuring data quality for photovoltaic system performance assessment and monitoring"

112. *D. Zirzow, J. Crimmins, J. Richards, C. Sillerud,*
"Bankability testing for new generations of PV modules"

POSTER LAYOUT – CITY LIGHTS BALLROOM

Poster Layout: City Lights Ballroom



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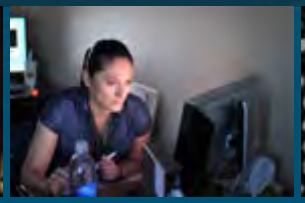
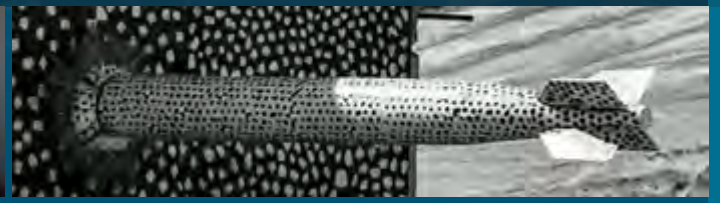
February 2020

Multi-site assessment of extreme weather impacts on PV plant performance and reliability





PRESENTED BY

Nicole D. Jackson

PV Reliability Workshop

February 26, 2020

SAND2020-2351 C

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- Gerry Robinson (LBNL)
- Ammar Qusaibaty (DOE)
- Chris Downs (Cypress Creek Renewables)
- Laura Kraus Lovenshimer (Strata Solar)
- May Cai (Trimark Associates)
- sPower
- Nexamp

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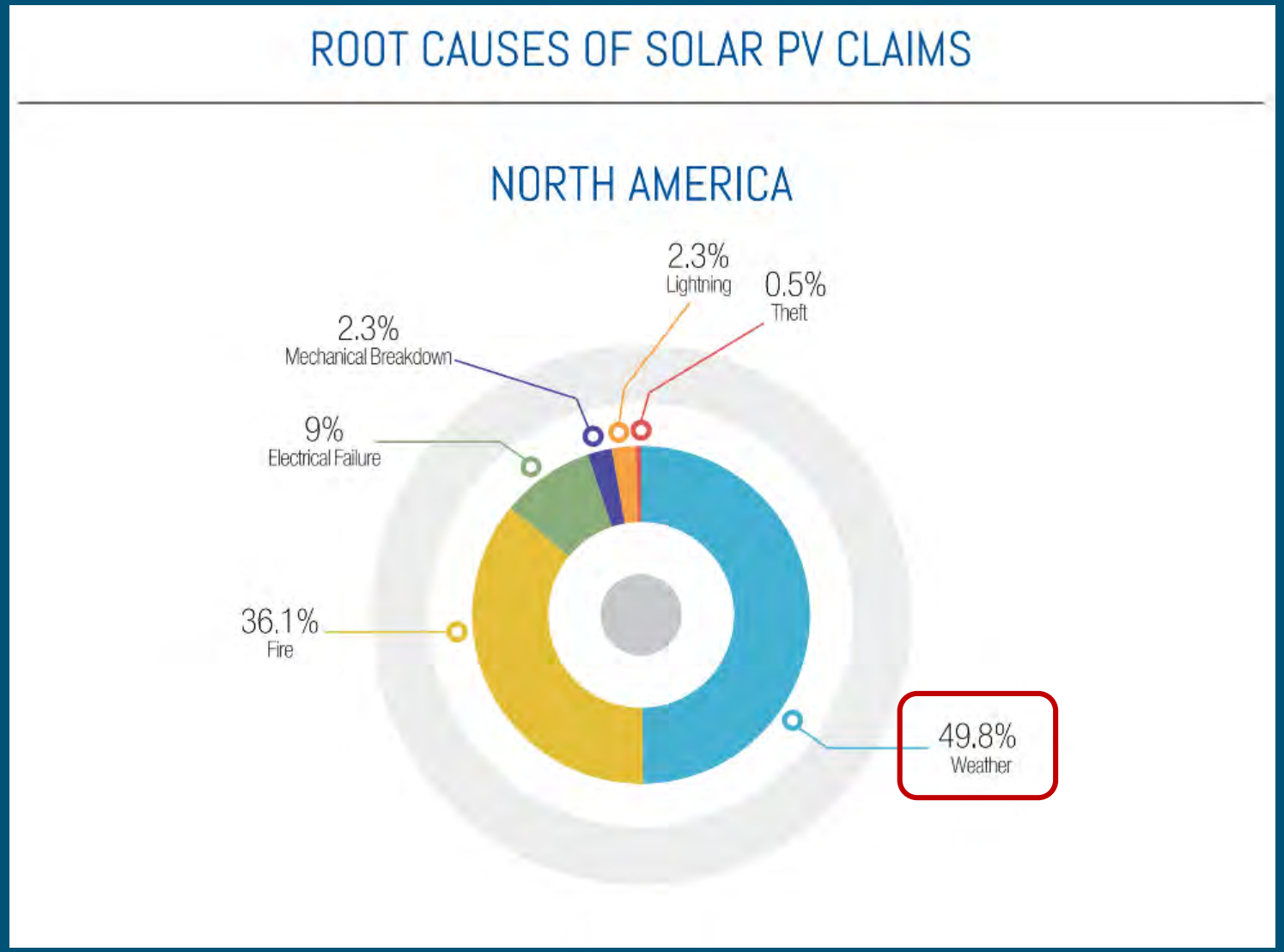
PV plants can be exposed to disruptions due to weather events such as hurricanes and hail storms

(BMR Energy 2017)

SBS News (2018)

There is an increasing prevalence of weather impacts to PV



(GCube 2016)

Study Objectives

- Analysis of site-level performance and weather data to identify trends
- Identification of performance variabilities across sites, climates, and event types

Multiple tropical storms affected the Carolinas in Fall 2018

- Hurricane Florence

NOAA (2018)

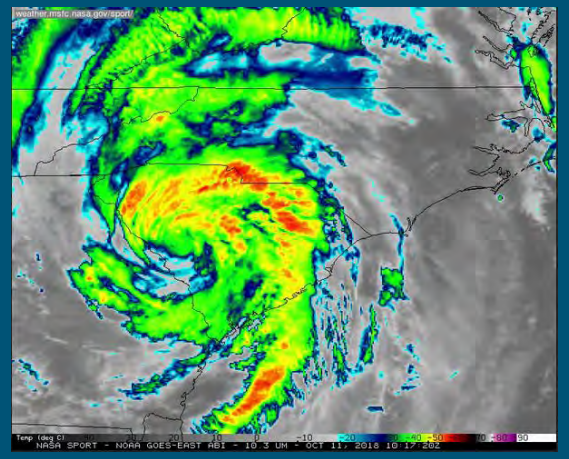
09/01
Named tropical storm

09/05
Becomes a hurricane

09/14
Makes landfall in NC

09/18
Hurricane downgraded

- Hurricane Michael



NASA (2018)

10/07
Named tropical depression

10/08
Becomes a hurricane

10/11
Reaches the Carolinas

10/12
Hurricane downgraded

Multiple datasets are combined to link performance, weather and O&M records

Industry Data

Site Characteristics

- DC Size
- Climate zone
- Latitude
- Longitude
- Asset clipping limit

Measured data

- Date
- Irradiance
- Energy delivered
- Output power
- Expected energy

O&M Logs

- Failure details
- Event duration

Site Metrics

Yield Loss

- Final system yield
- Reference yield

Performance metrics

- Performance ratio
- Energy performance index

Climate Data

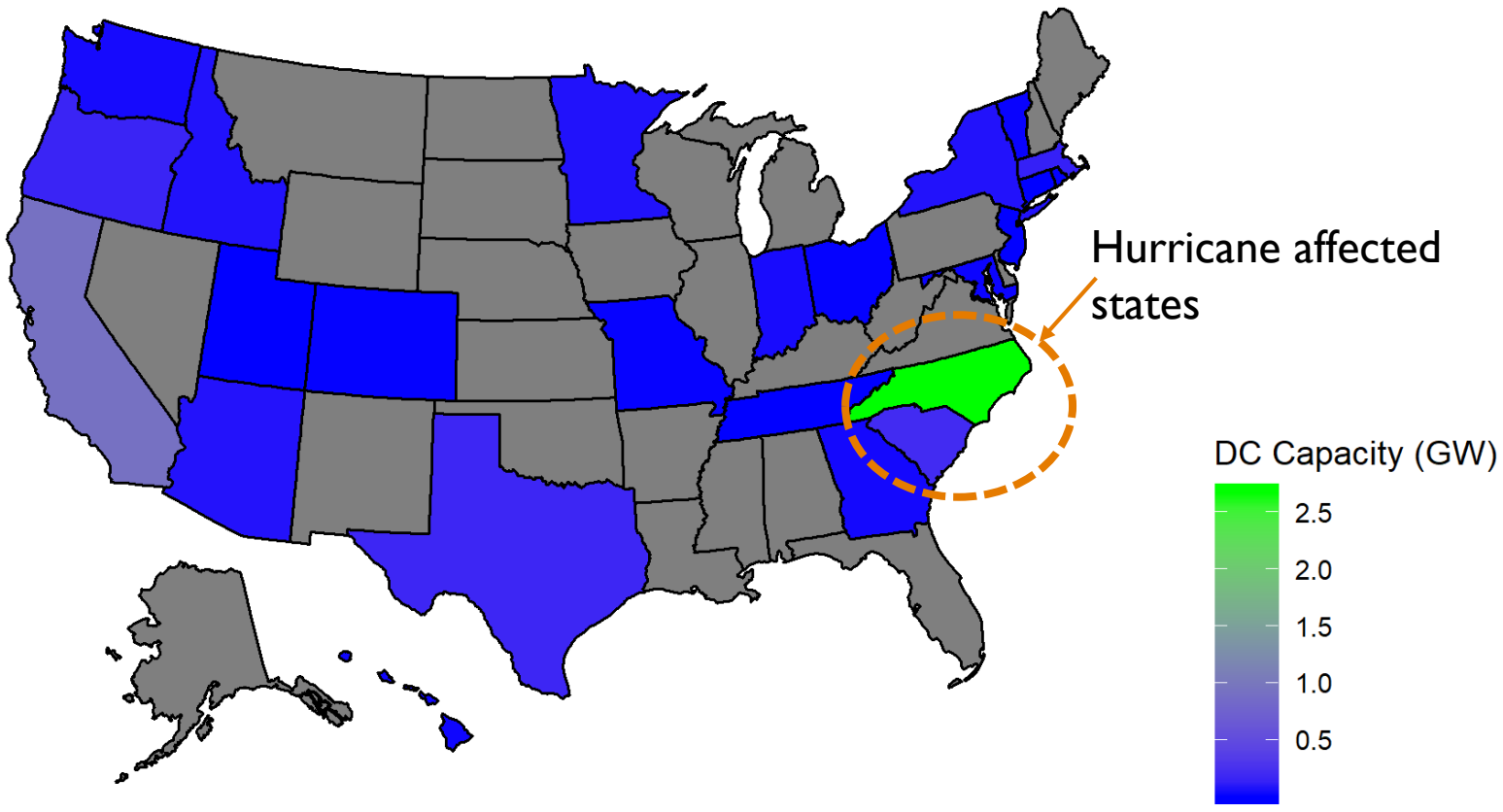
GHCN Weather Stations

- Precipitation
- Snow

PRISM

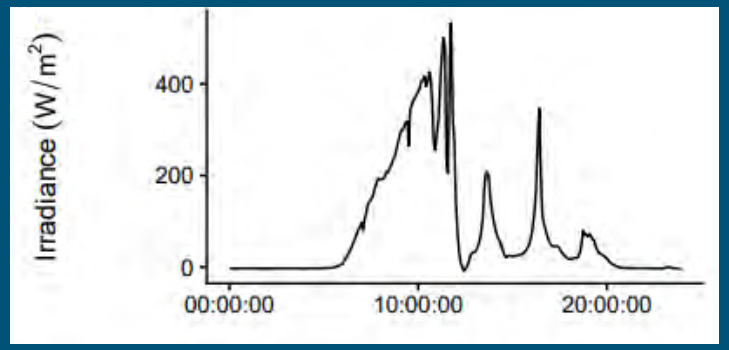
- Maximum temperature
- Minimum temperature

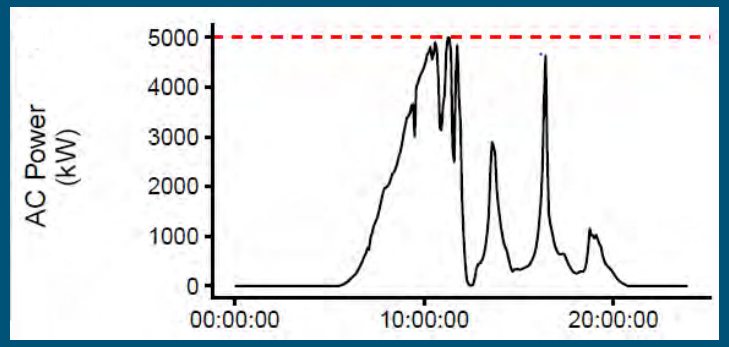
Performance data in the Carolinas can be paired with PVROM data for the period 2018-2019

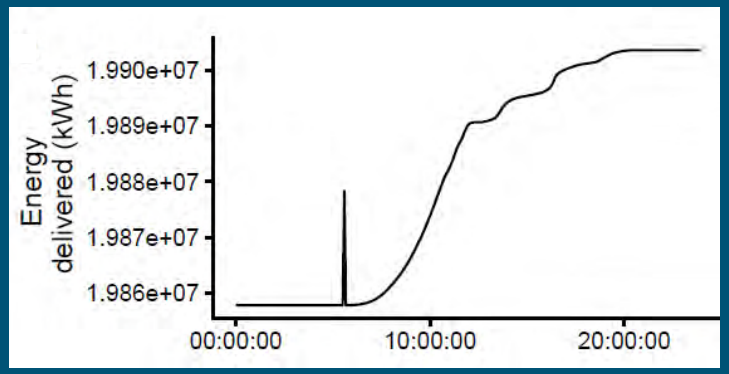


Data processing of site-level raw data

Raw Data





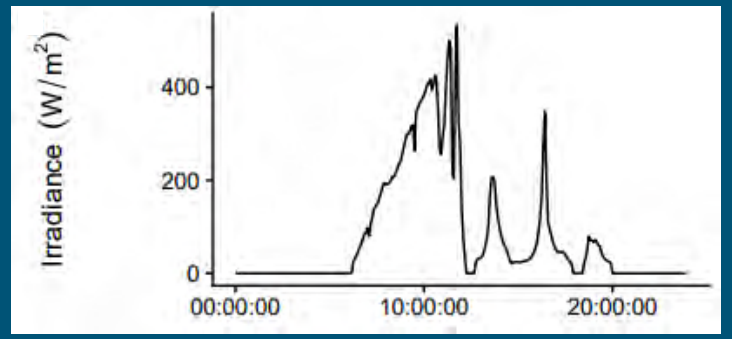


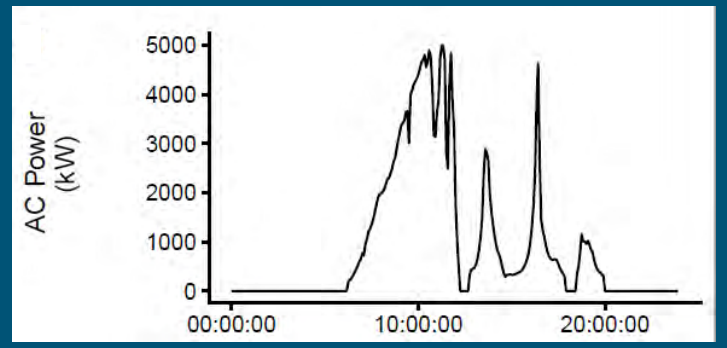
Removed negative values

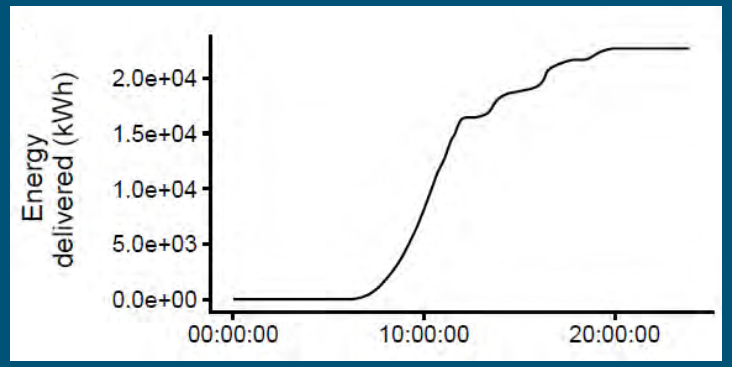
Entries with negative irradiance have AC power = 0

Removed errant spikes in cumulative energy delivered to grid

Clean Data







Multiple site metrics are evaluated at the daily time scale

Yield losses

- Final system yield

$$Y_f = \frac{E_{out}}{P_0}$$

- Reference yield

$$Y_r = \frac{H_i}{G_{i,ref}}$$

Performance metrics

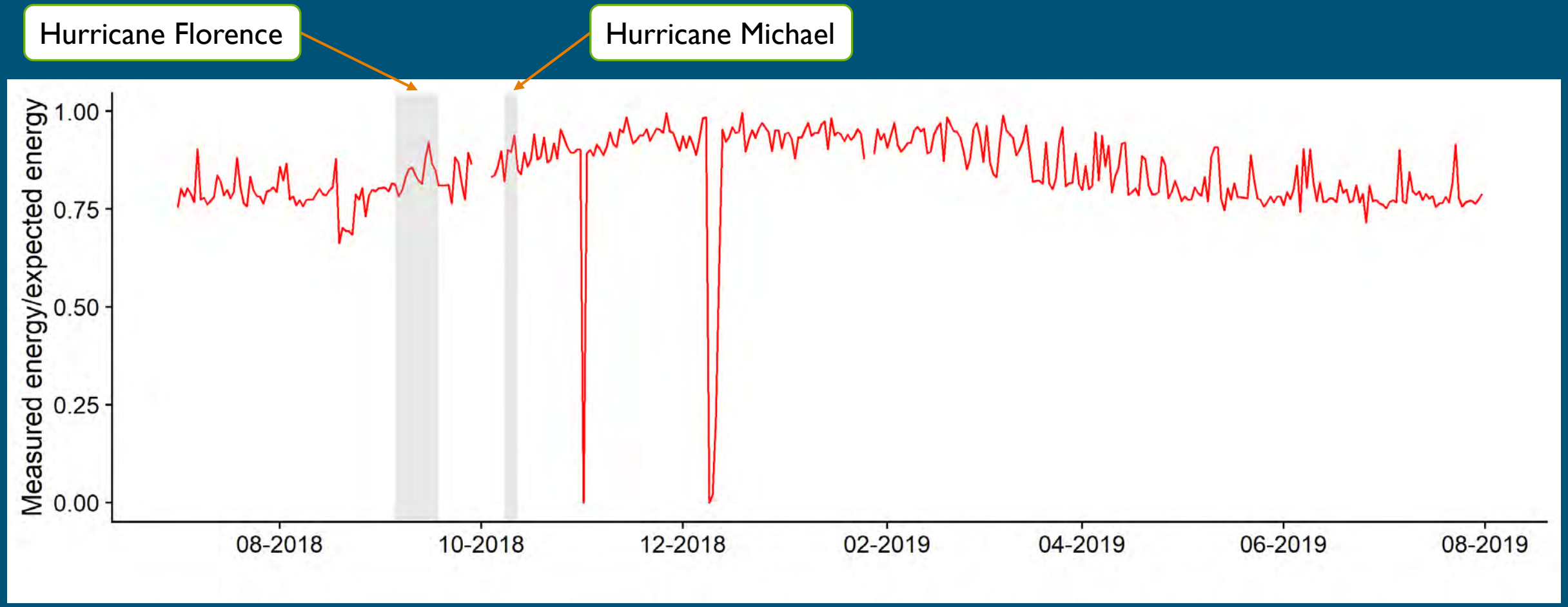
- Performance ratio

$$PR = \frac{Y_f}{Y_r}$$

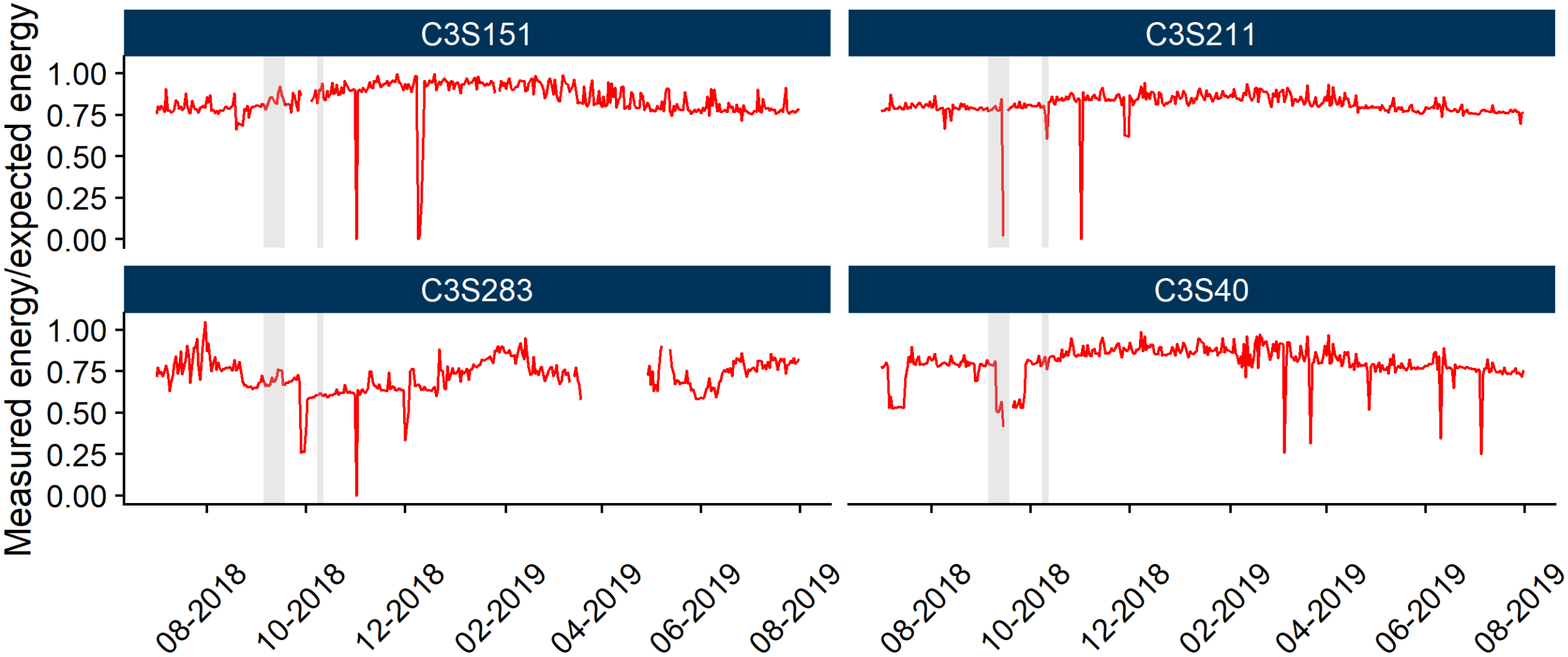
- Energy performance index

$$EPI = \frac{\text{Measured energy}}{\text{Expected energy}}$$

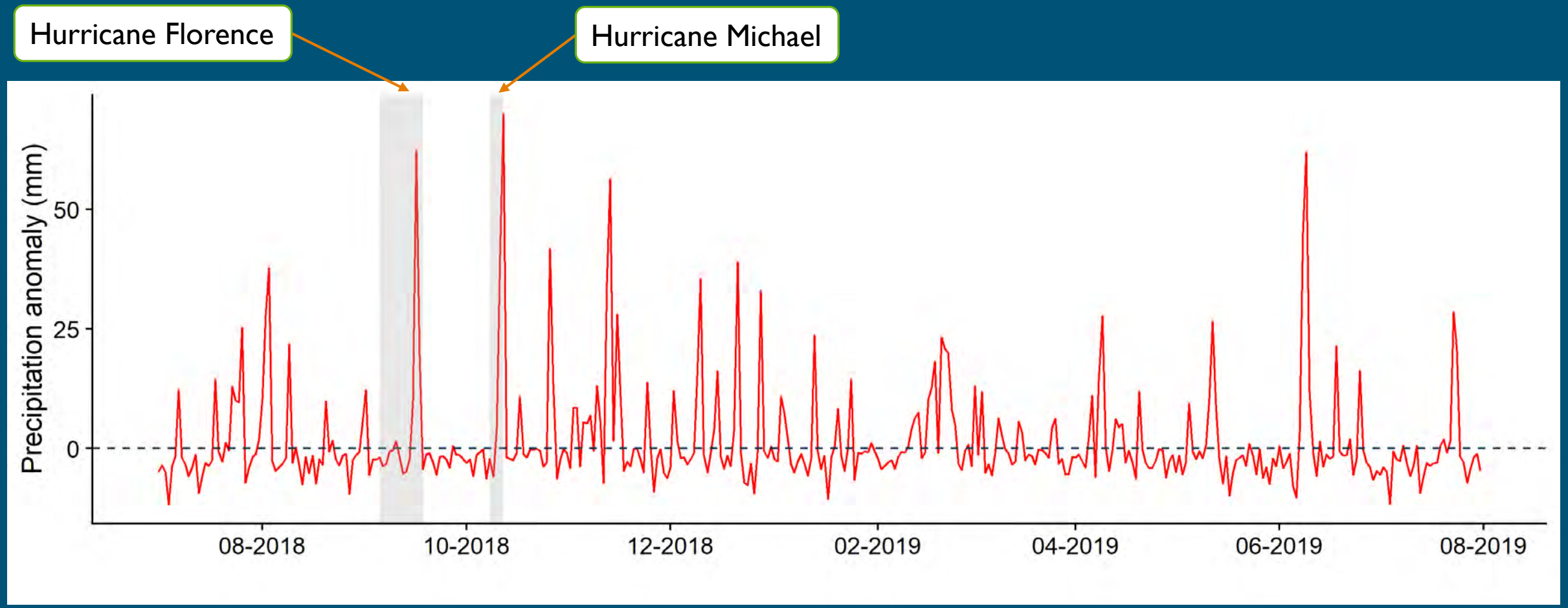
Sample daily performance for a North Carolina site with the hurricanes indicated



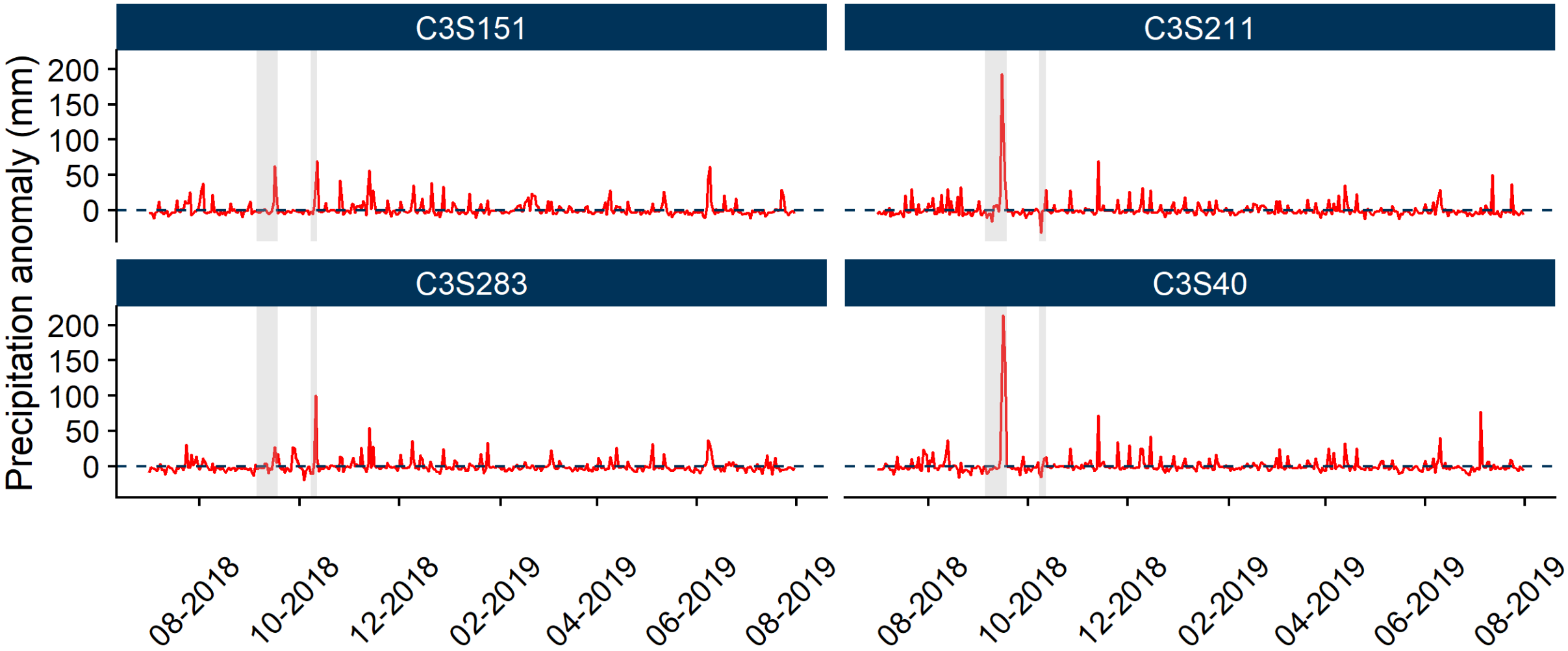
Site-level differences in performance response to hurricanes



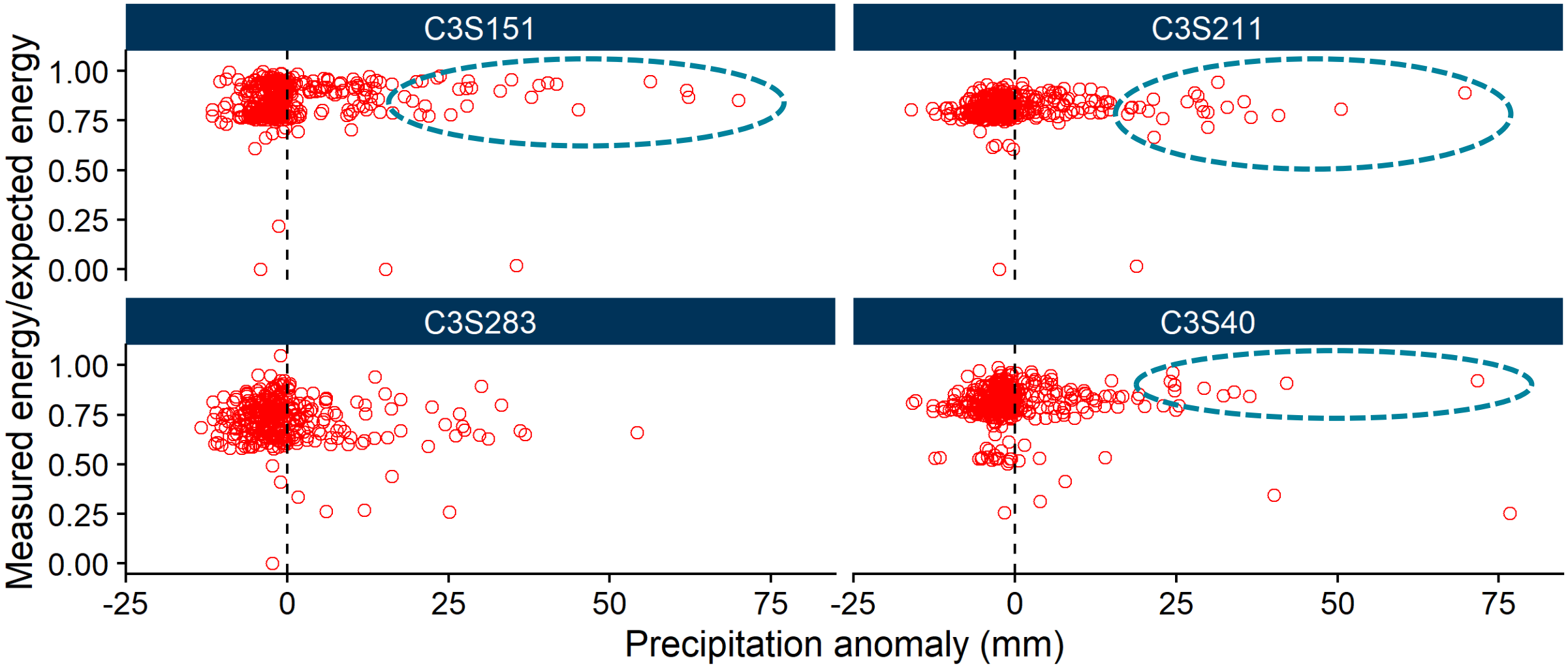
Precipitation anomalies developed by comparing daily precipitation data to its 30-year historical mean



Site-level differences in exposure to precipitation anomalies during hurricane events

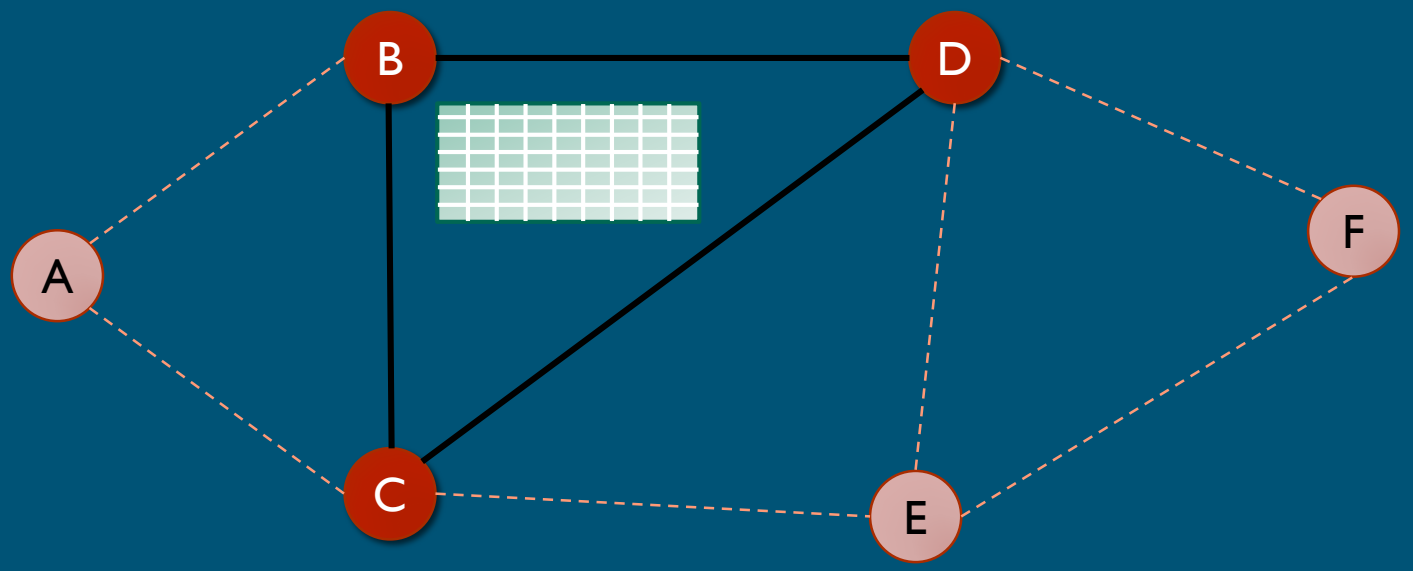


Multi-site comparison of precipitation anomalies with daily site performance suggest presence of other confounding factors



Ongoing work

- Continue analysis of performance data for remainder of sites
- Integrate remaining O&M records with weather and performance data
- Refine processing of site-specific climate data



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NASA (2018). Tropical Storm Michael moves into North Carolina [Digital image]. Retrieved from https://www.flickr.com/photos/gsfc/43438210310

GCube (2016). Root causes of solar PV claims in North America between 2011 and 2015 [Digital image]. Retrieved from https://www.solarpowerworldonline.com/2018/01/solar-industry-responding-increasing-intensity-natural-disasters/

Thank you for your time!

Nicole D. Jackson

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Storms and Other Events: Experiences with Cell Cracks

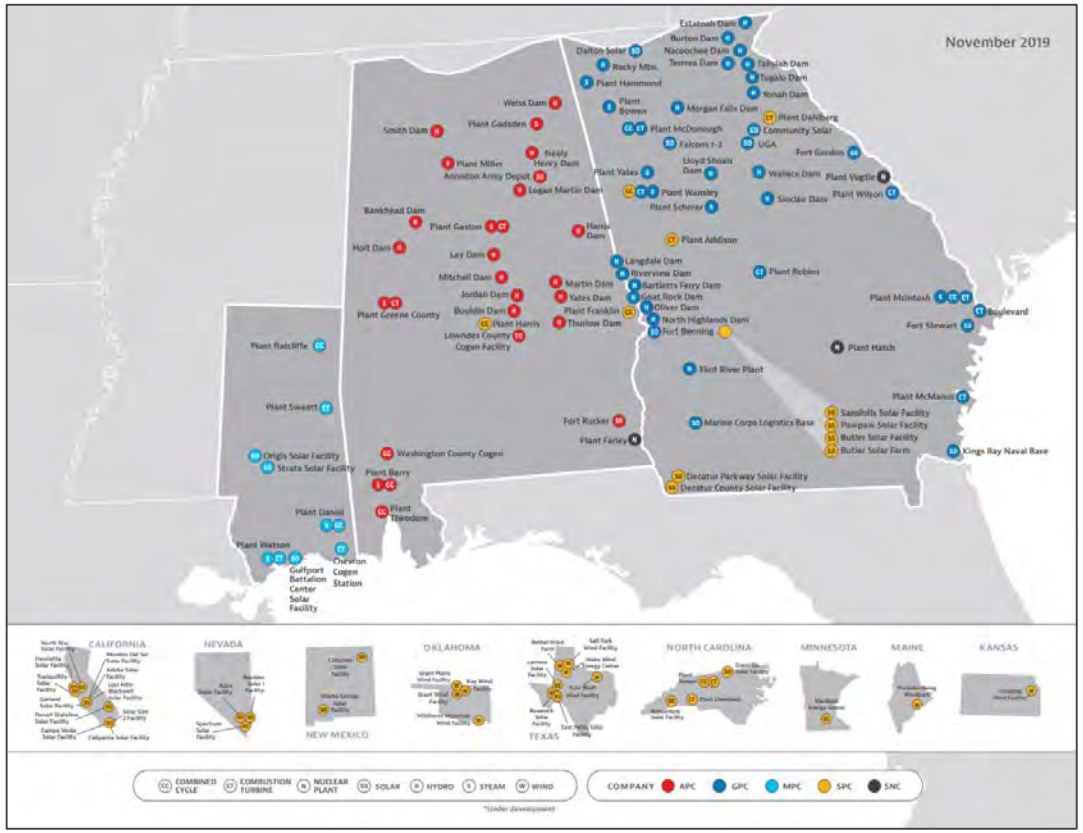
Will Hobbs, PE
Southern Company R&D
Feb. 26, 2020

Southern Company

Southern Company's Solar Portfolio

- Southern Company's regulated and wholesale utilities own:
  - 36 solar facilities
  - Over 1,800 MW of solar capacity

This presentation covers extreme examples from a small fraction of our retail and wholesale fleet.



Cell Cracks – Do they matter?

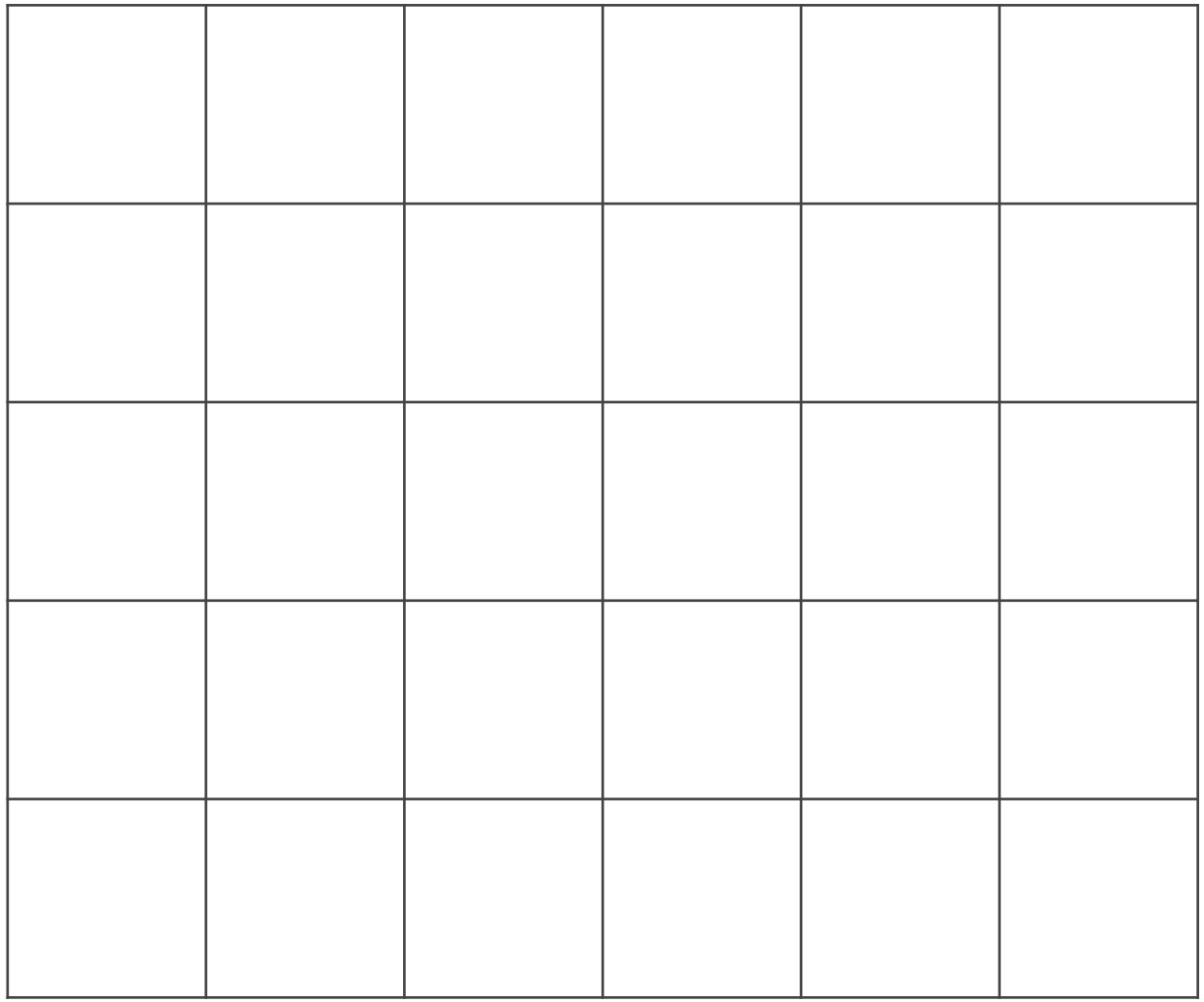
Storm #1 (Tornado)

Southern Company

Severe weather

Solar Plant

(YIKES!)



Storm Damage Assessment

Most of the plant looked like this:

Some of it looked like this:

But one corner looked like this:

Where do you draw the line on the map for replacement?

Original (Visual) Inspection

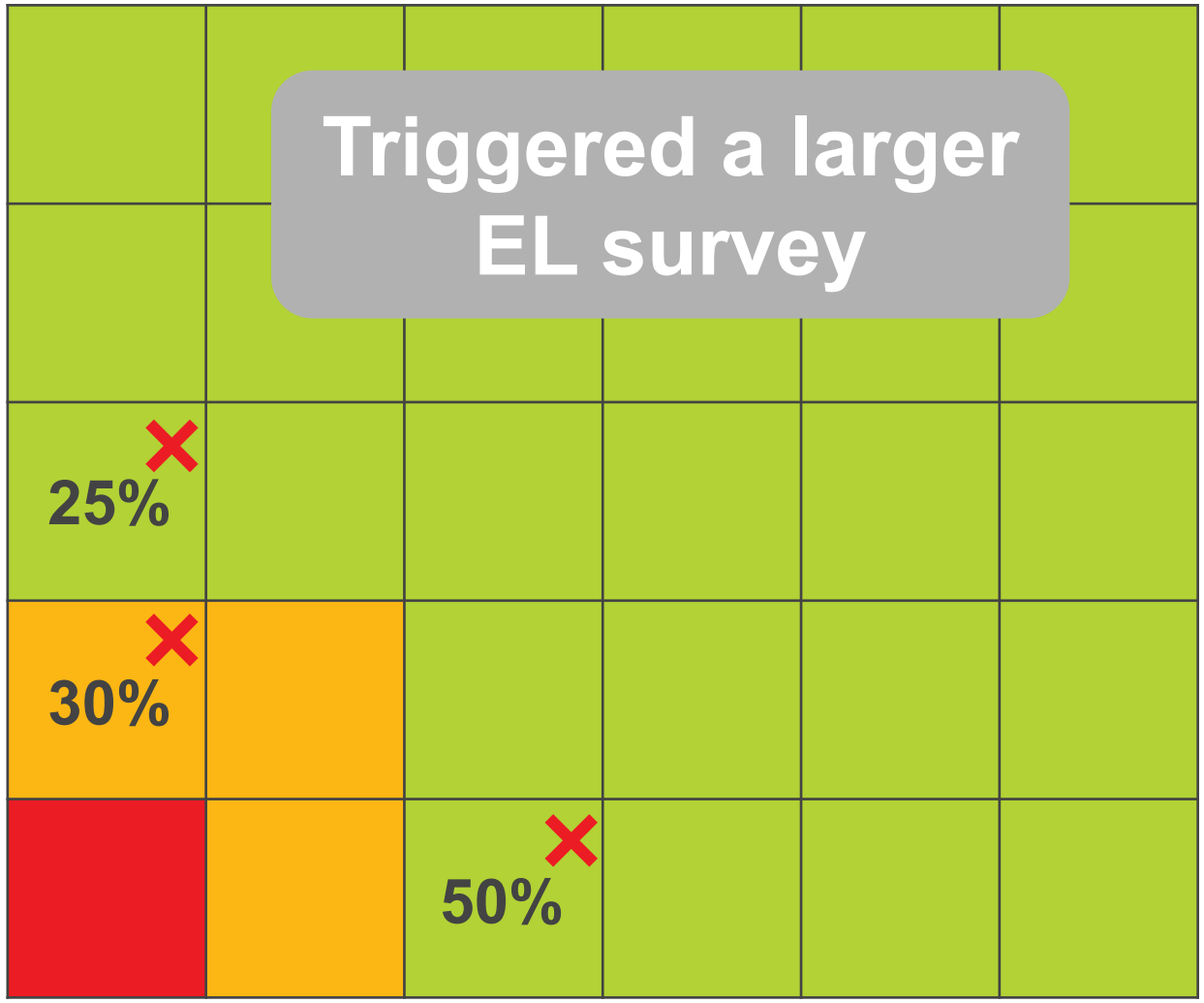
EL Spot-Check Results

Failure Rates:

Good → Unknown

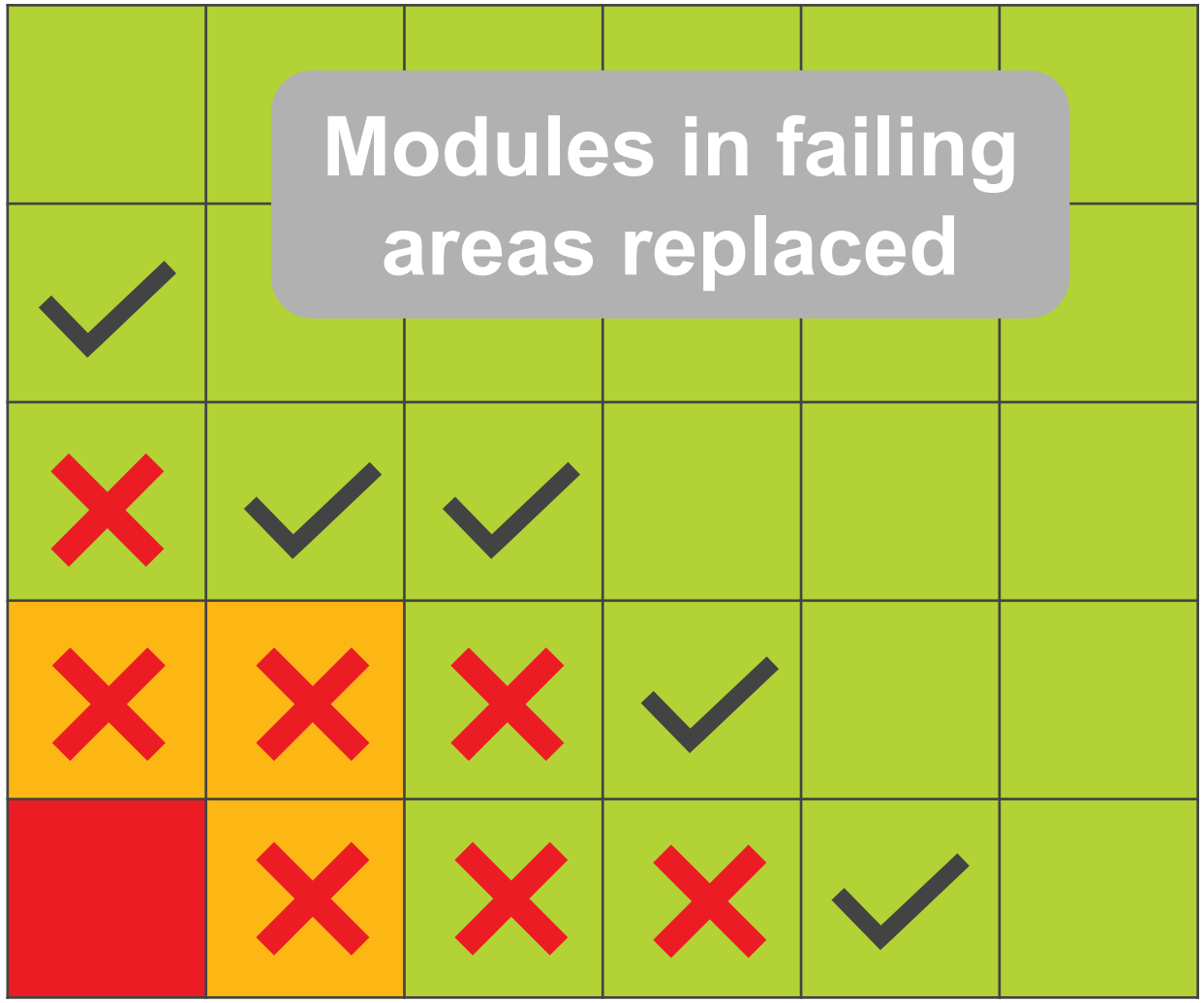
Unknown → Replace

Replace →



Larger (multi-week) EL survey

Detailed EL tests until failure rate dropped



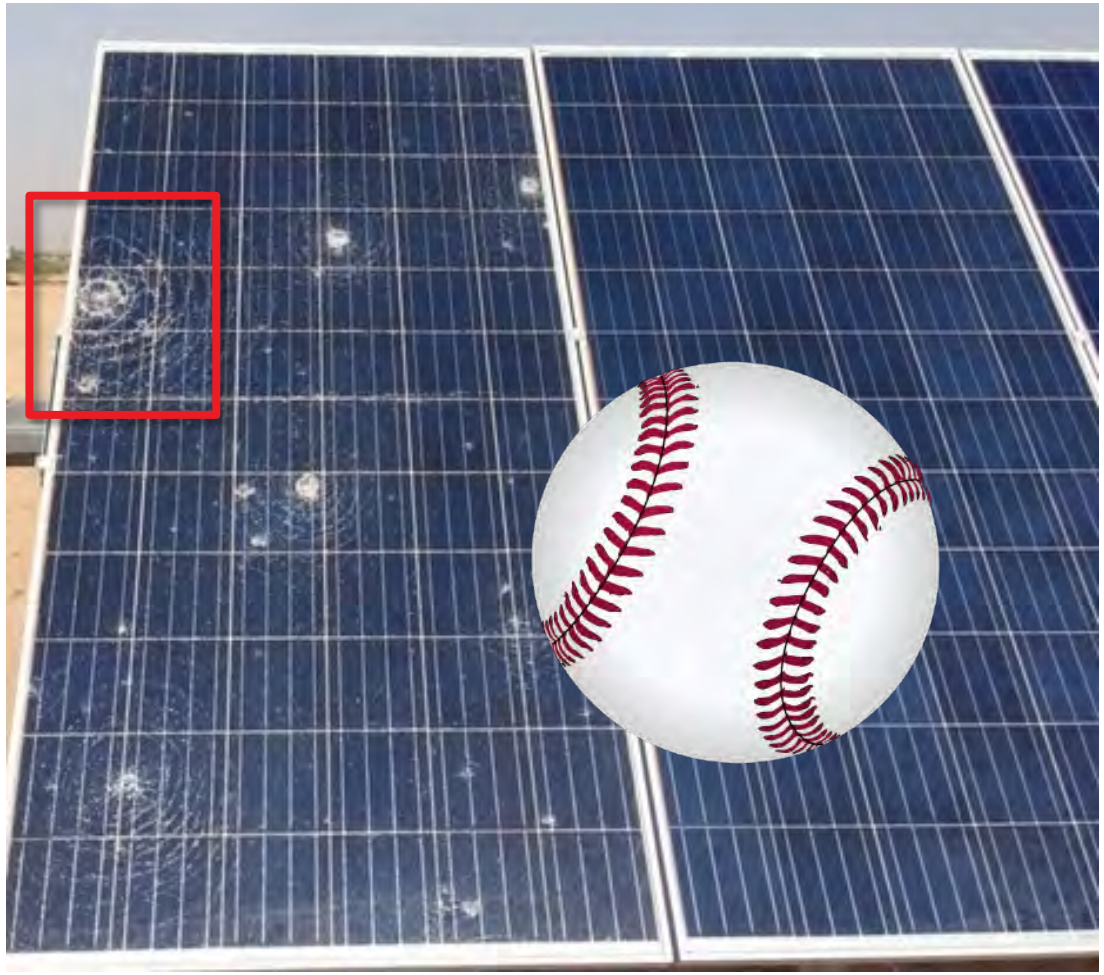
Storm #2 (Hail)

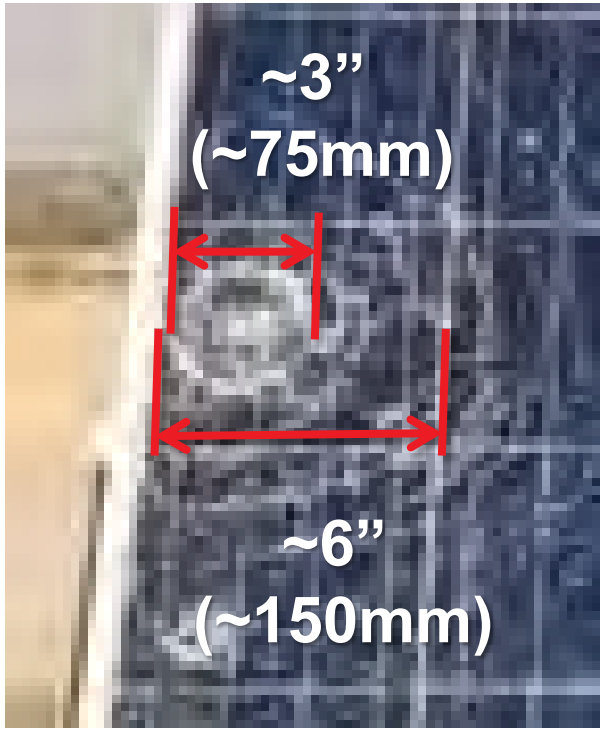
Southern Company

Substantial Hail Damage

- Approx. 3” (75mm) hail stones
- (Baseball-sized)
- Testing included:
  - Visual Inspection
  - Aerial IR
  - EL Testing

(All analysis for subset of plant with the most damage)



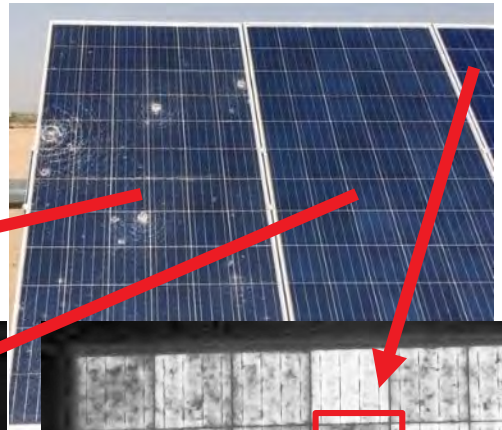


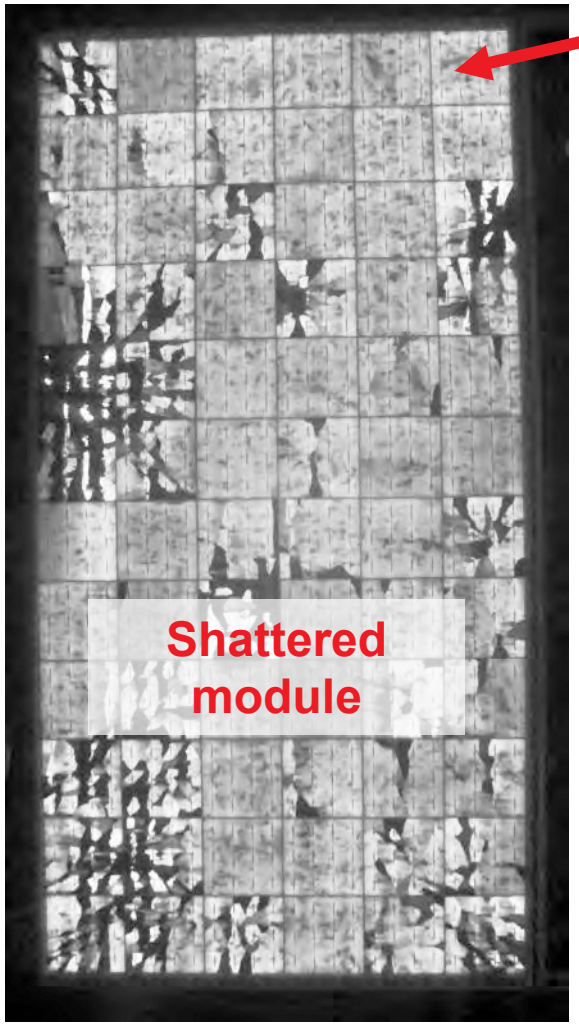
Visual Inspection

- Approx. 5% of modules shattered (1000s of modules)

EL Testing

- 400 Modules Tested



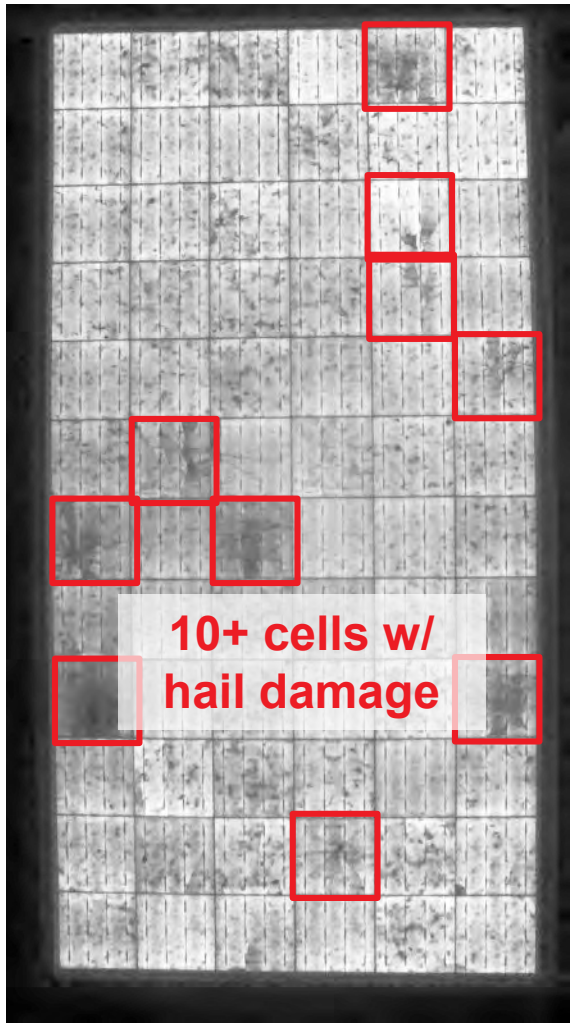


1st Module

2nd Module

3rd Module

…



A few inverters over

EL Results

- Extrapolated on per-inverter basis from visual inspection

- Estimated modules with one or more hail-damaged cells:

50%

Aerial IR Testing

- Fraction of modules with hot spots but no shattered glass:

0.3%

Considerations:

- Scan was performed 6 months after damage – more time may be needed for hot spots to form
- Hot spots may be transient – more testing planned

Remediation

- Shattered modules replaced
- Ongoing monitoring and repeated testing planned
- Many modules were “shuffled” during replacement process, complicating module-level inspections over time

Storm #3 (High Wind)

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Mono-Si Tracker Plant

- 85+ mph winds
- Only one tracker table damaged/destroyed
- Testing included:
  - Aerial IR
  - EL testing
  - UVF testing

Aerial IR

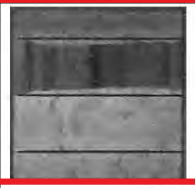
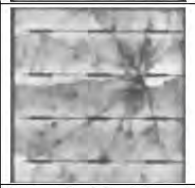
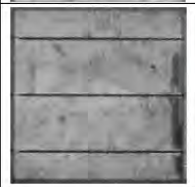
- Conclusion:
  Nothing Concerning

EL Testing

- Sampling:
  - ~120 Modules from 3 areas:
    - 2 area near damaged tracker table
    - 1 area near upwind corner of plant

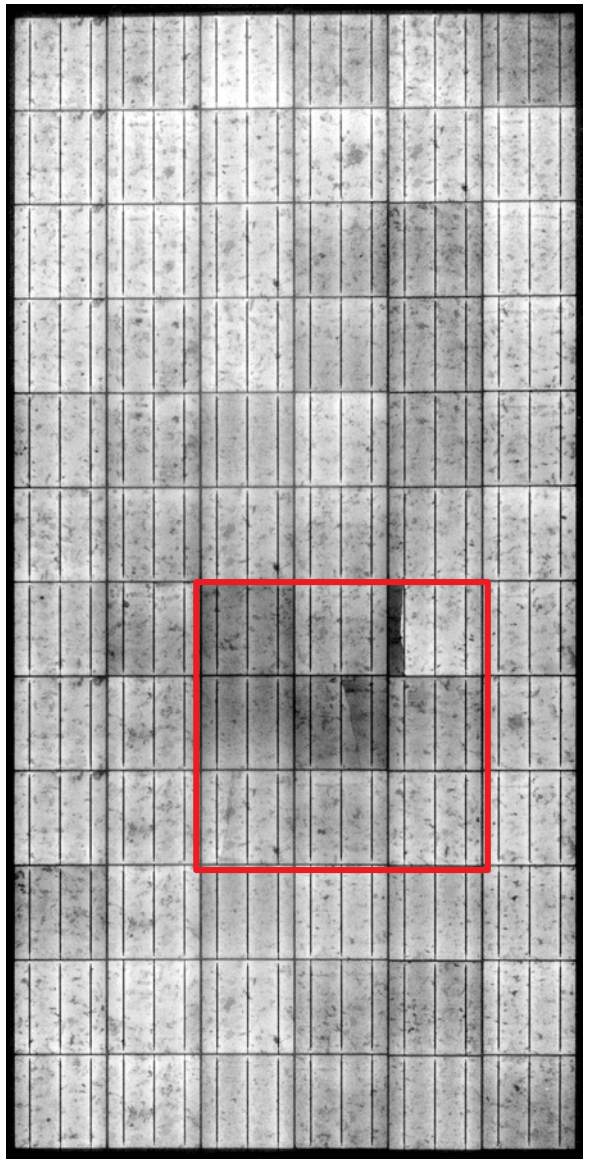
- Acceptable Criteria:
  - In-house (admittedly “relaxed”)

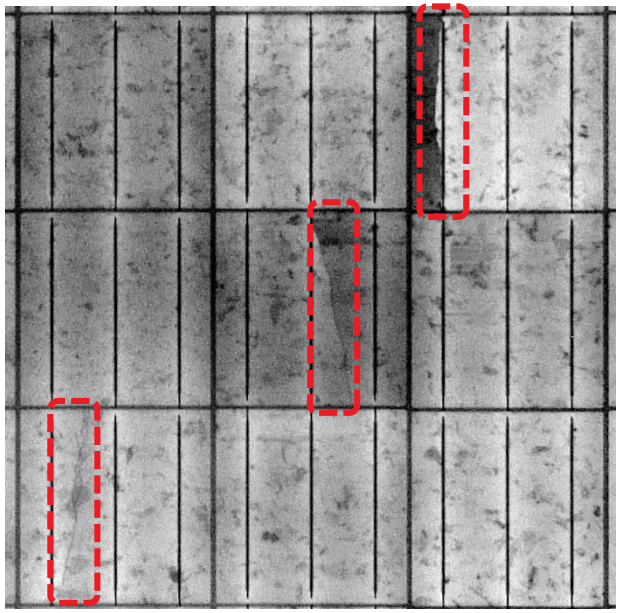
Defect Type	Acceptance Criteria (# cells per 72 cell module)	
A. Single Crack	A ≤ 20	Sum of A,…,F ≤ 20
B. Multiple Cracks	B ≤ 5	
C. Broken/Potentially Broken Cell	C ≤ 2	
D. Busbar Defect	G ≤ 1	
E. Dendritic/Spiderweb Crack	D = 0	
F. Backsheet Scratch	E = 0	
G. Dark Cell	F = 0	

Fault Type	Sample Image	Description	Acceptance Criteria (# Cells per 72-Cell Module)	
A. Single Crack		Cell with a single crack. May be identified by slight darkening to either side of crack.	A ≤ 20	Sum of A,…,F ≤ 20
B. Multiple Cracks		Cell with more than one crack.	B ≤ 5	
C. Broken/ Potentially Broken Cell		Cell with notable darkened area between cracks or a crack and the cell edge, or potential for darkening due to area surrounded by crack(s).	C ≤ 2	
D. Busbar Defect		Darkening around one or more busbars on a cell. Typically a broken busbar/tabbing wire or a soldering defect.	D ≤ 1	
E. Dendritic/ Spiderweb Cracks		Multiple cracks (more than 2) that branch out in a dentritic or spiderweb pattern. Typically caused by localized impact or pressure.	E = 0	
F. Scratch		Dark line across one or more cells, typically wider than darkening from a crack. Usually due to a scratch on the backsheet.	F = 0	
G. Dark Cell		Cell that is significantly darker than surrounding cells. Can be caused by cell mismatch or shorted cell, or PID.	G = 0	

EL Testing Results

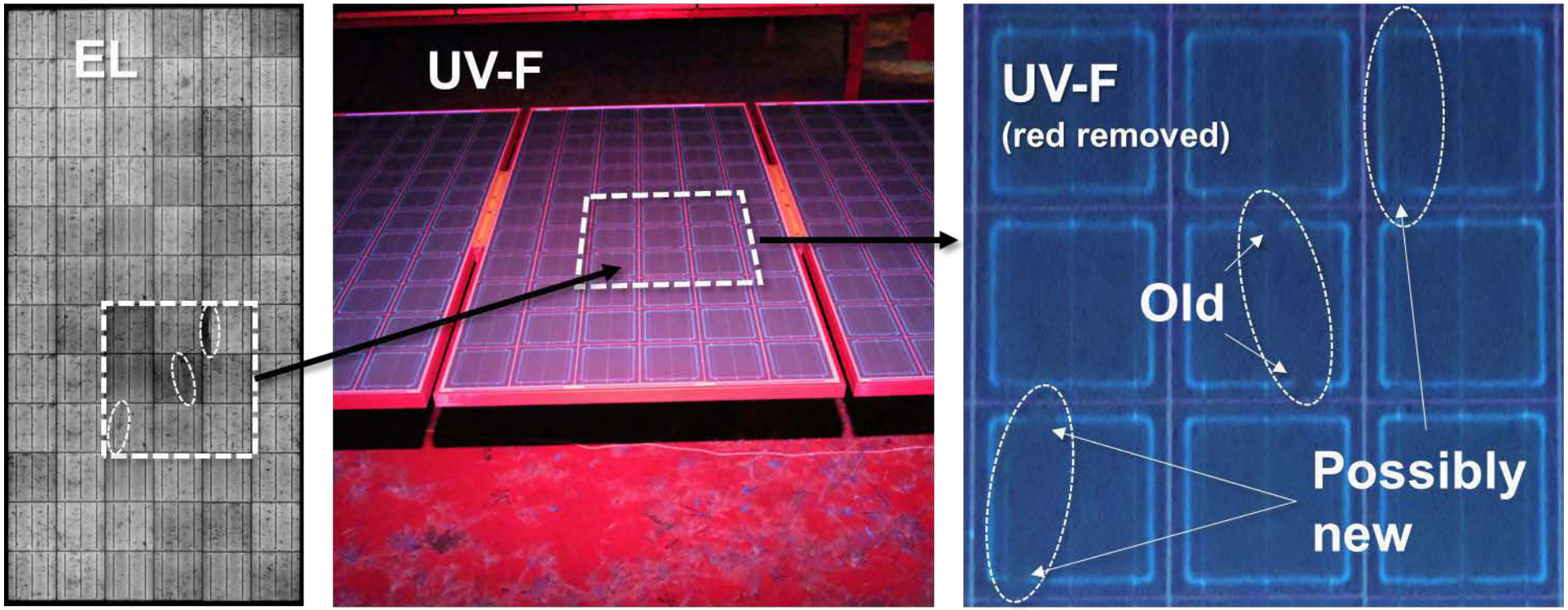
- Less than 3% failure rate
  - (3 modules, each failed by 1 fault)
- Not concerning
  - Especially w/ no pre-storm baseline





UVF Testing

- Same ~120 modules as EL
- Closely compared UVF and EL on ~50 modules with the most EL cracks
- UVF “bleaching” takes days/weeks (testing here was ~3 weeks after storm)

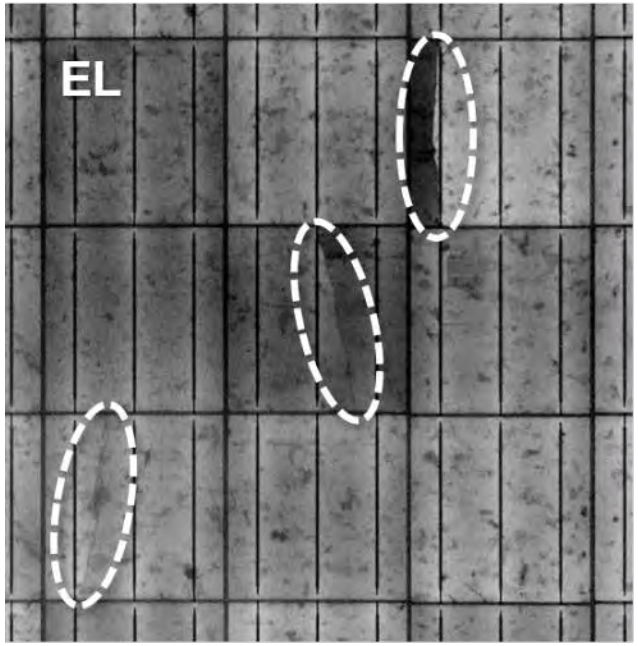


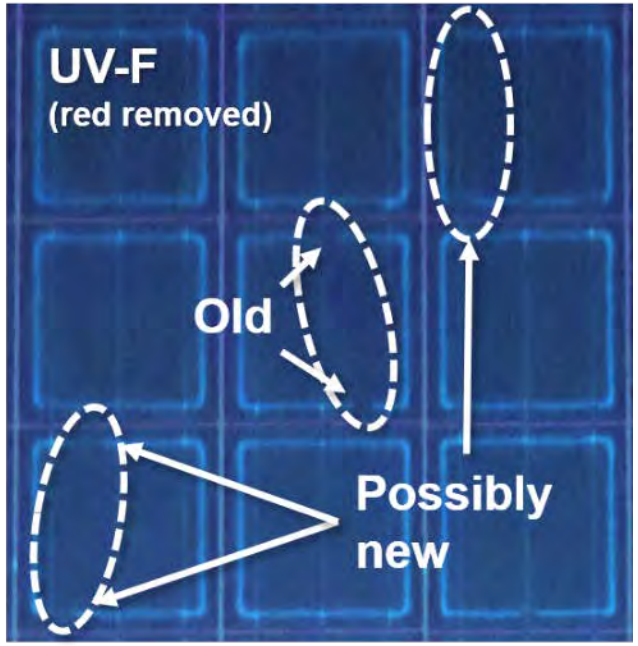
M. Köntges, et al. “Applications and Interpretation of UV Fluorescence Imaging for PV Plants”. Intersolar Europe Conference, Munich, Germany, 14th May 2019.
B. Gilleland, at al. “High Throughput Detection of Cracks and other Faults in Solar PV Modules using a High-Power Ultraviolet Fluorescence Imaging System”, IEEE PVSC 2019.

UVF Results – Crack Age

Crack Age Differentiation

- Distinguish possible new and old cracks
  - Fading and broadness
- 73% of cracks possibly new
- Identified ~2x as many cracks as EL





Tracker Tube Collars

- Appear to have allowed tubes to twist during storm
- 2-3X more EL defects in modules that span collars

Removal Damage

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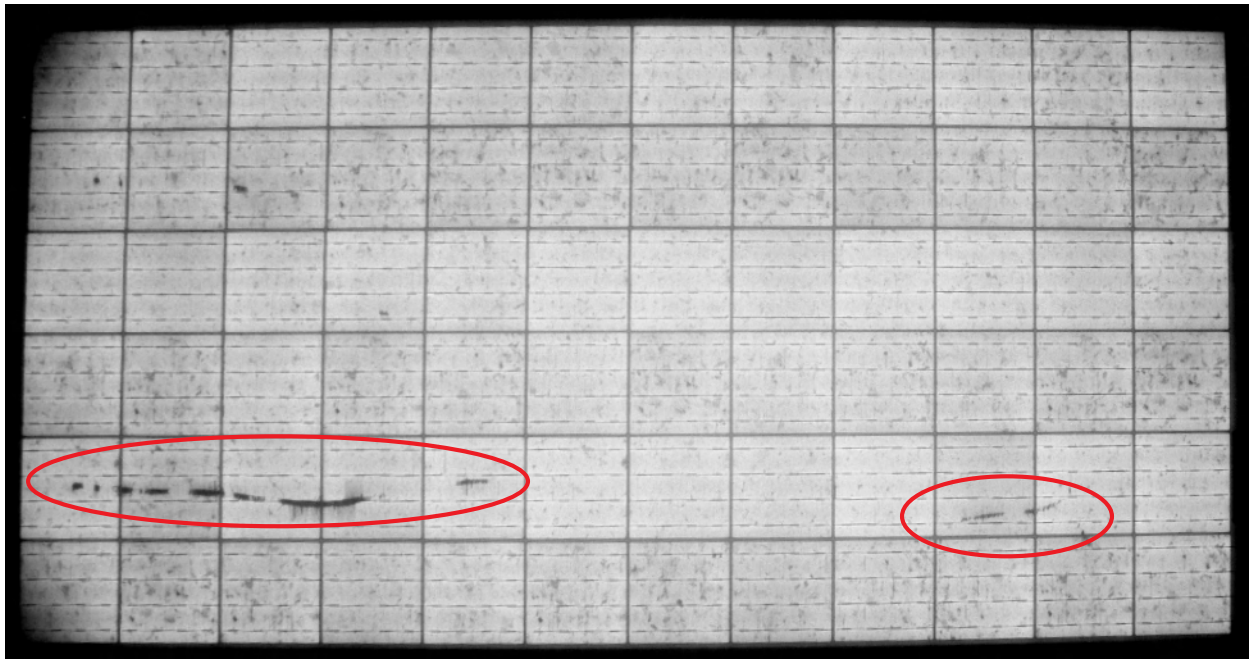
Removing Good Modules

- Removal and reinstallation of good modules
  - Common strategy to “re-sort” for repowering, hail damage recovery, etc.
- Site with 100s to 1000s of modules removed by EPC
- Randomly sampled ~25 modules
- Approx. 2/3 of modules had backsheet scratches w/ crushed cells

Cause (just a theory): Lack of well-designed workflow, packing materials



Other Considerations

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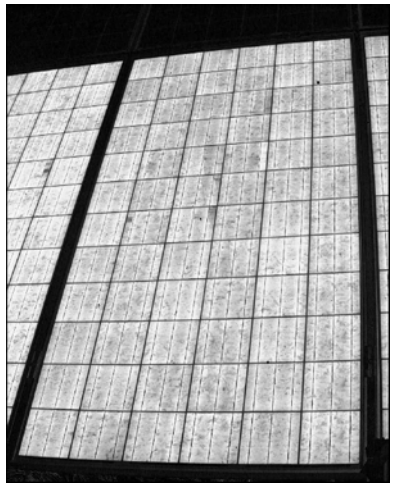
EL Challenges

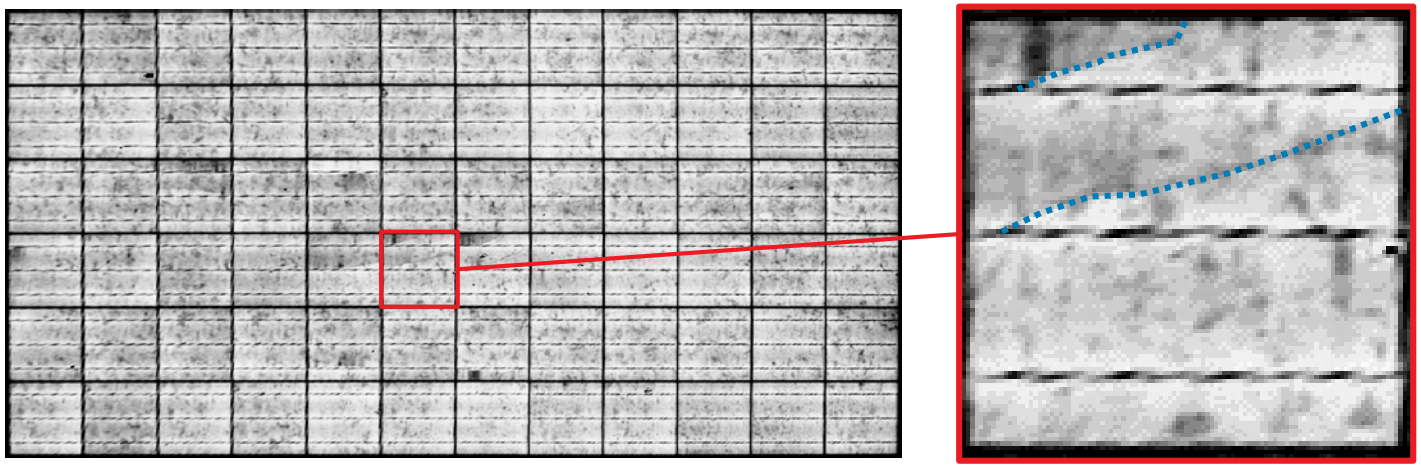
- Not all imaging techniques are equal

How many cracks?

Camera 1 (fast, low res)



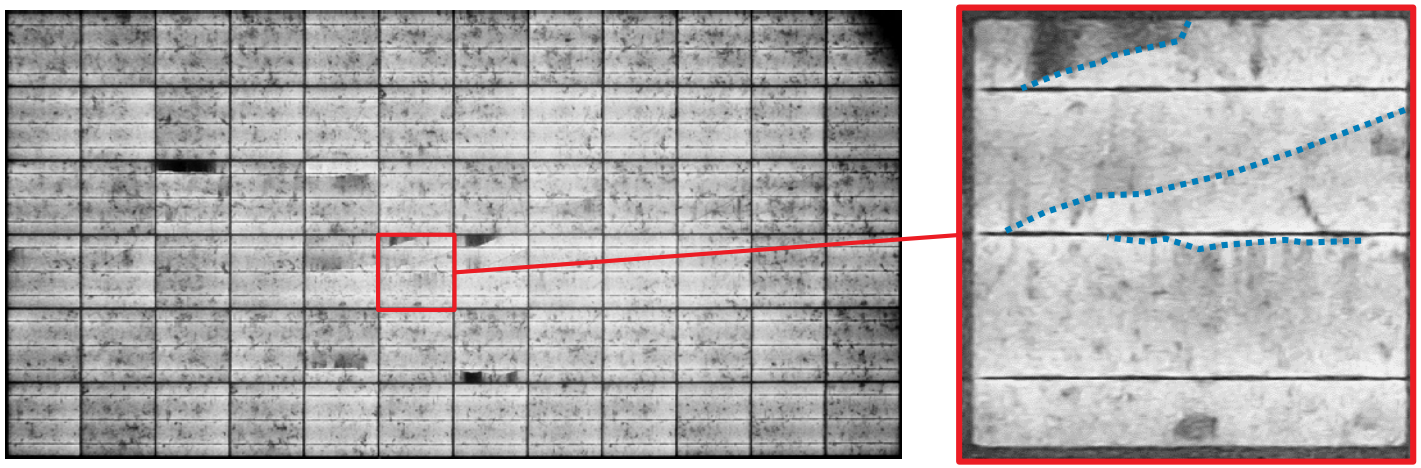
Processing



2?

Camera 2 (slow, high res)

Processing



3

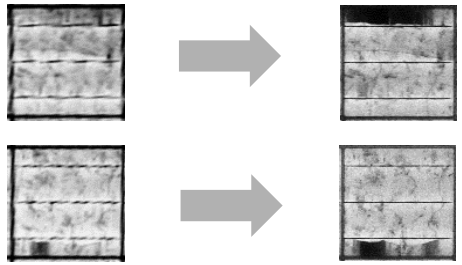
EL Challenges

- Not all review methods are fool-proof

Criteria:

[Detailed Criteria Document]

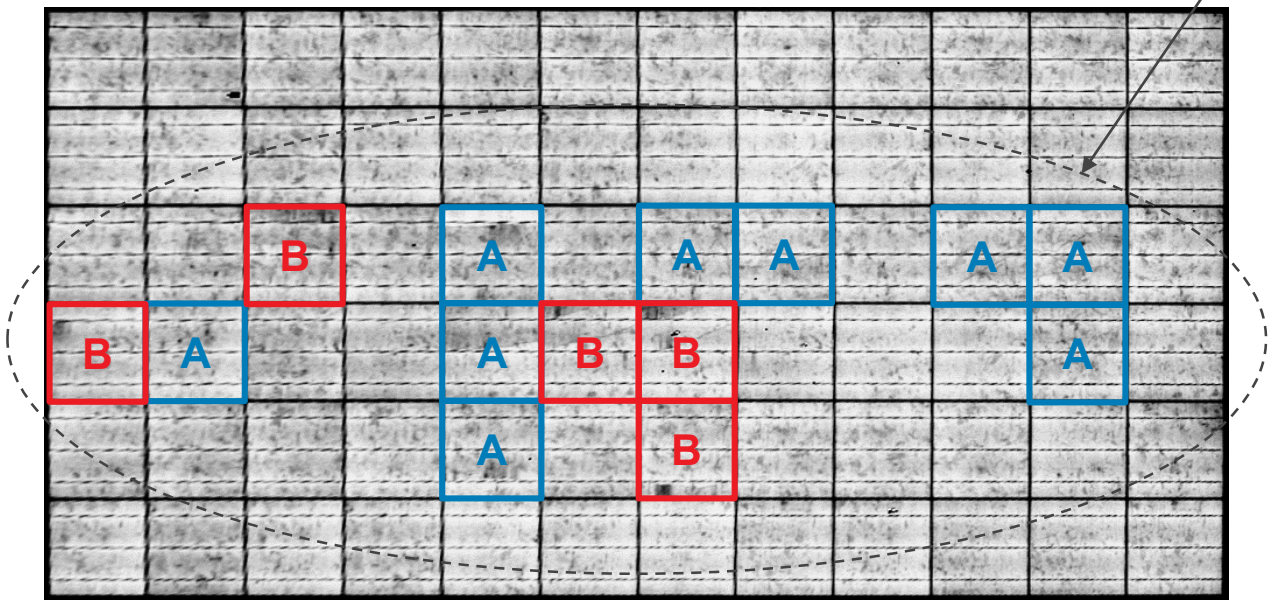
Cam 1 Cam 2



Be careful about "dark area" in criteria!

Camera 1 image (edited):

Team 2 review results



Team 1 judgement: ✓ **Pass**

(no additional detail)

Team 2 judgement: ✗ **Fail**

Additional detail is key for auditing

Questions?

whobbs@southenco.com

Southern Company

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Bankable Independent Engineering Review for Extreme Weather Conditions:

Structural Loads, Hydrological and Geotechnical Hazards

Presenter: Dan Berger, Senior Civil Engineer

Thanks to: Hamid Gerami, Structural Engineer and Eric Ntambakwa, Principal Geotechnical Engineer

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Outline

- What are Best industry practices for Project engineering, albeit Owners Engineering (OE), Due Diligence (DD) or Independent Engineering (IE), for Project success
- Civil, Geotechnical and Structural engineering similarities;
  - Project life cycle – planning, exploration/study, optimization and final design
  - Extreme weather study and reporting
  - Project design optimization
  - IE review risk identification

- Overarching concept of Independent Engineering review:
  - Creating a level playing field for all to adequately design PV power plants
  - Value add to Clients in identifying and quantifying risk and mitigation measures

- Take homes:
  - All Projects should follow the same approach of gaining adequate Civil, Geotechnical and Structural study and reporting and only then can the Civil and Structural designs be informed of all extreme weather and geotechnical risks.

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Engineering Discipline Coordination for Extreme Weather

Civil

- *Hydrology Report* defines flooding and scour risk
- *Civil Grading and Drainage Plan* development
- Project layout in coordination with the *Hydrology Report* recommendations and site constraints

Geotechnical

- *Geotechnical Report* defines;
  - Subsurface characterization
  - Geologic hazards
  - Soil strength and deformation
  - Design and construction recommendations

Structural

- Environmental loads – wind, snow, seismic, frost jacking, geologic and hydrologic hazard
- Strength tests
- Code compliance
- Vibration and corrosion analyses
- *Structural Plan* and calculation development

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Civil Design Process

Planning

- Scoping and identifying Project requirement
- Perform desktop constraints and Project boundary mapping
- Perform preliminary layouts – iterative process

Reporting

- A *Hydrology Report* to provide study and analysis of the 100-year storm event to include respective calculations, drainage exhibits and provides conclusions and recommendations with respect to; the 100-year stormwater flood inundation depths to the Project's electrical equipment and any site scour potential that could undermine any site foundations.
- *ALTA (American Land Title Association) Survey* for Project site control and topography. ALTA helps manage the title insurance industry to ensure tracking of property title history of ownership.
- Slope analysis heat mapping

Analysis and Design Optimization

- Finalize constraints mapping overlaid on Project *ALTA*
- Identify the selected racking vendor advantages/limitation
- Finalize *Civil Grading and Drainage Plan Set* to optimize pile reveal and be in coordination with the hydrology and geotechnical conclusions and recommendations.

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Site Civil Reviews - Why

- Why Civil design review is required?
  - The *Hydrology Report* forms the basis of design for the Civil and Structural design aspects of the Project.
  - Ensure the recommendations found in the *Hydrology* (1-100-year-storm) *and Geotechnical Reports* are in coordination with the *Civil Grading and Drainage Plan Set*.

  - Civil Engineers identify risks as it pertains to:
    - life safety
    - defective Engineering practices
    - reduction in annual energy production and downtime
    - abnormal construction practices and/or future O&M costs

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Site Civil Reviews - What

- What do Independent Engineers need for a Civil review?
  - *Hydrology Report*; studying the **1-100 year storm event**, analyzing the risk and/or mitigation measures associated with site flooding and scour potential.
    - Flood: By studying the topography of the greater watershed and the Project versus the studied flood depth elevation, in heat map format. Recommendations shall be made to ensure all electrical equipment is at or above the 1-100 year flood depth and/or meets freeboard requirement.
    - Scour: By analyzing stormwater velocities versus soil conditions for scour potential identification and mitigation to all Project access roadways and foundations, in heat map format.
    - And includes recommendations for temporary construction and permanent stormwater conveyance systems and retention or detention requirements to inform the Project's *SWPPP*.
  - *Geotechnical Report* – identifies recommendations roadway design, geotechnical hazard avoidance, and any soil stability.
  - *Civil Grading and Drainage Plan Set* – ensuring the recommendations made in the *Hydrology and Geotechnical Reports* are incorporated into the designs.

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Common Civil Issues

- *Hydrology Report* based on less than the 1-100 year storm event resulting in equipment flood inundation and scouring to foundations and other Project infrastructure.
  - AHJ might have lesser storm or no storm requirements for permit approval, therefore the Sponsor might not know the 1-100 year event is an industry standard.
- Design recommendations from the *Geotechnical and Hydrology Reports* not in coordination with the *Civil Grading and Drainage Plan Set*

- Less common:
  - The Project is within FEMA flood zone and needs further investigation to identify special flood insurance requirements.
  - A jurisdictional water bodies or other environmental constraint/buffer/setback is encroached upon, requiring possible work stoppage, fines, re-engineering and rework. Additional coordination with the permitting authority reviewer could be required.

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Geotechnical Report Process

Planning

- Scope and identify Project requirement
- Perform desktop Geologic review
- Identify Structural design requirements

Exploration, Testing and Reporting

- Initiate investigation:
  - reconnaissance, field exploration and sampling
  - Soil testing
  - Characterization of subsurface conditions
- Generate the *Geotechnical Report* with design and construction requirements

Analysis and Design Optimization

- Coordination with Structural Engineer of Record
- Assist with pile design optimization
- Performs final checks of soil strength, deformation, stability and durability

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Geotechnical Reporting – Why and What

- Why:
  - The Geotechnical report forms the basis of design for the Civil and Structural aspects of the Project.

- What is to be included in every report:
  - Subsurface characterization
  - Strength, deformation, settlement evaluation
  - Design and construction recommendations
  - Inputs for foundation design
  - Corrosion evaluation, thermal resistivity testing results and frost jacking identification
  - Evaluation of geologic hazards

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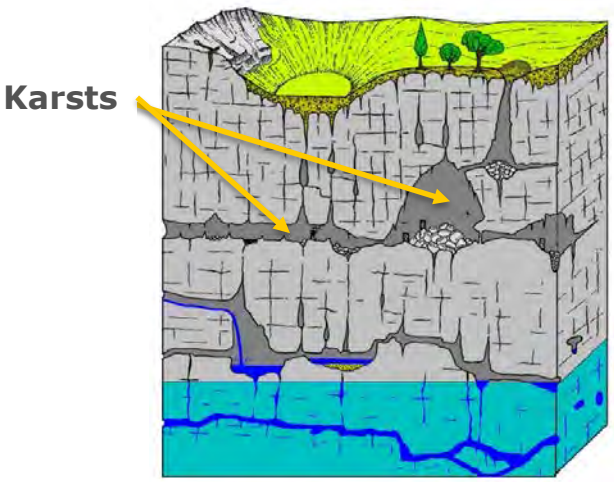
Common Geotechnical Issues

- Not receiving a Project-specific *Geotechnical Report.*
  - Unknown subsurface conditions and risk
  - Unknown design and construction recommendations

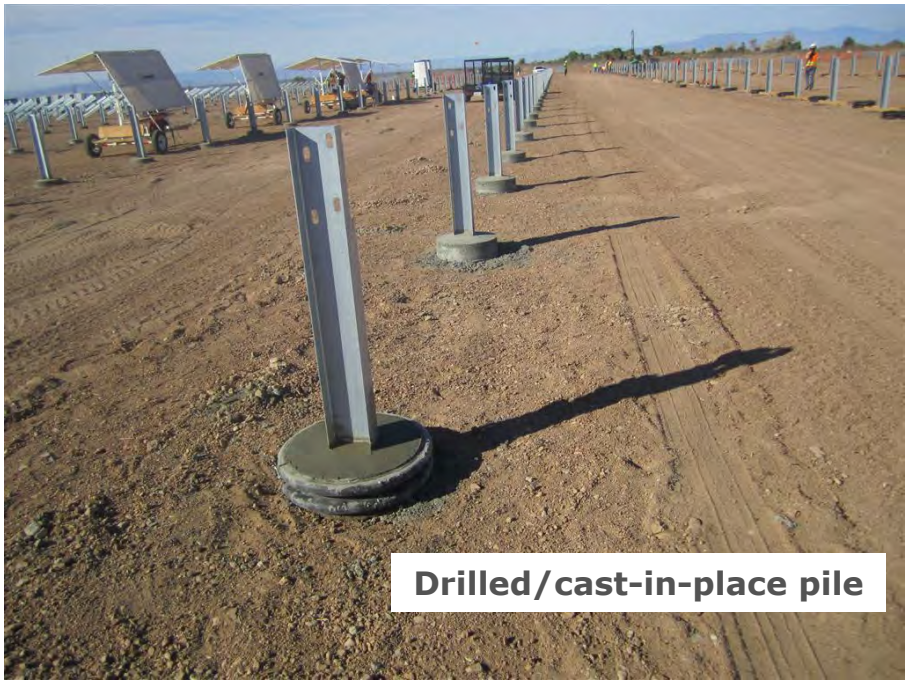
- Get *Geotechnical Report* but missing information leading to unknown risk;
  - Corrosion results
  - Thermal resistivity results
  - Frost jacking identification and recommendation
  - Access roadway design recommendation

- Get racking vendor's calculations and structural designs that are not based on the Project-specific subsurface conditions.



Ground Mounted PV Foundations

1. Driven pile (soil or soft rock)
2. Drilled hole cast-in-place pile (soil or rock or hard rock)
3. Ballasted (settlement prone soil, landfill, competent rock)
4. Helical or screw anchor (shallow bedrock, frost jacking, pre-drilling usually required)
5. Shallow foundation or strip footing (penetration not allowed)



Structural Design Process

Planning

- Scope and identify Project requirement
- Coordinate with Geotechnical and Civil Engineers of Records
- Identify need for Project-specific wind studies for extreme weather in hurricane prone locations.
- Ensure code compliance regarding environmental load calculations
  - ASCE 7, SEAOC, IEC, EuroCode

Testing and Reporting

- Review:
- Wind tunnel studies proving static and dynamic coefficients
- Aerodynamic instability analyses
- Project specific corrosion studies and pile load test results
- Field test results determining dynamic properties of the system
- Cyclic tests and fatigue analysis
- Stow strategy design for trackers
- Module integration tests

Analysis and Design Optimization

- *Finalizing Structural Plans* and calculations for the supporting structure
- Analysing strength tests on complex structural assemblies and mechanical drive system
- Validating foundations design using pile load test results
- Generating hurricane resistant design and O&M practices

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Structural Reviews - Why

- Why structural review is required?
  - Ensuring that the complete structural and mechanical load paths have been adequately designed. From panel, to clamp, to substructure, to connections, to foundation to earth.
  - Ensuring proper extreme weather loads, hydrology and geotechnical recommendations are incorporated into Structural design.
    - Wind speed, frost jacking, snow, corrosion attack, scour potential, geotechnical hazard risk and hurricane resistance design.
  - Ensuring proper connections are designed and employed. "95% of T-clamp module connections failed in hurricane prone rooftop locations", per 02/17/2020, Rocky Mountain Institute, *Solar Under Storm Part II: Designing Hurricane-Resilient PV Systems*.
  - Ensuring fatigue life of the structural components and mechanical drive system has been studied and meet the Project's expected lifespan.
  - Ensuring dynamic loads and aerodynamic failures of the supporting structures have been identified and addressed.
  - Validating the field test studies that determine the structural design input, such as natural frequencies and corresponding damping ratios of excitable modes for a quasi-static dynamic analysis of the supporting structures and pile foundations

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Structural Reviews - What

- What is needed for a Structural review?
  - Key documents divided into two categories:
    - ***Product*** specific: racking drawings, calculations, load calculations, wind tunnel reports, and tracker stow strategy design
    - ***Project*** specific: Structural drawings and calculations for the supporting structure and pile foundation
  - Recommendations and conclusions by the *Hydrology and Geotechnical Reports,* as well as the on-site pile pull test results
  - *Structural Plans* should specify:
    - Exterior and interior rows and pile row-to-row spacing
    - Full detail of all racking components and connections
    - Material and corrosion specifications
    - Environmental design loads: wind speed, snow, frost jacking, corrosion attack, scour potential and geotechnical hazard risk
    - Test references: Wind tunnel, aerodynamic instability analyses, field test results, cyclic tests and fatigue analysis, stow strategy design for trackers, module integration tests

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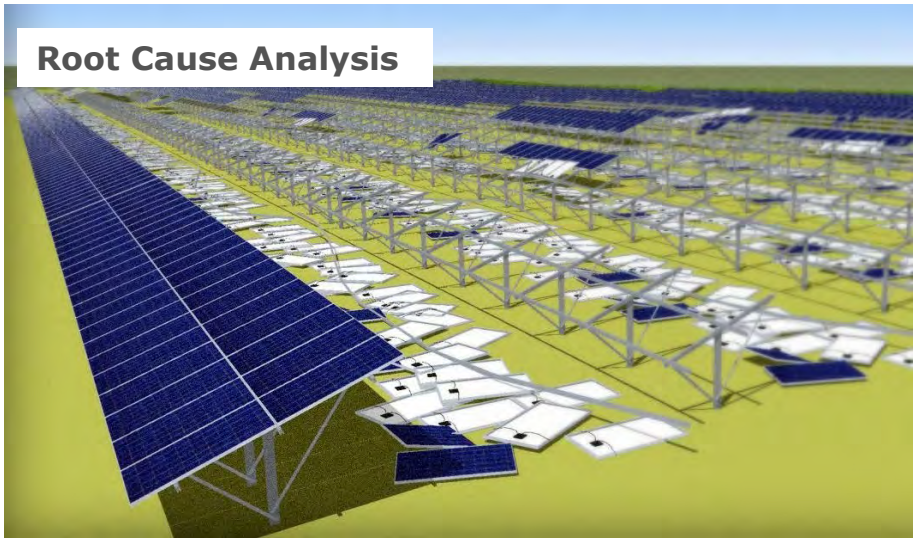
Wind Forces in Context

- Typical wind design for PV structure is 1 in 50 year at moderately windy site **750 Pa**
- Array at 25° tilt would cause:
  - Average downforce press over entire table - - - - - - - **750 Pa** (~3.75 Tons over a 50m2 table)
  - Average uplift suction over entire table - - - - - - - - - **1200 Pa** (~6 Tons over a 50m^2 table)
  - Local suction/pressure over a single panel - - - - - - - **2400 Pa**

Structural Common Issues

- Not receiving site-specific environmental loads
- Designs not using conservative load calculations for Projects prone to hurricanes
- Missing wind tunnel studies that address dynamic loads and aerodynamic instabilities
- Improper pile foundation design



Thank You!

Take home: All Projects should follow the same approach of gaining adequate Civil, Geotechnical and Structural study and reporting and only then can the Civil and Structural designs be informed of all extreme weather and geotechnical risks.

Offline questions:

dan.berger@dnvgl.com

DNV GL Renewables Services Home Page

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Hail Damage – A 2019 Case Study and Lab Trials

James Rand, Chris Thompson, Mason Reed, AJ Hendricks, Andrew Cooper
Core Energy Works
Paul Donley
Duke Energy

This white paper summarizes a talk given by James Rand at the 2020 NREL Photovoltaic Reliability Workshop, 26 February 2020.

Case Study: Severe Hail Damage

Core Energy Works (CEW) was contracted by Duke Energy to evaluate a hail damaged site in rural North Carolina. The site experienced a storm in 2019 that resulted in exceptionally large hail balls that did significant damage to the site and to the surrounding area. Photos from social media of the hail event are shown in Figure 1.

Figure 1: Photos of hail taken from social media from North Carolina hailstorm. For reference a baseball has a diameter of approximately 75mm (3"). "Baseball" size hail was reported in the local media as well[1]. Other weather-related sites reported 70 mm (2.75") hail for this storm.

Figure 2: Photo of the hail damaged modules and site details.

[1] "Wicked Storm Unleashes Fury", Roanoke-Chowan News-Herald, Published 5 June 2019 .

Figure 2 and Figure 3 show that modules with broken glass were found spread throughout the array, interspaced with modules with intact glass. Some information on the storm can be extracted from the photographs taken of the damaged modules. The impact that initially broke the module was clearly identifiable and is typically the largest impact site. After the glass was broken, subsequent strikes disrupted the broken glass and left visible marks. Figure 3 shows the range of hail diameters estimated from the size of these secondary impact marks. Because the secondary impact marks are larger than the actual diameter of hail, a correction factor was calculated by firing hail balls with known diameter at a broken panel and measuring the resultant pattern in a laboratory environment. The average hail diameter was found to be 44mm (1.7”) with a range of 26mm (1.0”) to 56mm (2.2”) for the small sample of panels evaluated. Social media reports suggest hail reached 75 mm in size (3”).

In addition to the size of the hail, the number of hail strikes was estimated by counting the secondary impacts. The average number of secondary strikes per panel ranged from 28 to 87, with an average of 47 impacts per panel. These numbers represent only the number of hail impacts AFTER glass broke and represents a lower limit to the number of hail impacts each module received.

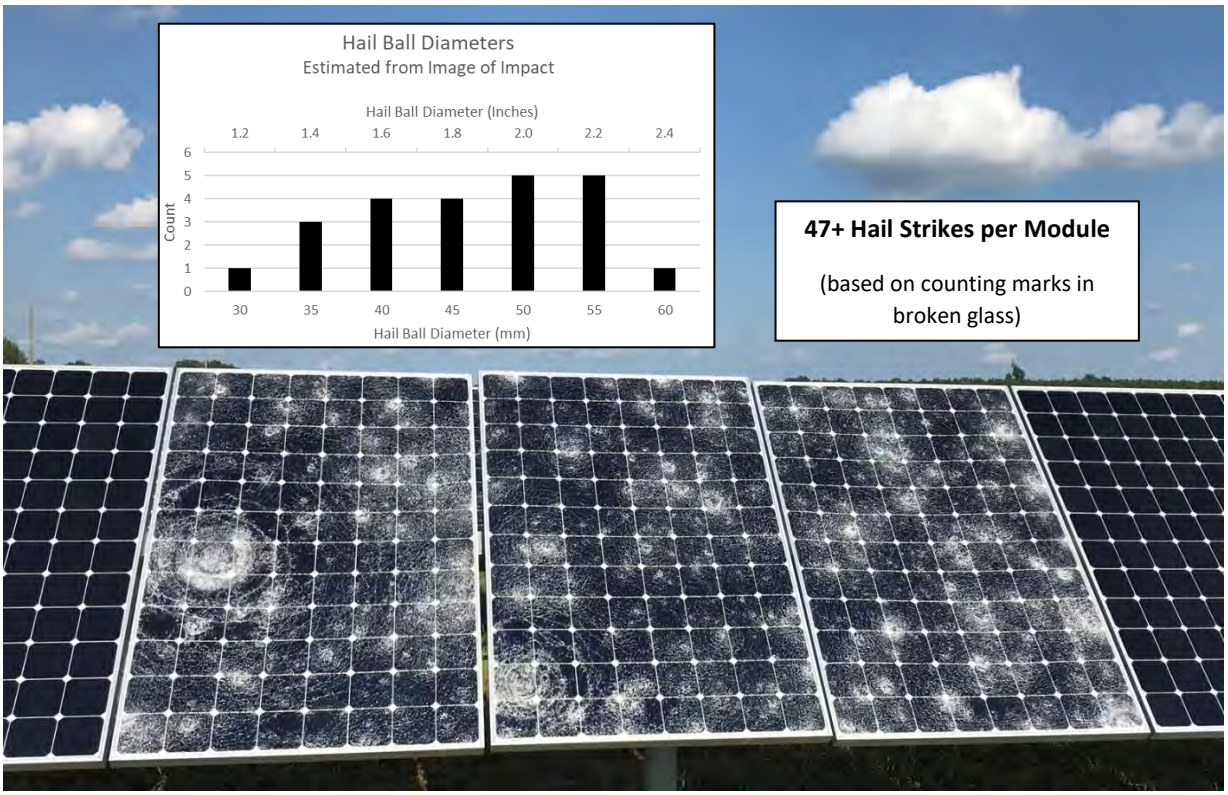


Figure 3: Estimating the hail ball size from the impact left on the broken glass.

Initial Testing by Electroluminescence

Sometime after the hail event, the site was visually inspected and 301 modules with intact glass were randomly selected for electroluminescence (EL) imaging. The modules were EL imaged in place on the rack. The EL results highlighted three classes of modules with intact glass: (1) undamaged; (2) lightly damaged; (3) storm damaged. Modules with broken glass could be easily visually identified as storm

damaged due to the clear impact areas. Undamaged modules had little or no solar cell cracking as a result of the storm. Lightly damaged modules were defined as modules with some damage that could not be clearly attributed to storm damage; the cracked cells had no clear impact center or star patterned cracks and may have resulted from rough handling during packaging, transportation, and installation. Storm damaged modules could be identified through EL by the clear impact points and star patterned cracks. Examples EL images from all three types of modules are shown in Figure 4, below:

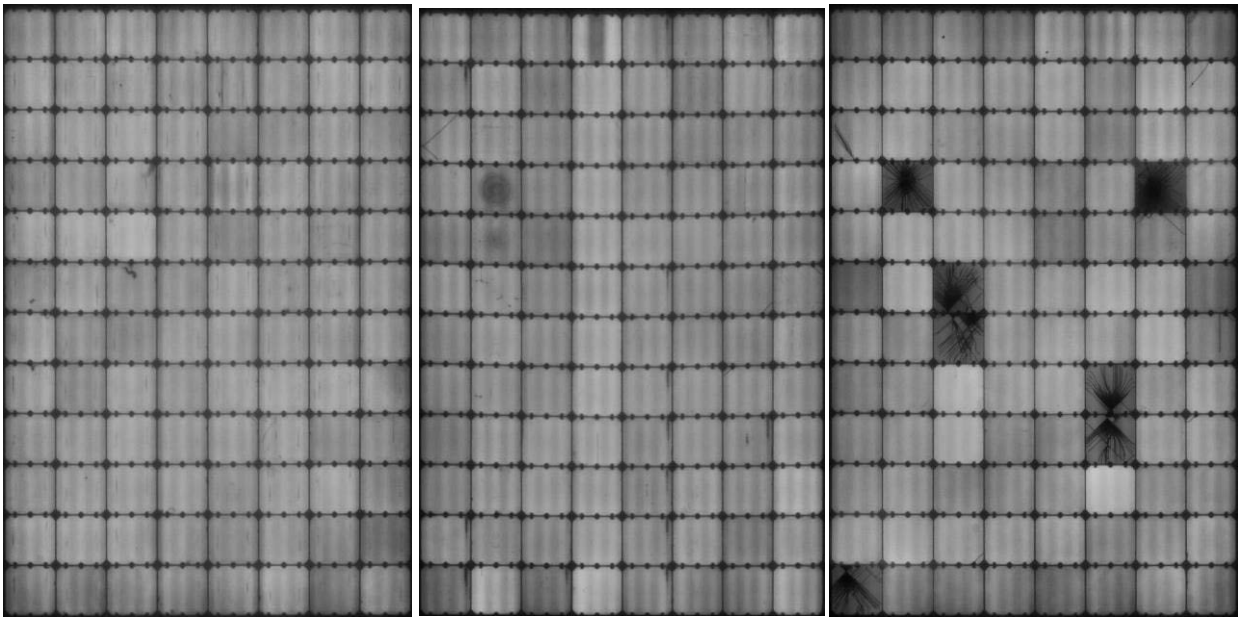


Figure 4: Example EL images taken on modules with unbroken glass: Undamaged (left;, lightly damaged (center); storm damaged (right).. shows the distribution of the 301 EL samples between these three categories. Most module with intact glass were undamaged (61.5%). This is quite an impressive result given that they were hit with on the order of 50 hail balls as big as 60mm!

Table 1: Results for a random sample of 301 EL images on modules with intact glass

	Undamaged	Lightly Damaged	Storm Damaged
Module Count (301 total)	185	19	97
Percent of Modules Tested	61.5%	6.3%	32.2%

An analysis of the physical distribution of undamaged modules vs modules with broken glass across the site reveals no correlation between the density of modules with broken glass and the probability that modules with unbroken glass in the same area will be undamaged (see Figure 5, below). In other words, you cannot conclude that regions with high glass breakage also have high levels of cell damage within the modules that do not have broken glass in the same area.

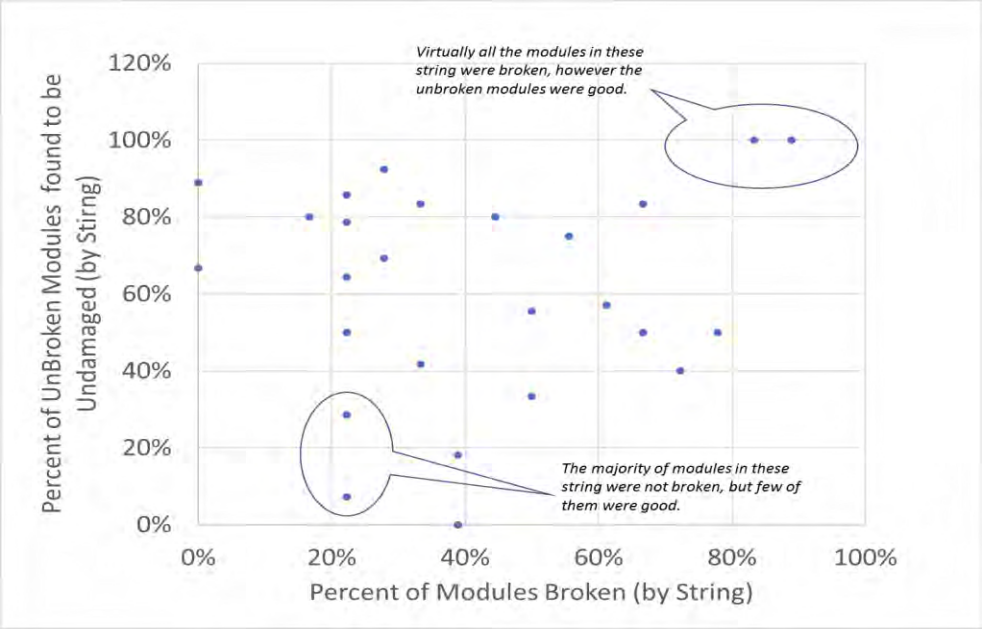


*Figure 5: The percent of undamaged modules vs modules with broken glass for each of the strings tested. The data suggests that the percent of modules with broken glass is **not** a good indicator that modules in the same string are damaged.*

A follow up visit was conducted in which 100% of the 19,950 modules were counted as one of three categories: (1) broken glass; (2) unbroken good; (3) unbroken damaged. Figure 6, below, shows the results of the 100% inspection grouped by tracker number. Modules with broken glass are easily identified visually. However, visual inspection is not able to distinguish between a storm damaged and undamaged module when the module glass is unbroken. An alternative inspection method is needed as discussed in the next section.

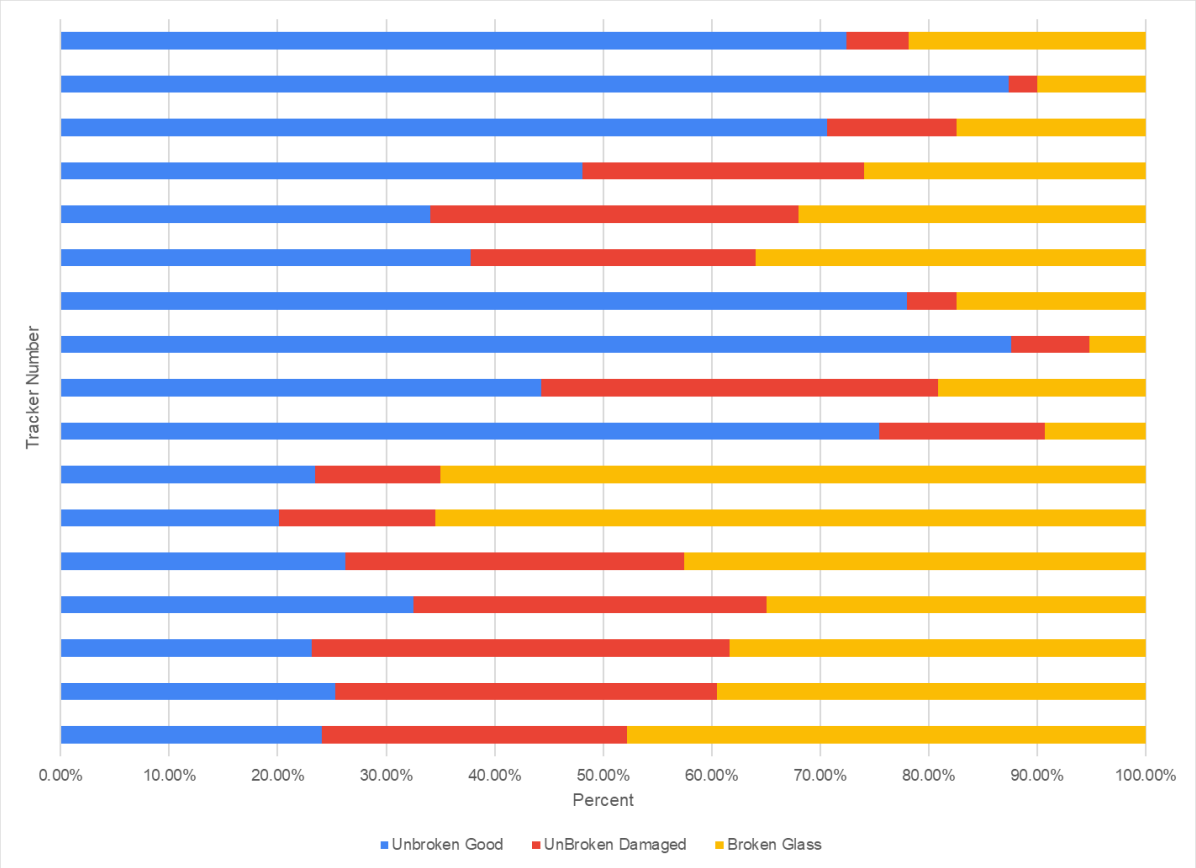


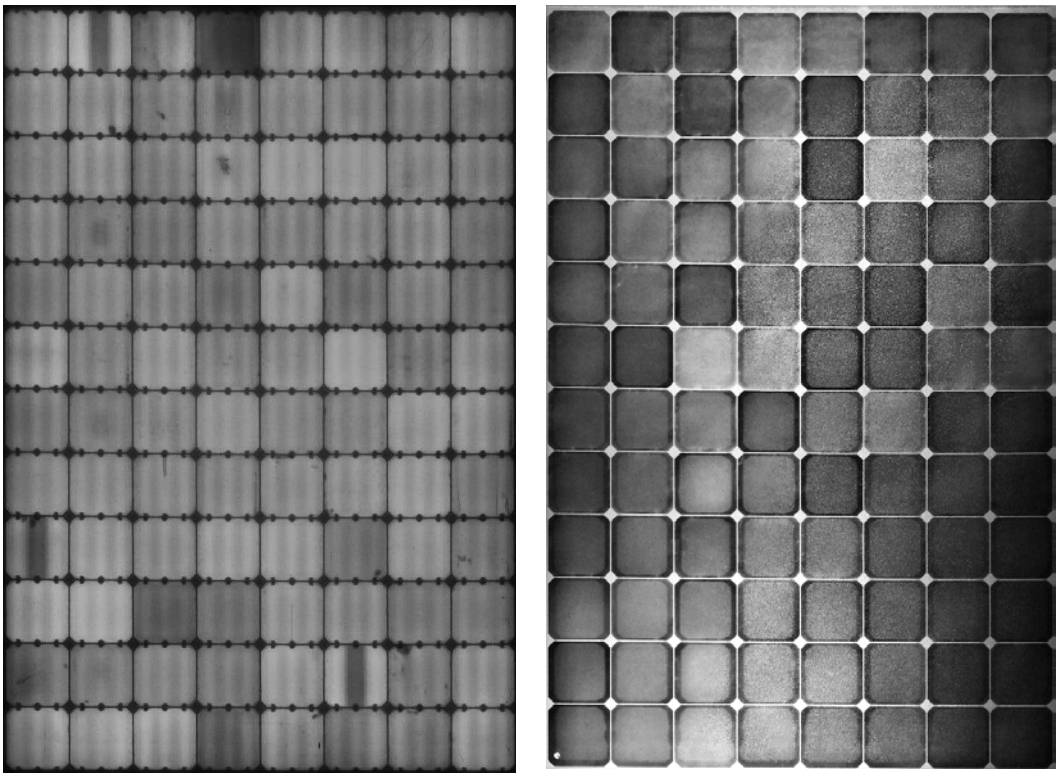
Figure 6: Classification of 100% of modules at the site as "unbroken good"; "Unbroken damaged"; or "Broken glass" and grouped by tracker number. The data shows a range of damage from as little as 13% damaged to as much as 80% storm damaged. There are approximately 1000 modules in each tracker section.

Using UV Fluorescence to Identify Broken Modules

Given that approximately 14,000 modules had intact glass on the site, and potentially 30% of those modules were storm damaged, testing of individual modules was needed. Doing EL on all 14,000 would have been time consuming and costly. Fortunately, these modules had an EVA formulation and other materials compatible with UV fluorescence detection of cracked cells (UVF). If oxygen can diffuse to the EVA, an oxidation process occurs that destroys the chemical compounds responsible for fluorescence[2]. In an un-damaged cell, oxygen can only diffuse to the frontside EVA through the gaps between cells. However, for cracked cells, oxygen can penetrate along the cell cracks and react with the EVA creating an 'image' of the cell cracks[3].

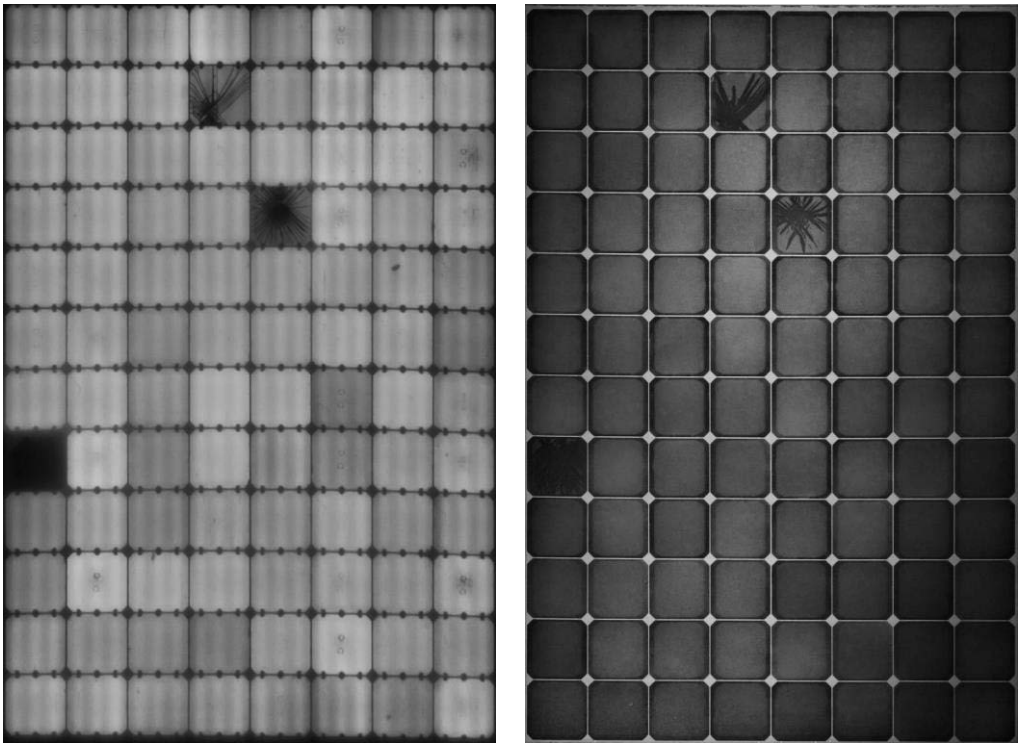
[2] F. J. Pern, "Factors that affect the EVA encapsulant discoloration rate upon accelerated exposure," Solar Energy Mater. Solar Cells, vol. 41/42, pp. 587–615, 1996

[3] M. Kontges, S. Kajari-Schroder, and I. Kunze, "Crack Statistic for Wafer-Based Silicon Solar Cell Modules in the Field Measured by UV Fluorescence", IEEE Journal of Photovoltaics, vol. 3, No. 1, January 2013



EL UVF

Figure 7: EL (left) and UVF(right) of the same un-damaged module. Please note that UVF is not sensitive to variations in EL due to electrical factors.



EL UVF

Figure 8: EL(left) and UVF(right) of storm damaged module, UVF clearly shows location and nature of cracked cells.

Figure 7 and Figure 8 above show EL and UVF images of undamaged and storm damaged modules. The UVF clearly reveals every cracked cell, and the pattern of the cracked cells. UVF measurements are contactless and rapid. The storm damaged modules with intact glass were identified rapidly and at low cost without dismounting or disconnecting the modules.

Using UVF, the full effect of the hail storm on the entire site was found (Table 2, below). In total, 48.5% of modules on the site were found to be good, and 51.5% were damaged by the storm. The project was able to save approximately 10,000 modules from the landfill with a cost effective and rapid assessment.

Table 2: Total statistics for entire site after UVF analysis

Module Class	Percentage of total (%)
Undamaged	48.5%
Storm Damaged -Broken Glass	30.4%
Storm Damaged - Internal Cell Damage (glass intact)	21.1%

Testing Modules Indoors with High Energy Hail Strikes

A study is presently underway to examine the vulnerability or tolerance of different module designs to hail damage. CEW obtained five types of panels from a variety of manufacturers. Hail strikes were emulated in the lab by firing round ice balls at panels with a pneumatic hail cannon. The panels were mounted per manufacturers specifications. Two separate tests were conducted: a hail damage threshold test, and a hailstorm test. The data presented represents only one module per test. No replication studies have yet been conducted. However, the data is still instructive. This type of rough handling study is a continuation of the work initially funded by DOE and SunPower and has continued with this hail testing with funding from CEW and SunPower.

Hail Damage Threshold Test

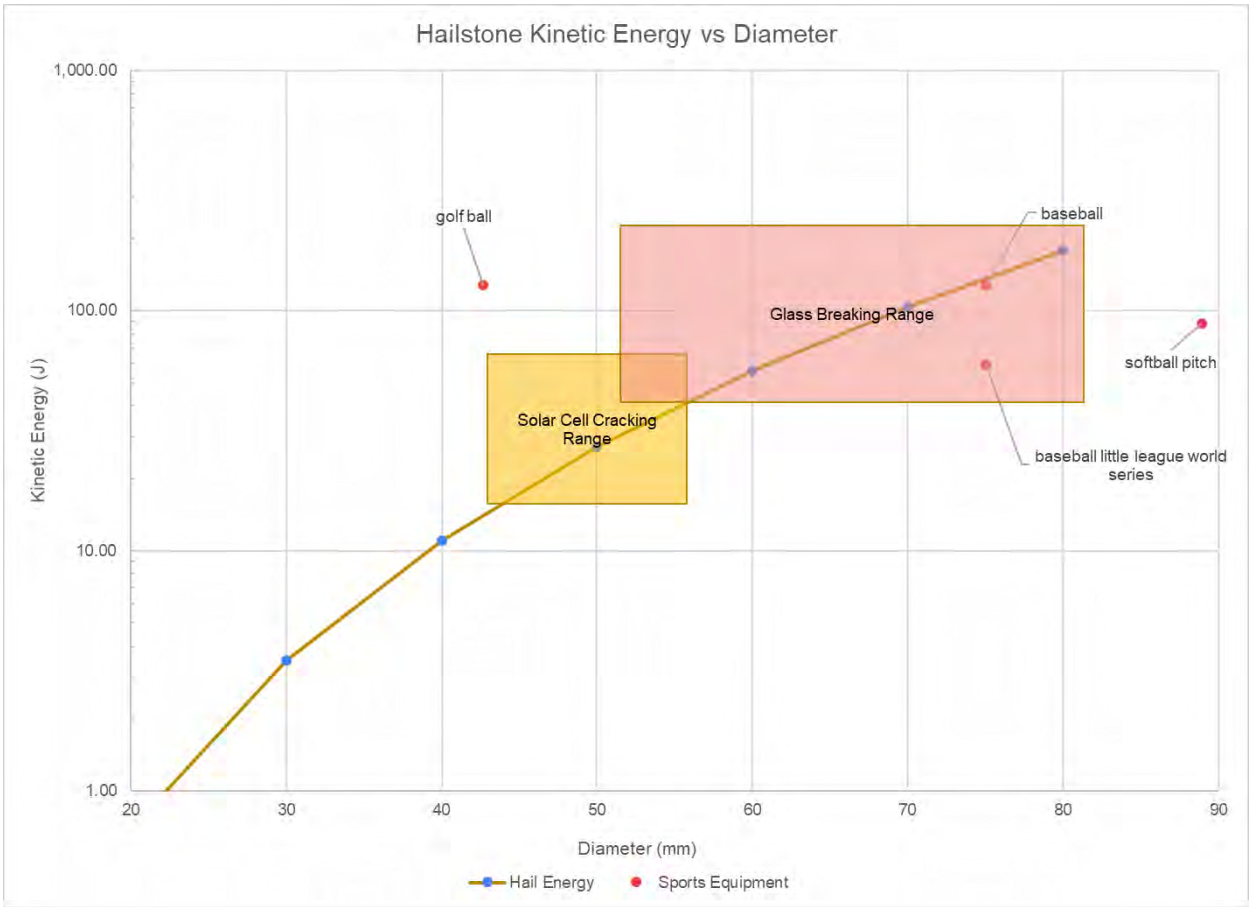


Figure 9: The natural behavior of hail ball in terms of energy (x axis) vs size (y axis) is shown based on calculating terminal velocity of a sphere. The range for solar cell cracking and glass failure are marked. Included for reference are a few common human launched spheres.

In the hail damage threshold test, increasingly energetic hail impacts were fired at modules under test to emulate the kinetic energy of larger and larger hail balls. The kinetic energy (E_K) of a projectile is given by $E_k(J) = \frac{1}{2}mv^2$, where m is the mass of the ice ball in grams and v is the velocity in m/s. The velocity is given by the equation for terminal velocity of a sphere[4], where $v = \sqrt{\frac{4 \cdot \rho_{ice} \cdot d \cdot g}{3 \cdot \rho_{air} \cdot c_w}}$, where ρ_{ice} is the density of ice (870 kg/m^3), ρ_{air} is the density of air (1.2 kg/m^3), d is the diameter of hail, and c_w is the air drag coefficient, for a slightly rough sphere 0.5. The mass of a sphere of ice is given by $m = \frac{4 \cdot \pi \cdot \left(\frac{d}{2}\right)^3}{3} \cdot \rho_{ice}$. Using all three equations, a plot of hail diameter vs energy at terminal velocity can be calculated (Figure 9).

For these tests, 38mm (1.5”) ice balls were used, and the air pressure in the cannon was varied to change the velocity. For this study hail ball velocities of 24 m/s (54mph) to 56 m/s (125 mph) were used.

[4] Swiss Hail Impact Protection Register (HSR), CFIAA Test specification No. 00a General Part A, www.hagelregister.ch

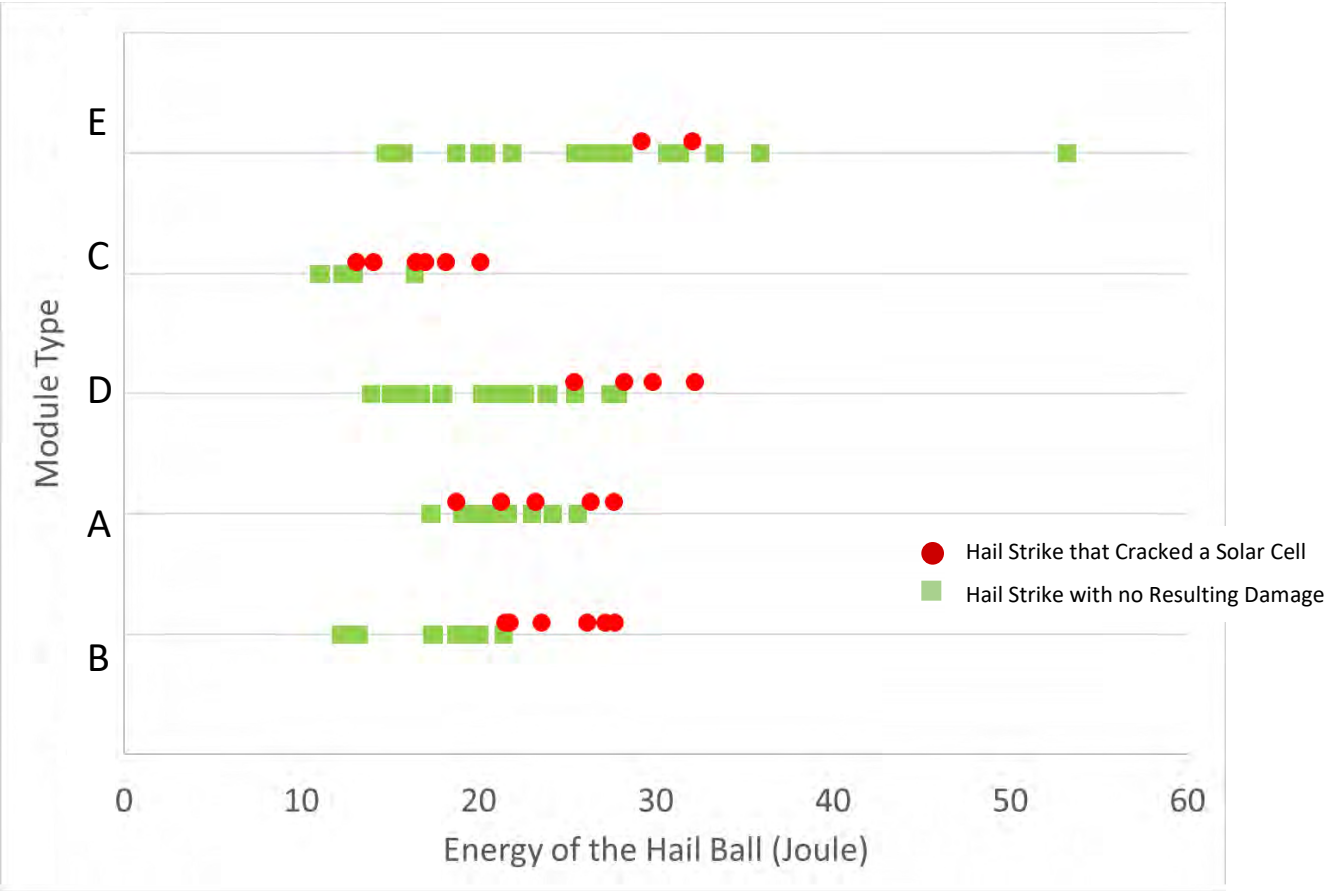


Figure 10: Hail damage threshold testing for five different module types.

In the Hail Threshold Test, modules were subjected to three hail strikes at a given kinetic energy and the energy incremented upward in 2.5J steps with a starting energy of 15J. IV and EL images were taken after each hail shot. If 2 out of 3 shots at a given energy level cracked a solar cell, the damage threshold was reached. Figure 10, above, shows the results for testing five different modules. Green marks indicate a strike caused no damage to the module and red marks indicated a broken/shattered solar cell. For module types E, D, & B, a clear threshold for damage is observed. For module type E no clear threshold was found, the shot energy increased until the module glass failed (i.e. the glass breakage energy threshold was lower than the threshold required to crack a cell for this module design). Please note that a broad or diffuse threshold energy for cell cracking is a likely indicator of a wide variation in pre-existing cell damage (i.e. critical crack length of brittle materials). Such examples may be certain types of half-cell modules where the process used to cleave the cell in two halves may have left micro-cracks of various sizes along the scribe.

The cell damage threshold ranged widely, from 12J to 30J. The equivalent hail diameter ranged from 1.6 inches to 2.24 inches, much greater than the required IEC 61215 minimum testing specification of 1”. The IEC 61215 test does allow for hail impact testing over a range of hail diameter from 12.5 to 75 mm, however, 25 mm is the largest diameter required by the test.

Comparing these indoor results to the storm event discussed previously, where the hail had a median diameter of 1.8” and a maximum of 2.4”, almost all the panels represented in the study would have been heavily damaged. Only module type E would be predicted to survive in such a violent storm.

Hailstorm Stress Test

A secondary question raised from the field case study is how performance is impacted by hail damage. To begin to answer this question a second test was carried out – the Hailstorm Stress Test. The hailstorm stress test consisted of 30J shots across the module, evenly distributed between substrings. The test was designed to measure the effect a severe hail event on module power output. Module IV and EL tests were performed after every hail shot.

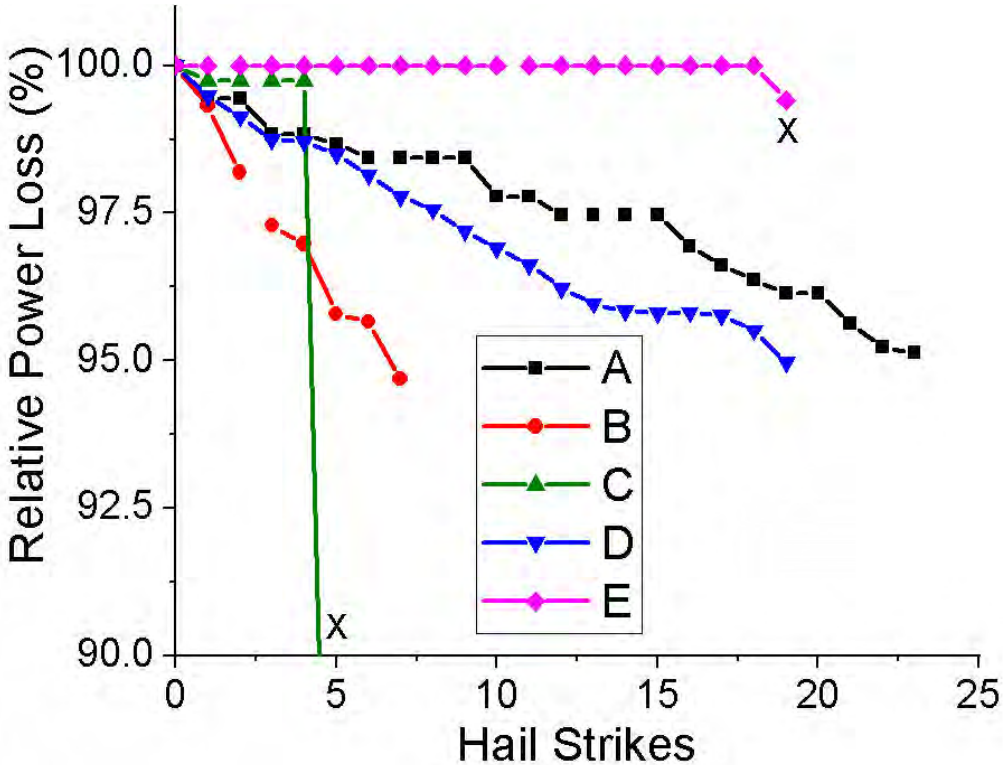


Figure 11: Relative power loss vs number of 30J hail strikes on 5 different modules types.

Figure 11 shows the relative power loss of each module vs the number of 30J hail strikes the module has endured. Modules were shot with consecutive hail balls until either maximum power (P_M) was reduced to 95% of the initial value or the glass failed, whichever came first. Two modules suffered glass failure, type C broke on the 5th shot and type E on the 19th shot. Modules found to have a relatively high cell damage threshold, as determined from the earlier testing, were not necessarily more tolerant to power loss due to that cell damage; type B, for example, lost 5% output power after only 7 hail shots. Other module designs were easily damaged (low cell thresholds) but had performance that was resilient in the face of that cell damage; module A, for example, withstood 25 shots and many cracked cells before failing 5% in power. These results indicate there is an interplay between cell damage threshold energy and cell interconnect topology that will determine the ultimate performance of that module after hailstorm damage. Of course, exposure to hail below the cell and glass breakage threshold is not

threatening to module performance, but predicting performance in a storm exceeding the cell breakage threshold will require testing well beyond that required in typical certification testing.

Figure 12 shows the initial and final EL image of each of the 5 modules tested. Note the end point of the test was different for each module, some breaking glass, others reaching the 5% degradation in power.

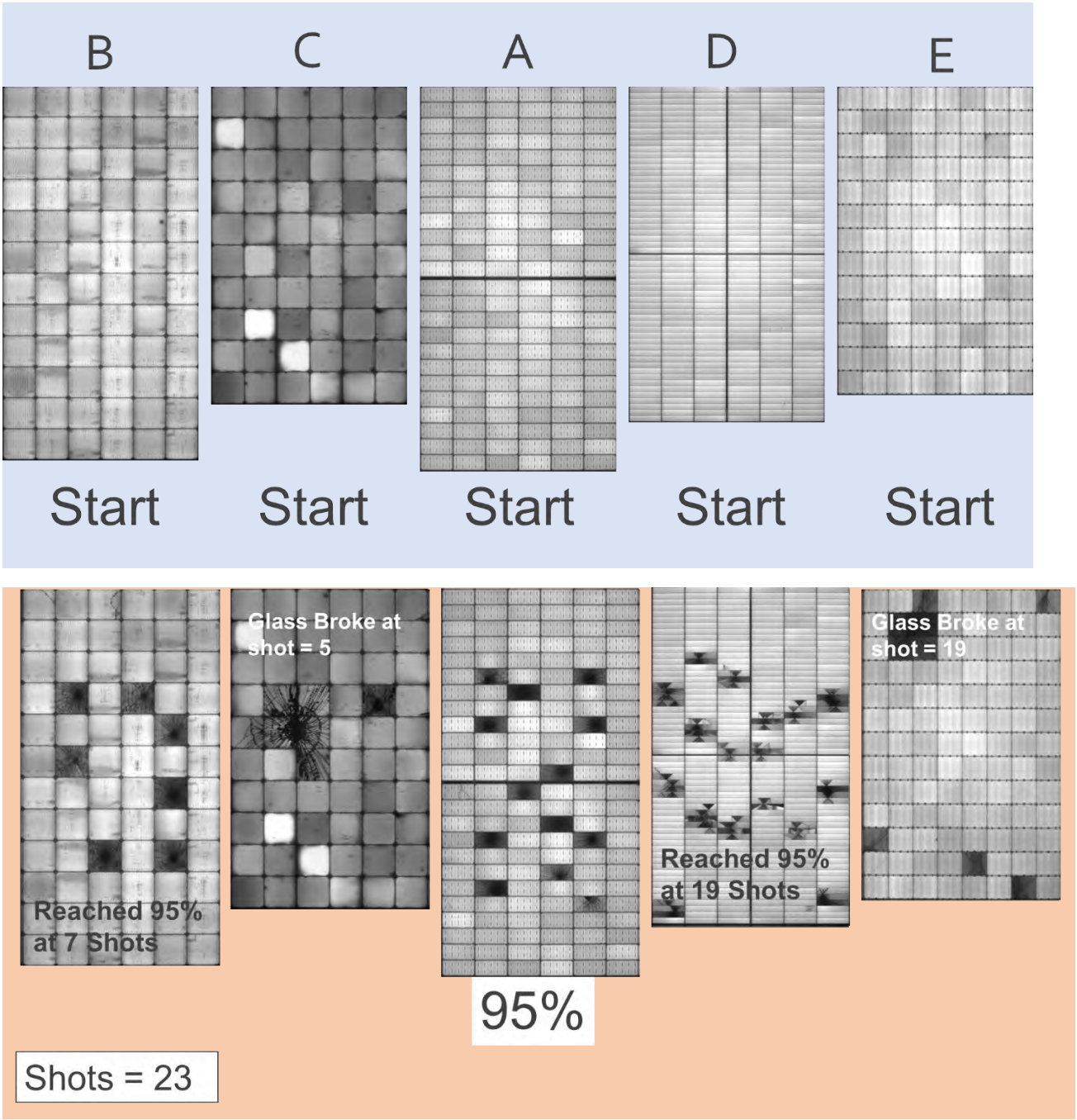


Figure 12. EL images of the five different modules tested. The top images are of the modules just prior to Hail Storm Stress Testing, and bottom image is after testing. The modules endured from as few as 5 shots to as many as 23 before reaching the end point of the test – either broken glass or a degradation of power to 95% of the starting point.

Industry Impact

Hail damage can pose a serious risk to photovoltaic stakeholders. Recent large hail damage insurance claims have resulted in insurance companies dropping or limiting hail coverage[5]. The size and frequency of reported hail has steadily increased over the last 40 years. Observations of hail with diameter > 1.25 inches has increased from ~1600/yr in 1990 to over 3000/yr in 2014. Hail with diameter > 2" has increased from 340 observations in 1990 to 529/yr in 2014[6]. Figure from Allen and Tippet [6] show the increase in reported hail frequency and size over time.

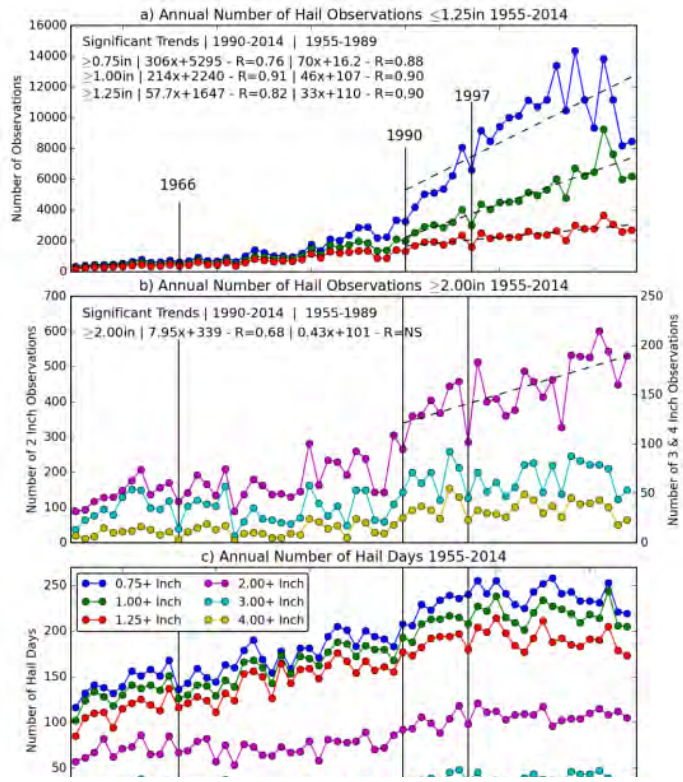


Figure 13: Frequency of hail observations over time by size, from Allen and Tippet

Conclusion

The resiliency of a solar module to hail damage is a critical issue for installations in hail prone climates. The effects of hail can be devastating and can extend beyond broken glass. Hail can result in cracked/shattered solar cells not visible to the eye. Cracked cells can reduce power and potentially cause hot-spots. EL and UVF testing can provide critical information after a hail event to access damage in some cases, but UVF may not be useful in many modern module bills of materials.

There are module designs that are shown to be more tolerant to hail than others. Significant differences are shown to exist in the size of the hail needed to crack solar cells and break glass in the small sample tested here. Furthermore, once solar cell cracks exist, the impact to module power varies greatly from module to module based on the solar cell and module designs.

About CEW

Core Energy Works is an independently owned engineering services company with expertise in all things related to photovoltaic modules. CEW engineers work primarily on modules mounted in the field, having IV tested over 10,000 modules and EL imaged over 5,000 modules at 75 utility and commercial sites across the US. In addition, CEW offers a drone-based IR array imaging service. CEW operates a warehouse in Newark DE with a full suite of module testing capability, from single module testing on AAA pulse tester for STC to evaluating full container loads for quality or potential damage.

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[5] A. Sagar, "Texas hailstorm set to generate $70-$80mn solar loss", The Insurance Insider, https://insuranceinsider.com /articles/129613/texas-hailstorm-set-to-generate-70mn-80mn-solar-loss, October 23rd, 2019

[6] J.T. Allen, M.K. Tippet, The Characteristics of United States Hail Reports: 1955-2014, Electronic Journal of Severe Storm Meteorology, **10**(3), pp1-31, 2015

PVQAT

International PV Quality Assurance Task Force

PVQAT: Overview

Tadanori Tanahashi (AIST)
& PVQAT TG Leaders

NREL PV Reliability Workshop (Feb. 26, 2020) Lakewood, CO USA

PVQAT

International PV Quality Assurance Task Force

PVQAT updates

- Topic 1: PVQAT Structure & Activities

- Topic 2: Recent Topics in PVQAT Task Groups

PVQAT

International PV Quality Assurance Task Force

PVQAT updates

- Topic 1: PVQAT Structure & Activities

- Topic 2: Recent Topics in PVQAT Task Groups

PVQAT: We are…a Liaison of IEC TC82

Establish Standards

IEC

IECRE

Establish ODs

Support

PVQAT

OPEN FORUM
(Volunteers)

Collaborative Research

<Web Meeting>

Support

PV Reliability WSs

NREL — Sandia National Laboratories — BROOKHAVEN NATIONAL LABORATORY

PV Reliability Workshop

SOPHIA

SOPHIA Workshop PV-Module Reliability

RCPV — AIST

SAYURI-PV

International Energy Agency
Photovoltaic Power Systems Programme

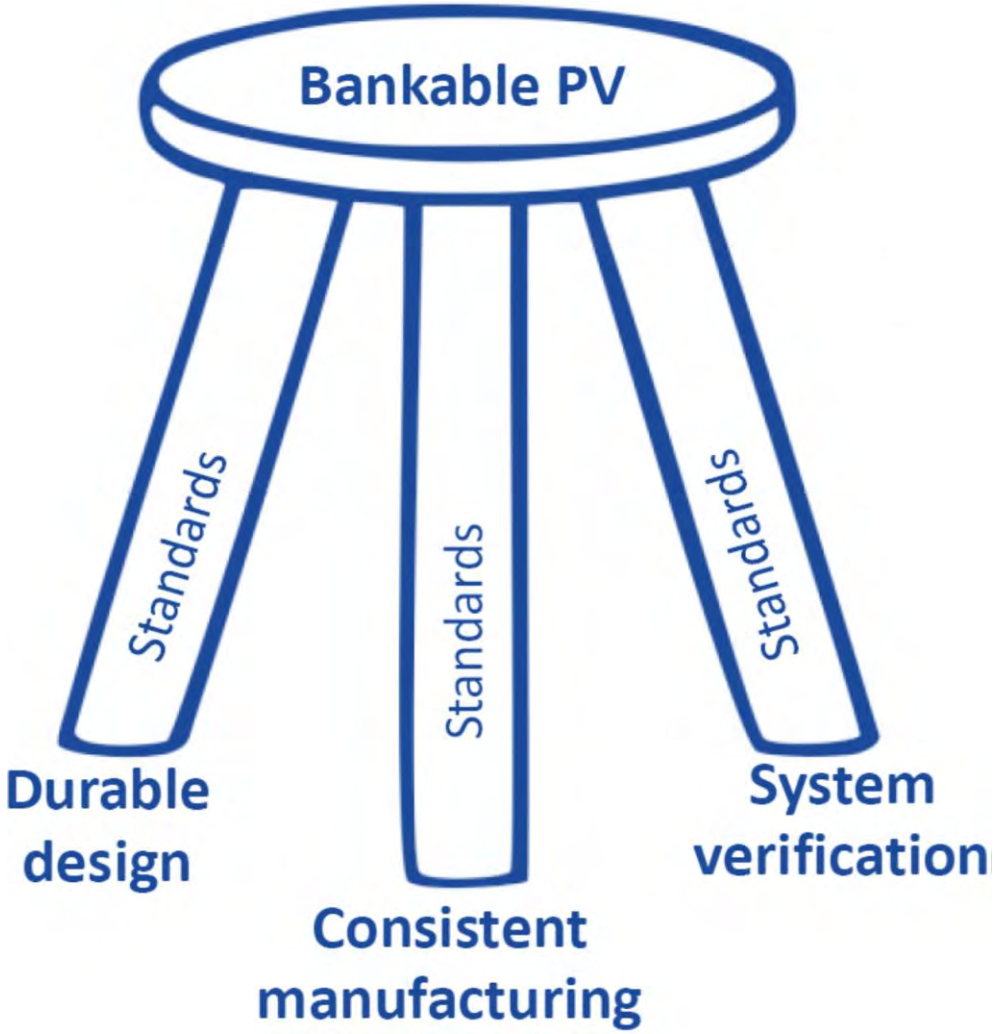
Tasks 13 + others

PVQAT: Approach to "Bankable PV"

- A rating system to ensure durable design of PV modules for the climate and application of interest.

- A guideline for factory inspections and quality assurance (QA) during manufacturing.

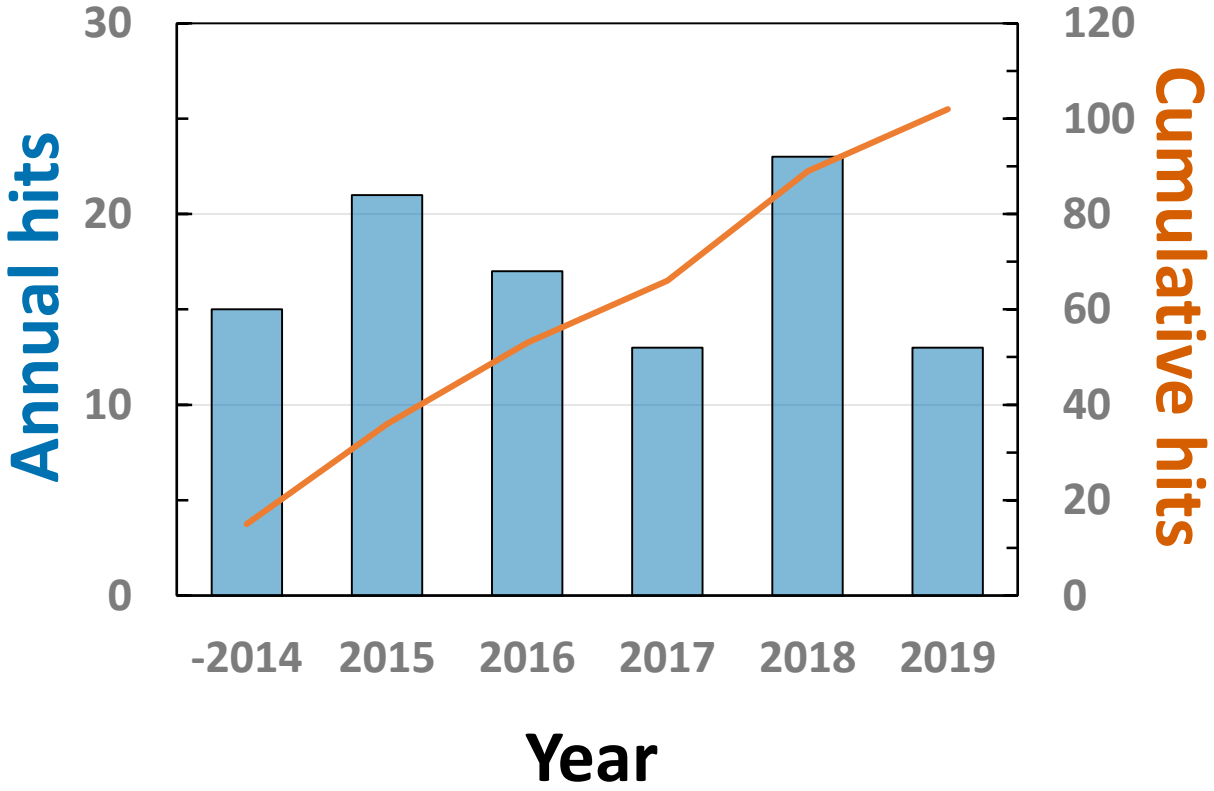
- A comprehensive system for certification of PV systems, verifying appropriate design, installation, and operation.



Penetration of “PVQAT” into PV Community & Society

“PVQAT”: Hits in Internet Search

Google Scholar



Patents / Cited Ref. are not Included

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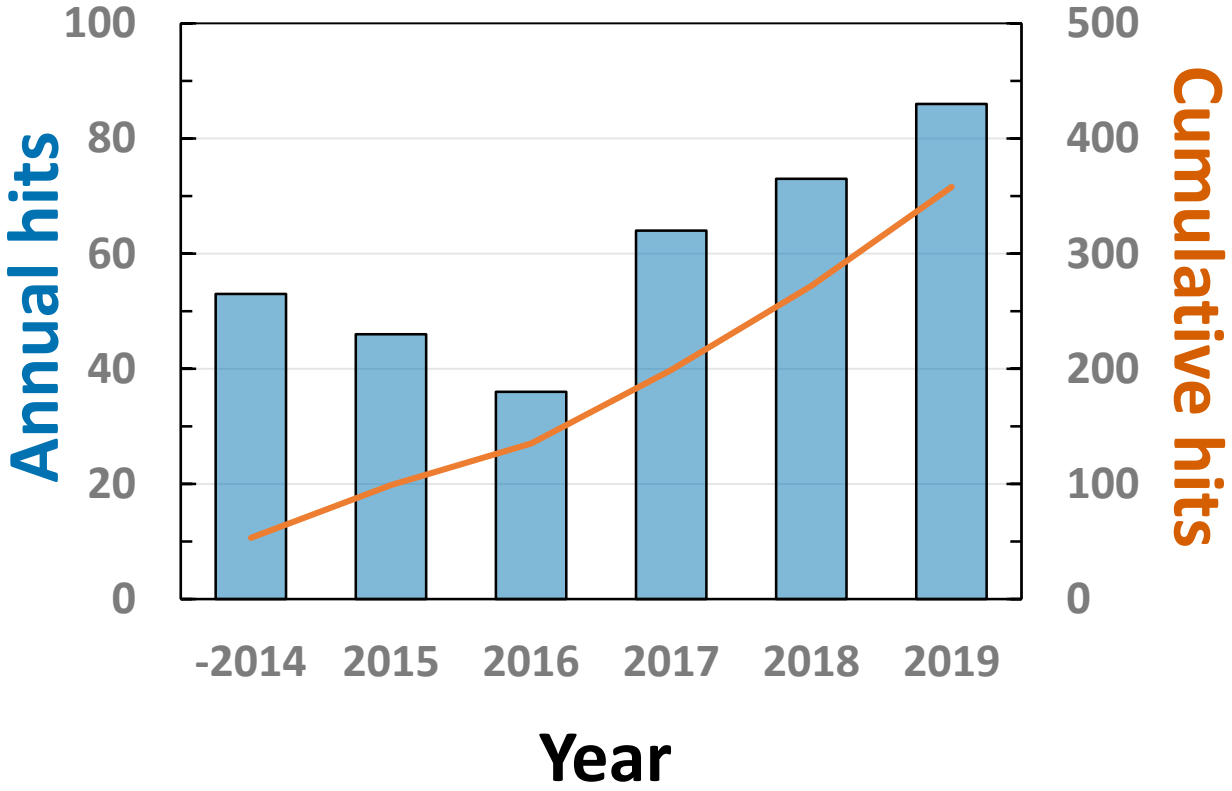
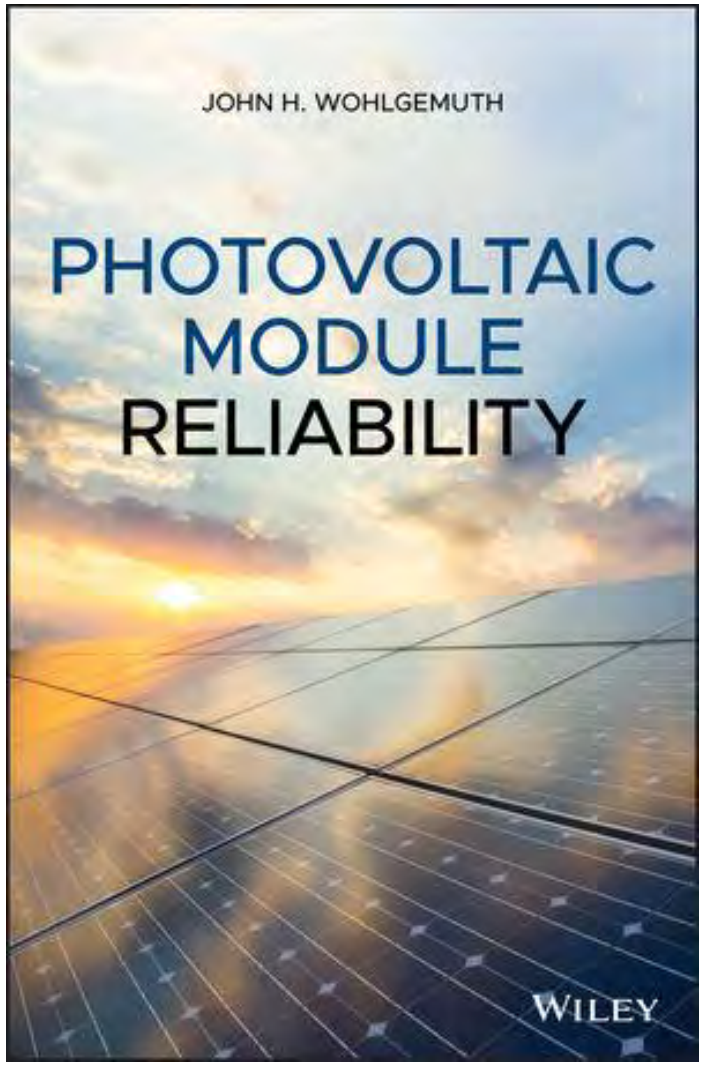


All Hits in Google (English)

Most Recent Topic



J. H. Wohlgemuth, "*Photovoltaic Module Reliability*", John Wiley & Sons, Inc., 2020.

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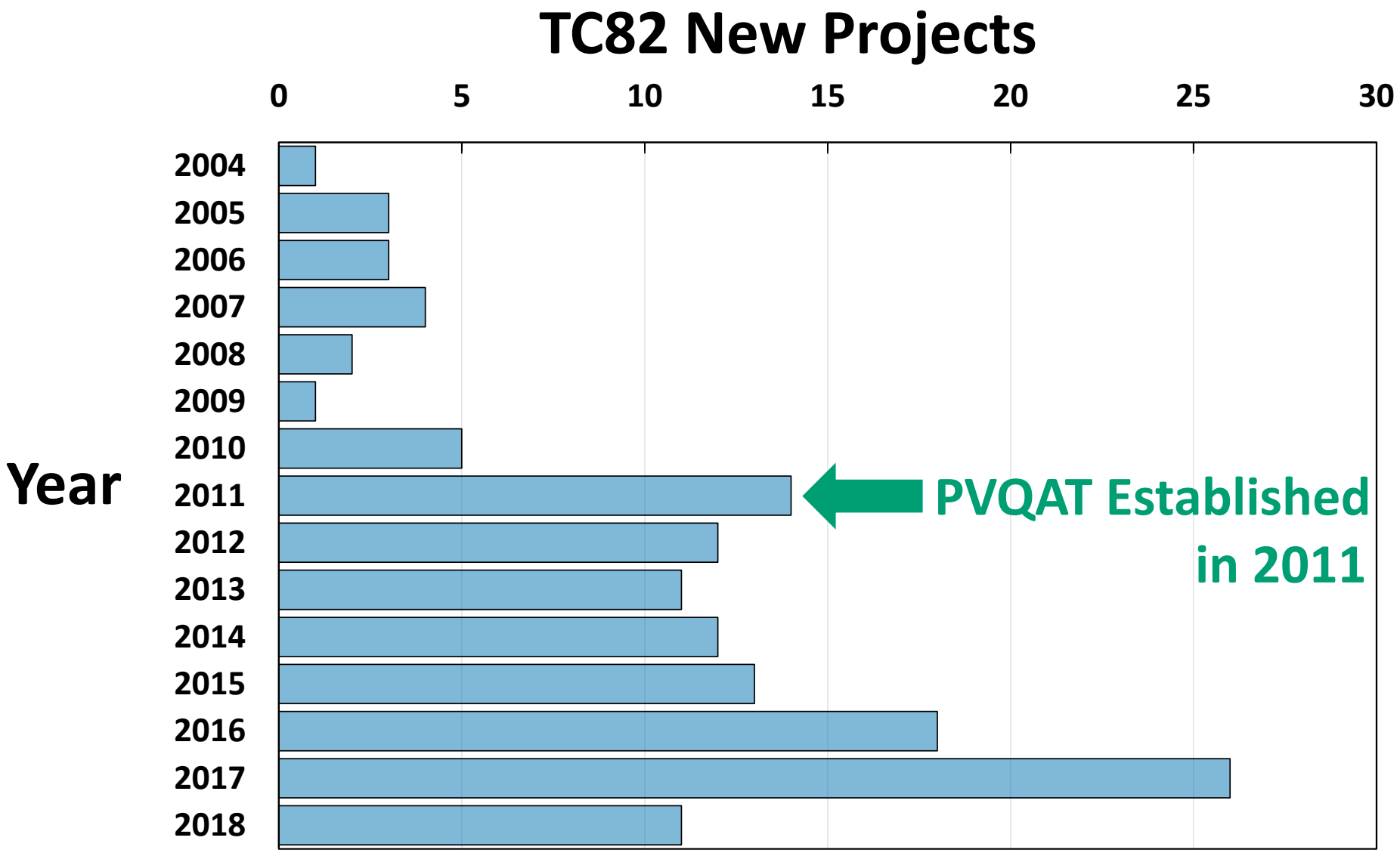
1 Introduction
2 Module Failure Modes
3 Development of Accelerated Stress Tests
4 Qualification Testing
5 Failure Analysis Tools
6 Using Quality Management Systems to Manufacture PV Modules
7 **The PVQAT Effort (pp. 165 – 194)**
8 Conformity Assessment and IECRE
9 Predicting PV Module Service Life
10 What does the Future Hold for PV and a Brief Summary

https://www.wiley.com/en-us/Photovoltaic+Module+Reliability-p-9781119459026

PVQAT: Contributions to IEC TC82 / IECRE



Courtesy of Tony Sample & George Kelly

PVQAT: Contributions to IEC TC82 / IECRE (1/3)

Task Group 1: Manufacturing Consistency

IEC 62941 (QMS Guideline) has been published in Dec. 2019

Task Group 2: Thermal and Mechanical Fatigue

IEC 62892 (ATC) has been published in Apr. 2019.

Task Group 3: Humidity, Temperature, and Voltage

Discussing on IEC TS 62804s & Combined Tests

Task Group 4: Diodes, Shading, and Reverse Bias

Contributed to IEC TS 63126 (High Temp.) through BPD Test Protocols

Task Group 5: UV, Temperature, and Humidity

- Interlaboratory studies for IEC 62788-1-7 (UV durability of encapsulants) and IEC 62788-7-2 (specimen temperature during weathering).
- Collaboration with IEA PVPS Task 13 (Subtask 1.1)

PVQAT: Contributions to IEC TC82 / IECRE (2/3)

Task Group 6: Communication (inactive)

Task Group 7: Snow and Wind Loading

Non-Uniform Dynamic Mechanical Loading Test is discussed.

Task Group 8: Thin-Film Photovoltaic Modules

IEC TS 63140 (Shading) has been approved to CD (July 2019)

Task Group 9: Concentrator Photovoltaic Modules (CPV) (inactive)

Task Group 10: Junction Box & Connectors

Discussing on the Connector Pair Assembly UCET Test

Task Group 11: System Verification and Power Electronics Testing

PE subgroup: IEC 62093 ED2 = Draft is circulating as 2nd CD.

PVQAT: Contributions to IEC TC82 / IECRE (3/3)

Task Group 12: Soiling and Dust

- Quarterly webinars on topics related to soiling of PV.
  Annual international soiling workshop
- TG12.3 contributes to IEC 62788-7-3 (abrasion test methods for solar devices)
- Collaboration with IEA PVPS Task 13 (Subtask 2.4)

Task Group 13: Cells

IEC 63202-1 <WG8: LID of c-Si PV Cells> has been published in June.

IEC TS 63202-2 <WG8: EL for c-Si PV Cells > is in Approved for DTS

TG13: Details will be presented by Qi Wang (Jinko)

- If I have missed any update, please let me know.

PVQAT

International PV Quality Assurance Task Force

PVQAT updates

- Topic 1: PVQAT Structure & Activities

- **Topic 2: Recent Topics in PVQAT Task Groups**

TG3 (Humidity, Temperature, and Voltage)

Contact: Peter Hacke. peter.hacke@nrel.gov

1. Standardizing Activities

- IEC TS 62804-1:2015 (PID in c-Si PV Modules): Stability Period is Extended to 2021
  Cited into IEC 61215s CDV (MQT 21)
- IEC TS 62804-1-1: 2020 (Delamination in c-Si PV Modules):
  Published in Jan. 2020
- IEC TS 62804-2 (PID in Thin Film PV Modules): in CD Stage (to DTS)
- IEC TR 63279 (Sequential / Combined Acc. Stress Test): DTR has been Approved (Feb., 2020)

Congrats!!

2. Under Discussion (Potential NPs)

- IEC TS 62804-1 New Edition (PID in c-Si PV Modules): Light-Irradiation Effects on PID
  New Cell Technologies (PERC/PERT...)
  Bifacial Modules (Front/Rear ± Light)
- Combined Accelerated Stress Test (C-AST):
- Economics of testing
- Future: compare field results to various test results.

Prep. of NWIP drafts:

Part 1: Climatic Chambers
Part 2: Stress Test Sequences
Part 3: Outdoor testing
Part 4: Conformal Requirements

TG5 “X” (UV+T+RH → UV Weathering of PV Modules & Materials)

- Members from including Americas, Europe, India, Asia....

  Contact: David MILLER David.Miller@nrel.gov

- Recent studies:

  -Optical durability of contemporary encapsulants (EVA, PO, …) for IEC 62788-1-7. *Volunteers needed*.

  -Specimen temperature during artificial weathering for IEC 62788-7-2. Compared to outside weathering. *Volunteers needed*.

- Recent meeting topics:

  -Embrittlement & cracking of backsheets.

  -Use of water spray during UV weathering.

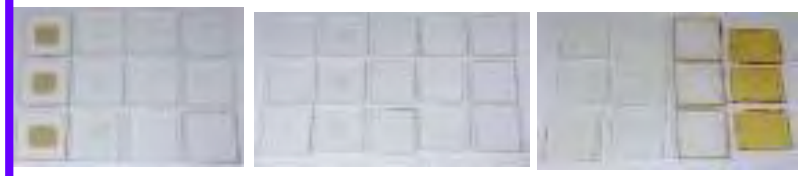
  -**Advanced accelerated tests**

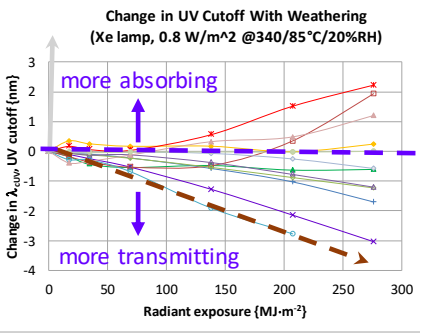
  (Anticipated 2020 focus)

  Accelerated aging test sequence, e.g., MAST at DuPont (DH→UV → TC).

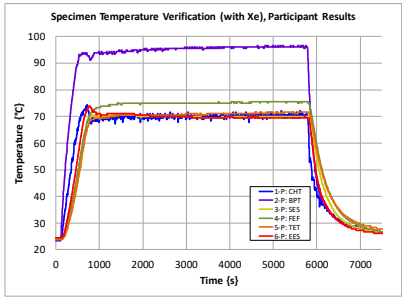
  Combined stress testing, e.g. Köhl et. al.

  Diurnal-based accelerated test sequence, e.g. C-AST at NREL





Series of images of the specimens after completing A5 weathering, shown with change in UV cut-off wavelength.



Configuration and data for verification of IEC 62788-7-2 method A3 weathering (Xe chamber).

- Recent publications:

Miller et. al., (TG5 Study 1: encapsulant optical durability), PIP, 27 (5) 2019, 391-409. paper: https://doi.org/10.1002/pip.3103 presentation.

Miller et. al., (TG5 Study 1: encapsulant strength of attachment), in press PIP..DOI:10.1002/pip.3255

PVQAT TG7 (founded on PVRW, 2018-March)

1. Leader: S.T. Hsu (Anderson), ITRI
2. Hold the web-meeting every two months
   - ➢ Last meeting (11)：2020-Feb-20
     - Round-robin test survey (ITRI)
     - The impact of non-uniform wind-load in single tracker (CanadianSolar)
     - Fastener loosening accelerated test (King Design)
   - ➢ Next meeting (12)：2020-April-30
     - TBD
3. Standardization in IEC TC82
   - Pre-NWIP (NP) stage：Photovoltaic (PV) Module – Cyclic (Dynamic) Non-uniform Wind Load Testing
   - Specifies three types of wind velocity (BS = 13, 15, 17) in terms of their test data (wind direction (β =0°, 180°), module tilt (α=10°-40°))

TG7 team: 46+ attendee, 31+ organization	
Taiwan	ITRI , King Design
USA	SunPower, SUNSET, UL, NREL, First Solar, Constellation, Matrix Engineering, Purdue University-Northwest, Lawrence Berkeley National Lab, Key Renewables, NEXTracker, UC Merced
Canada	Relsol
Germany	ZAE Bayern
France	ARaymond
Japan	AIST, Mitsui Chemicals, JET, Toshiba, TTI
Korea	KTL
China	CanadianSolar, Trinasolar, Yingli Solar, SUNGROW, SIMIT, Arctech Solar, Fujian Metrology Institute, Xiamen Institute of Products Quality Supervision and Inspection

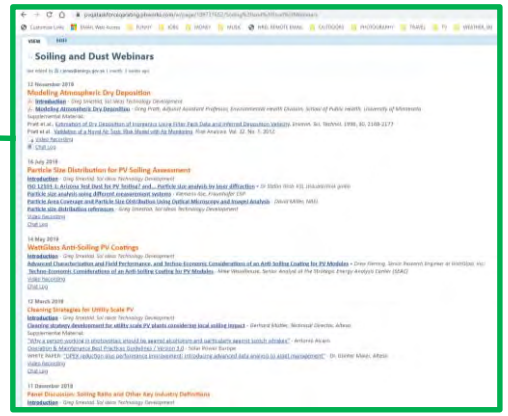
TG12 (Soiling of PV)

International PV Soiling workshop (all general topics)

- Annual in autumn.
- Contact: Lin SIMPSON <Lin.Simpson@nrel.gov>

Task Group 12 Webinars (all general topics)

- Quarterly webinars on soiling topics.
- Contact: David MILLER <David.Miller@nrel.gov>



Task Group 12-1 (sensors and the monitoring of soiling)

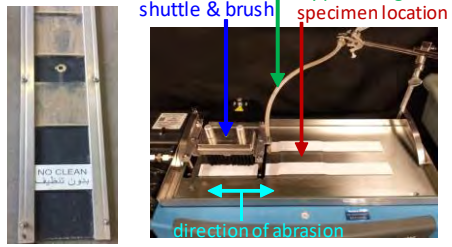
- Contributed to IEC 61724-1 (quantifying effect of soiling on PV systems).
- Interest in interlaboratory precision study.
- Contact: YuePeng DENG <Yuepeng.Deng@FIRSTSOLAR.COM>.

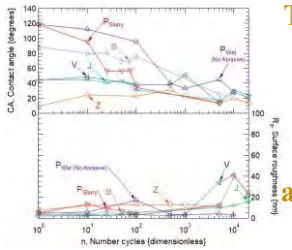
Task Group 12-2 (solutions for cleaning)

- Module cleaning best practices (manual & robotic methods).
- Reference: Einhorn et. al., IEEE J PV, 9 (1), 2018, 233-239.
- Contact: Lin SIMPSON <Lin.Simpson@nrel.gov>

Task Group 12-3 (antireflective and/or anti-soiling coatings)

- Focus on PV abrasion methods, developing: IEC 62788-7-3.
- References: Miller et. al., J PV, 10 (1), 2020, 173-180. (paper, presentation) http://www.nrel.gov/docs/fy16osti/66334.pdf
- Contact: David MILLER <David.Miller@nrel.gov>





The performance of field coupon specimens (top left) will be compared to artificial abrasion (top right and below)

Task Group 12-4 (modeling/analysis of effects of soiling on PV systems)

- Example soiling-loss & -rate from PV installation power production data.
- Reference: Deceglie et. al., Proc. IEEE J PV, 2018.
- Contact: Leo MICHELI <lmicheli@ujaen.es>

See: http://www.pvqat.org (PVQAT effort)

also: http://pvqataskforceqarating.pbworks.com (minutes, references, attachments, meeting recordings. Contact: David.Miller@nrel.gov)

TG11 PV Systems/ Power Electronics

Contact: Peter Hacke peter.hacke@nrel.gov

Focused on developing method for standardized testing to:

(1) stress testing the inverters and components fairly with respect to their efficiency at removing heat,

(2) evaluating critical components used in the inverter with respect to the components' ratings.

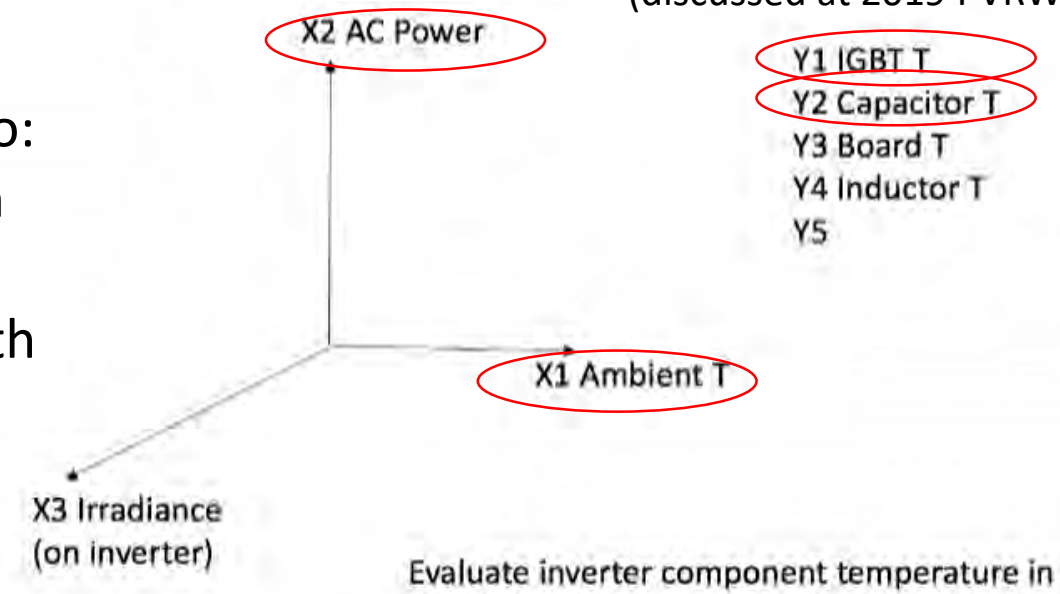
Down-selection of stress levels, factors, and critical components for such analysis in IEC 62093 ed 2 circled in red

IEC 62093 "Power conversion equipment for photovoltaic systems – Design qualification testing"

reached CD 2 stage Nov. 2019

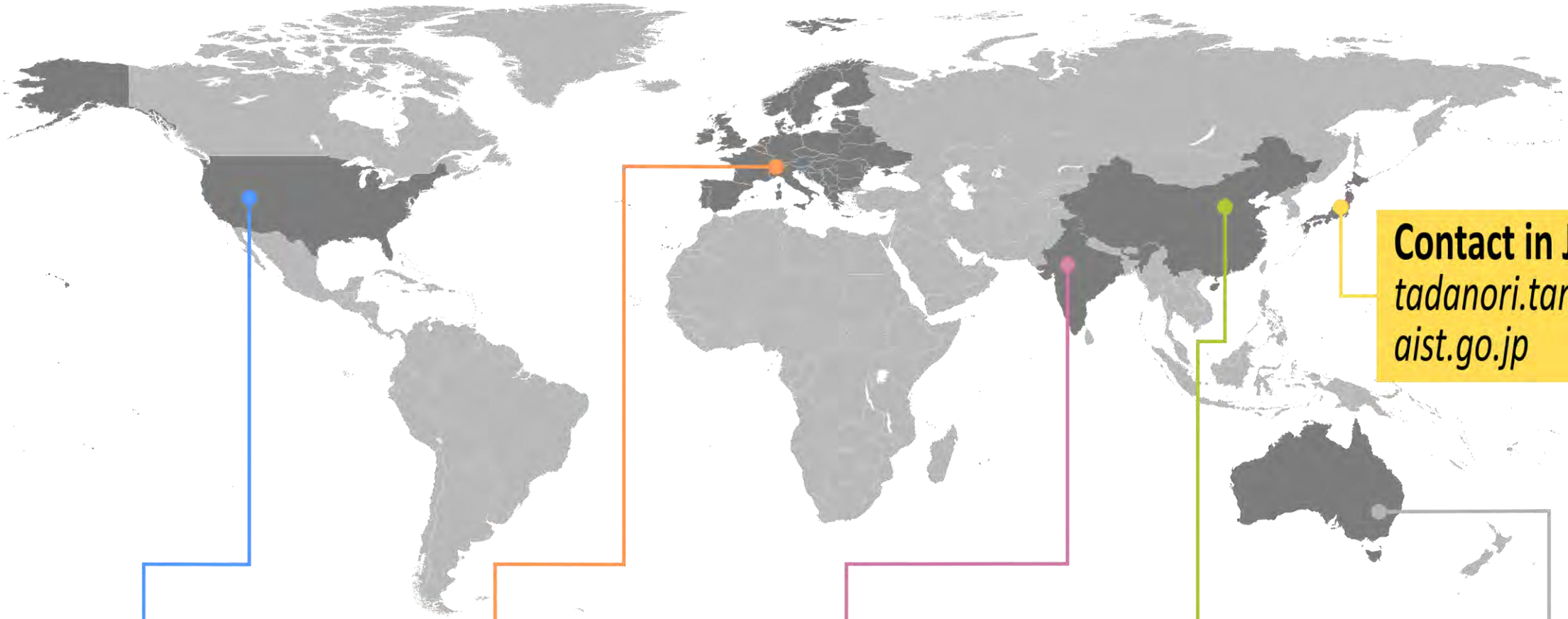
Interdependent Stress factors

Critical components Based on PVQAT TG 11 FMEA
(discussed at 2019 PVRW)



Evaluate inverter component temperature in operating regime, or regime space (Xs)
Measure Ys
Choose TC or dry heat upper temperatures based on the above

PVQAT: International Contact



Contact in Japan:
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Contact in Australia:
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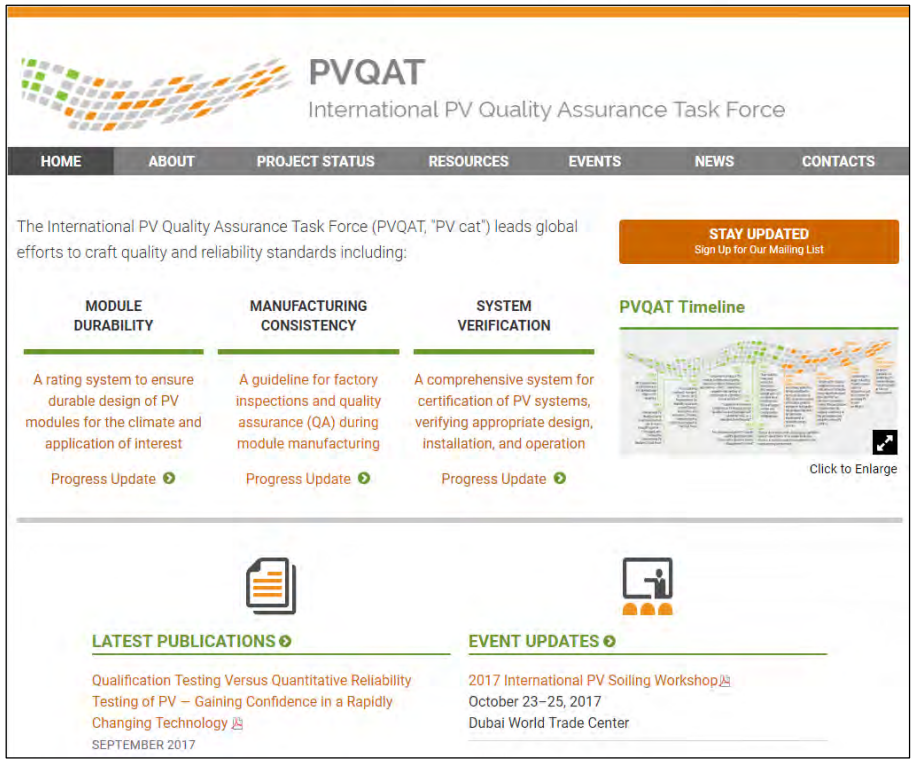
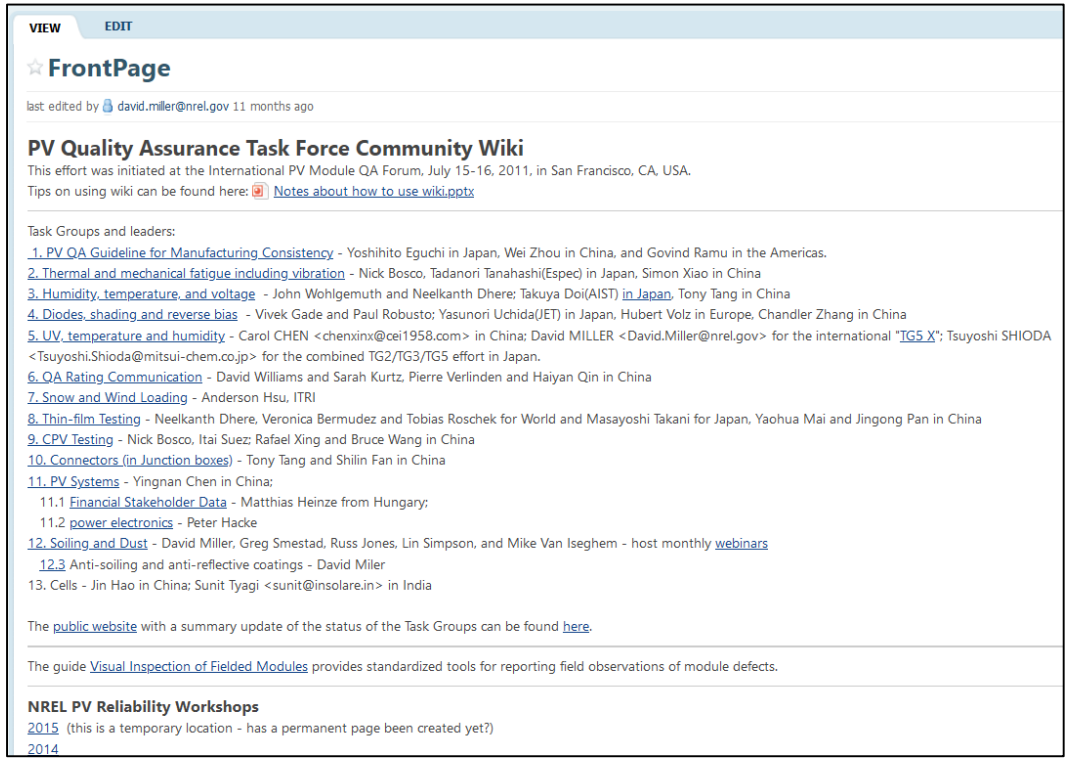
PVQAT

International PV Quality Assurance Task Force





PVQAT Web Site

http://www.pvqat.org/

PVQAT Wiki

http://pvqataskforceqarating.pbworks.com/

We are seeking volunteers

To volunteer for PVQAT, individuals may directly contact to TG Leader, according to http://www.pvqat.org/contacts/

PVQAT India Updates

Narendra Shiradkar, Anil Kottantharayil and Juzer Vasi

Assistant Professor & In-charge, PV Reliability Group,
National Centre for Photovoltaic Research and Education (NCPRE),
Department of Electrical Engineering,
IIT Bombay, India
Email: naren@ee.iitb.ac.in

Outline

- Rationale for PVQAT – India
- Reliability issues in Indian conditions
- Role and scope for PVQAT - India

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Why PVQAT India?

- India initially had a 20 GW by 2020 PV deployment target in 2010, then it was revised to 100 GW by 2022. Already deployed ~35 GW by 2019.
- New target under consideration is ~300 GW by 2030. Lot's of PV is about to come and there're lot's of fielded PV plants out there to learn from.
- Hot climate, cost sensitive market, deployment in harsh, inhospitable environments have been posing unique challenges to ensure reliability. New standards are needed to address them.
- IIT Bombay and Beauro of Indian Standards (BIS) have signed a MoU in 2019 to collaborate on standards development. PVQAT has been a successful model to quickly transfer research into new standards.
- Time difference makes it difficult for people from India to participate in regular PVQAT calls and there are some unique issues which may not fall under any of the existing groups of PVQAT. Therefore, a separate group of volunteers – PVQAT India is created.

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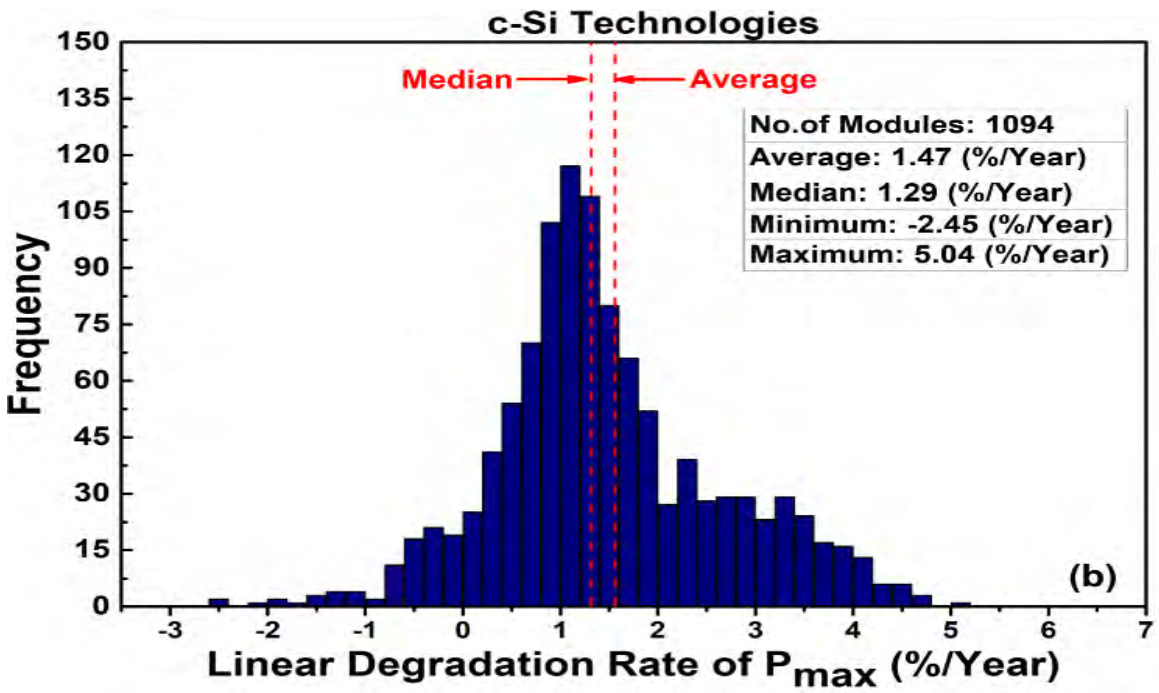
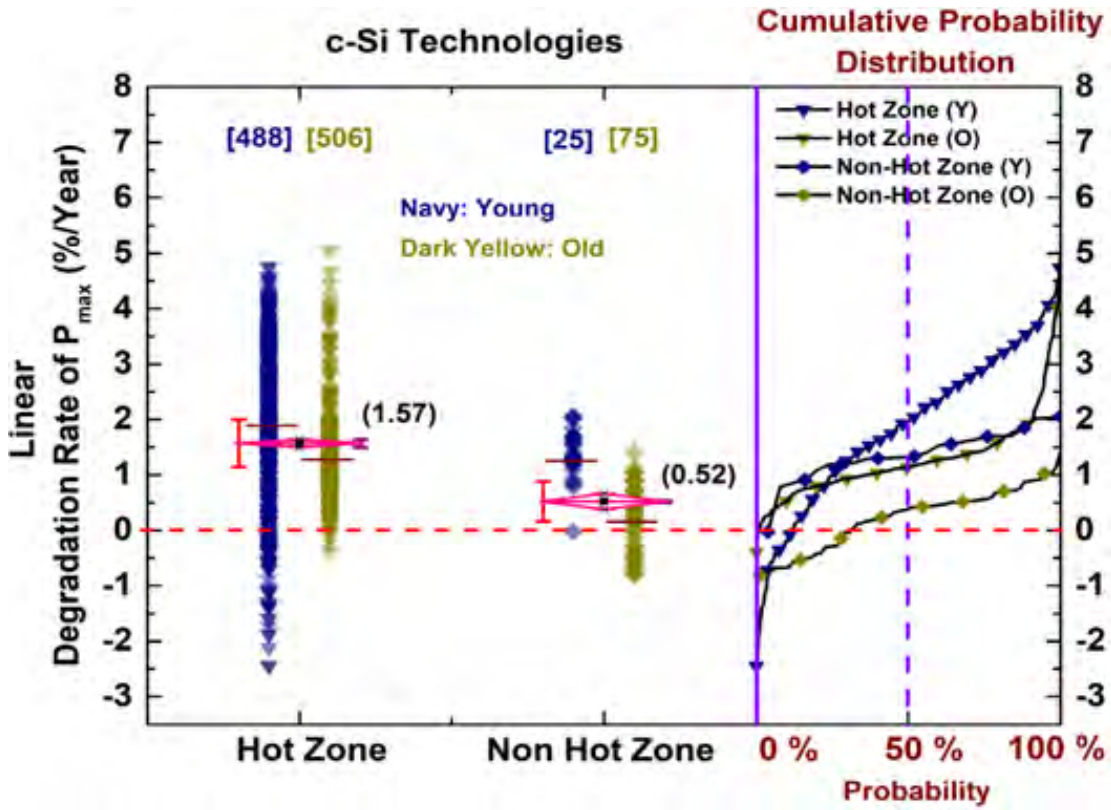
Degradation Rates in India: AIS 2018

Module Degradation Rates from All India Survey (AIS) of PV Module Reliability 2018 by NCPRE

LID Discounted Degradation Rates



Hot Climate Effect



System Performance Loss Rate would be even higher!

Source: http://www.ncpre.iitb.ac.in/ncpre/research/reports.html

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Combination of Factors Leading to Unique Issues

- Hot Climate
- Cost Sensitive Market
- High Soiling
- Scarcity of Water
- Harsh Microclimates: Pollutants in Air, Floods, Cyclones, Salty Land..
- Transportation and Road Quality
- Wildlife

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The Need for Standards Specific to Indian Conditions: An Example

- Currently, there's no standard for testing whether the water on-site is suitable for cleaning the PV modules.
- Option 1: Use whatever water available on-site (typically from bore wells)
- Option 2: Use whatever closest standard available for qualifying the quality of on-site water for PV module cleaning.

Option 1: Effect of Cleaning with Unsuitable Water

Option 2: BIS Standard: IS 10 500: 2012

- It's a drinking water standard!
- If the on-site water fails, the suggestion is to install RO plant.
- In already water-scarce environment, an RO plant would waste 4 liters of water for every liter it cleans.
- Significant waste of scarce resource and high cost
- Doesn't help to paint picture of PV as a 'green' technology especially in areas where water is scarce.

Courtesy: PV Diagnostics

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Soiling: Severity & Extent of the Problem

Example 1

Soiling is intense and the dust is fertile!

Example 2

Soiling is so bad that shading is not a problem anymore!

Both pictures are from Mumbai and indicate that mitigation of soiling losses is one of the highest priorities for the success of PV in India

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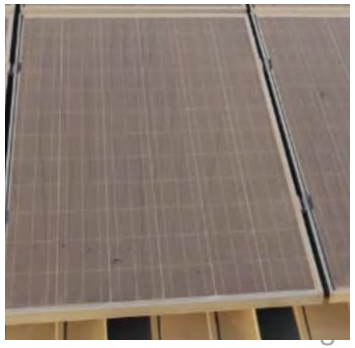
Soiling: Effect of Microclimate

- Several companies involved in coal based power generation chain have been given mandate to deploy certain amount of PV capacity.
- PV plants are often setup in already available land next to coal based power plants / mines.
- Coal ash from power plants / dust from mines is known to significantly aggravate the problem of soiling.
- Some of these plants require daily cleaning, thus significantly increasing the O&M costs.
- PV plants deployed in industrial areas have been known to face issues of staining on the glass due to pollutants in the air sometimes.



Iron containing dust led to permanent red staining

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Soiling: Solutions and Further Problems

Vertically Mounted Bifacial Modules

Advantages:

- Negligible soiling loss
- Flattening the 'afternoon peak'
- Good for borders and facades

Challenges:

- Row to Row shading
- Difficulty in implementing for large plants / rooftops
- Enhanced structural requirements due to higher wind loads

Robotic, Waterless Cleaning

Advantages:

- Faster cleaning
- Saves water
- Saves man hours of O&M team
- Scalable to large PV plants

Challenges:

- Standards for Assessing the effect on Module Reliability are needed
- Evaluating Cleaning Efficacy
- Difficult to use in small rooftops

Anti-Soiling Coatings

Advantages:

- Potentially a low cost solution
- Potential savings in water

Challenges:

- Short life of Coatings
- Standards and Durability tests for coatings are needed

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Factors Leading to Cell Cracks

- In All India Survey of PV Module Reliability 2016, it was found that the cell cracks were responsible for higher performance and reliability issues seen in rooftop mounted & small systems.
- Cell cracks in modules are often attributed to improper transportation, handling and installation.
- Training personnel is certainly helpful but it's not sufficient for eliminating this problem because of the often encountered floating nature of contract labor used in the PV installation / transportation.
- Moreover, in some parts of the world, relatively heavy wild animals (such as monkeys) are known to sit / slide on the PV modules. This can lead to cracks no matter how much amount of care is taken during transportation, handling and installation.

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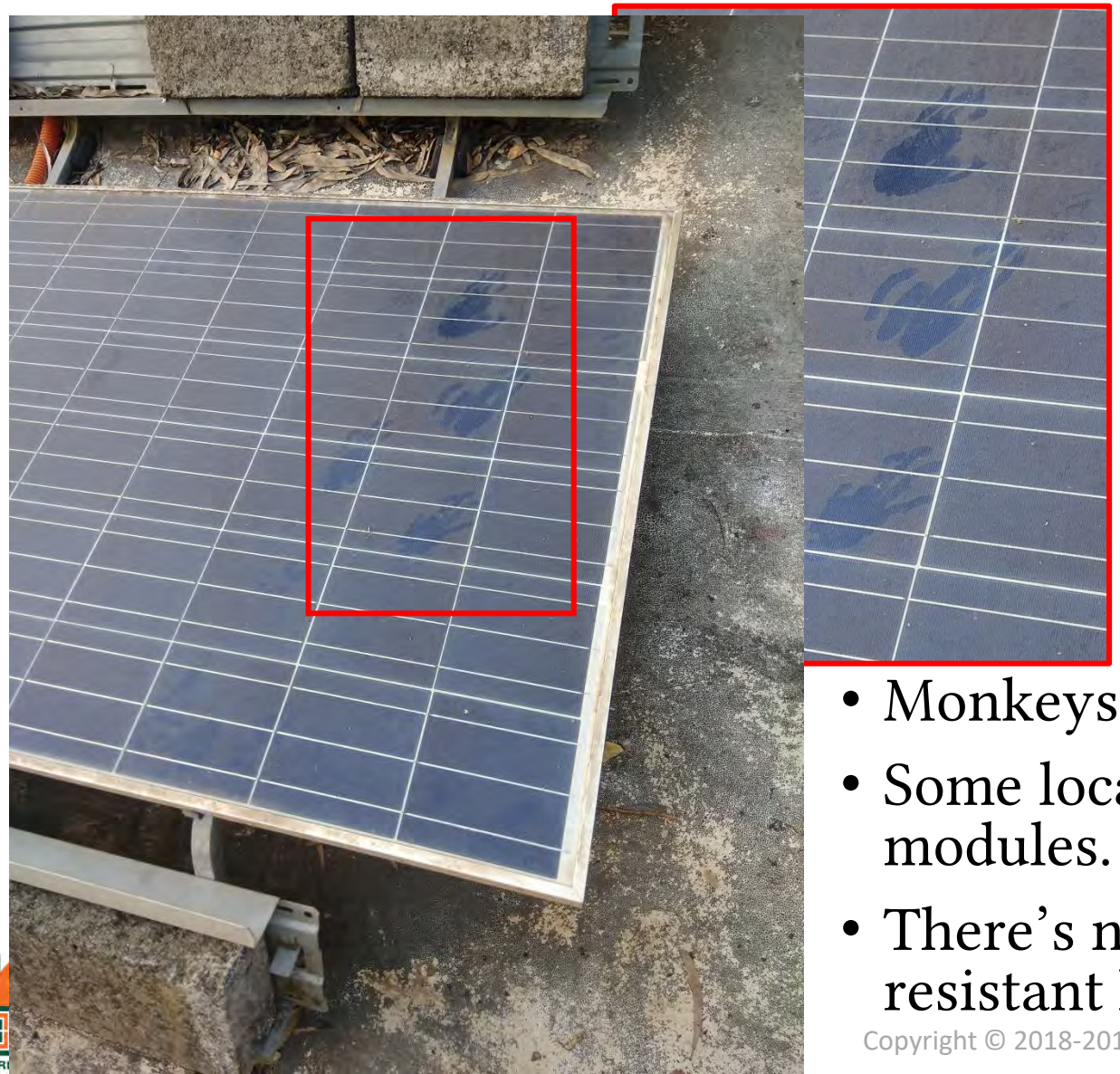
Motivation for Crack-Resistant PV Modules



- Monkeys on PV Modules (Mumbai)
- Some locations may demand crack-resistant PV modules.
- There's need for a test that can identify crack-resistant PV modules in a trustworthy manner.

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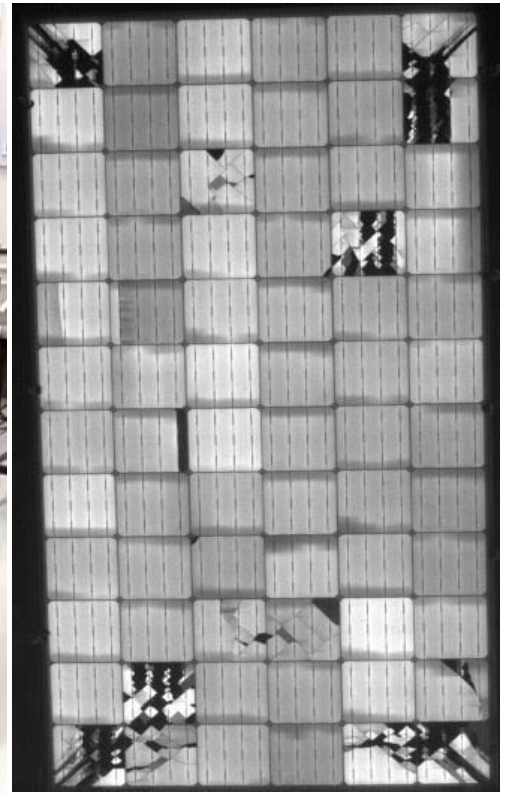
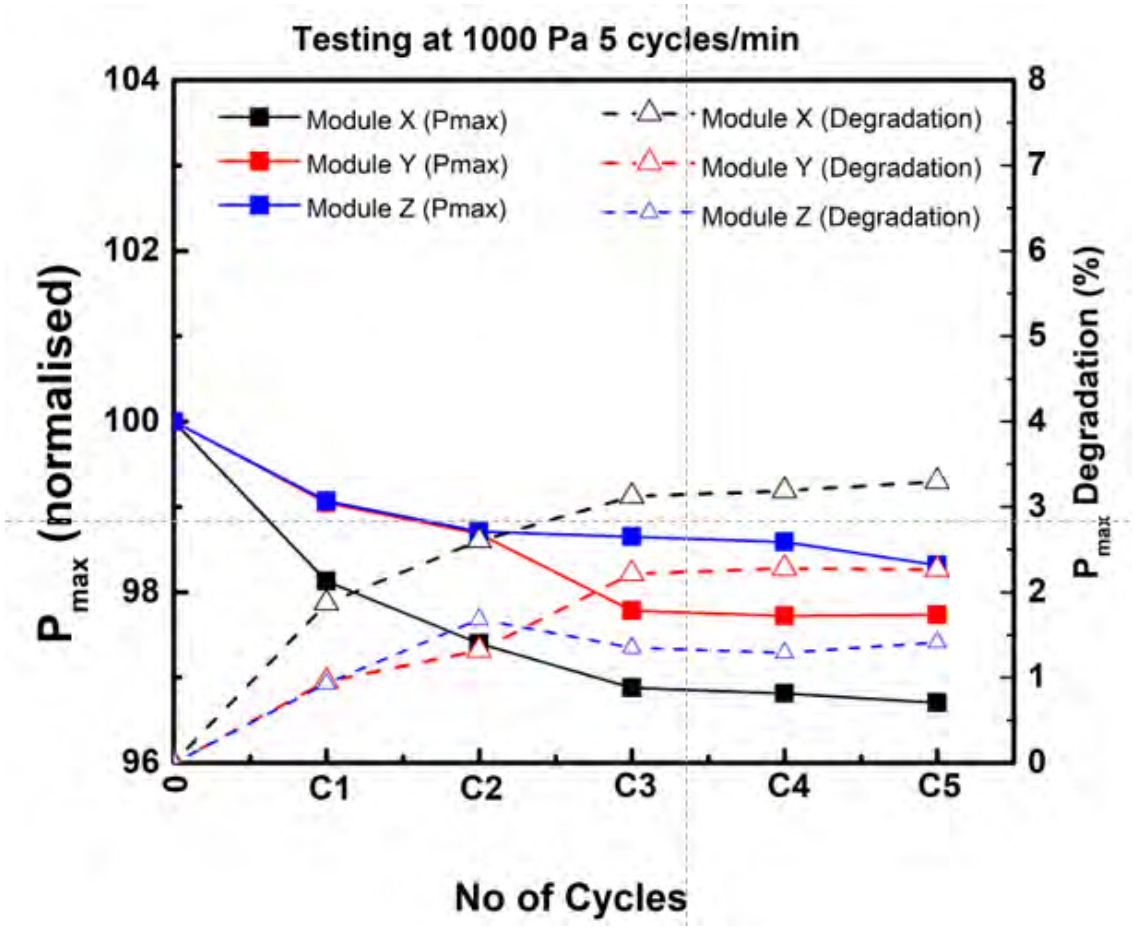
Accelerated Test for Predicting Worst-Case Power Loss from Cell Cracks





Goal: A standard for predicting worst-case power loss from cell cracks

Current status: An accelerated test involving customized DML cycles has been demonstrated that can result in maximum power loss from cell cracks.

Courtesy: Rajiv Dubey (PhD Student, IIT Bombay)

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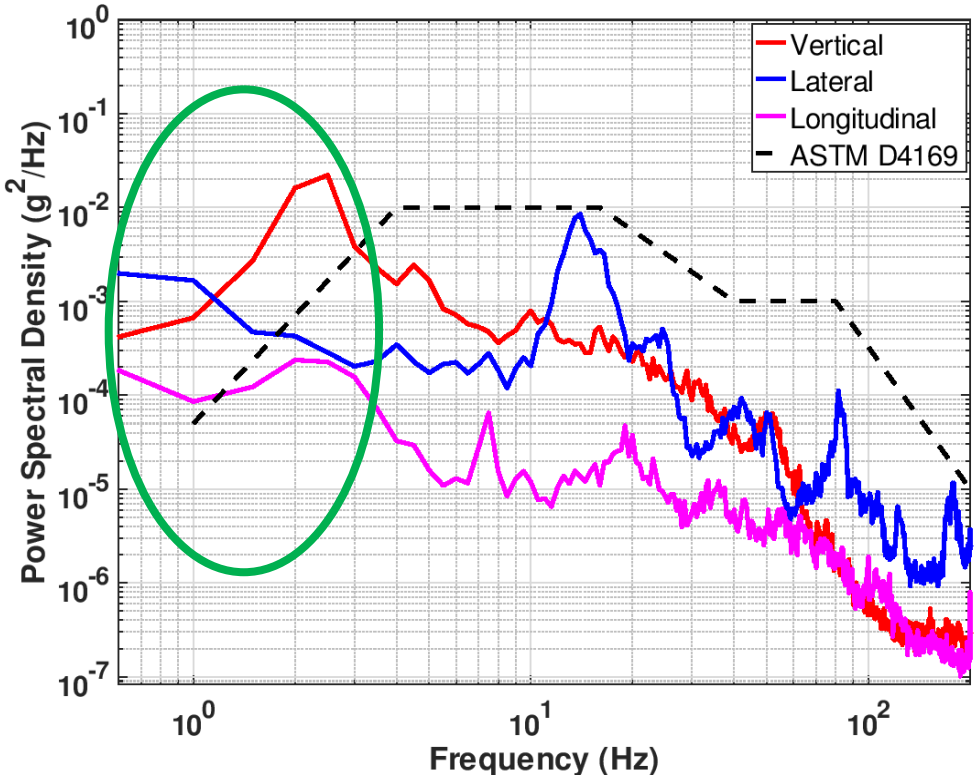
Effect of Road Conditions



- It has been shown through data collected on trucks carrying PV modules that the vibration profiles experienced even on the best Indian roads can be more severe than those given in ASTM D4169.
- A more realistic vibration stress profile representative of Roads should be incorporated in the standard.
- Also, there's need to have a standard and vibration test capability that can simulate effect of transportation on representative roads.

Courtesy: Devan P. V. (MS Student, NCPRE, IIT Bombay)

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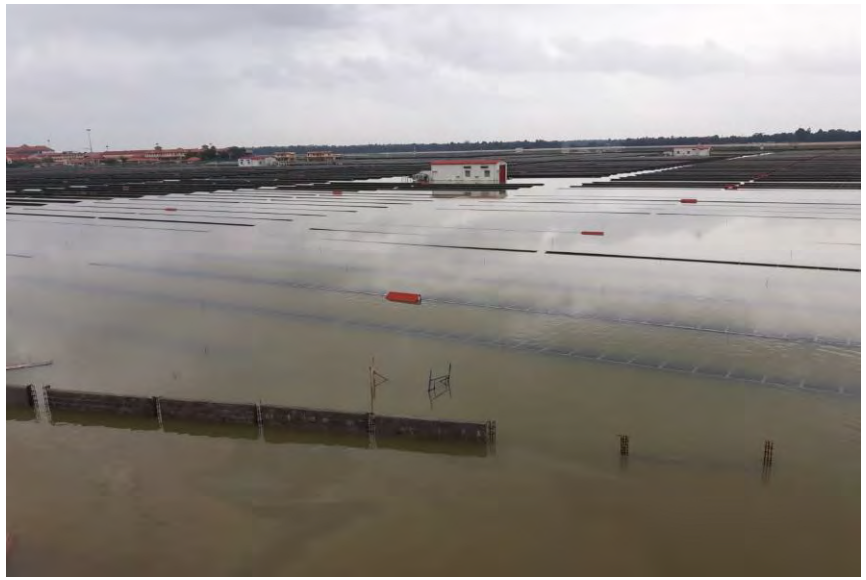
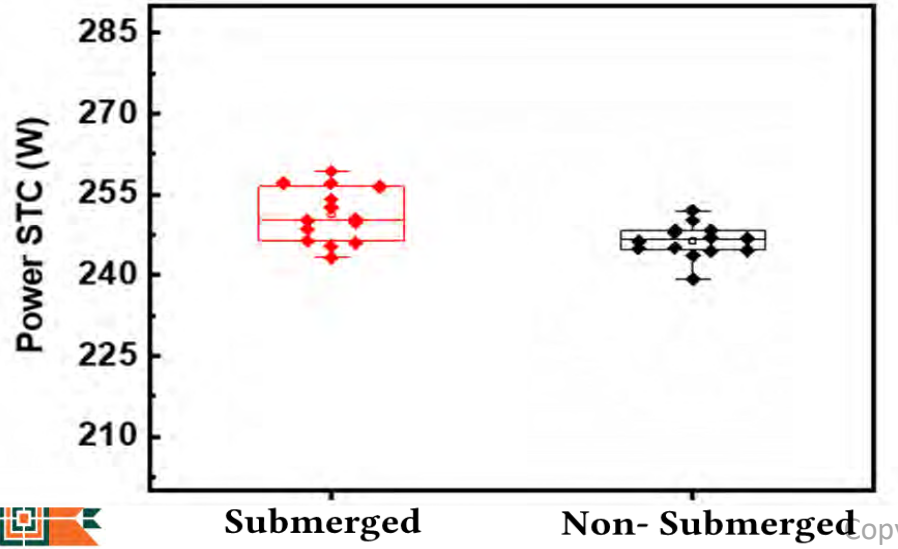
IP Rating for PV Modules – Submersible Modules at No Additional BOM Cost?





- Modules Submerged in 1-3 feet of water for 2 days.
- Junction Boxes – IP 67 rated with pottant.
- Negligible Jbox failures were observed for submerged modules.
- Negligible degradation was observed for submerged modules.
- Some of the existing modules may actually pass the IP 67 rating without any changes in BOM!

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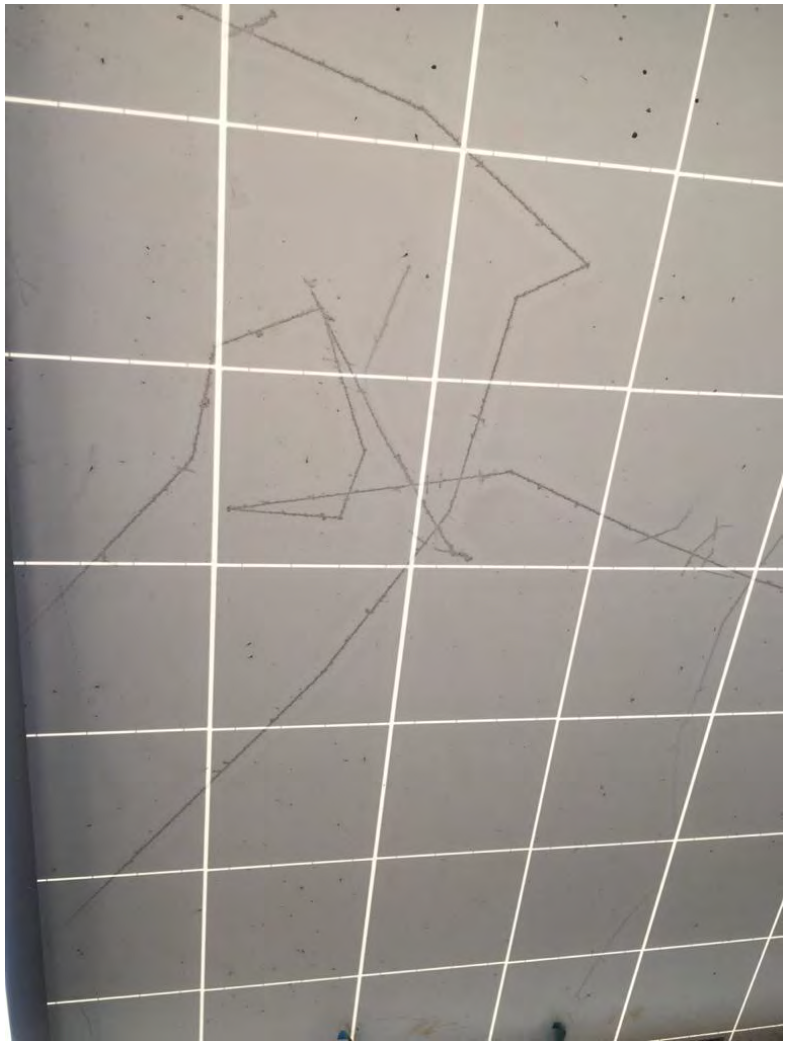
A New Backsheet Degradation Mode?



- Mysterious marks were seen on backsheets for a site in Mumbai (Tier 1)
- Marks disappear when the backsheet is wiped with damp cloth, but reappear after few days (they don't leave noticeable residue on cloth when 'cleaned')
- Now seen at 2 more sites in India in humid climatic locations.
- All sites are 1-2 year old!

Courtesy: PV Diagnostics

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Target Areas for Research & New Standards

- Hot climate effects on PV reliability (e.g. IEC TS 63126)
- Reliability Evaluation of Anti-Soiling Coatings
- Simulating the Effect of Transportation on Typical Roads
- Accelerated test for predicting worst-case power loss from cell cracks
- IP rating for PV modules (to identify submersible PV modules)
- Thermal cycling, high temperature reverse bias operation tests for bypass diodes.

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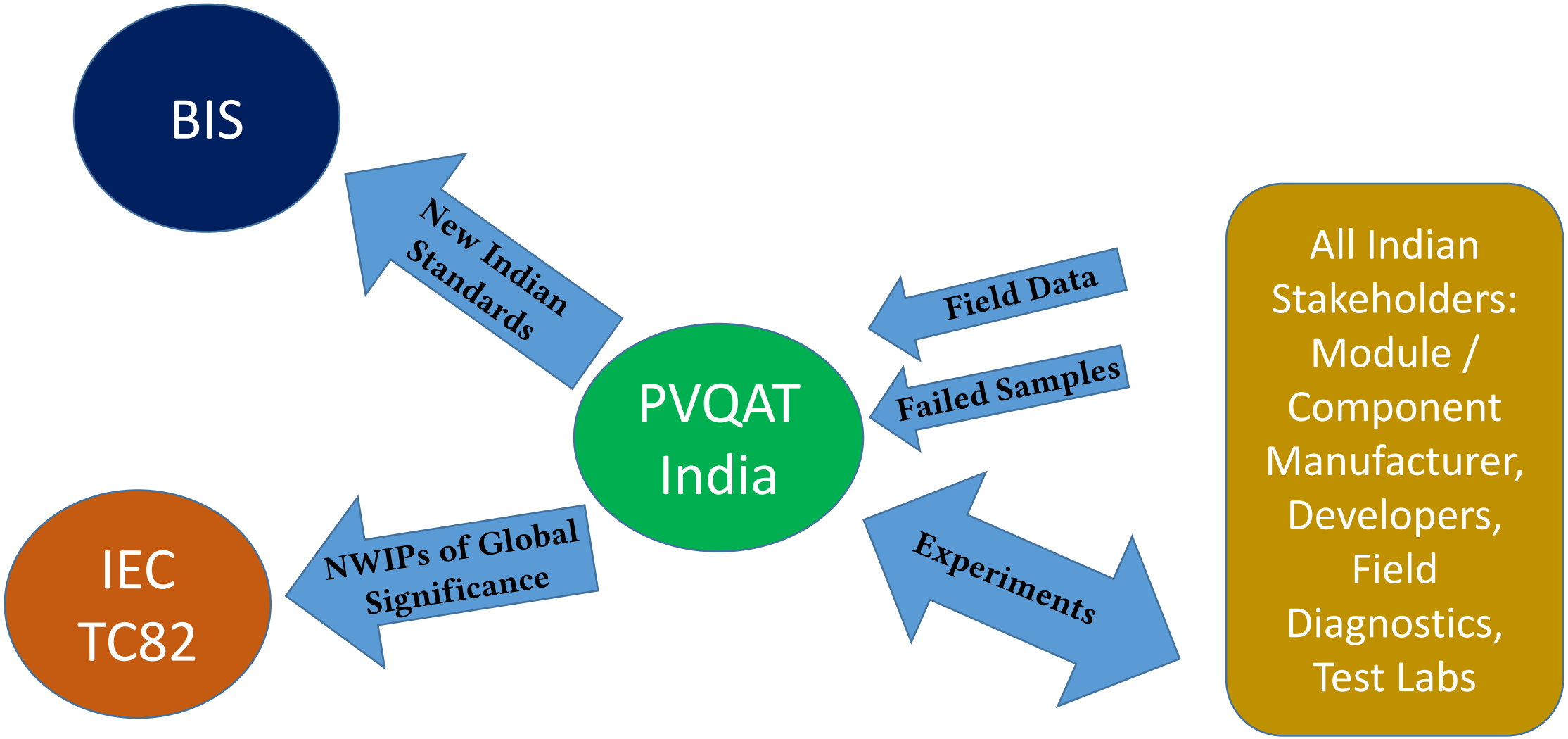
Identification of New Issues and Development of New Standards



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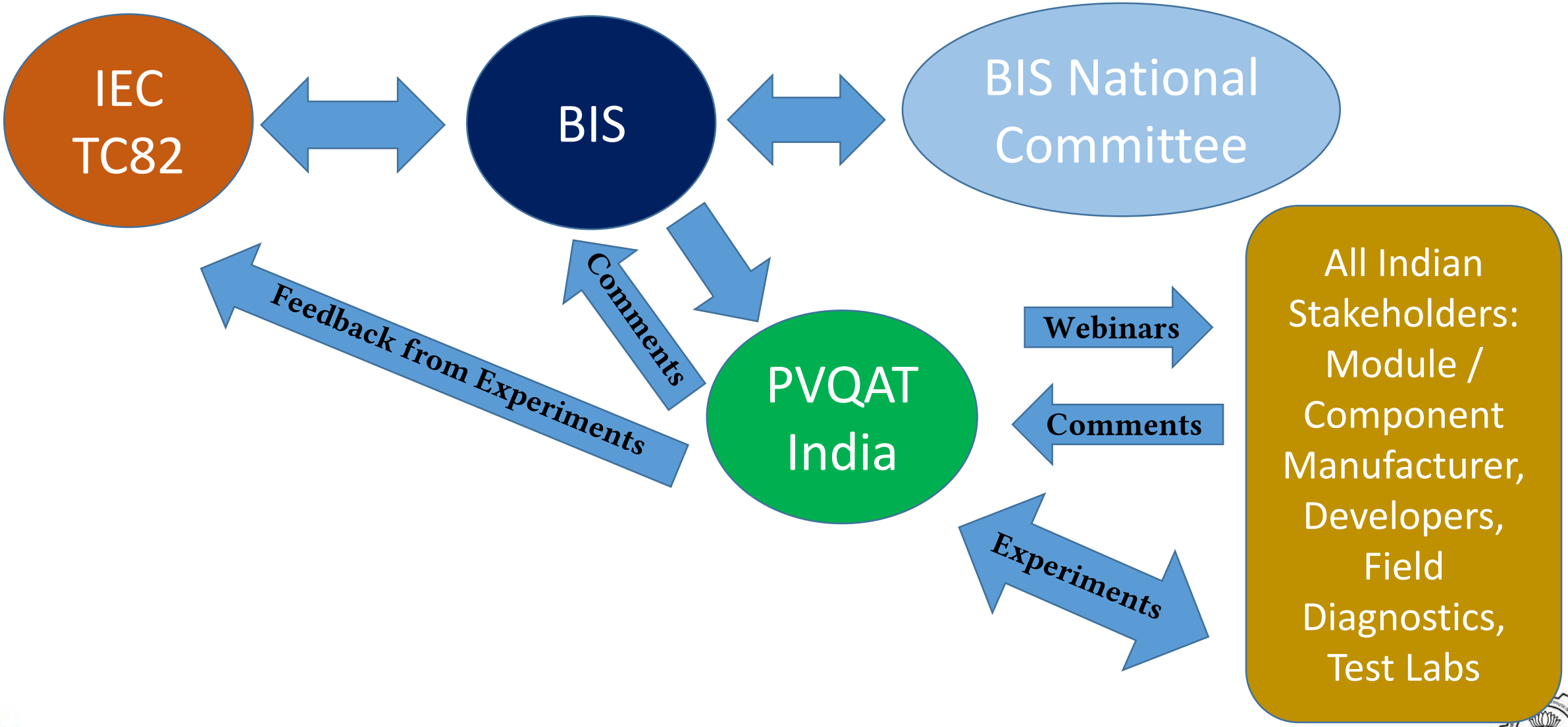
Sensitization to Upcoming IEC Standards and Acquiring Feedback



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Role of NCPRE / IIT Bombay in PVQAT India

- IIT Bombay – established in 1957 and consistently ranked #1 in India.
- NCPRE – A center founded in 2010 with funding of ~$15M by MNRE at IIT Bombay working in wide areas related to PV.
- NCPRE, IIT Bombay would lead the research necessary to generate data for new standards. It would also gather field data of failures and other issues from the stakeholders.
- Resources from test labs and module manufacturers part of PVQAT India would be used for generating baseline data for upcoming standards whenever required.
- Dissemination of new standards in making and acquiring feedback from Indian stakeholders.

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Work Updates

- IIT Bombay and Beauro of Indian Standards (BIS) signed an MOU in 2019 to collaborate on standards development (not just limited to PV).
- IIT Bombay hosted a workshop for Indian stakeholders on December 2, 2019 titled: "Accelerating the Research and Data Driven Standards Development for Improving Quality and Reliability of PV".
- About 25 people from industry participated.
- The Idea of PVQAT-India was presented to the stakeholders and it was greatly appreciated.
- Since then, we have begun monthly conference calls.
- We can have a call every quarter for PVQAT personnel outside of India at a convenient time where updates would be provided.

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To Summarize.. Objectives – PVQAT India

- Identify the issues in India that are not addressed by existing standards.
- Collect data from field and perform targeted research to generate useful data to guide the development of new standards / accelerated tests.
- Develop new drafts of standards at domestic (BIS) level, while the issues that are of global interest can be taken up at IEC level.
- Sensitize and update the Indian stakeholders on the relevant IEC drafts under making and collect feedback from them, which would be sent to IEC through BIS.
- Leverage the expertise in PVQAT to accelerate the standards development for PV in India.

Please reach out to me (naren@ee.iitb.ac.in) if you would like to share insight / data from your experience of PV related issues in India.

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Development and Researches of PVQAT TG13

Qi Wang, Ning Li, Lin Zhang, Xinyu Zhang, and Jin Hao

R&D Center, Zhejiang Jinko Solar

NREL PV Reliability Workshop
February, 26, 2020, Lakewood, CO USA

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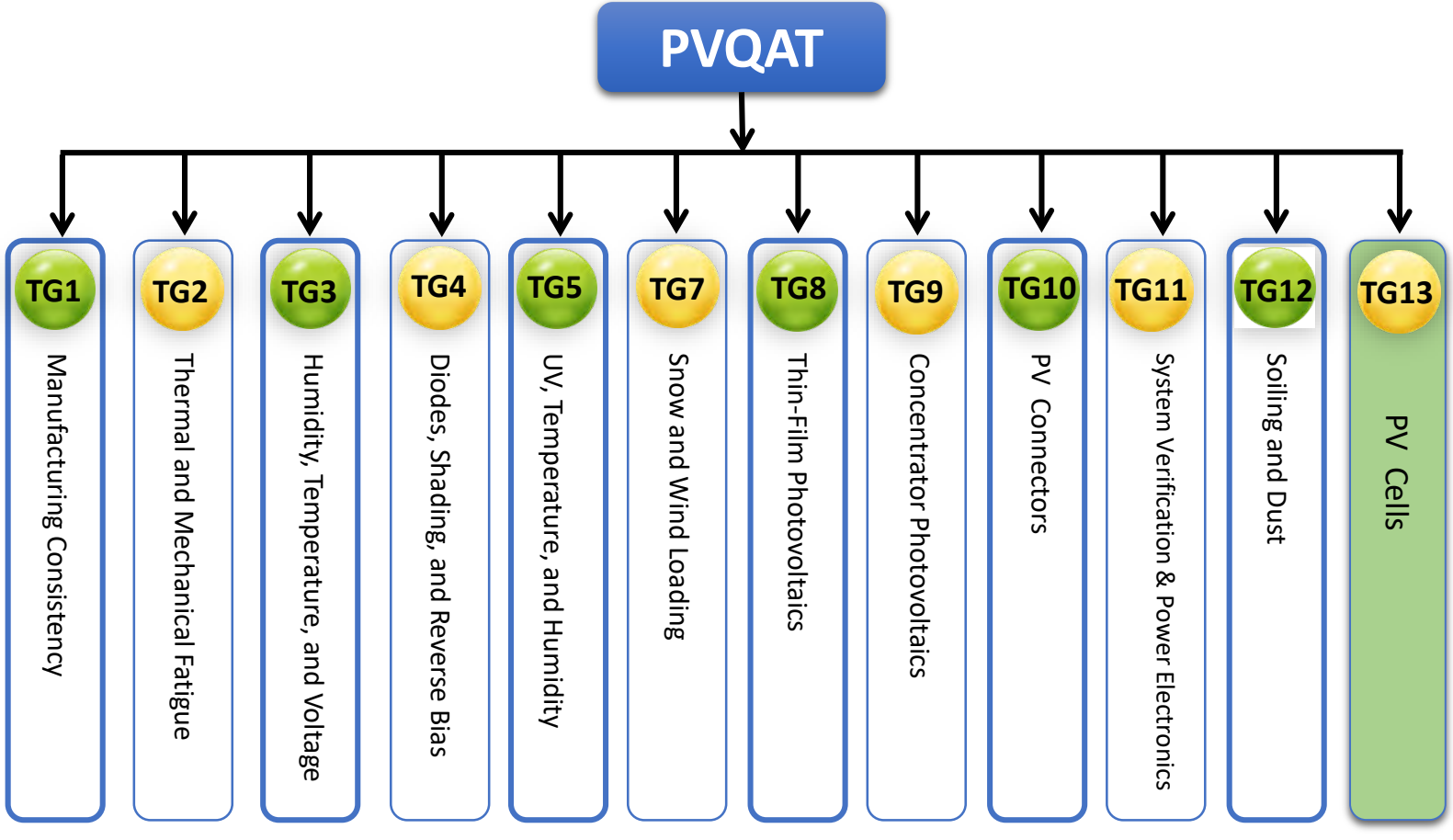
1 PVQAT TG13 Introduction

2 Research of TG13

3 Next meeting of TG13

1. PVQAT and TG13 Introduction

The Photovoltaic Quality Assurance Task Force (PVQAT) leads global efforts to craft quality and reliability standards for solar energy technologies



Leaders:

Jin Hao (CN)

Sunit Tyagi (IN)

1. Members of PVQAT TG13

No.	Company	Name	No.	Company	Name
1	Jinko	Hao Jin	12	CECEP	Xianfang Gou
		Xinyu Zhang			Su Zhou
2	Yingli	Dengyuan Song			Weitao Fan
		Feng Li	13	Risen Solar	Hongxing Cui
		Jinchao Shi	14	Chint New	Yurong Lu
3	UL	Liang Ji	15	JA Solar	Xinwei Niu
4	SPIC	Zhi Zhang	16	TÜV Rheinland	Gang Zhou
5	GCL	Yuepeng Wan	17	Suntech	Rulong Chen
		Chun Zhang	18	Inventec	Chialung Lin
		Jian Sheng	19	NSP	Andy Chueh
6	Trina	Yifeng Chen	20	Gintech	Chung-Chi Liau
7	SIMIT	Zhengxin Liu	21	Tainergy	Sid yang
8	SYSU	Xuemeng Wang	22	Semilab	Li Huang
9	Akcome	Yanqing Ge	23	CCIC-CSA	Qiang Jiang
		Haitao Huang	24	Zhonghuan	Xiang Li
10	Talesun	Zhichun Ni	25	Huansheng	Bin Li
		WEI Qingzhu	26	Jolywood	Guixiang Zhu
11	Canadian	Fangdan Jiang	27	Intertek	Hanao Gu
		Tao Xu	28	Lerri	Hua Li
		Guangchun Zhang			

International

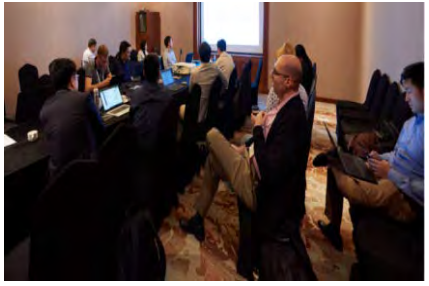
National

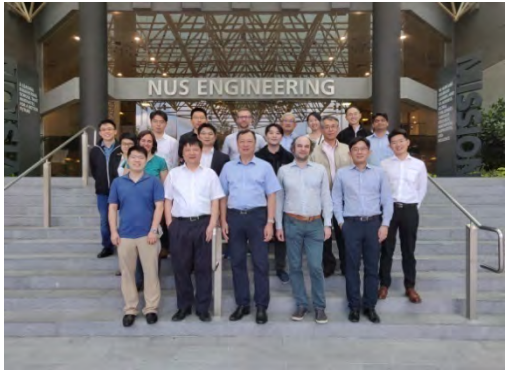
No	Name
1	Gilles Arnoux
2	Krishnamurthy Chalapathi
3	Vahid Fakhfouri
4	Tim Graham
5	Kazutaka Iwamoto
6	Bengt Jaeckel
7	Dominika Radacki
8	Eric Schneller
9	Anfrew Tay
10	Paul Robusto
11	Sarah Kurtz
12	Vikrant
13	M Koentopp
14	Corrales Asociados
15	Cheien Tony
16	Elias Urrejola

1. Meetings

This meeting held with IEC TC 82 WG8.

- **Held**
  - **Oct, 2018 – Busan, Korea**
  - **June, 2019 – Shanghai, China**
  - **Nov, 2019 – Singapore**
- **Planned**
  - **April, 2020 – Australia**
  - **TBD, 2020**

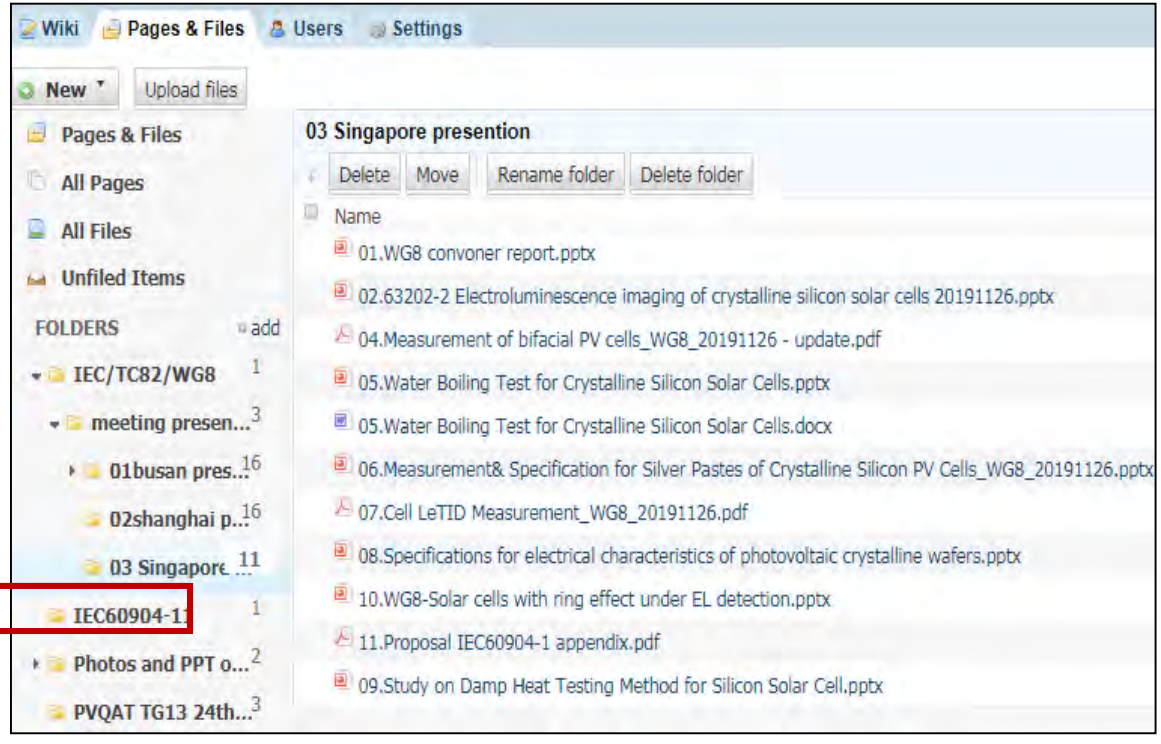




1. Standards Files and Presentations

All the information had been updated to the website.

- website: www.pbworks.com
- workspaces: **iectc82wg8.pbworks.com**
- Latest meeting had been held in Singapore, if you are interested, please join WG8 workspaces in pbworks.



1 PVQAT TG13 Introduction

2 Researches of TG13

3 Next meeting of TG13

2. Researches inside TG13

IEC Standards

- **IEC 63202** Photovoltaic cells - Part 1: Measurement of light-induced degradation of crystalline silicon solar cells **(Published)**

- **IEC 63202** Photovoltaic cells - Part 2: Electroluminescence image for crystalline silicon solar cells

New Proposals

- **P**hotovoltaic Crystalline Wafers Part 2: Recommended Geometric Dimensions of wafers
- **C**urrent-voltage characteristics measurement for silicon photovoltaic (PV) cells with capacitance effect
- **M**easurement of current-voltage characteristics of crystalline silicon bifacial photovoltaic cells
- **W**ater Boiling Test for Crystalline Silicon Solar Cells
- **M**easurement & Specification for Silver Pastes of Crystalline Silicon Solar Cells

Reports

- **M**easurement of Light And Elevated Temperature Induced Degradation of Crystalline Silicon Photovoltaic Cells
- **P**hotovoltaic Crystalline Wafers - Part 3: Specifications for electrical characteristics of wafers
- **M**easurements of damp heat (DH) degradation of crystalline silicon photovoltaic cells
- **S**olar cells with ring-like defects under EL detection
- **S**olar cell UV degradation

These standards, proposals and reports are researches in PVQAT TG13

2.1 IEC 63202 Photovoltaic Cells - Part 1: Measurement of Light-Induced Degradation of Crystalline Silicon Solar Cells

IEC 63202-1:2019
Edition 1.0 (2019-06-20)
Photovoltaic cells - Part 1: Measurement of light-induced degradation of crystalline silicon photovoltaic cells

EN-FR

•This standard published at Jun 2019. This document is to provide standardized PV cell LID information to help PV module manufacturers in minimizing the mismatch between cells within the same module, thereby maximizing power yield.

Apparatus

- **Solar simulator 1 :** Solar simulator for *I-V* curve measurements in accordance with IEC 60904-9.
- **Solar simulator 2 :** Class BBB (or better) steady-state solar simulator in accordance with IEC 60904-9.
- **Environmental chamber :** irradiance sensor ,capability to control cell temperature , Relative humidity ≤ 50 % , no corrosive or contaminating contents .

Key parameters

- **Irradiance :** 1000±50w/m^2
- **Cell temperature:** 60±5℃
- **quasi-stabilization condition :** $\frac{P_{max} - P_{min}}{P_{average}} < 0.5\%$

Or cumulative exposure has reached 20 kWh/m^2.

- When the purpose of the test is to observe LID performance, the test may be continues beyond 20 kWh/m^2.

2.2 IEC 63202 Photovoltaic Cells - Part 2: Electroluminescence Image for Crystalline Silicon Solar Cells

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January 2018, Project Accepted by TC82 → July 2018, First CD circulated to WG8 → December 2018, Comments from WG8 received → Comments Review (2019.3) → Nov. 2019 revision included to form CD2 → Jan.-Feb. 2020, CD2 or DTS version will submit IEC to circulate

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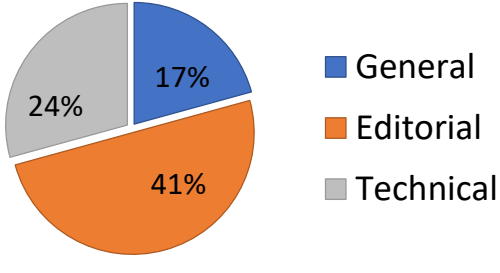
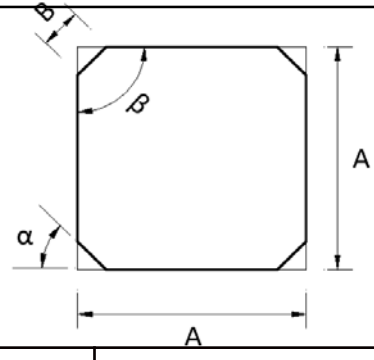


Comments of the CD draft

2.3 Photovoltaic Crystalline Wafers -Part 2: Recommended Geometric Dimensions of wafers

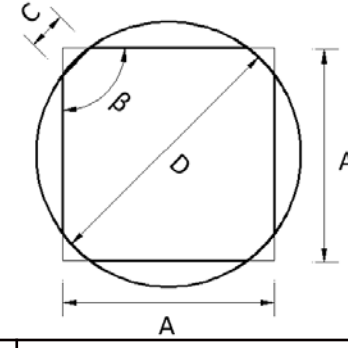
This standard specifies the geometrical dimensions of crystalline silicon wafers for use in photovoltaic solar cell manufacture. It provides standardized dimensional characteristics of wafers based on the large-scale production of wafers and solar cells. It also provides recommendations on the future wafer sizes.



Square Wafer Dimensions

Symbol in Figure 1		Dimensions		
Dimension Name		A (mm) Wafer Edge Length	B (mm) Chamfer Length	β (°) Right Angle
Nominal Size (mm)	156.75	156.75±0.25	1.5±0.5	90±0.3
	158.75	158.75±0.25	1.5±0.5	90±0.3
	166.00	166.00±0.25	1.5±0.5	90±0.3

Pseudo-Square Wafer Dimensions



Symbol in Figure 2		Dimensions		
Dimension Name		A (mm) Wafer Edge Length	D (mm) Diameter	β (°) Right Angle
Nominal Size (mm)	156.75	156.75±0.25	210±0.25 220±0.25	90±0.3
	158.75	158.75±0.25	210±0.25 213±0.25 223±0.25	90±0.3
	166.00	166.00±0.25	213±0.25 223±0.25 233±0.25	90±0.3

Note: If the wafer edge length is more than 166 mm, it is recommended that the increase step be an integral multiple of **1 millimeter**.

2.4 Current-Voltage Characteristics Measurement for Silicon Photovoltaic(PV) Cells with Capacitance Effect

This proposal specifically applies to cell power rating measurements in industrial settings (production lines). Although this is one of the most common measurement applications in the PV industry, but it is not covered in detail by current IEC 60904-1 describes how to measure I-V curves and so is necessarily limited on the amount of detail used to describe best practices for industrial cell power rating measurements .

1 ） This guide for tests the current-voltage (I-V) characteristic of crystalline silicon with capacitance effect cell of the production line, and regulates the efficiency test bench for cell production lines in mass production.

2） This guide for test the current-voltage (I-V) characteristics of crystalline silicon cells in production lines and checks the efficiency of the calibrated cell in circulation.

3) Provide a standardized basis for evaluating and guiding how to suppress the effects of solar cell capacitance effects, and also provide a primary evaluation factor for the evaluation of test uncertainty for current-voltage (I-V) characteristics measurement of crystalline silicon solar cells.

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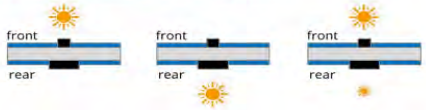
- This proposal focus on measurement methods (**Bifacial illumination and Equivalent illumination**) and equivalence study.

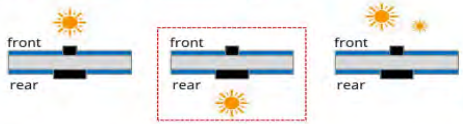
Deviation analysis

Bifacial illumination



- ✓ No sampling of φ(Isc).
- ✓ Rseries is related to bifacial illumination, reflecting actual outdoor operation.
- ✓ Thus, no Isc(BiFi) & Pmax(BiFi) deviation.

Equivalent illumination



- ✓ G_E=1000+200*φ(Isc) W/m^2, φ(Isc) is an input to derive G_E.
- ✓ With known front and rear STC, no sampling of φ(Isc), Isc(G_E) & Pmax(G_E) deviation is quite low.
- ✓ Using average φ(Isc) to derive G_E, the actual φ(Isc) deviation >±3% will produce quite high Isc(G_E) & Pmax(G_E) deviation.
- ✓ Rseries is related to single side illumination, not exactly the case of bifacial illumination, although produce Isc(G_E) equivalent to Isc(BiFi).

Suggestion of methods

	For Lab	For Production *(with φ(Isc) deviation)*
Bifacial illumination	Preferred	
Equivalent illumination	Alternative method, with low deviation	For φ(Isc) deviation from average ≤±3%, with acceptable Isc(G_E) and Pmax(G_E) deviation

1 Scope

2 Normative references

3 Terms and definitions

4 Apparatus

4.1 For measurement by bifacial illumination

4.2 For measurement by equivalent illumination

5 Measurement of bifacial PV cells in lab

5.1 Measurement by bifacial illumination

5.2 Measurement by equivalent illumination

6 Measurement of bifacial PV cells in production

6.1 Measurement by bifacial illumination

6.2 Alternative measurement by equivalent illumination

7 Report

ANEX 1 - Fitting of bifacial I-V characteristics

ANEX 2 - Deviation analysis of equivalent illumination method

2.6 Water Boiling Test for Crystalline Silicon Solar Cells

Scope

This document defines water boiling test for crystalline silicon solar cells. Since boiling test is an essential method for measuring quality of different cells, this document helps manufactures to assess the boiling characteristics of cells by unified method within reasonable cost and time. It is applied to crystalline silicon solar cells whose conductive metal pastes are solidified by firing process under high temperature.

Test Procedure

At least 8pcs of cells

2 cell

Adhesion test before

4 cells

IV measurement before

Water Boling Test

IV measurement after

2 cell

Adhesion test after

End

Assessment Criteria & Appearance Checking Criteria

Severity Evaluation	Phenomena Assessment Criteria		Appearance Checking Criteria			
	bubbling	**turbidity**	**bulging**	**aluminum powder shedding off**	**blackening**	**yellowing**
1	**Area:** no requirements **Number:** 1 **Frequency:** 1 bubble/min	/	/	/	/	/
2	**Area:** <1cm² **Number:** 1 **Frequency:** 2 bubbles/min or 3 bubbles/min	/	/	/	**Total area:** < 4cm² **Color:** light blackening	**Total area:** < 4cm² **Color:** light yellowing
3	**Area:** 1cm² **Number**: 3 **Frequency:** 2 bubbles/min or 3 bubbles/min	**solution:** clear **suspended substance:** invisible	/	/	**Mark points: Area:** ≥0.25cm² **Color:** severe blackening	**Mark points: Area:** ≥0.25cm² **Color:** severe yellowing
4	**Area:** 1cm² **Number:** 3 **Frequency:** >3 bubbles/min	**solution:** clear **suspended substance:** little substance is visible	**Area:** < 0.25cm² **Number:** 1	**Area:** < 0.1cm² **Number:** 1	**Total area:** ≥4cm² **Degree:** severe blackening	**Total area:** ≥4cm² **Degree:** severe yellowing
5	**Area:** 1cm² **Number:** >3 **Frequency:** >3 bubbles/min	**solution:** discolored **suspended substance:** clearly visible	**Area:** > 0.25cm² **Number:** >1	**Area:** >1cm² **Number:**>1	**Total area:** ≥20cm² **Degree:** severe blackening	**Total area:** ≥20cm² **Degree:** severe yellowing

2.7 Measurement & Specification for Silver Pastes of Crystalline Silicon Solar Cells

- This draft standard defines procedures for the measurement methods and specifications of silver pastes which are used as electrode in crystalline silicon photovoltaic cells; cell types include (but are not limited to) p-type BSF (mono & multi), PERC, n-type PERT, n-type TOPCON and SHJ (low temperature).
- The content of this standard includes appearance, granularity, solids percentage and viscosity, and covers the basic requirements for the safety label, SDS, COA documents, shelf life and conditions of storage and transport.

No.	Test Items	Requirements
1	Appearance	Uniform silver-grey , no visible solvent leakage, agglomeration
2	Solids percentage	Depend on paste recipe, absolute tolerance is ±0.5%
3	FOG (4th scratch / 50%)	<16/8
4	Viscosity, Pa.s@25℃	Depend on paste recipe and test procedure, tolerance is ±15%

Recommended Requirements

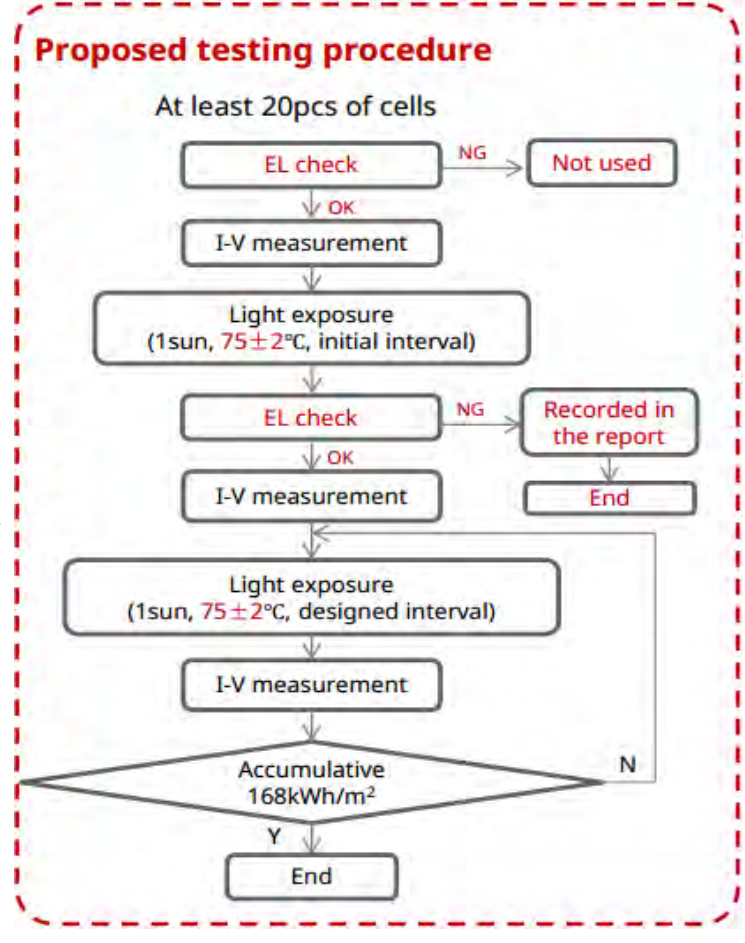
2.8 Measurement of Light And Elevated Temperature Induced Degradation (LeTid) of Crystalline Silicon Solar Cells

This proposal describes procedures for measuring the light and elevated temperature induced degradation (LeTID) of crystalline silicon photovoltaic (PV) cells in simulated sunlight.

This document is to evaluate and reduce LeTID risk of PV cells, and thus improve energy yield of PV modules

- **Proposed cell LeTID test conditions:** 75°C (cell temperature under light soaking), 1000W.m^{-2},light soaking, 168h.
- **The testing interval** of multiple I-V measurement is designed to be 0.5, 1, 2, 4, 8, 16, 24, 48, 96, 168 hours.
- **Provide more useful information** by cell LeTID standard than module.
- **After** each illumination step, **calculate the degradation ratio** of all the sampled cells using the following equation:

$$\Delta P_{max}(i) = \frac{P'_{max}(i) - P_{max}(i)}{P_{max}(i)}$$



2.9 Photovoltaic Crystalline Wafers - Part 3

Specifications for Electrical Characteristics Of Wafers

• This proposal specifies the recommended values for **conducting types**, **resistivity and minority carrier lifetime** of photovoltaic crystalline silicon wafers, which are used to constrain and regulate the production of photovoltaic crystalline silicon wafers.

• This proposal is applicable to quasi-square or square monocrystalline silicon wafers made from monocrystalline silicon rods produced by Czochralski method (CZ) and square polycrystalline silicon wafers made from polycrystalline silicon ingots produced by directional solidification (DS) method.

Table 1: Recommended resistivity of wafers (Ω•cm)

Type \ Specification	Ⅰ	Ⅱ	Ⅲ
p-type mono silicon wafer	0.5~1.5	0.8~2.6	1~3
n-type mono silicon wafer	0.2~1.4	0.5~3.5	1~7
p-type poly silicon wafer	0.5~1.5	0.8~2.6	1~3

Table 2: Radial resistivity variations of wafers

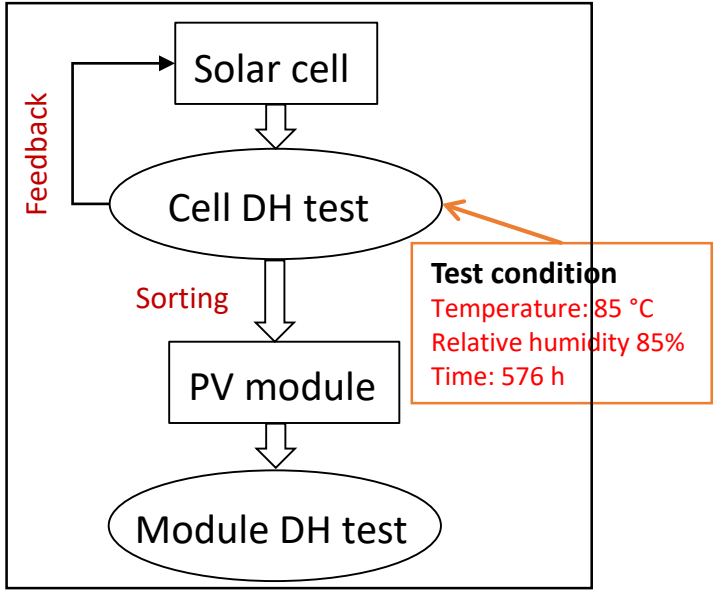
Type	Radial resistivity variation
n-type mono silicon wafer	≤20%
p-type mono silicon wafer	≤15%
p-type poly silicon wafer	

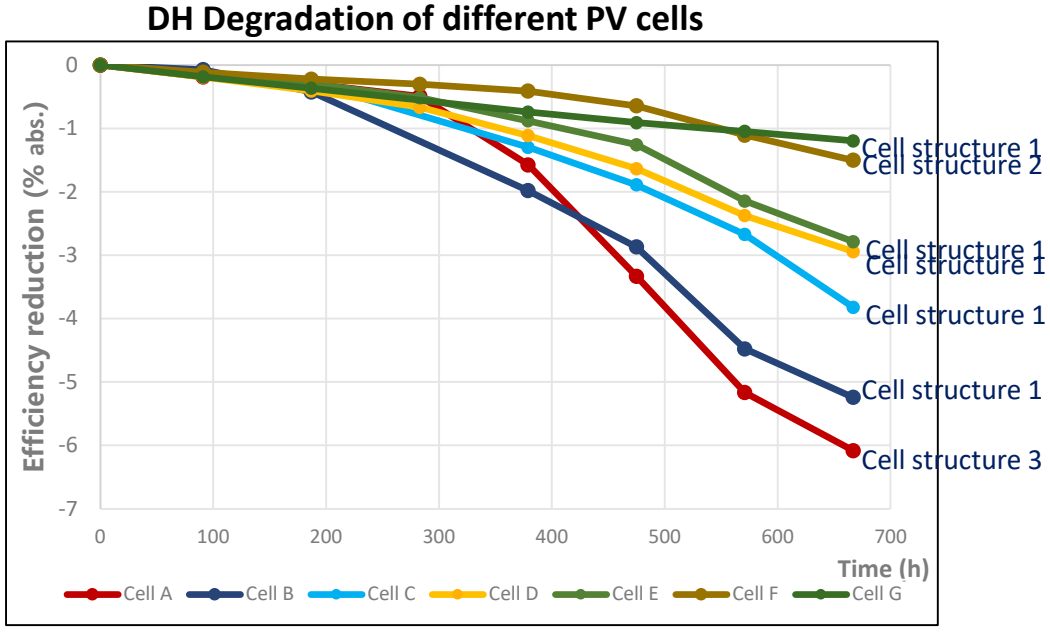
Table 3: Recommended values of the minority lifetime of wafer

Type \ Specification		Ⅰ	Ⅱ
p-type mono silicon	Square rod	≥16	≥10
	wafer	≥1.2	≥1.5
n-type mono silicon	Square rod	≥500	≥1000
	wafer	≥1.2	≥1.5
p-type poly silicon	Block	≥4	≥4
	wafer	≥1	≥1.2

2.10 Measurements of Damp Heat (DH) Degradation of Crystalline Silicon Photovoltaic Cells

- **This proposal** describes the method for measuring the cell damp heat (DH) degradation of crystalline silicon photovoltaic (PV) cell.
- **This proposal** is to evaluate degradation behavior of PV cells under a condition of high temperature and high humidity.





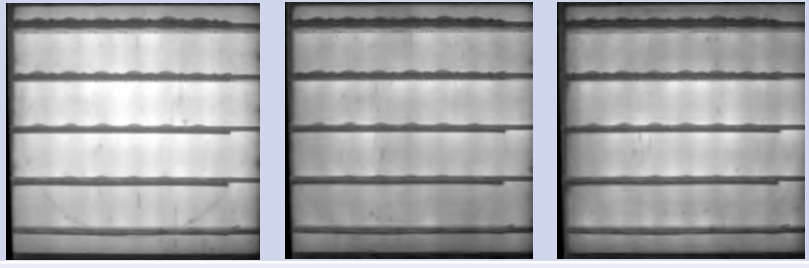
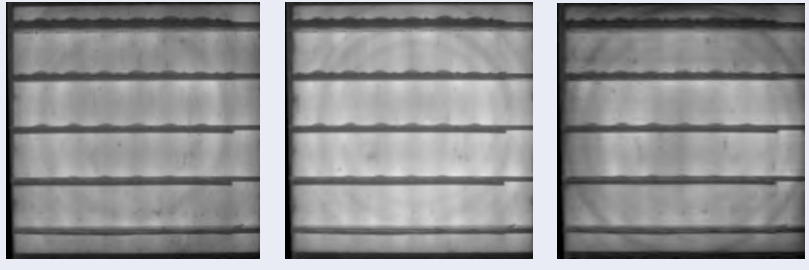
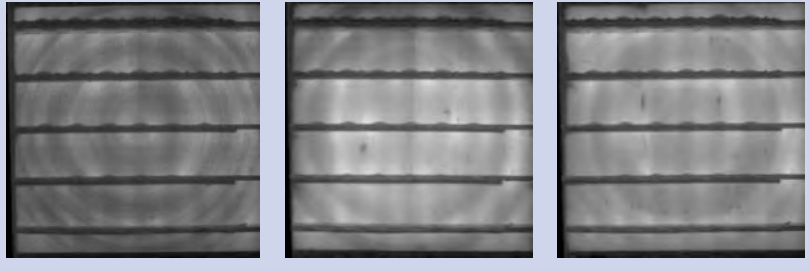
- Different cell fabricating process results in different DH degradation rate and degradation distribution.
- Different cell structure exhibits different degradation behavior.

2.11 Solar Cells with Ring-like Defects under EL Detection

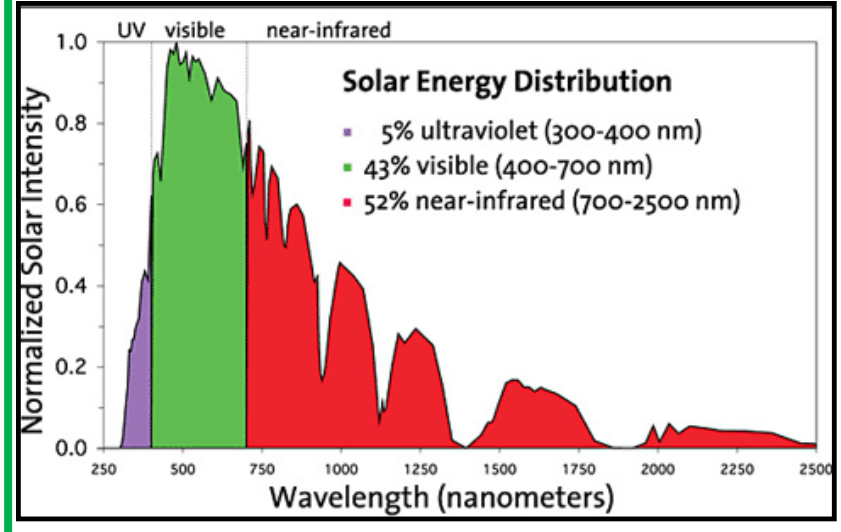
- This document is applicable to N-type crystalline silicon photovoltaic cells with ring effect under EL testing.
- This document provide a recommend classification of different black ring cells.
- We researched the characters of this three types ring cell in LeTID, and then make the module to research, such as: LID, PID T, reliability test(DH1000,TC200,TC50+HF10), hot spot test (without shelter), and hot spot test (shelter 50%).and find below information:

- No obvious effect on cells LeTID test with/without ring effects
- Black ring has no obvious effect on modules LID test.
- Black ring has no obvious effect on modules PID test.
- Wide deep ring has some influence on the back reliability.
- Hot-spot test(without shelter): no significant influence
- Hot-spot test(shelter 50%):
  - Incomplete ring（131.5℃）≈BL（130.3℃）
  - Wide deep ring （135.4℃）＞ BL（130.3℃）
  - Wide deep ring has some influence on the hot spot test （with shelter 50%）

Recommended Classification of black ring cells

Name	Example
Type A Incomplete rings	
Type B Complete rings	
Type C Wide and dark rings	

2.12 Solar Cells UV Induced Degradation

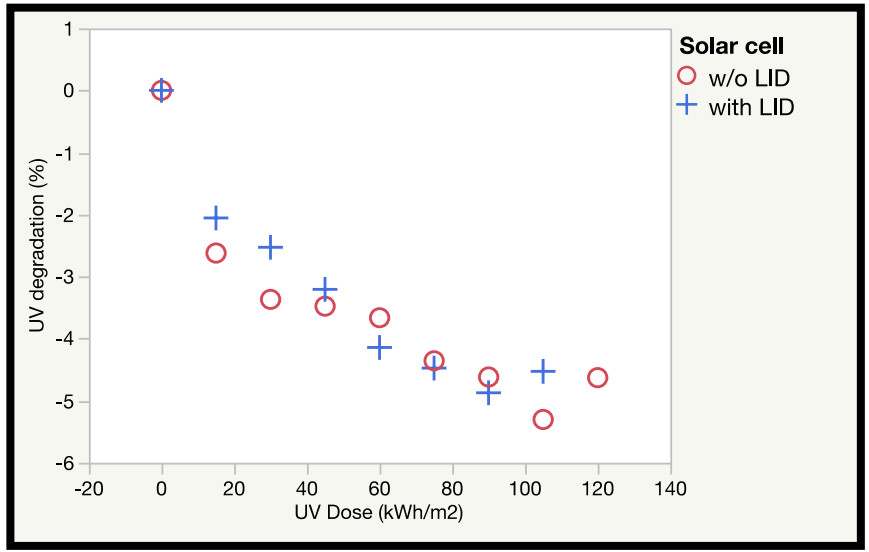


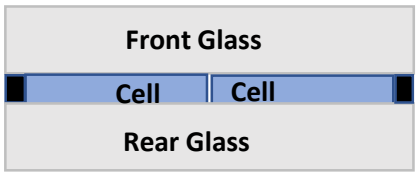
IEC LID Std (10kWh/m²)	
UV	VIS-NIR
0.5kWh/m²	9.5kWh/m²

Current LID Std did not cover UV Degradation. Using LID std, n-type cells don't have LID but UV degradation

2.12 Solar Cells UV Induced Degradation

- UV degradation is independent from LID process





- 20 PERC cells from the same bin
- EL: no crack

Condition of LID Process
Temperature: 60±5℃,
Exposure dose： 8kWh/m^2

UV Conditions
UV： 280-400nm, 280-320nm (3-10%)
Uniformity： <15%
intensity： 120-250W/m^2

1 PVQAT TG13 Introduction

2 Researches of TG13

3 Next meeting of TG13

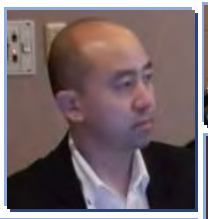
3. Next Meeting of TG13

Next meeting

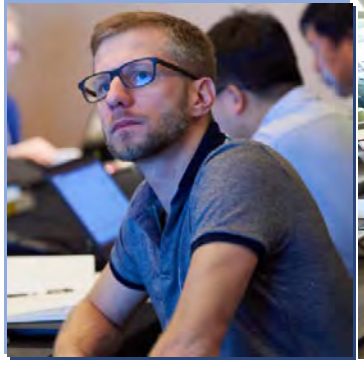
- **Time: April 2020**
- **Place: Newcastle, Australia**

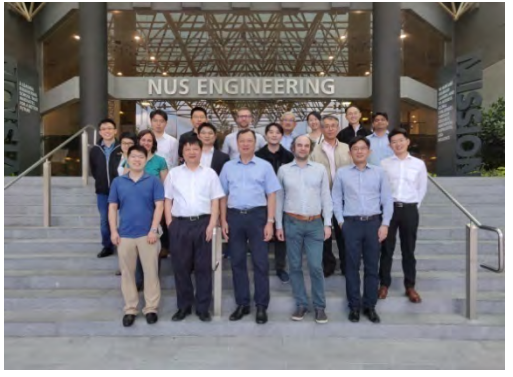
Please contact Lynn Li, if you are interested in attending this meeting

Email: ning.li@jinkosolar.com



Thank You





NREL
NATIONAL RENEWABLE ENERGY LABORATORY

PV Reliability of 100,000 Systems

PV Reliability Workshop

Lakewood, CO

Dirk Jordan, Bill Marion, Chris Deline, Teresa Barnes– NREL

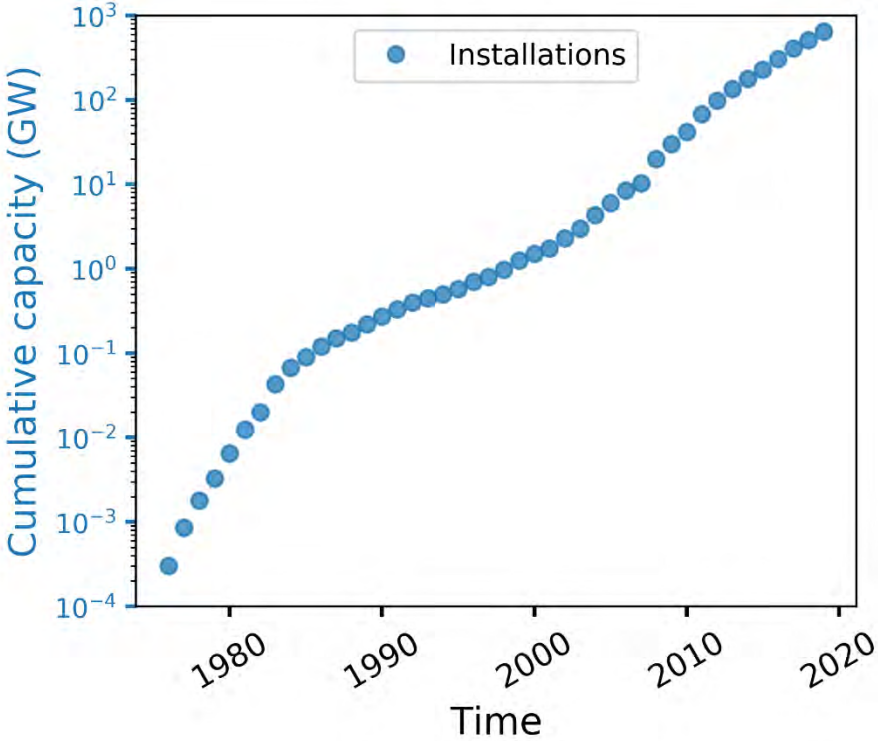
Mark Bolinger, LBNL

2/26/2020

Outline

- Motivation
- Performance of 100,000 systems
- Hardware failures & lost production
- Installation quality & reliability
- Failures & climate
- Project, utility, data acquisition, weather issues
- Conclusion

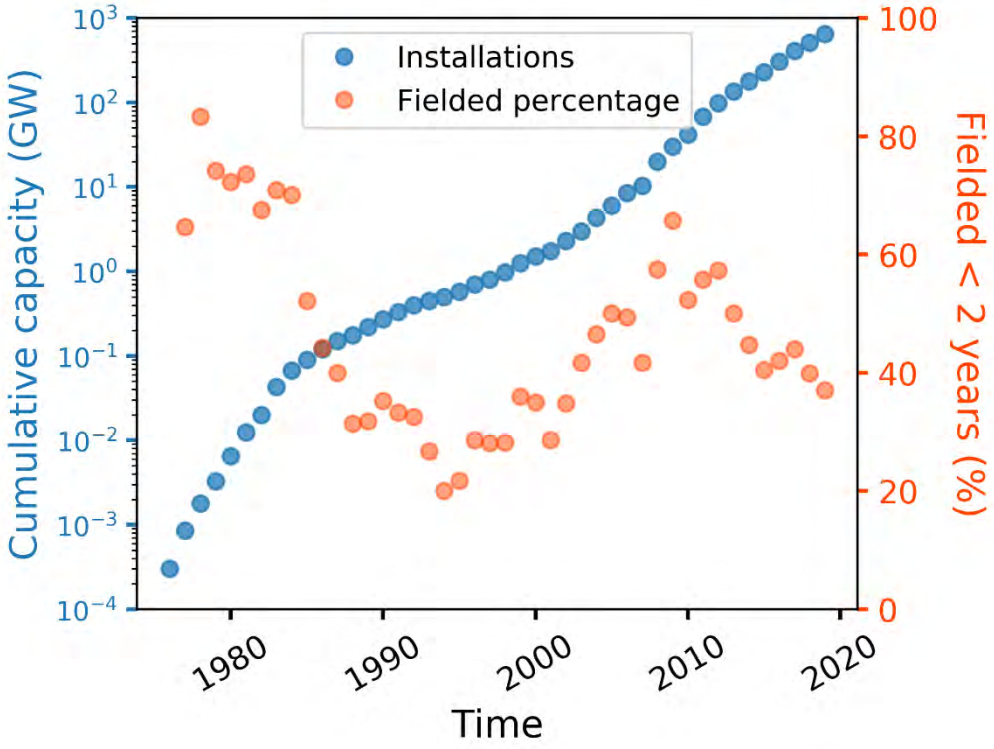
Motivation



Jäger-Waldau, PV Status Report 2018.
Renewables 2019 Global Status Report.

Jordan, TamizhMani, J. Physics D, 2020.

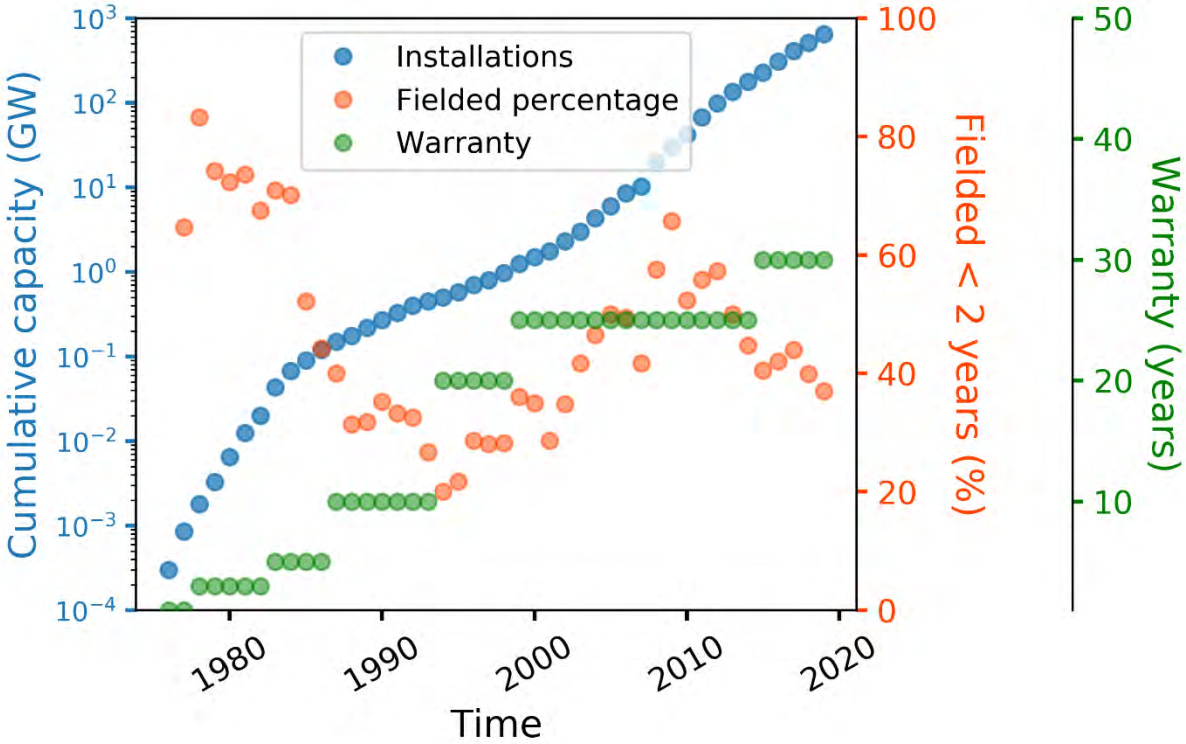
Motivation



Jäger-Waldau, PV Status Report 2018.
Renewables 2019 Global Status Report.

Jordan, TamizhMani, J. Physics D, 2020.

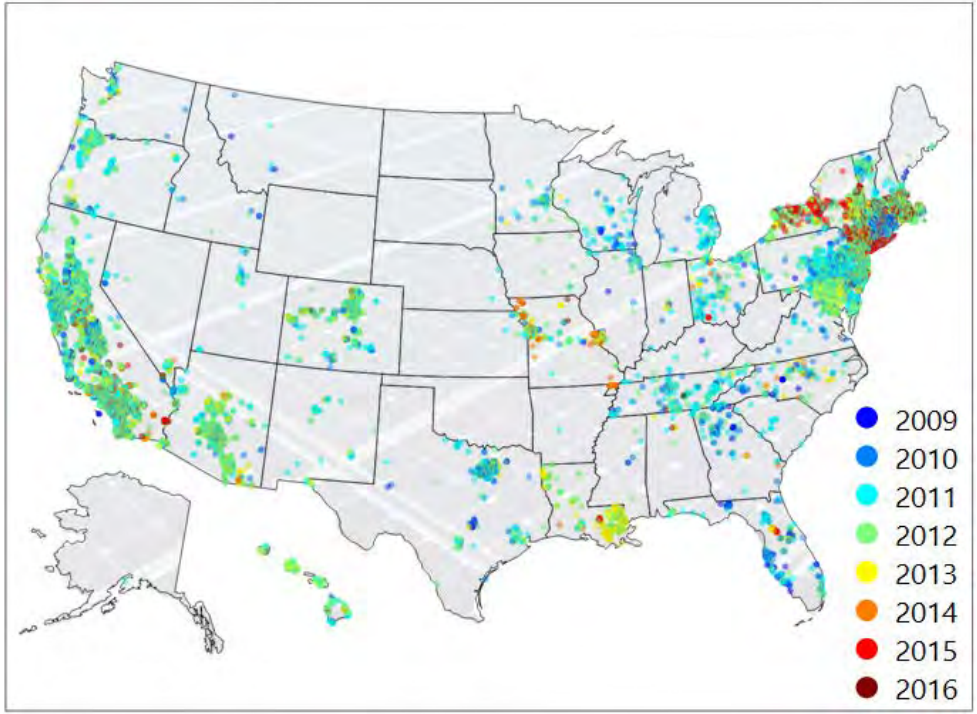
Motivation



Jäger-Waldau, PV Status Report 2018.
Renewables 2019 Global Status Report.

Jordan, TamizhMani, J. Physics D, 2020.

1603 data



100,000 systems, >7GW capacity, ca. 7% of all systems in the US

> 60,000 systems 5 years of data

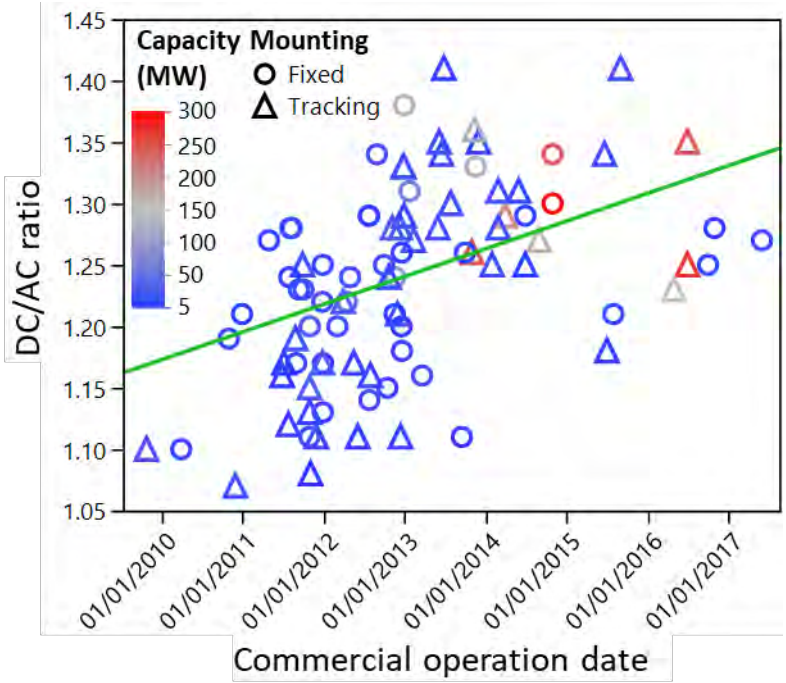
400-500 utility-scale systems

- Annual production data for 5 years, location, predicted production, size, no mounting configuration
- Comments regarding the performance
- Systems >5MW through Lawrence Berkeley NL monthly production data, mounting & module info

Jordan et al., Progress in PV, 2020.

Inverter clipping & DC/AC ratio

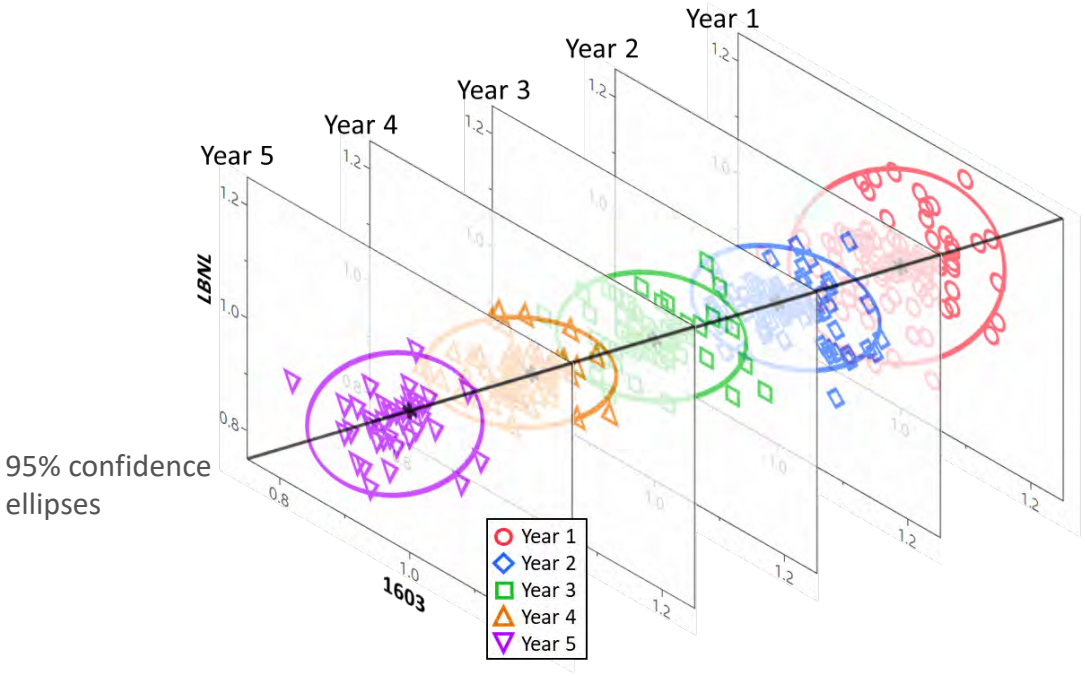
Systems > 5 MW



- DC/AC ratio has been going up consistently over the past 7 years.
- Not all utility scale systems installed are on 1-axis trackers, some are still fixed tilt systems.

Measured/ PVWatts predicted ratio

Systems > 5MW

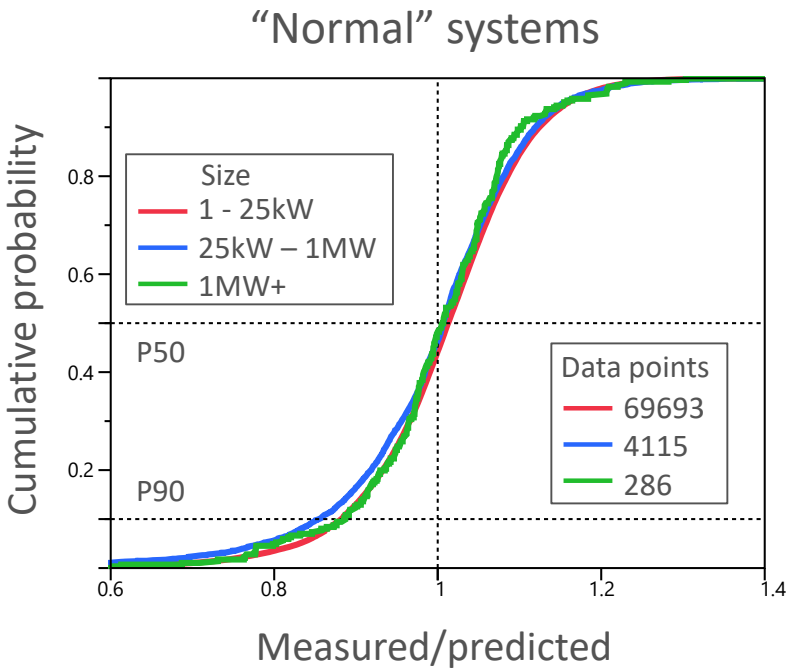


95% confidence ellipses

Predicted production: PVWatts
Measured production: 1603, LBNL

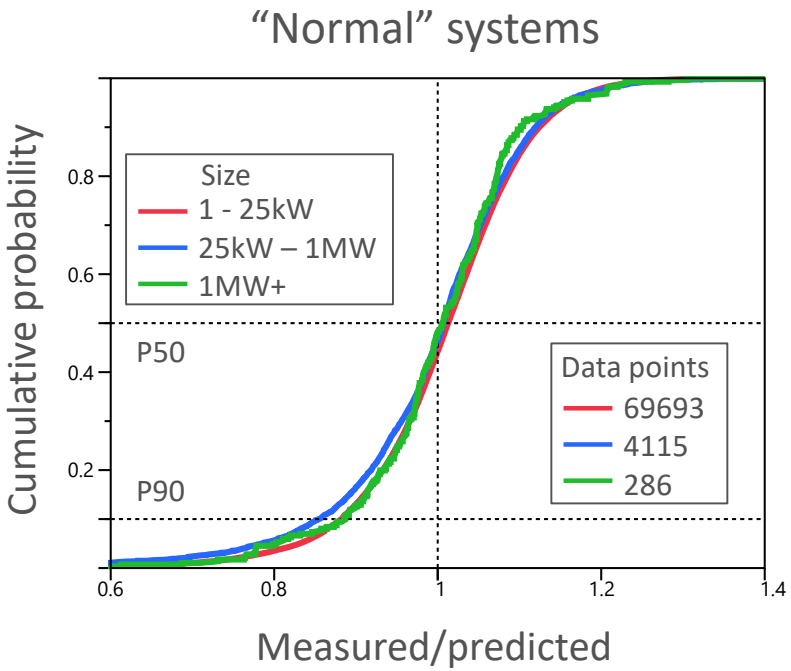
- Most measured/predicted ratios scatter around 1.0 ±0.1
- Variation: PVWatts generated estimates based on typical meteorological year (TMY), used default values

How is the overall fleet performance?



- 80% to 90% of normal systems performed within 10% of the predicted production or better.
- 56% of the systems were still performing above P50 or the median at 5 years.

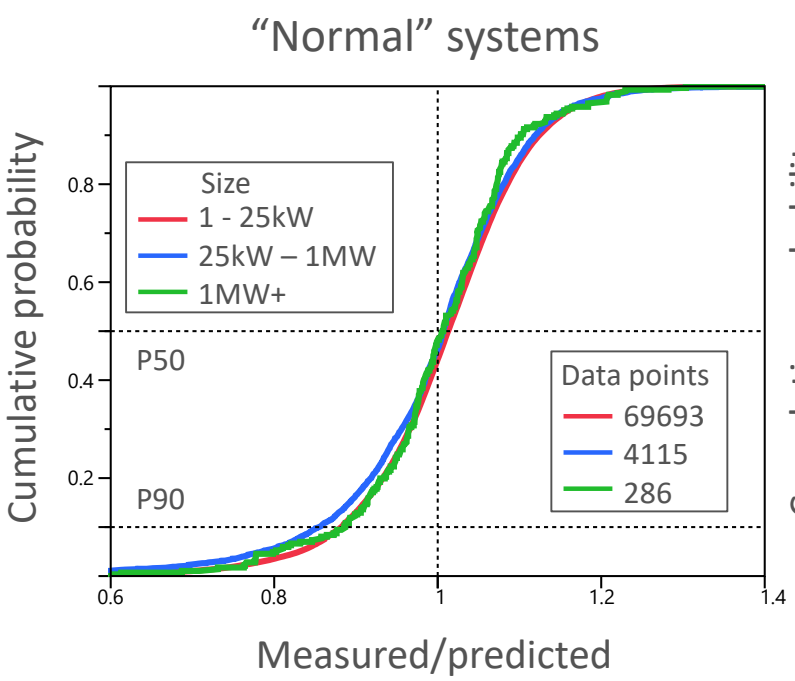
How is the overall fleet performance?

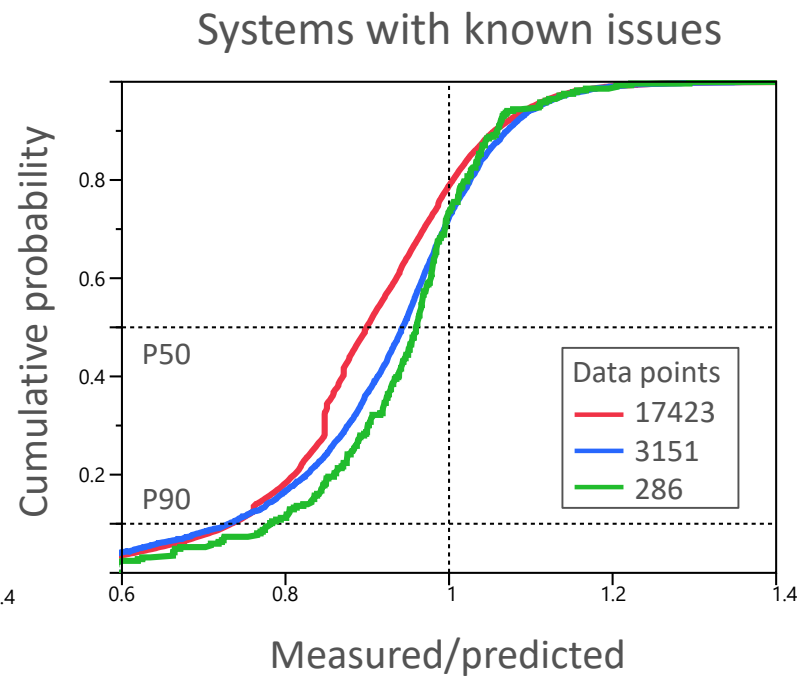


Fitch found that 86 percent of the time solar projects performed right around their P50 forecast (10 percent below P50 or better)

- 80% to 90% of normal systems performed within 10% of the predicted production or better.
- 56% of the systems were still performing above P50 or the median at 5 years.

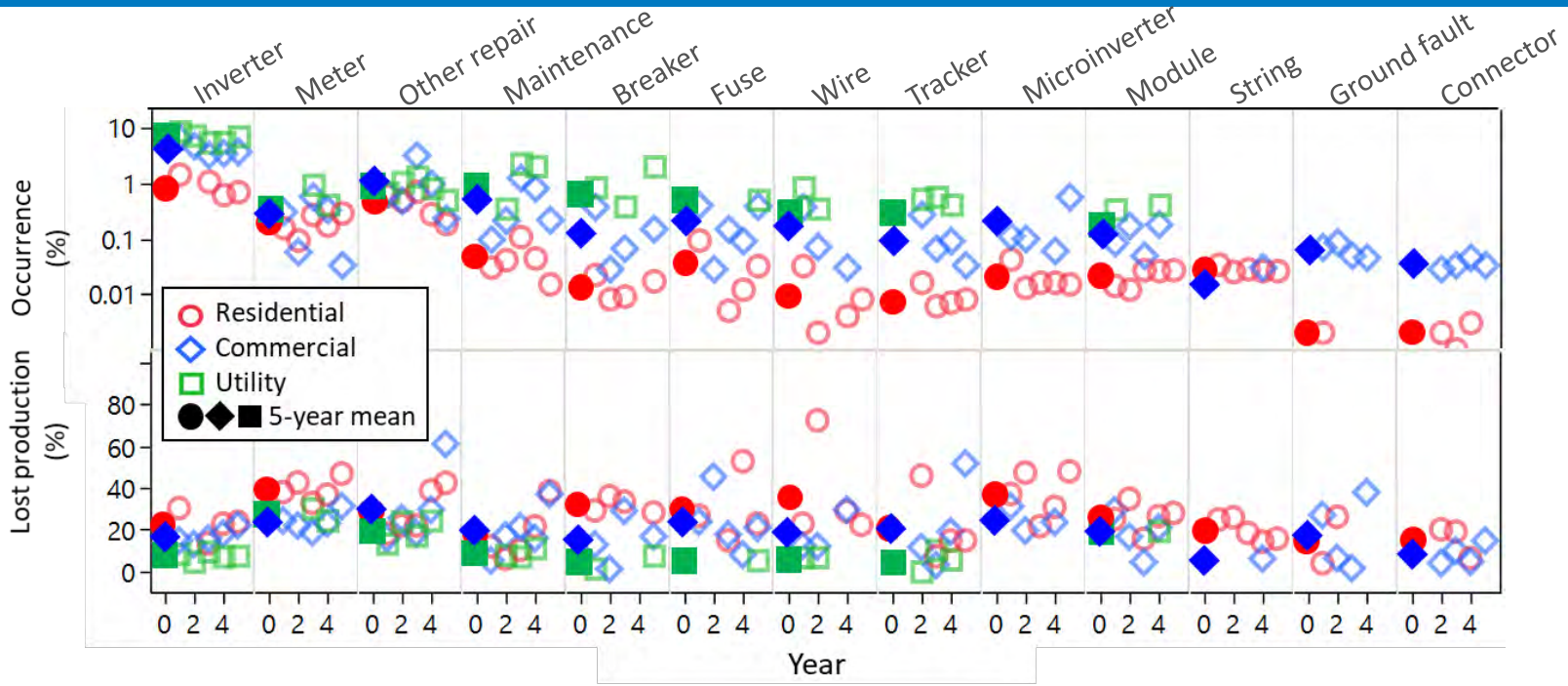
How is the overall fleet performance?





- 80% to 90% of normal systems performed within 10% of the predicted production or better.
- 56% of the systems were still performing above P50 or the median at 5 years.
- Residential systems more impacted than commercial/utility systems → more later!

Hardware failures



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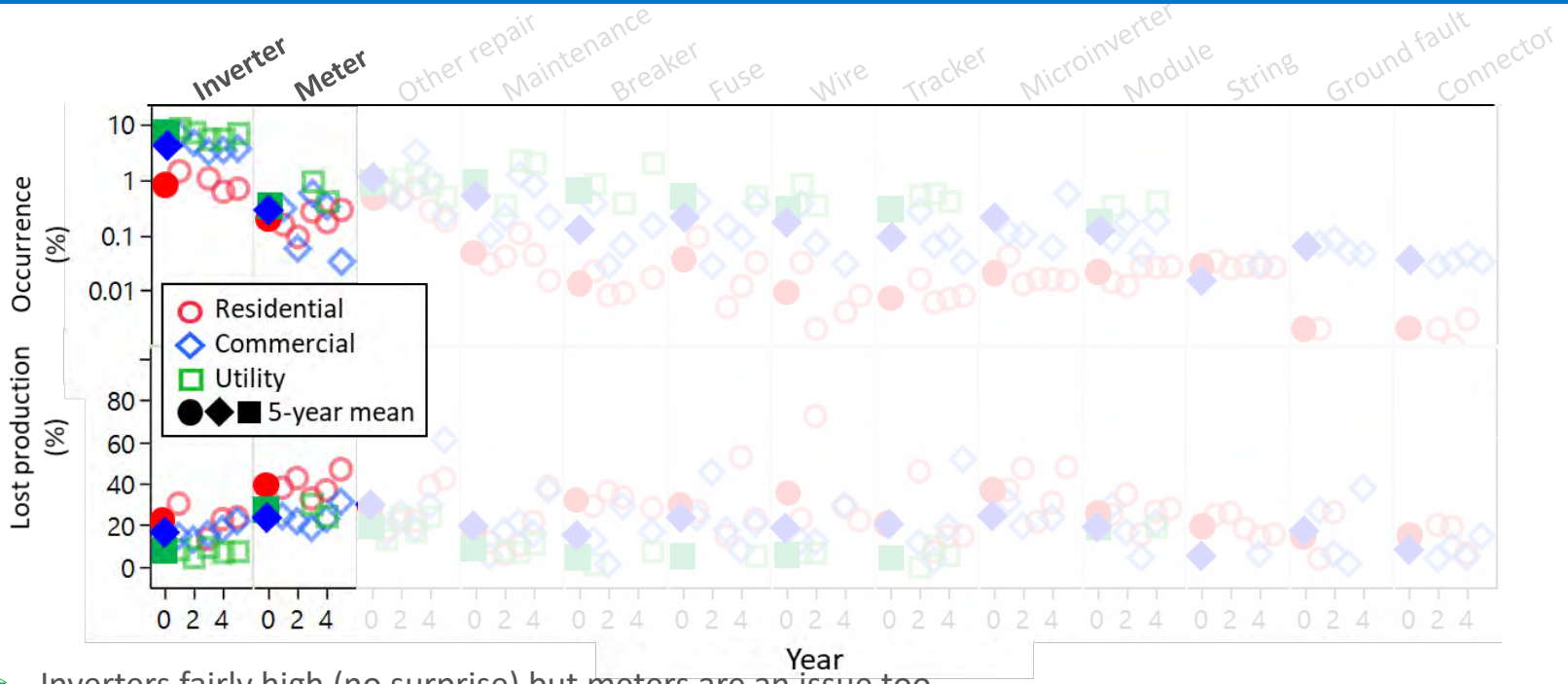
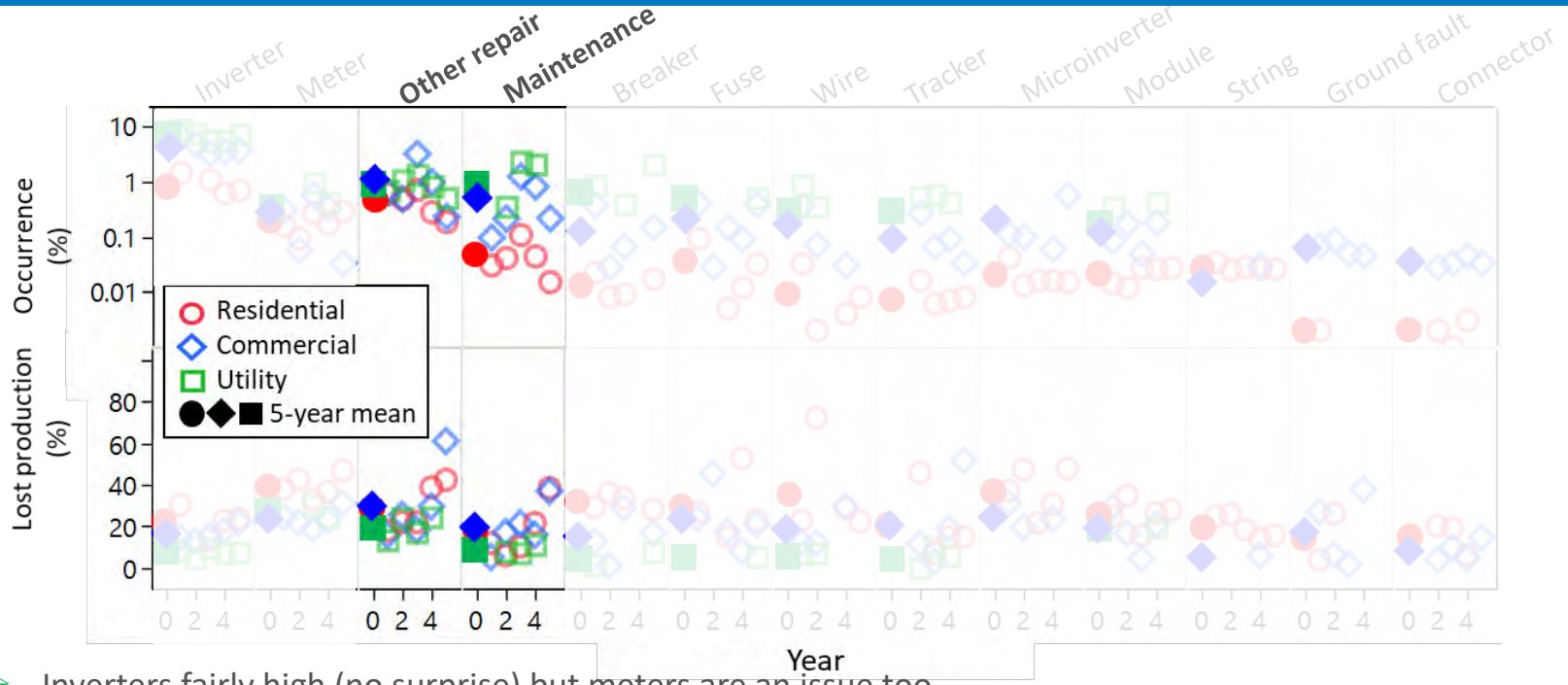


- Inverters fairly high (no surprise) but meters are an issue too.

Hardware failures



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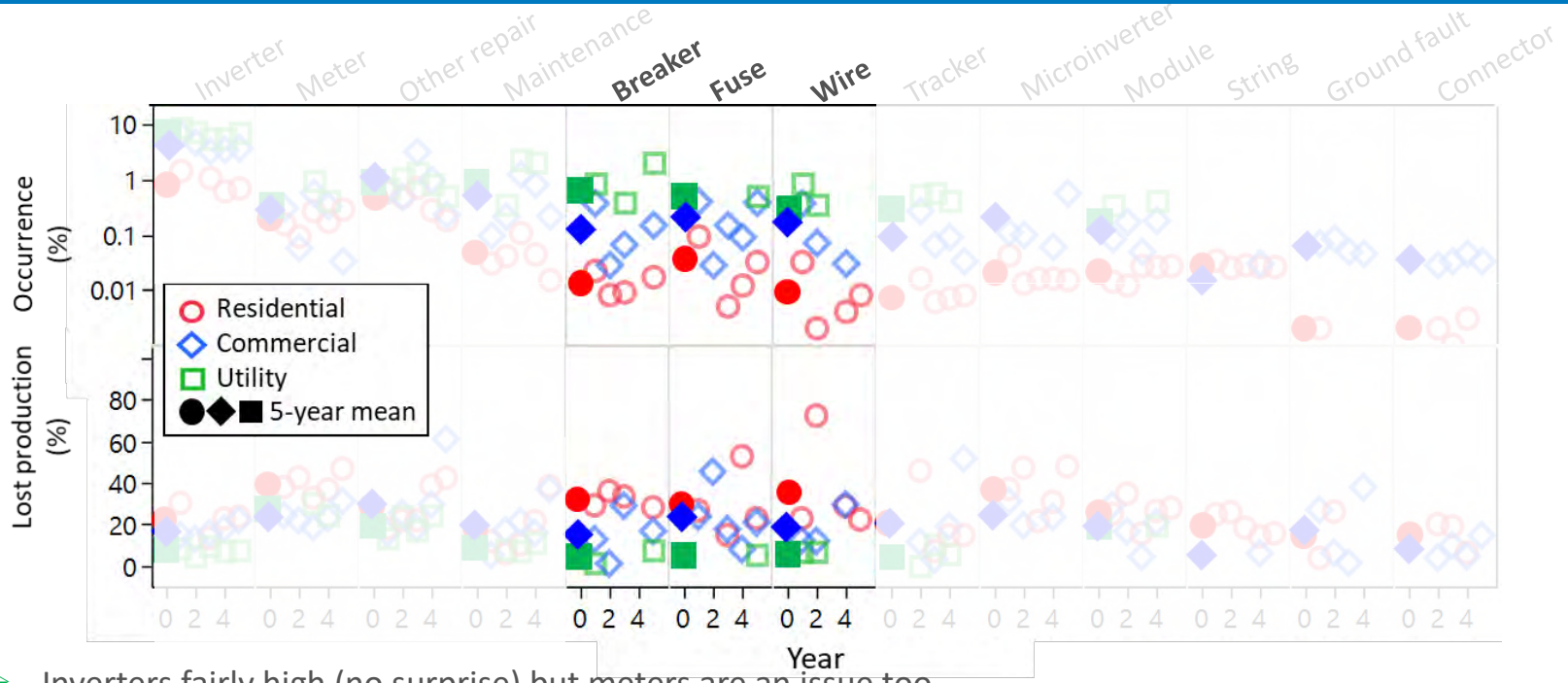
- Proactive maintenance has less impact than reactive repairs

Hardware failures



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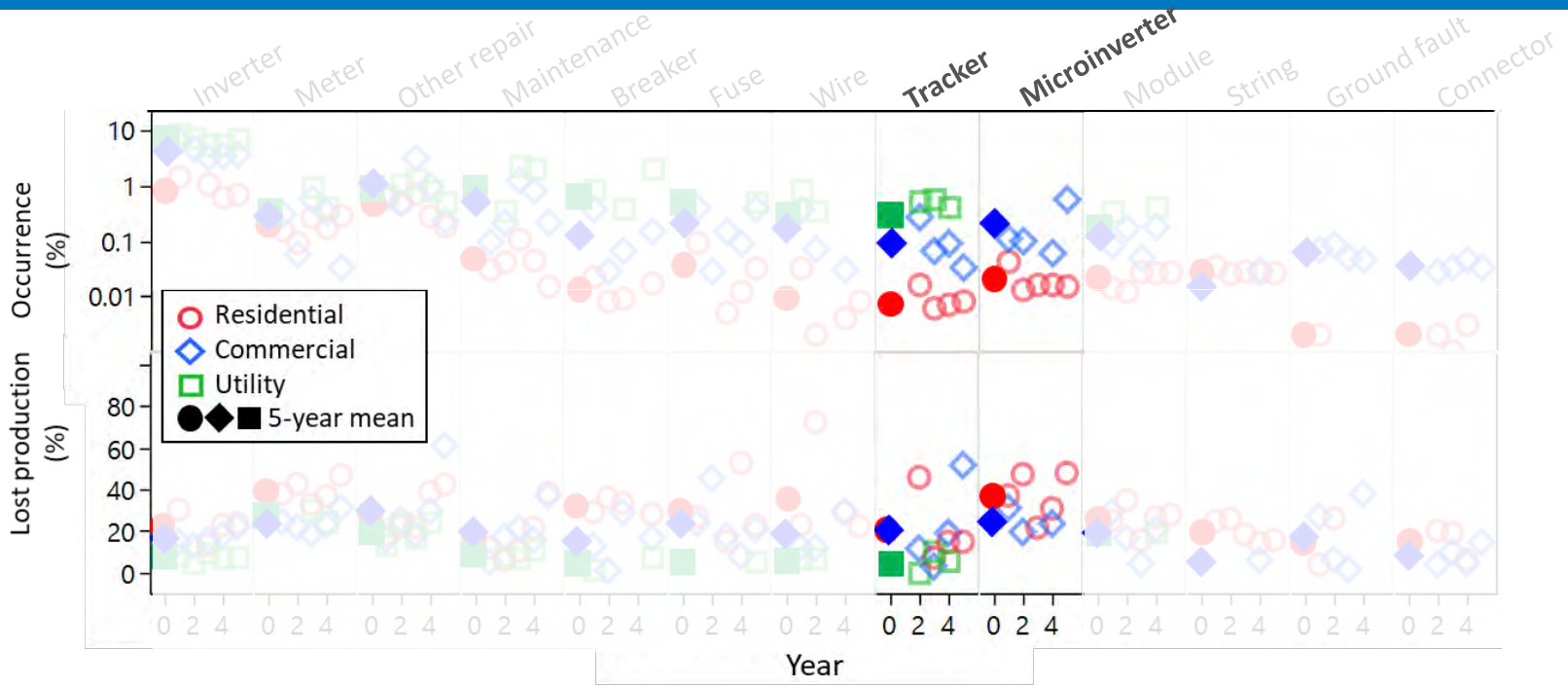

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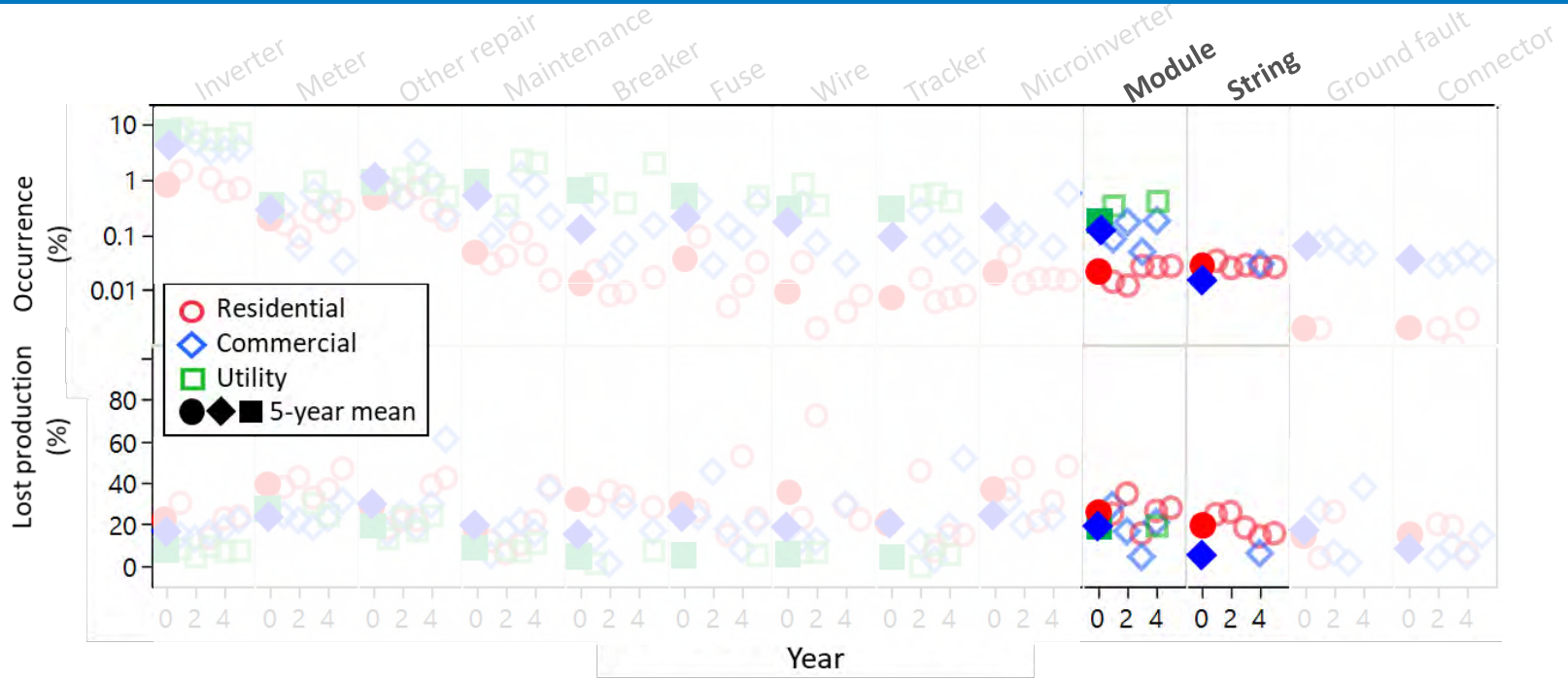

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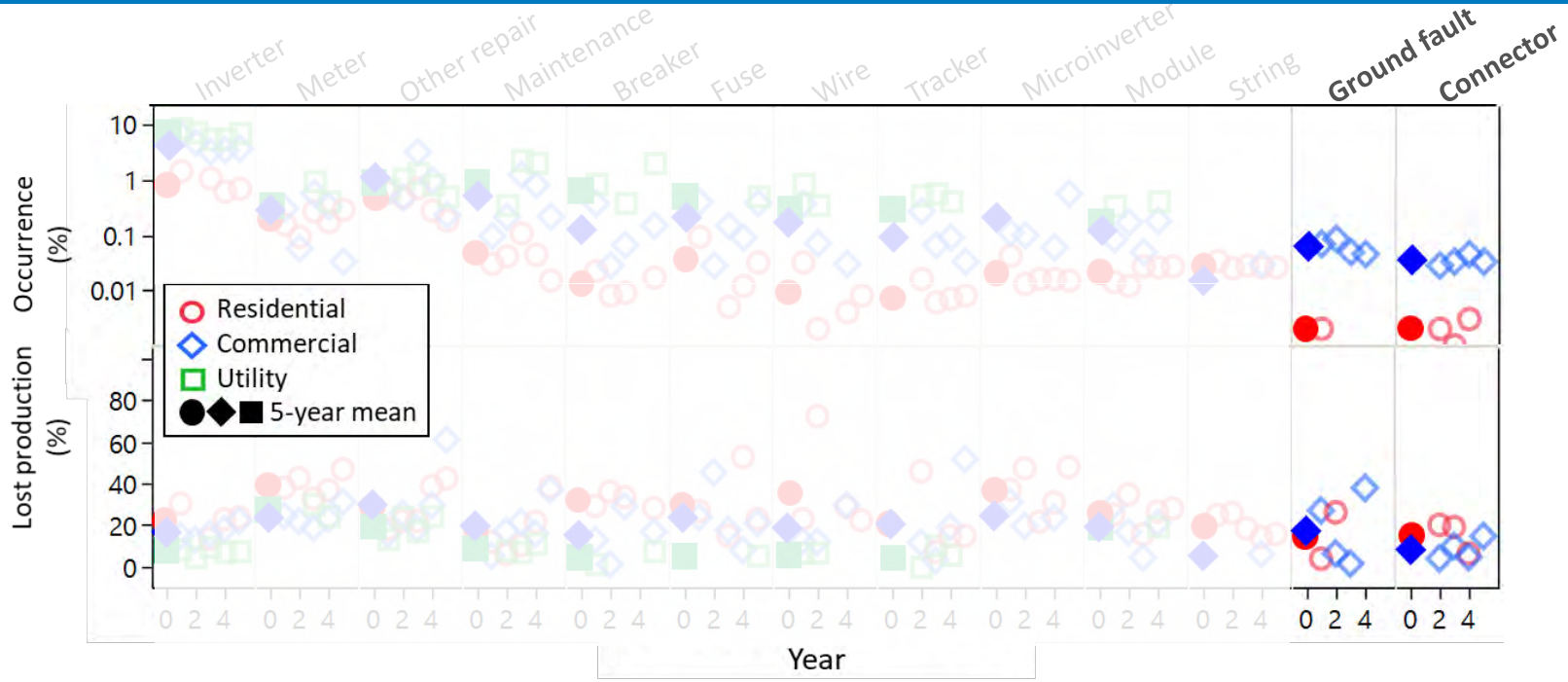
Jordan et al, Progress in PV, 2017.

Hardware failures



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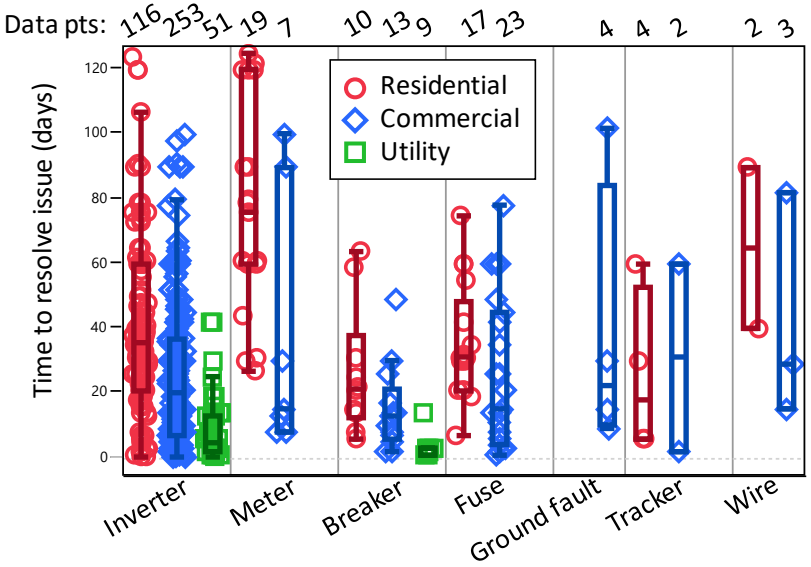
Jordan et al, Progress in PV, 2017.

How long does it take to fix things?

Some performance comments state when issue started & was resolved!

Time to resolve inverter issues:

Utility: 6 days
Commercial: ca. 3 weeks
Residential: > 1month



- Utility (days) < commercial (weeks) < residential (month)

Nonrecoverable ⟷ recoverable "degradation"

Some performance comments state when issue started & was resolved!

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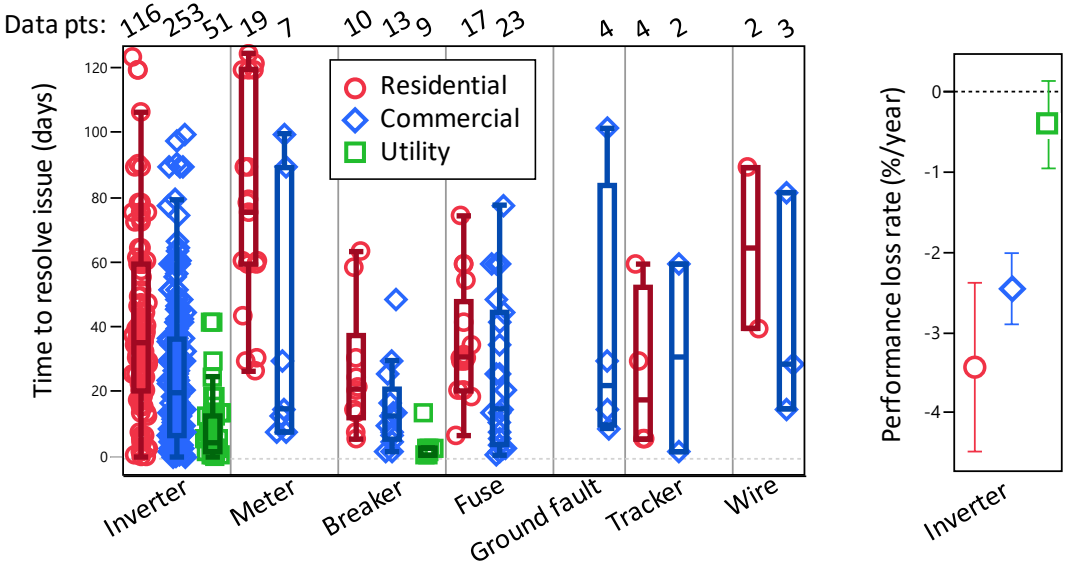


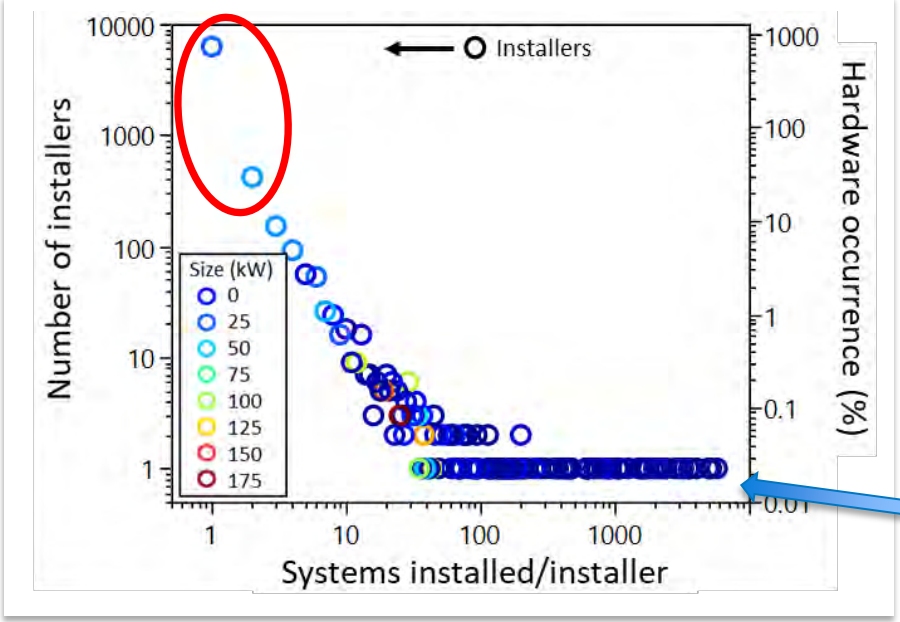
- Utility (days) < commercial (weeks) < residential (month)
- Issues resolved within days → no impact, issue resolved within weeks → apparent degradation
- Maintenance issues (recoverable degradation) imitate nonrecoverable degradation

K. Kiefer et al. EU PVSEC, Marseille, France, 2019

Installations & quality assurance?

Wires (undersizing),
Strings (connected backwards)
Breakers, fuses (early failure)
Ground-faults
Connector (improper crimping)

Installation quality



Big residential installers

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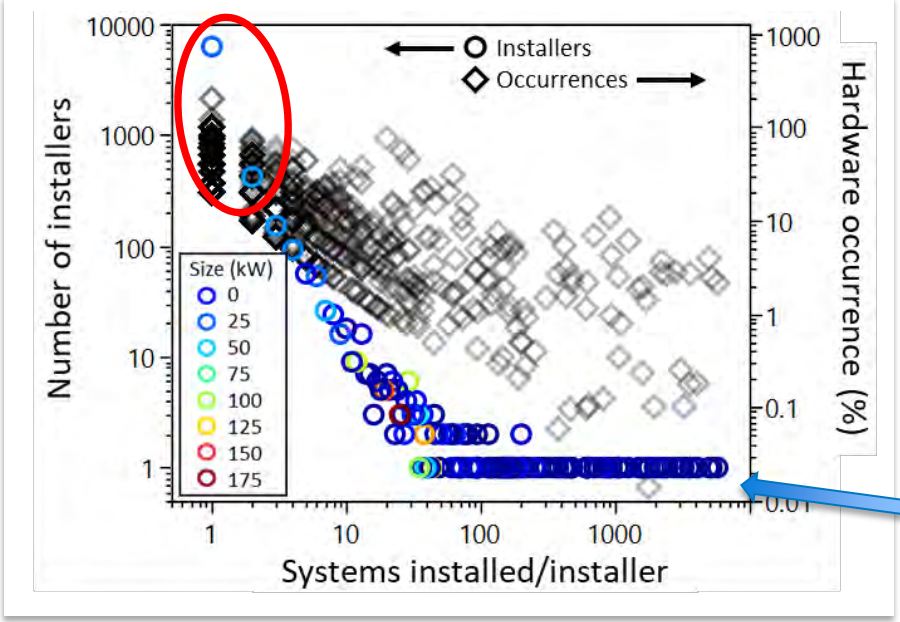


Occurrence:
Difficult to annualize because different issues can take different times
1 hardware issue/year = 100%

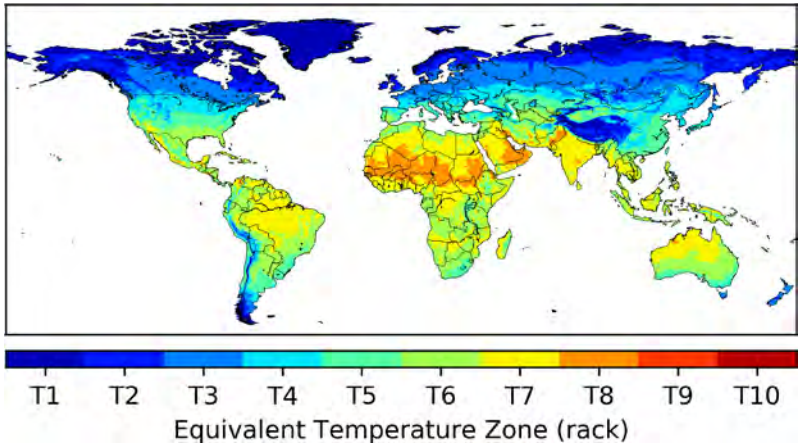
Big residential installers

Installers who install 1-2 systems have more hardware issues than installers who install many systems

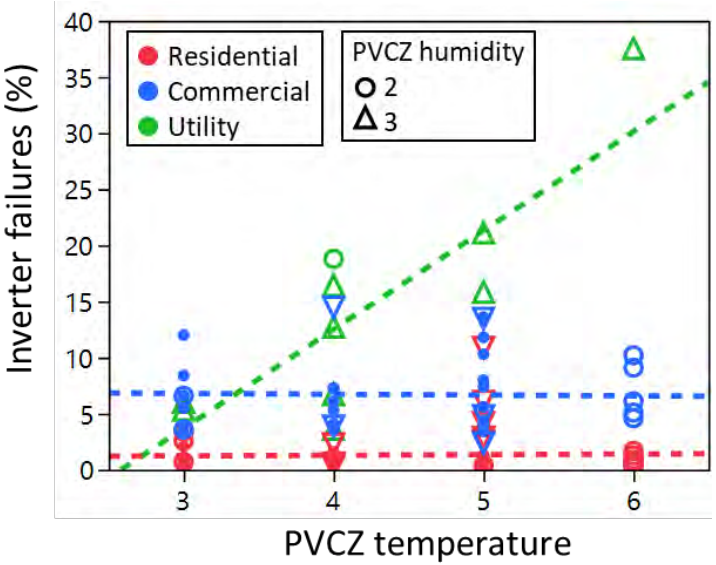
IECRE certification, NABCEP training could be beneficial

Inverter issues & climate

PVCZ: PV climate zones



Karin et al. PVSC 2019



Higher inverter failure rates in hotter climates for utility-scale systems
No discernible trend for commercial or residential systems

Inverter issues & climate

Utility-scale

Inverters are exposed & easily visible

Residential

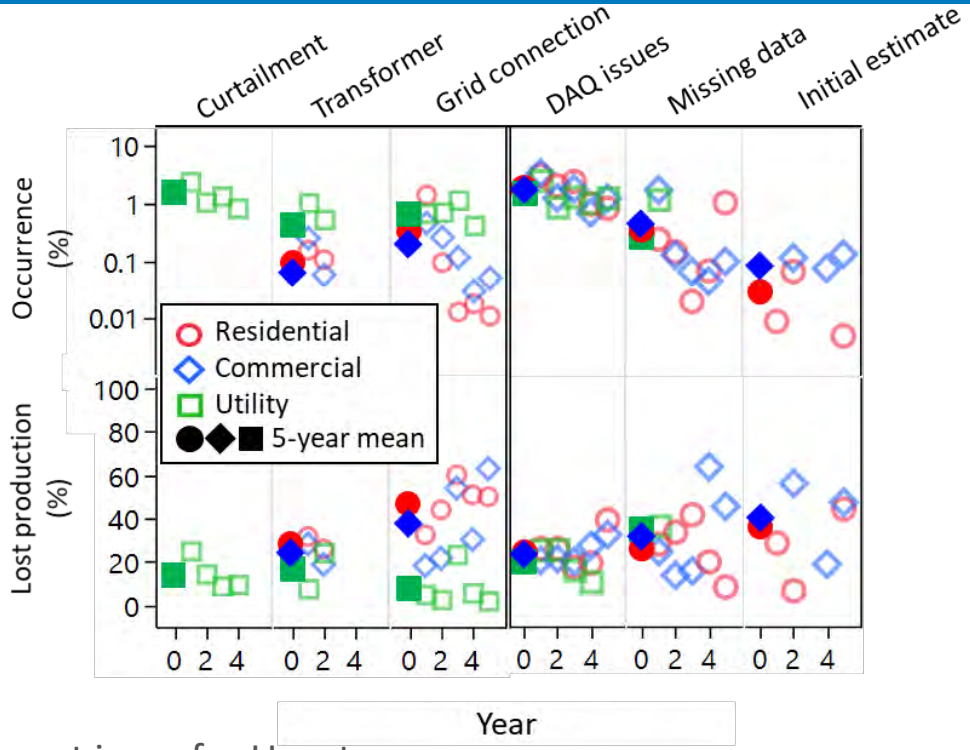
Same inverter manufacturer, same location (PA),

Arrow points out inverter location

Inverter location residential, commercial systems depends often on the orientation of the building

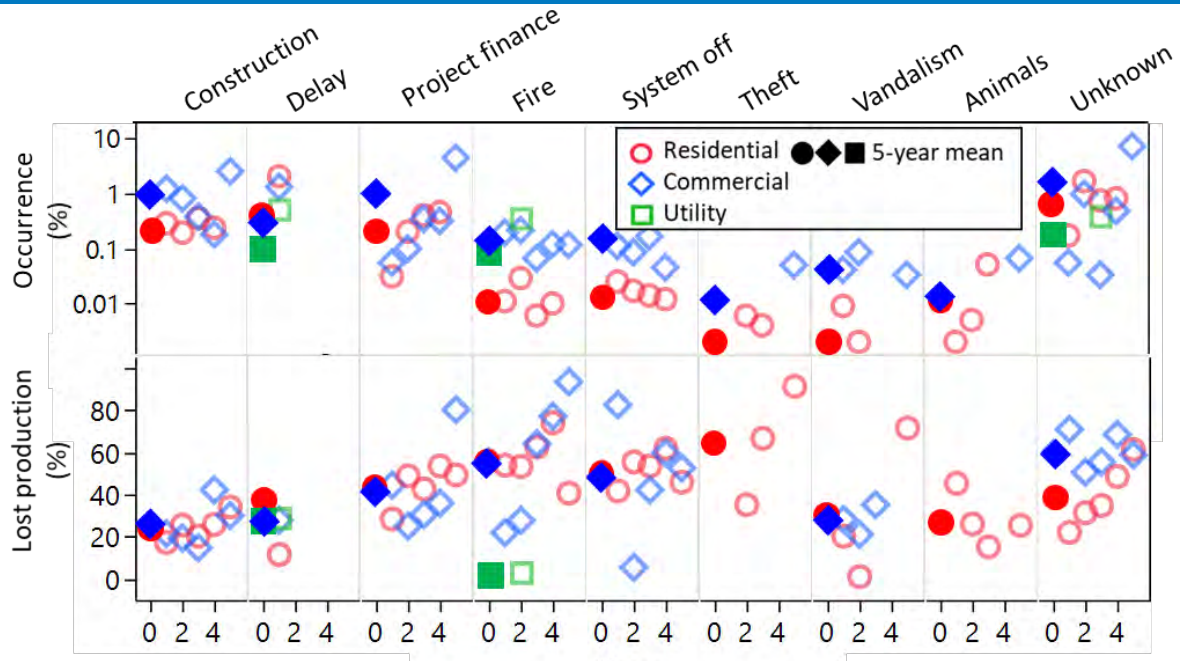
Preference for inverters: More shade the better

Utility & data collection issues



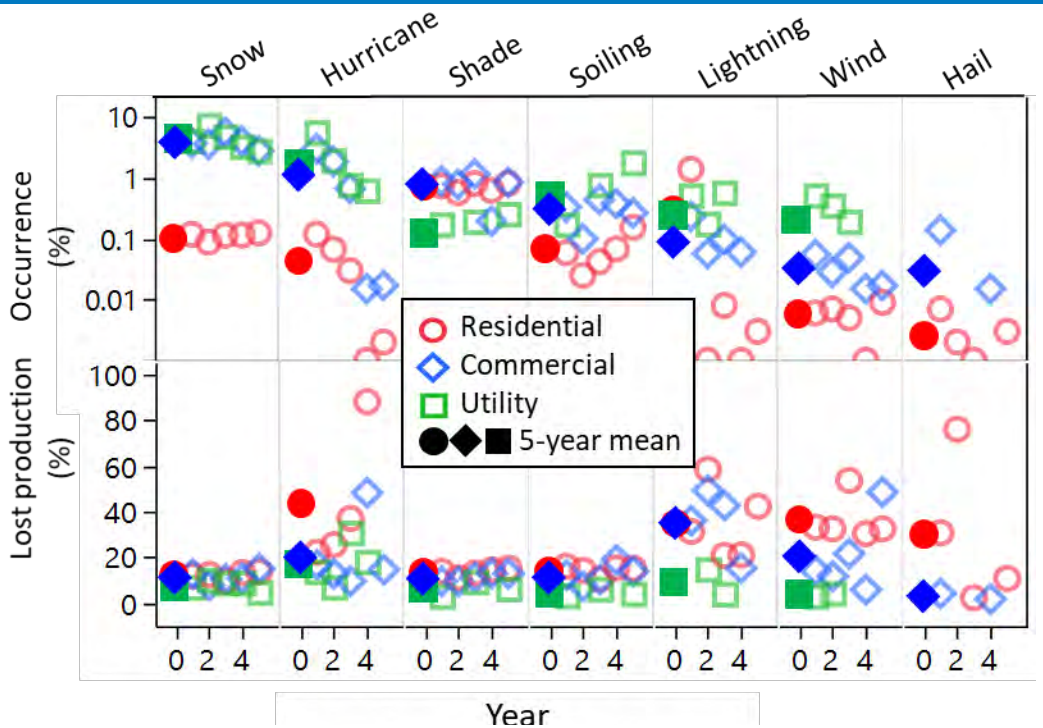
- Curtailment the largest issue for U systems
- Transformers & interconnection issues leading to outages
- Initial estimates that are incorrect typically impact residential (R) & commercial (C) systems
- Missing data (incomplete year) impacts residential & commercial systems, utility better monitored

Project issues



- Roof repairs/renovations on R and smaller C systems
- Delays typically impacts residential & commercial in the first year
- Fires (not PV caused), forest fire impact utility line & tripped utility system
- Project finance: bankruptcies, death of owner etc.
- Theft – R: mostly modules, C: mostly copper wire, U: better supervised

(Unusual) weather issues



- Snow probably underreported for R systems, overall small impact on power
- Soiling, snow bigger impact for larger systems though U often cleaned
- Shade impacting all system sizes, less for U systems
- Lightning strikes directly to PV rare, great impact due to strikes nearby or substation.

Conclusion

- ☺ No widespread failures
- ☺ Most systems perform as expected (80-90% within 10% of predicted)
- ☺ Module failures are low (0.2-0.02%)
- ! Inverter failures are most common failure (some may be related to installation best practices; shade them!)
- ! Installation quality can have an impact on reliability (strings, meters hooked up backwards, connectors, fuses)

Acknowledgments

Thank you

Edward Settle
Jason Coughlin
Doug Gagne
Ellen Neubauer

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NATIONAL RENEWABLE ENERGY LABORATORY

Degradation Case Studies: From the Field to the Lab

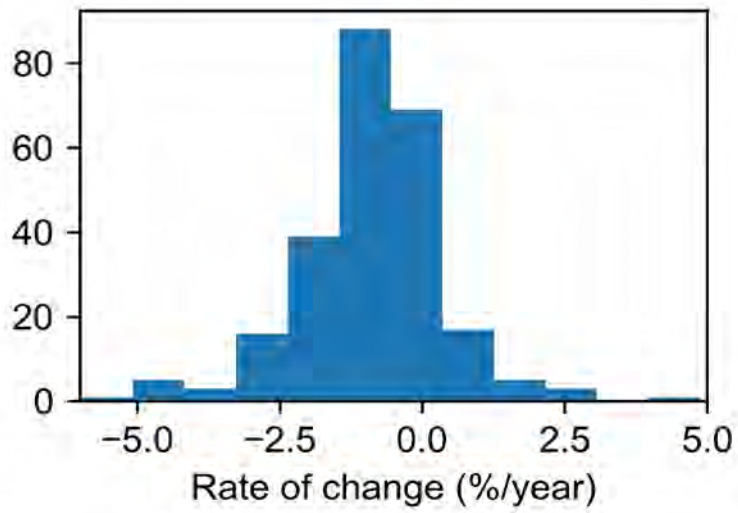
Michael G. Deceglie, Timothy J Silverman, Steve Johnston, Ingrid Repins
National Renewable Energy Laboratory

Jim Rand, Mason Reed
Core Energy Works

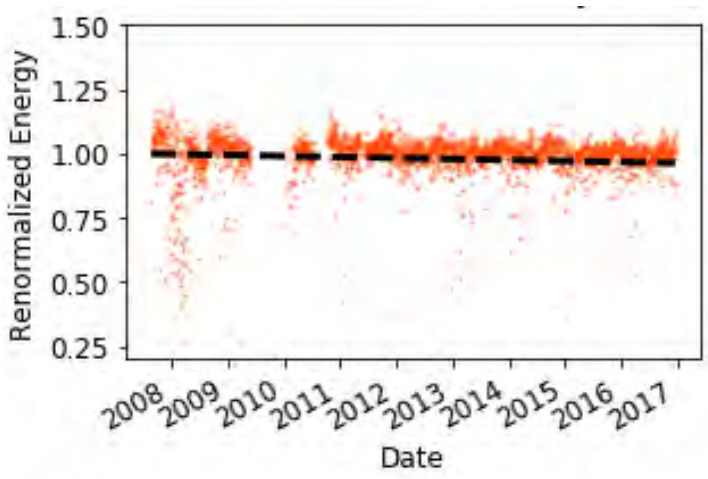
Case Studies vs. Fleet Analysis

Fleet analysis

- Trends in large numbers of systems
- Consistent methodology critical
  - But can gloss over details

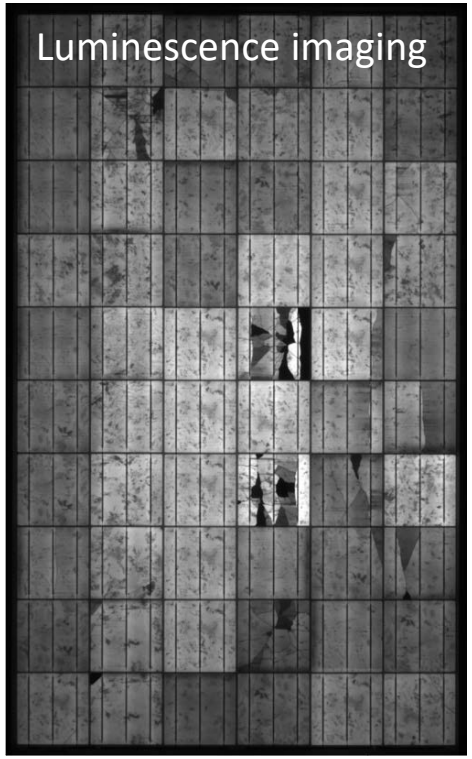


Outdoor time series



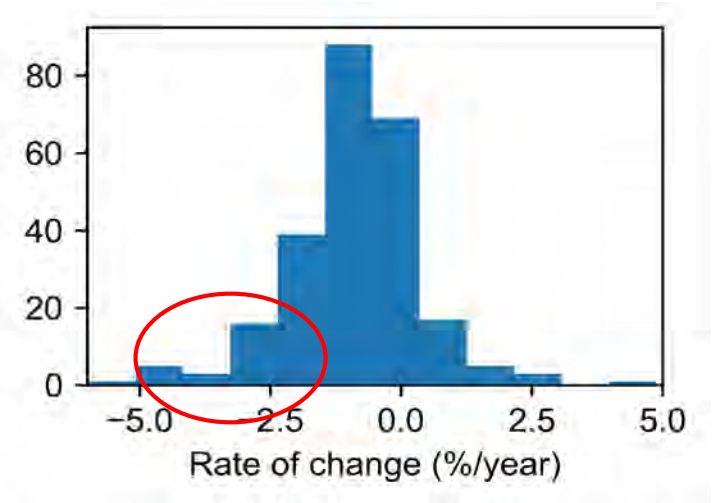
Case Study

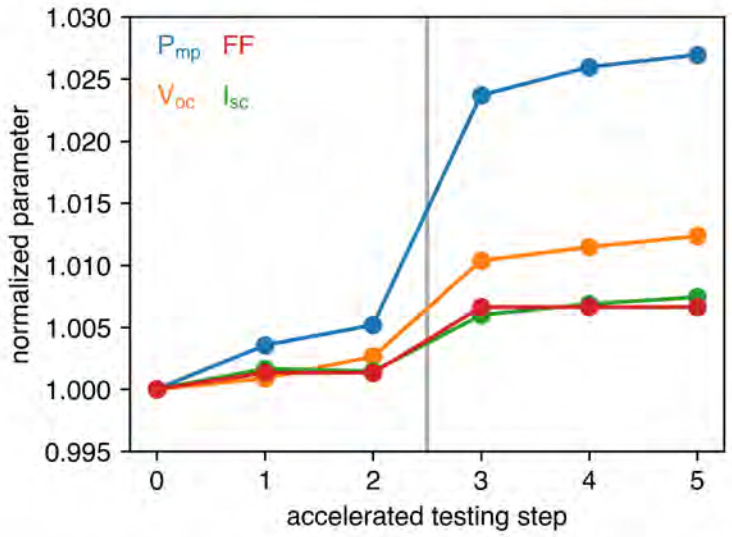
- Detailed analysis on a small number of systems
- Methodology tailored to specific observations



Case Study Methodology

Identify system underperformance (supported by fleet analyses) → Characterize in the field → Select and harvest sample modules → Study in the lab





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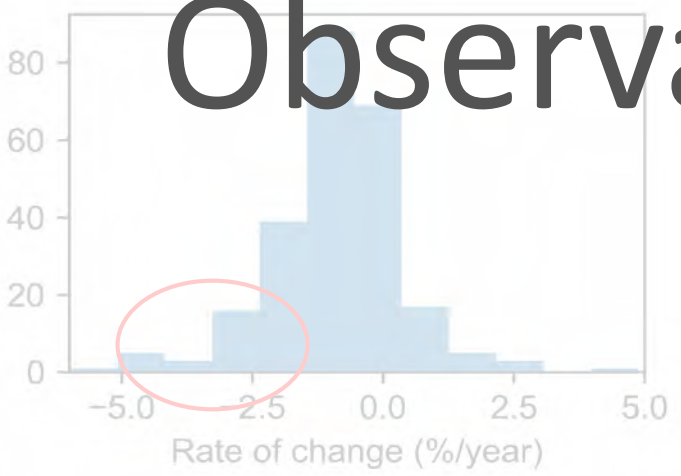
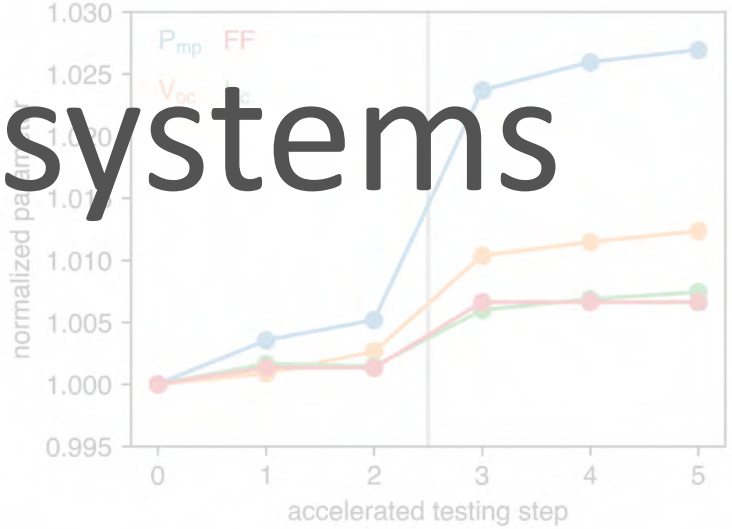
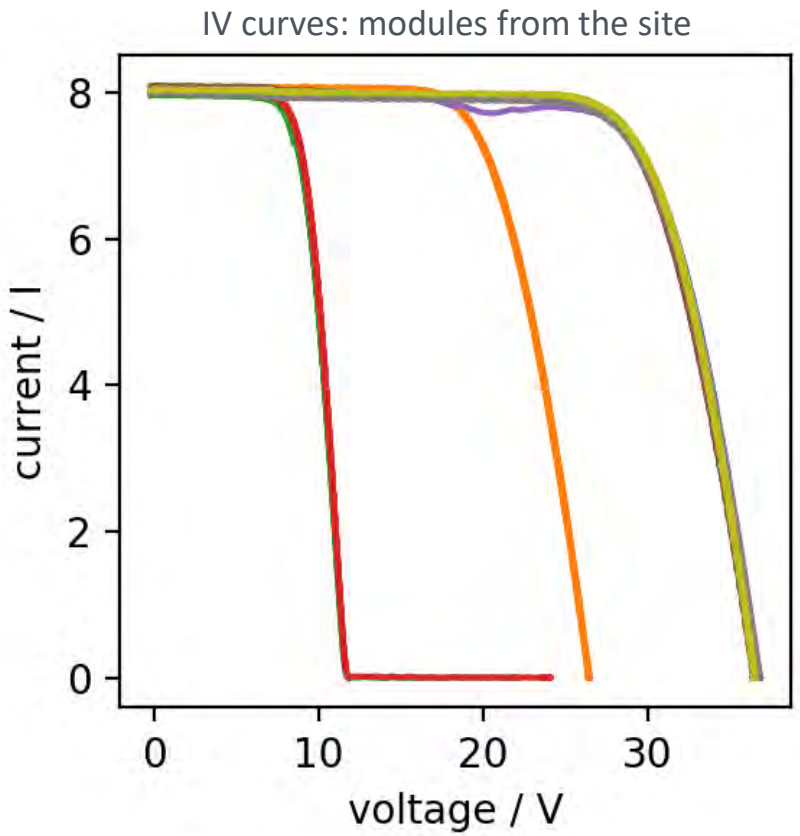




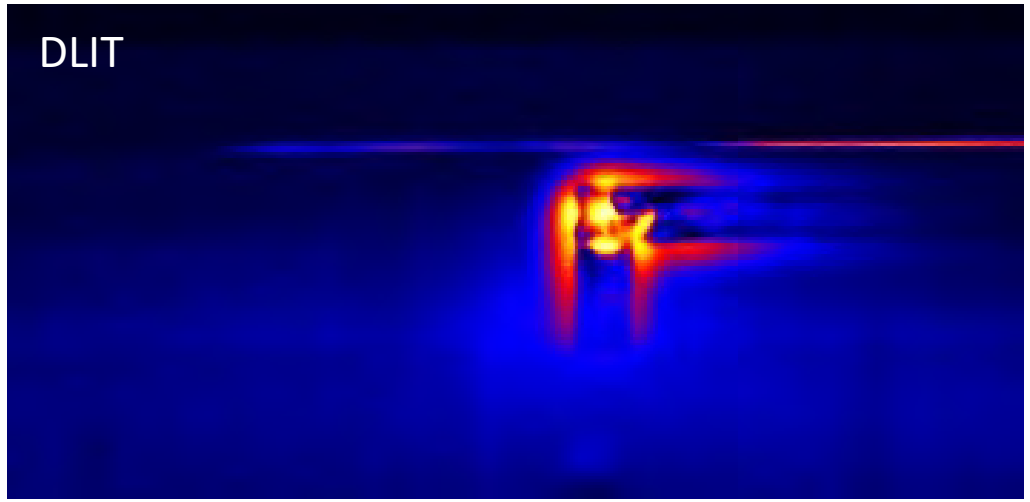
Observations from 5 systems

Site 1: Solder Bonds

- System identified as underperforming
- Field characterization revealed substring outages in a subset of modules
  - Informed sample collection for detailed laboratory study
- Laboratory IV measurements support substring outages within module

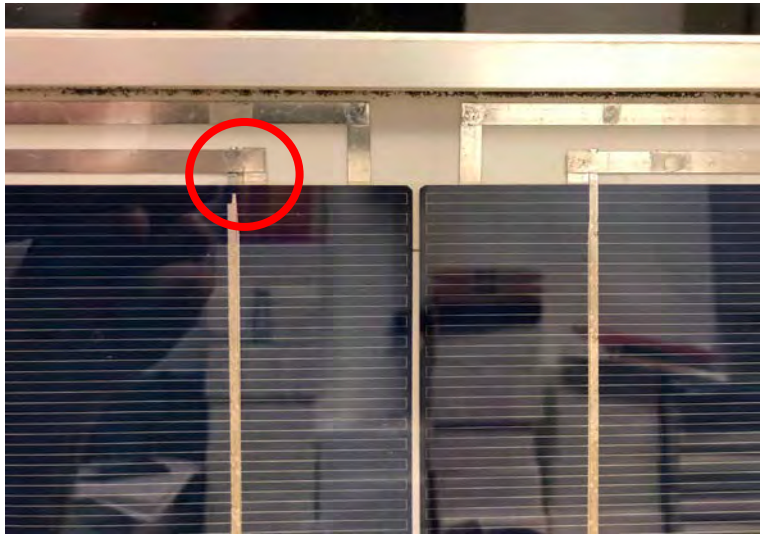


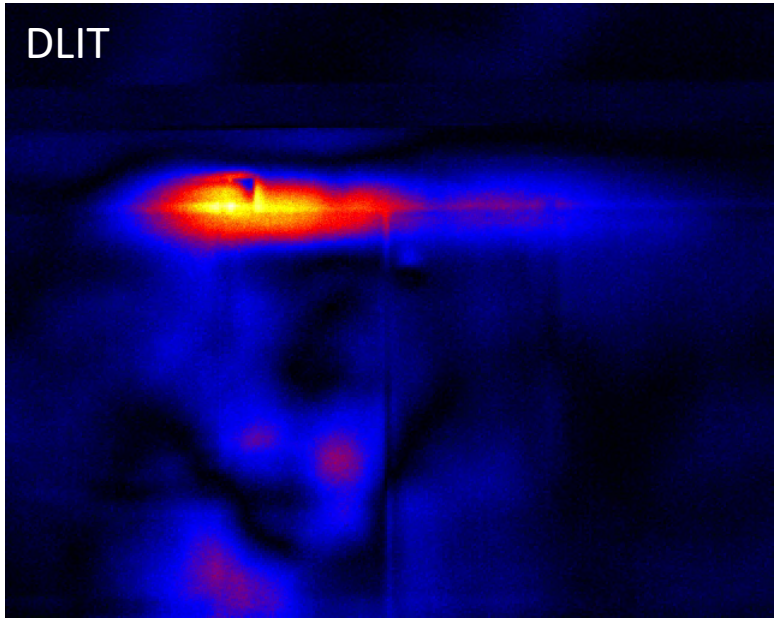
Thermography



Dark lock in thermography (DLIT) reveals areas of power dissipation

Site 1: Ongoing work

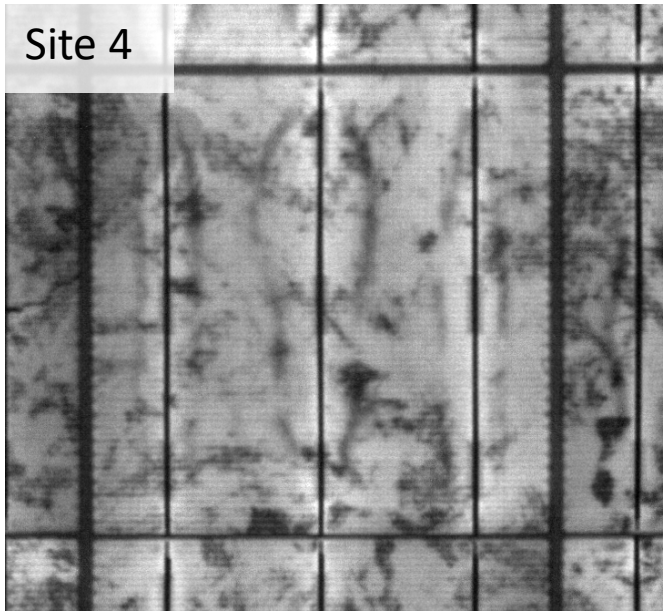


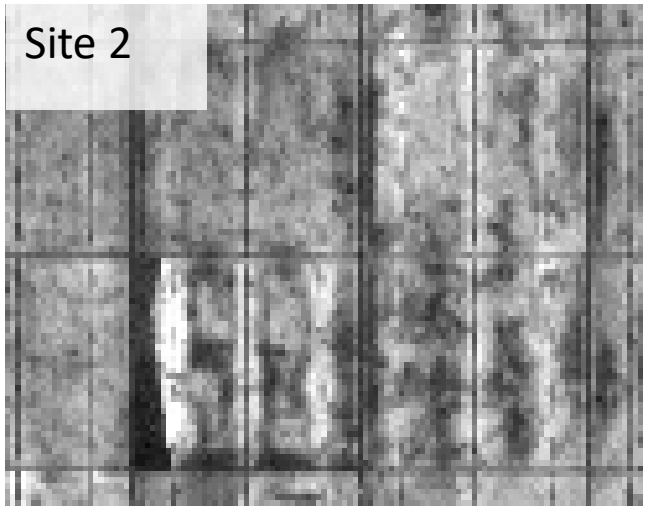


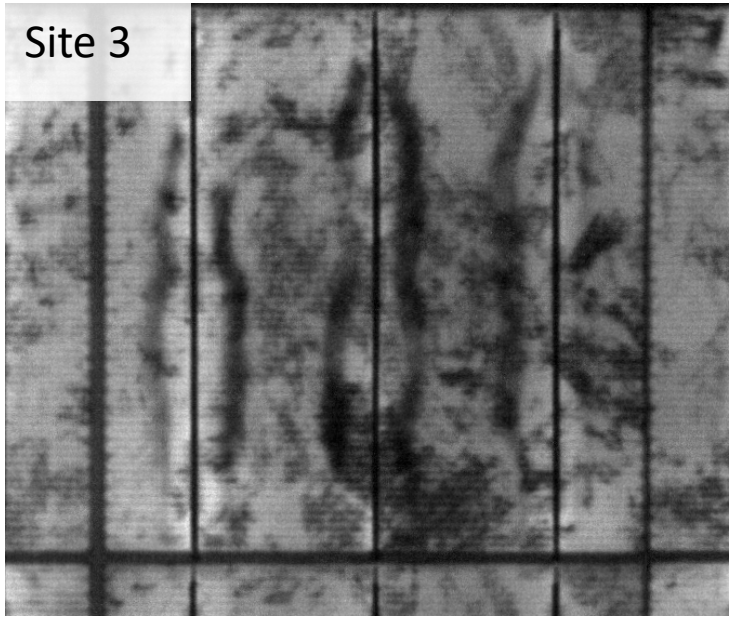
- On some modules we see thermal signatures, but no visible damage
  - Early stages of failure?
- Next steps: Destructive evaluation and microscopic characterization

Sites 2-4: Metallization problems

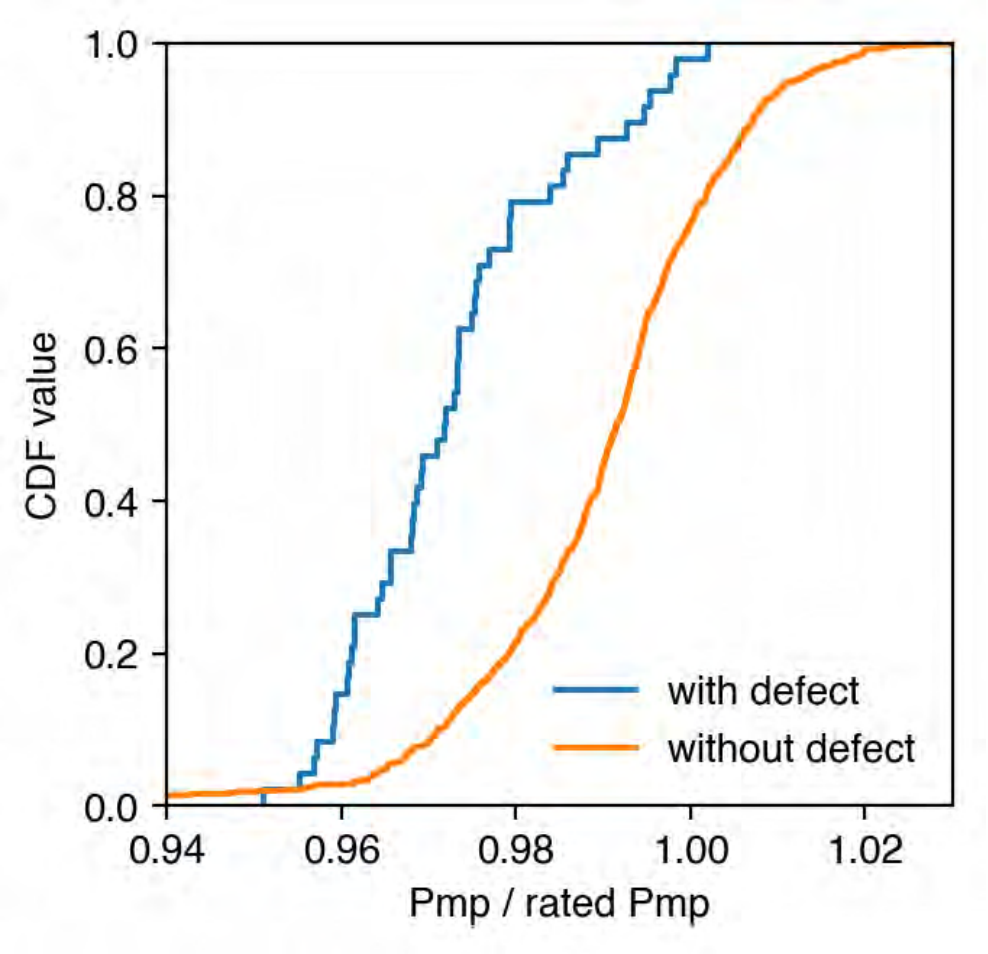
- Sites identified as underperforming
- Field EL revealed common features
- Multi-Si modules of similar vintage
- In operation for ~6-8 years
- 6–12% of modules affected







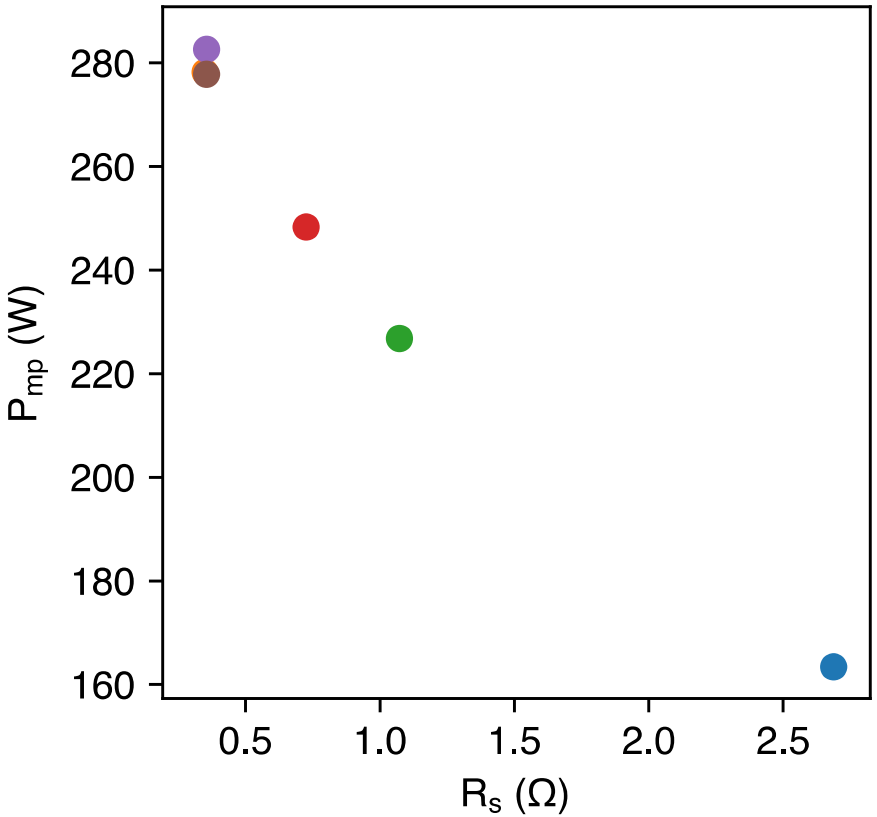
Field IV results



- 800 tested modules surveyed at sites 3 and 4
- These modules have significantly ($p<0.001$) more power loss
  - Median 3% with defect
  - Median 1% without defect
- **The feature is associated with power loss**

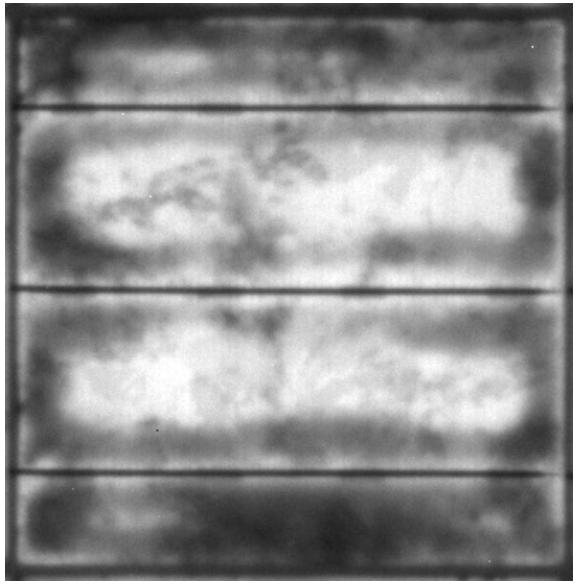
Laboratory Characterization (site 2)

Module power vs. extracted R_s

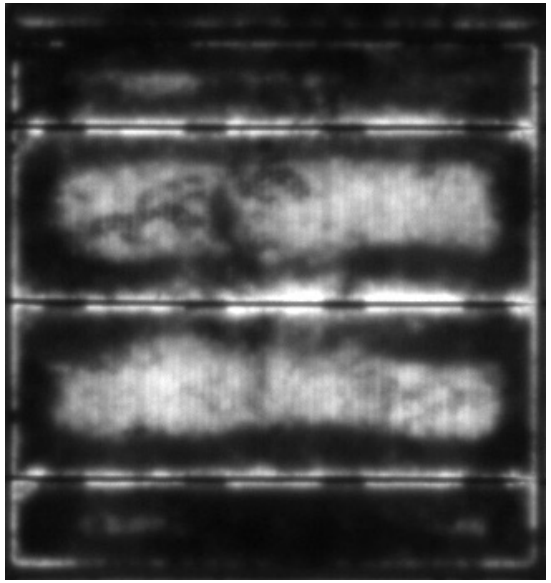


Electroluminescence

$I_{sc}/10$



I_{sc}



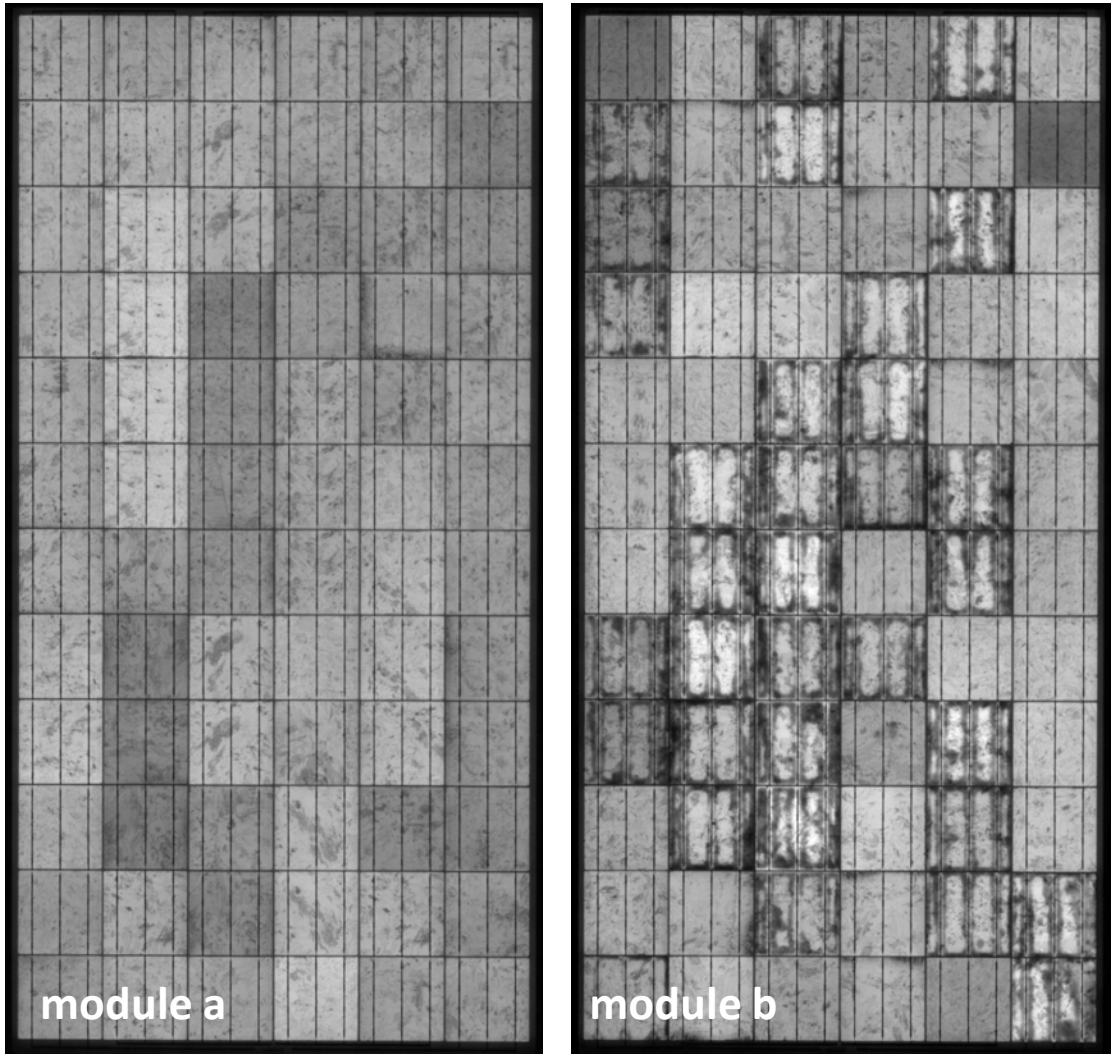
Increased contrast at high current suggests R_s issue

Laboratory intensity-dependent IV measurements and EL imaging are consistent with a distributed series resistance problem

Metallization problem: ongoing work

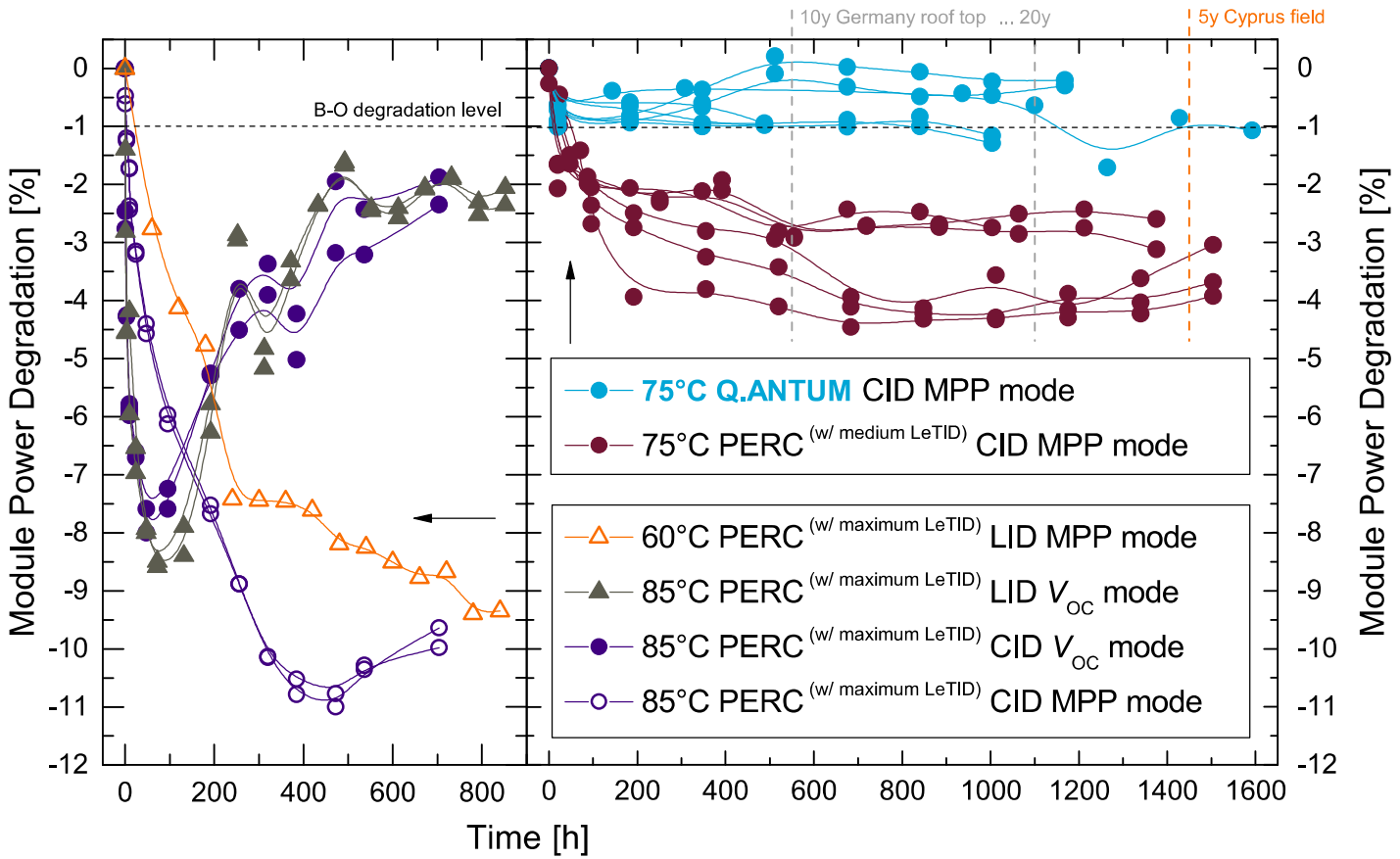
- Begin destructive microscopic evaluation
- Compare affected and unaffected cells/modules
- Evaluate gaps in standards

EL from site 2 modules



LeTID: Light and Elevated Temperature Induced Degradation

- Recently emerged in variety of Si technologies
- Generally slower that B-O light induced degradation (LID)
- Degradation and regeneration can be observed with appropriate accelerated testing

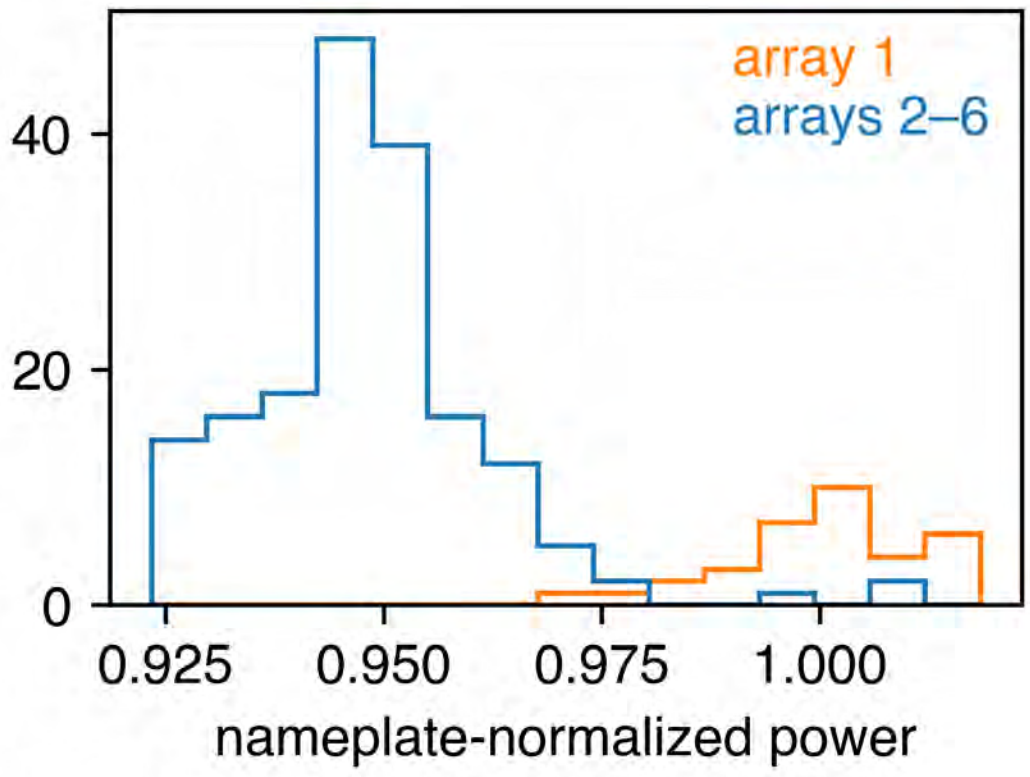


F. Kersten et al. Solar Energy Materials & Solar Cells 142 (2015) 83–86

Site 5: LeTID

- Utility scale plant, identified as under performing by owner
- Includes 6 arrays, each with own meter
- Field IV measurements on small fraction of modules shows array 1 out-performing the others
- Harvested typical modules from array 1 and 2–6 (and high outliers from 2–6)

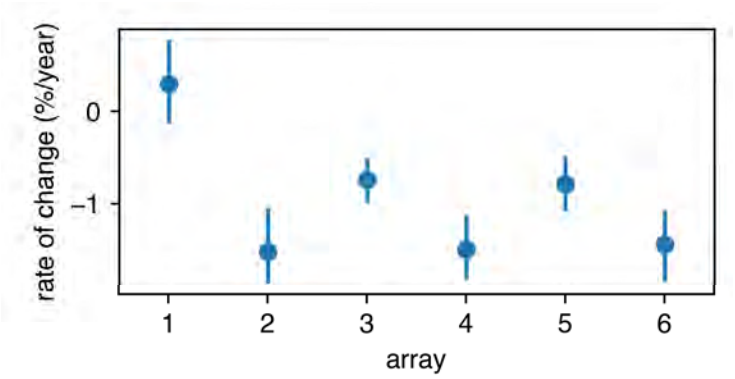
Histogram of field IV curves

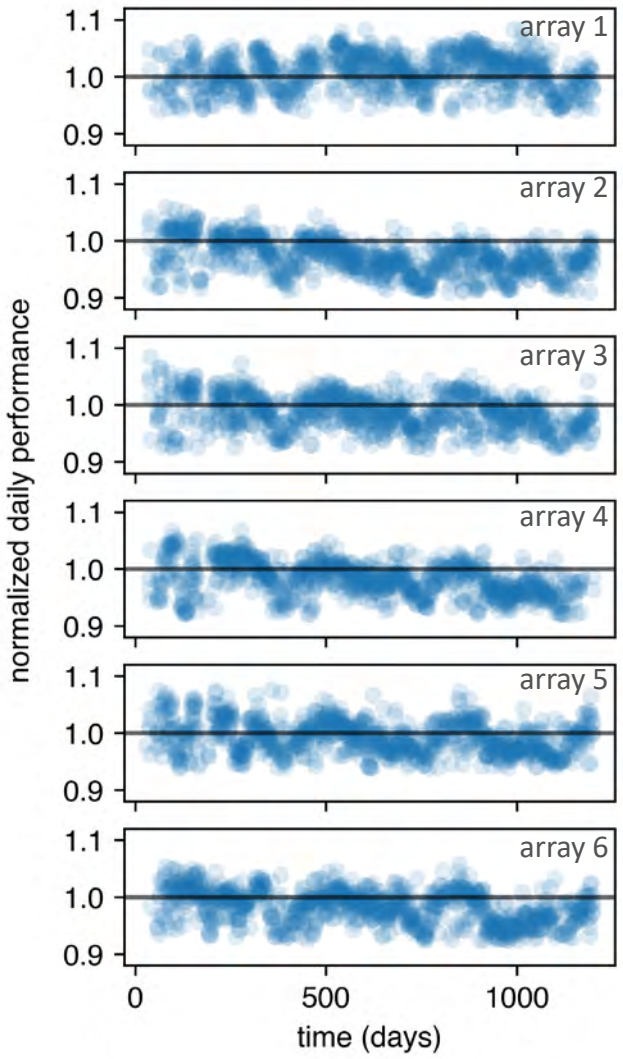


Deceglie et al. "Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System," 2020 (Submitted)

Self-consistent pattern: Rd, PL, IV

- Ran an RdTools degradation array-by-array based on meter output
- Significantly more rapid degradation in arrays 2–6 than array 1



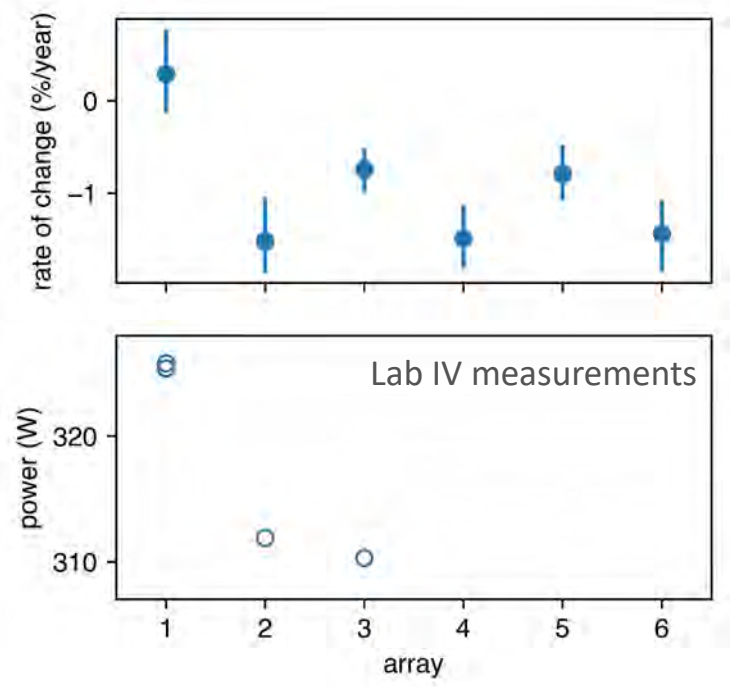


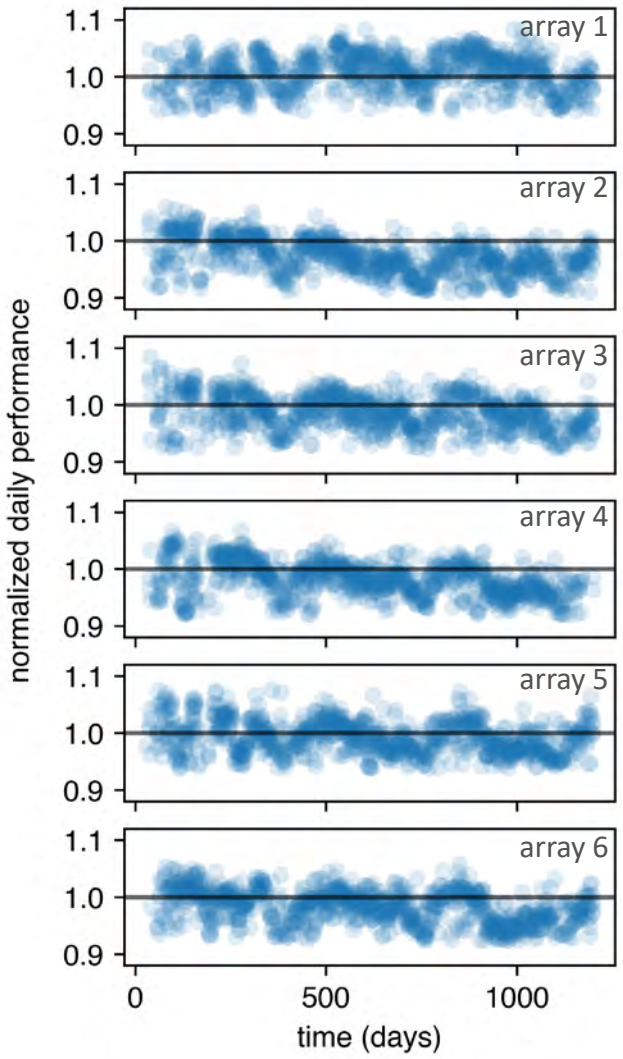
Deceglie et al. "Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System," 2020 (Submitted)

https://github.com/NREL/RdTools

Self-consistent pattern: Rd, PL, IV

- Ran an RdTools degradation array-by-array based on meter output
- Significantly more rapid degradation in arrays 2–6 than array 1
- Laboratory light IV supports array-level observations



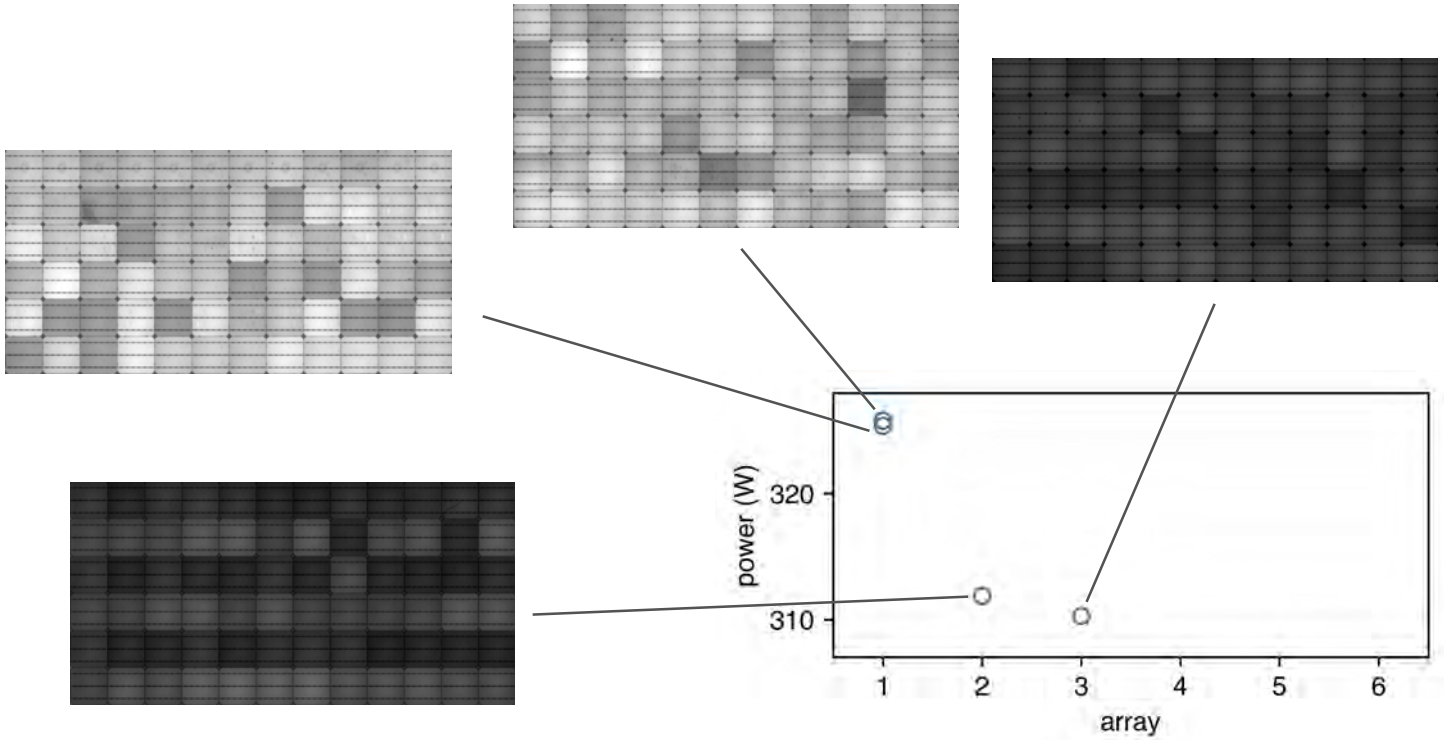


Deceglie et al. "Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System," 2020 (Submitted)

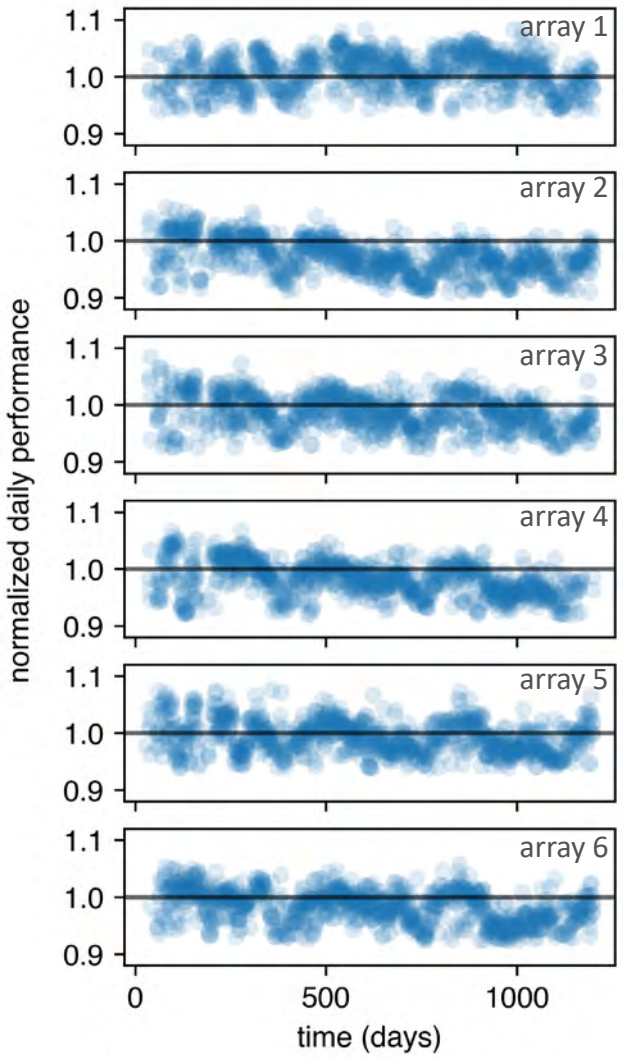
https://github.com/NREL/RdTools

Self-consistent pattern: Rd, PL, IV

- Ran an RdTools degradation array-by-array based on meter output
- Significantly more rapid degradation in arrays 2–6 than array 1
- Laboratory light IV supports array-level observations
- Laboratory photoluminescence dimmer for degradation affected-modules



Lab IV measurements



Deceglie et al. "Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System," 2020 (Submitted)

https://github.com/NREL/RdTools

Effects of accelerated testing

- Subject a field-degraded module to accelerated testing conditions known to advance LeTID
  - “Degradation” (Steps 1–2): 75°C , I_{sc} – I_{mp}
  - “Regeneration” (Steps 3–5): , 85°C, I_{sc}

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Effects of accelerated testing

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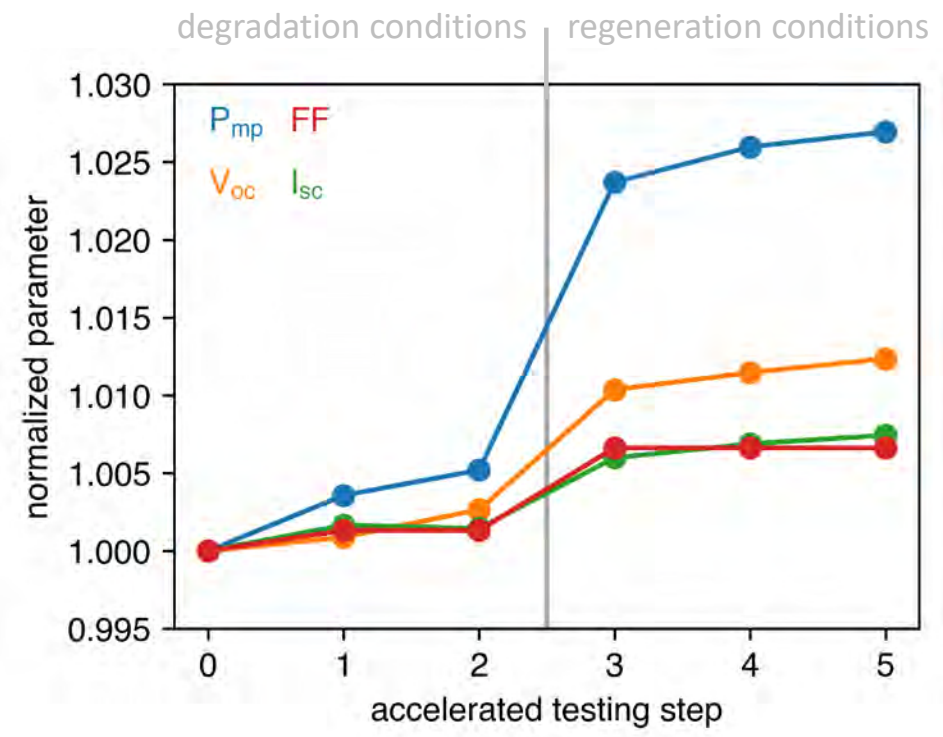
- **Module is field degraded, not much change in degradation phase**
- **Regeneration phase improves module performance**



Deceglie et al. "Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System," 2020 (Submitted)

Effects of accelerated testing

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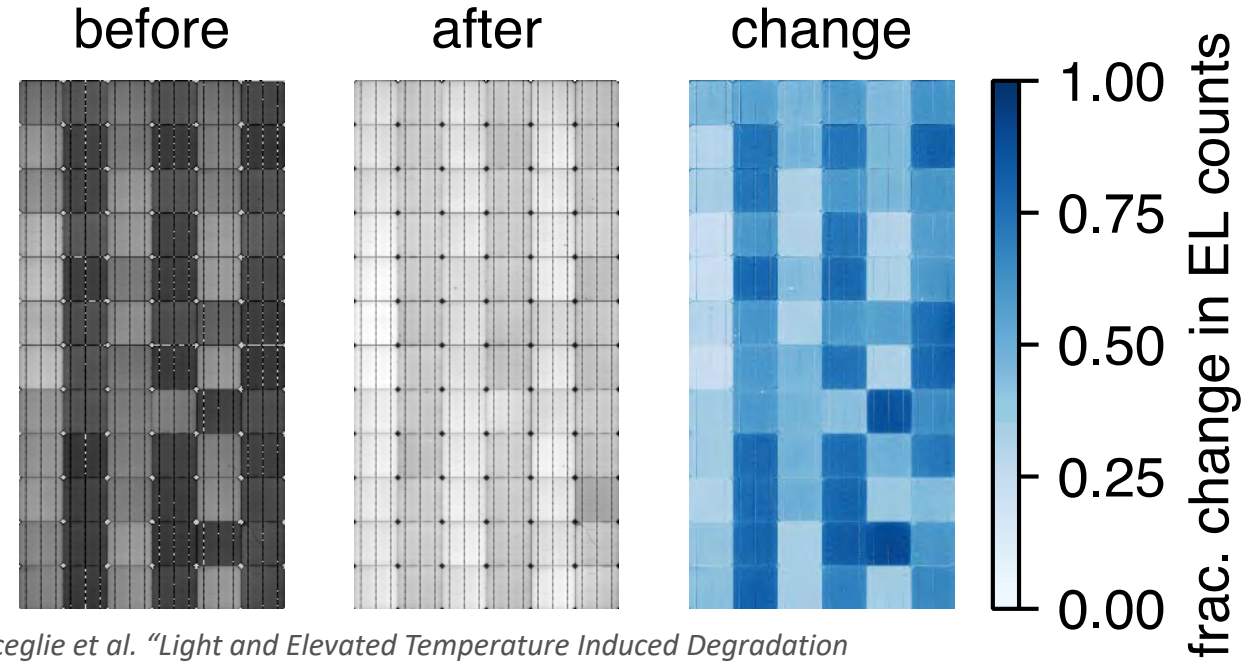
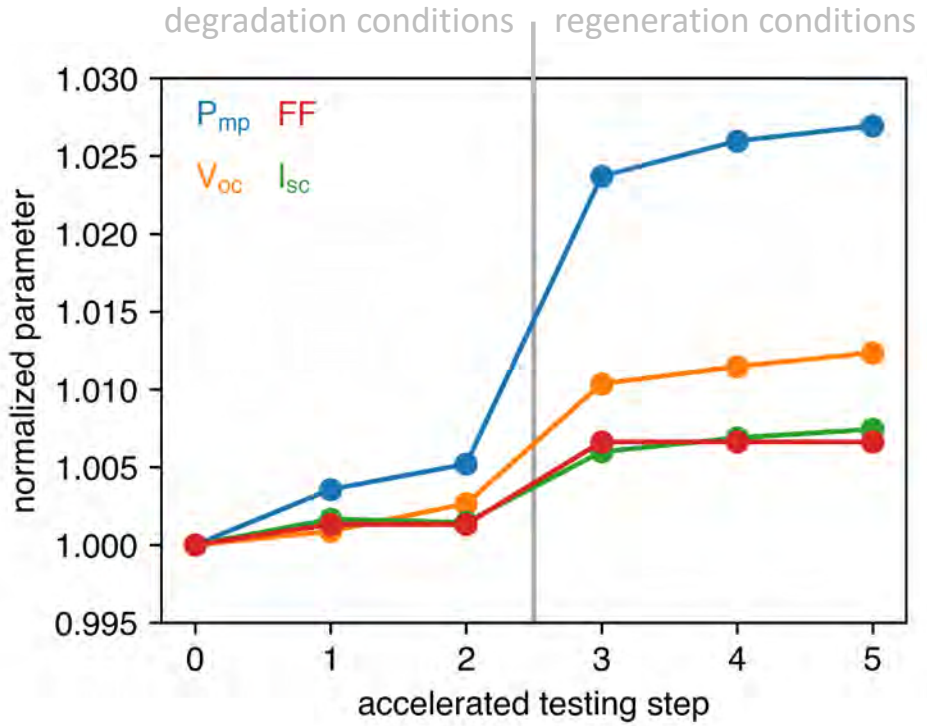
  - "Degradation" (Steps 1–2): 75°C , I_{sc} – I_{mp}
  - "Regeneration" (Steps 3–5): , 85°C, I_{sc}
  - Each step is a week of chamber exposure
- Module is field degraded, not much change in degradation phase
- Regeneration phase improves module performance
- **EL becomes brighter and more uniform**

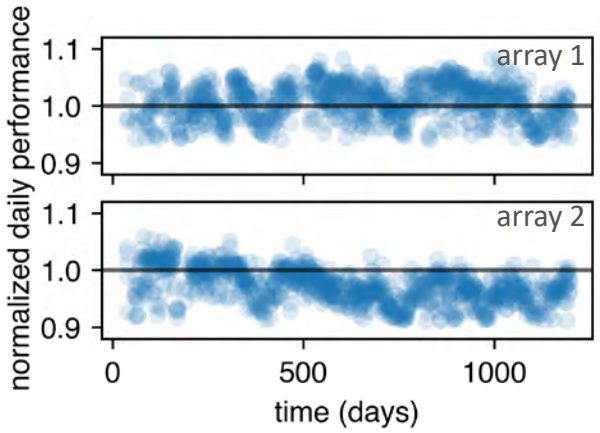


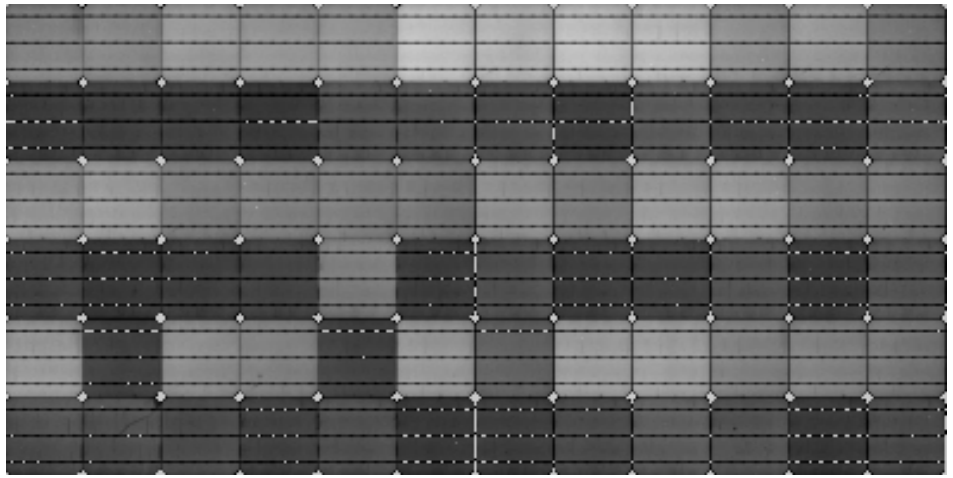


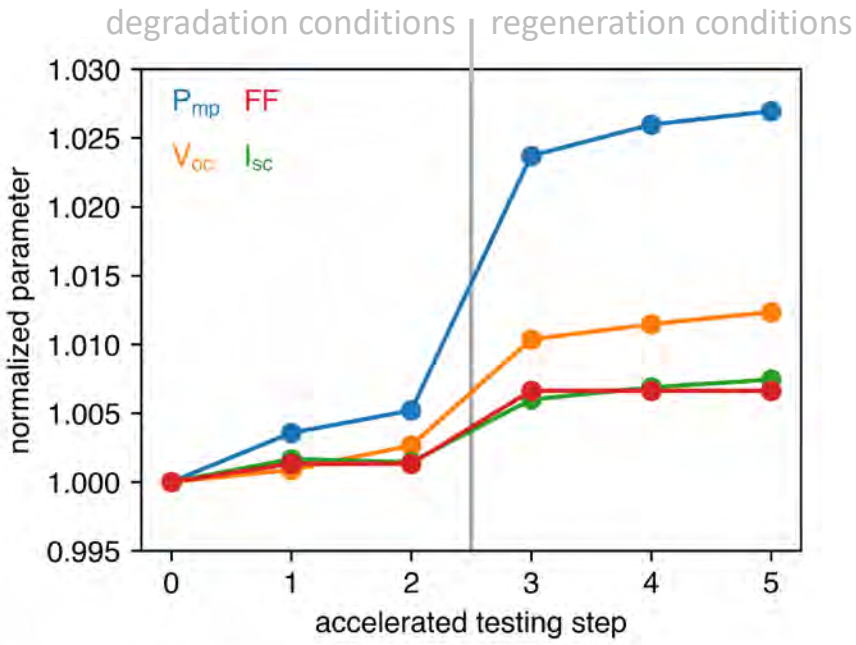
Deceglie et al. "Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System," 2020 (Submitted)

Consistency with LeTID

- Degradation in the field occurred on the timescale of years
- Response accelerated tests designed to probe LeTID
  - Timescale
  - Response to temperature and bias current
- Cell-to-cell variations

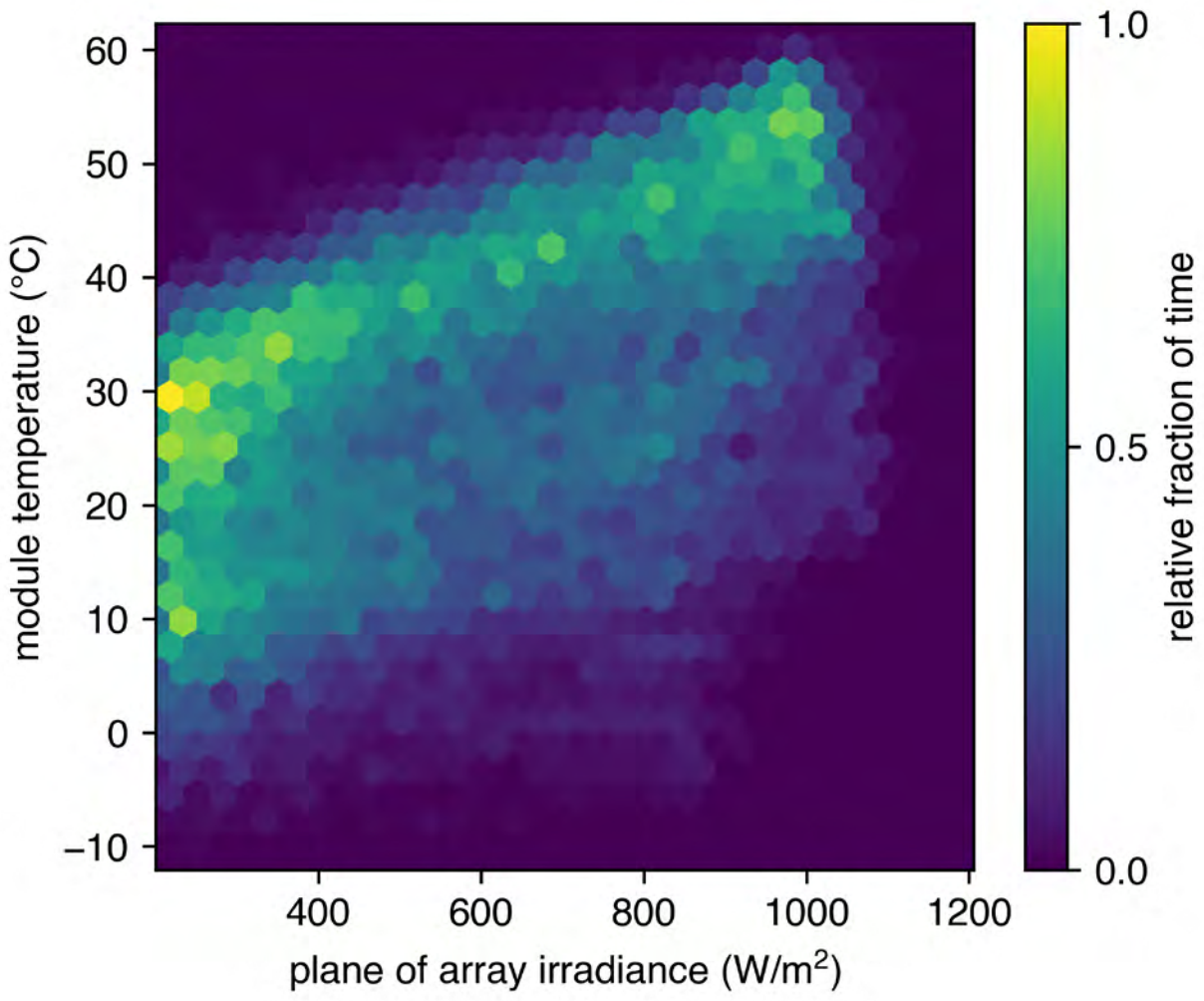






Deceglie et al. "Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System," 2020 (Submitted)

LeTID: Site conditions



We have observed LeTID in a moderate climate

Deceglie et al. "Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System," 2020 (Submitted)

Conclusion

Identify system underperformance (supported by fleet analyses) → Characterize in the field → Select and harvest sample modules → Study in the lab

- Degradation case studies are critical to effective standards
- Start with real systems exhibiting underperformance
- Three different degradation modes across 5 sites, all affecting energy yield
  - Bus junction failure
  - Metallization problem
  - LeTID in a utility-scale system

Thank you

www.nrel.gov

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NREL
Transforming ENERGY

IEC Standards and PV System Certification

George Kelly

PV Module Reliability Workshop

Lakewood, Colorado, US

26-February-2020

Abstract

- To address the industry's need to assure investors of the value of their PV power plants, the International Electrotechnical Commission (IEC) has established a new conformity assessment system for renewable energy (IECRE).
- This presentation provides an analysis of the progress of standards activities in IEC TC82 and the publication of standards required for IECRE certifications for PV systems.

- There is presently important activity devoted to defining the requirements for various types of PV system certificates, intended to provide additional value to investors and end-users.
- Specifically, IECRE is seeking participants in a "stakeholder group" for PV end-users (including system owners, developers, financers, insurers, and regulators).

ACKNOWLEDGMENTS

Masaaki Yamamichi (RTS)

Thomas Sauer (Exxergy)

ARESCA

American Renewable Energy Standards and Certification Association

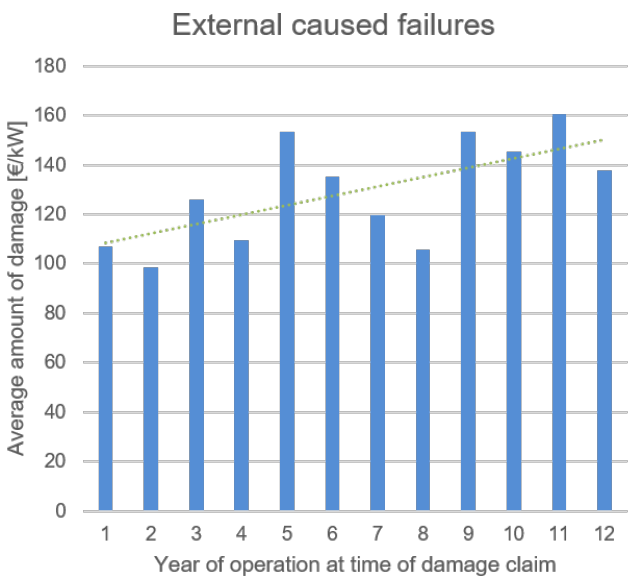
www.aresca.us

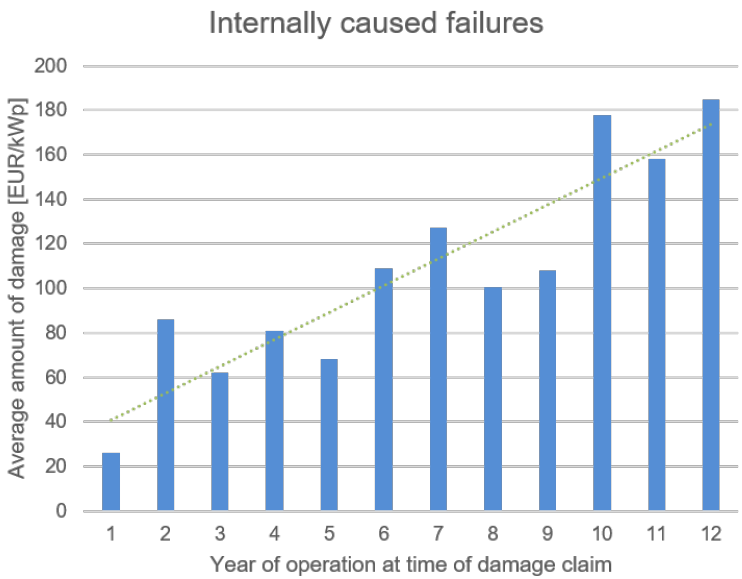
Background

- Industry Growth
  - Demand increasing steadily >20% per year
  - Significant increase in large commercial plants
- Concern for Quality / Bankability
  - Doubts about adequacy of existing standards
  - Need for improved understanding of reliability
  - Validation of product lifetime for investors
- Need for Conformity Assessment
  - Assurance of security for investments in PV

Analysis of insurance claims

- Failure patterns match logical expectations

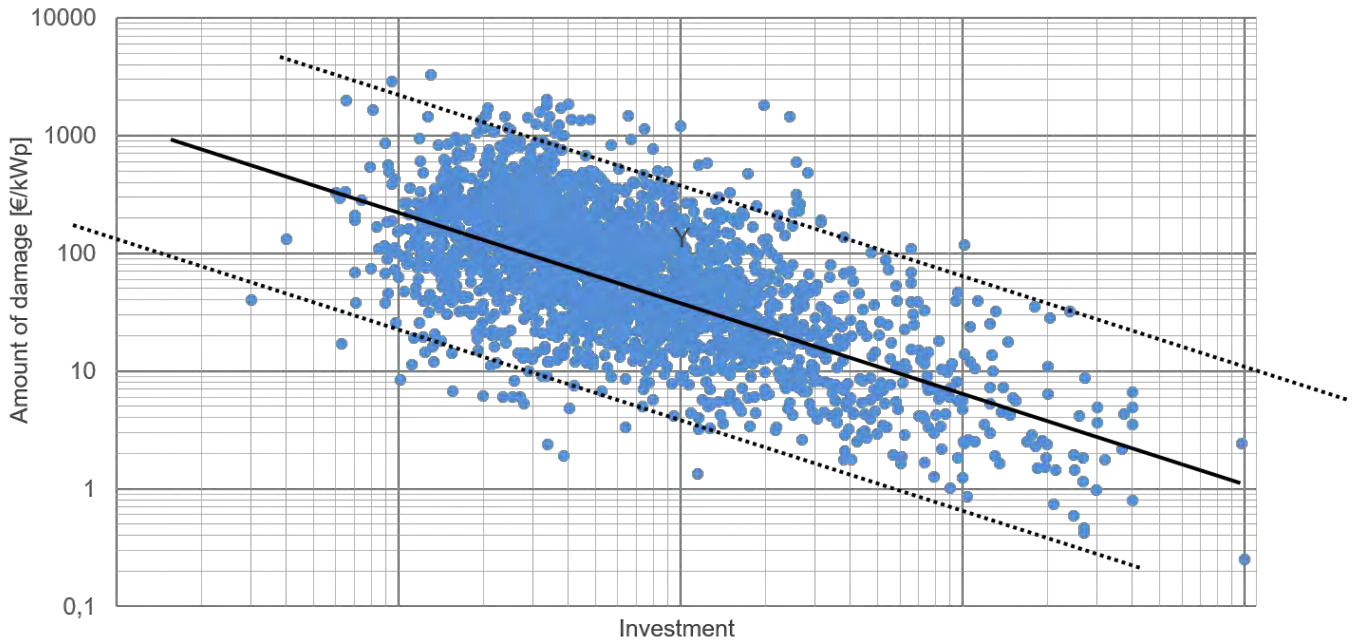




Source: EXXERGY® analysis on >3.600 insurance claim cases 2012 - 2017

Damages can be significant

- Relative cost is higher for smaller systems



Source: EXXERGY® analysis on >3.600 insurance claim cases 2012 - 2017

Principles for balancing risk and cost

- Benefit from standardization
  - Create and adopt international standards (only one set)
  - Learn from each other (define best standards more quickly)
- Oversight at every stage
  - Design and planning
  - Construction
  - Operation
- Emphasize consistent quality control:
  - Require continuous learning
  - Don't assume that *a single* success implies future successes
- Efficient implementation
  - Don't duplicate inspections
  - Leverage internal quality management actions

Importance of Conformity Assessment

IEC Standards ⟷ Two sides of one coin ⟷ IECRE conformity assessment

A one sided coin has no value!

International Standards

- Provide rules, guidelines or characteristics for activities or their results
- Consensus of international experts in an open and transparent process
- Made available to the public, for common and repeated use
- Basis for Conformity Assessment and for certification of products and systems

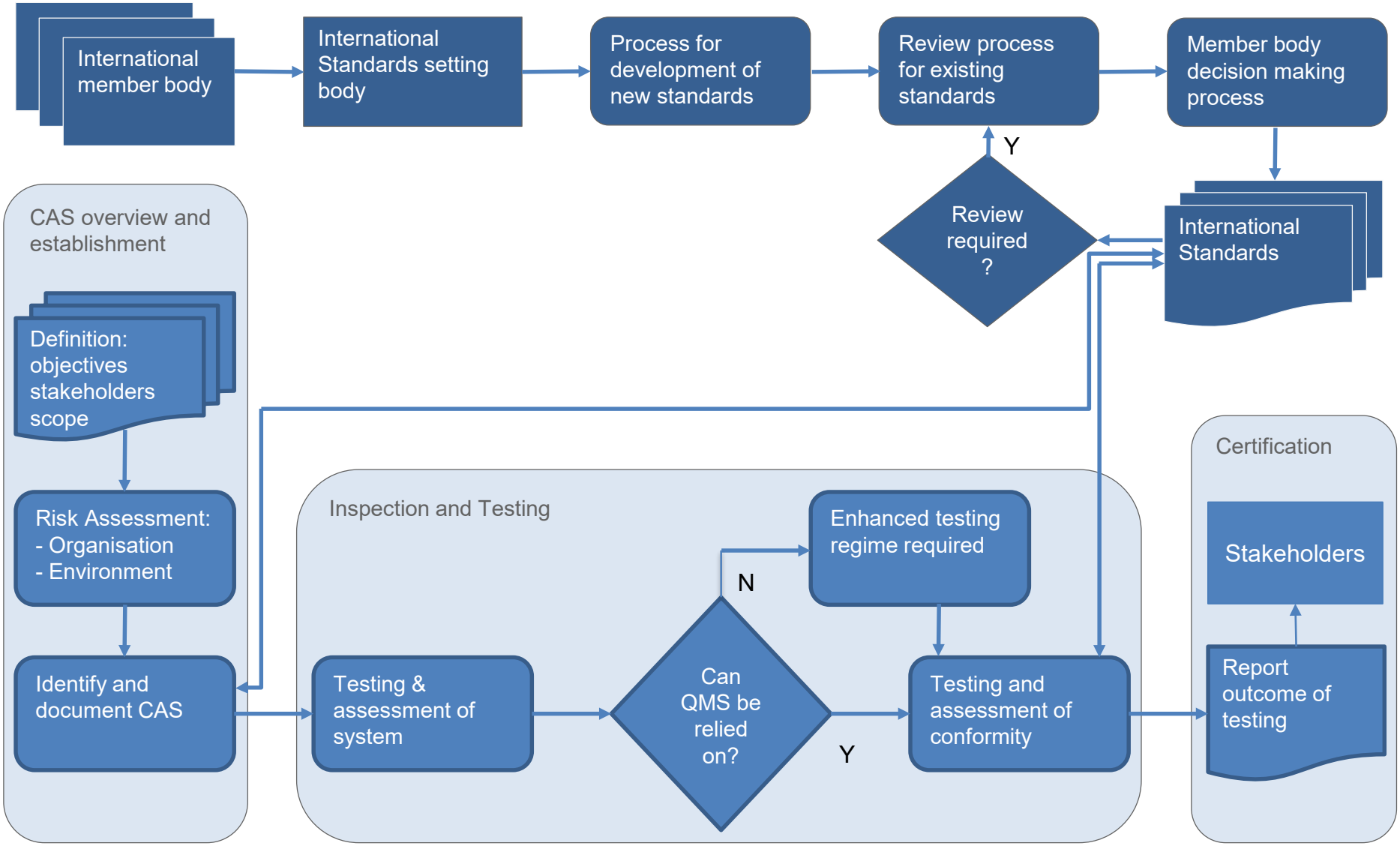
Conformity Assessment

- Evaluation against international standards
  - May use national or regional standards if no international standard is available
- Improved quality and performance
  - Assurance that PV plant will operate as designed for its expected lifetime
- Increased confidence for investors
  - Financial return meets expectations
  - Risk is reduced

What is conformity assessment?

- Conformity assessment is a widely used process used to show that a product, service, process, body, person or system meets specified requirements
- The specified requirements are usually expressed as a form of Standard, prepared and adopted by an overarching member body. The predominant purpose of a Standard is to achieve a minimum acceptable level of consistency
- The process of conformity assessment includes sampling and testing, inspection, supplier's declaration of conformity, certification, and management system assessment and registration
- It also includes accreditation of the competence of those activities by a third party and recognition (usually by a government agency or official body) of an accreditation program's capability

Generic standards development and conformity assessment processes



Available PV Standards

Standards Development Organization		Membership	Focus of Activities
International Electrotechnical Commission	IEC	National committees	Performance and safety of products, systems, and services
ASTM International (formerly American Society for Testing and Materials)	ASTM	Individual experts	Measurement principles and specialty tests
Semiconductor Equipment Manufacturers' Institute	SEMI	Member companies	Primarily manufacturing-related (materials and equipment)
Underwriters' Laboratories	UL	Invited experts	Product safety
International Code Council	ICC	Invited experts	Building and fire codes
Institute of Electrical and Electronics Engineers	IEEE	Individual experts	Grid-connection codes

Why IEC standards and conformity assessments?

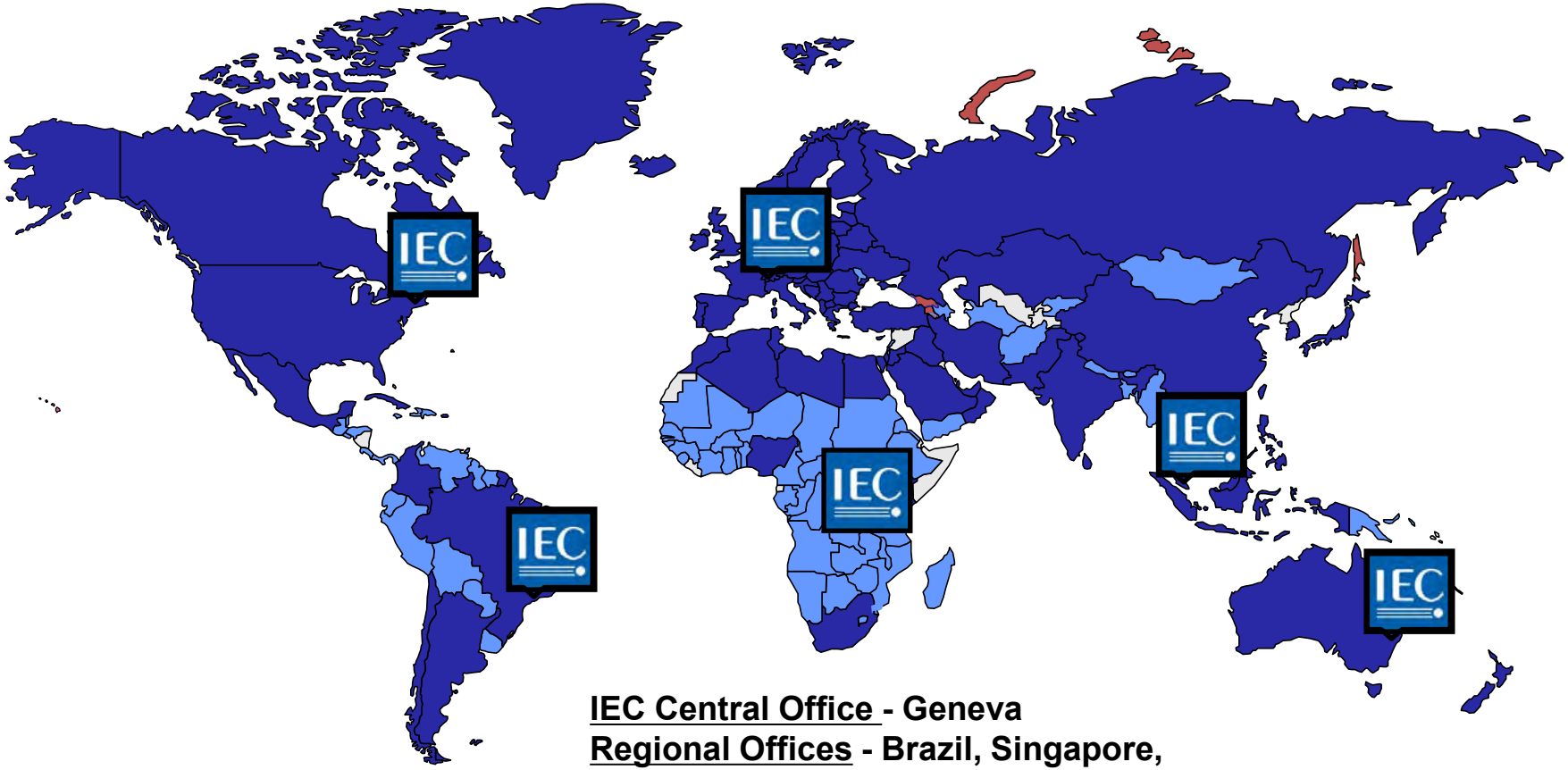
- Harmonized international consensus standards throughout RE industry
- Harmonized conformity assessment
- Harmonized interpretation
- Reduced risk
- Peer assessment
- Transparency
- Mutual acceptance
- Broad stakeholder engagement
- Unique RE international CA system

Benefits of IEC Systems

- IEC Brand
  - Global recognition – multiple industries
  - International recognition (e.g. WTO + UN)
  - IEC Reports and Certificates used nationally
- Open and Transparent Process
  - Clear Rules in process and results
  - Consistency in processes among participating Certification Bodies & Test Labs
- Industry and market provide direct input
  - CA systems driven by market demand

IEC Global Reach

83 Members **83 Affiliates**

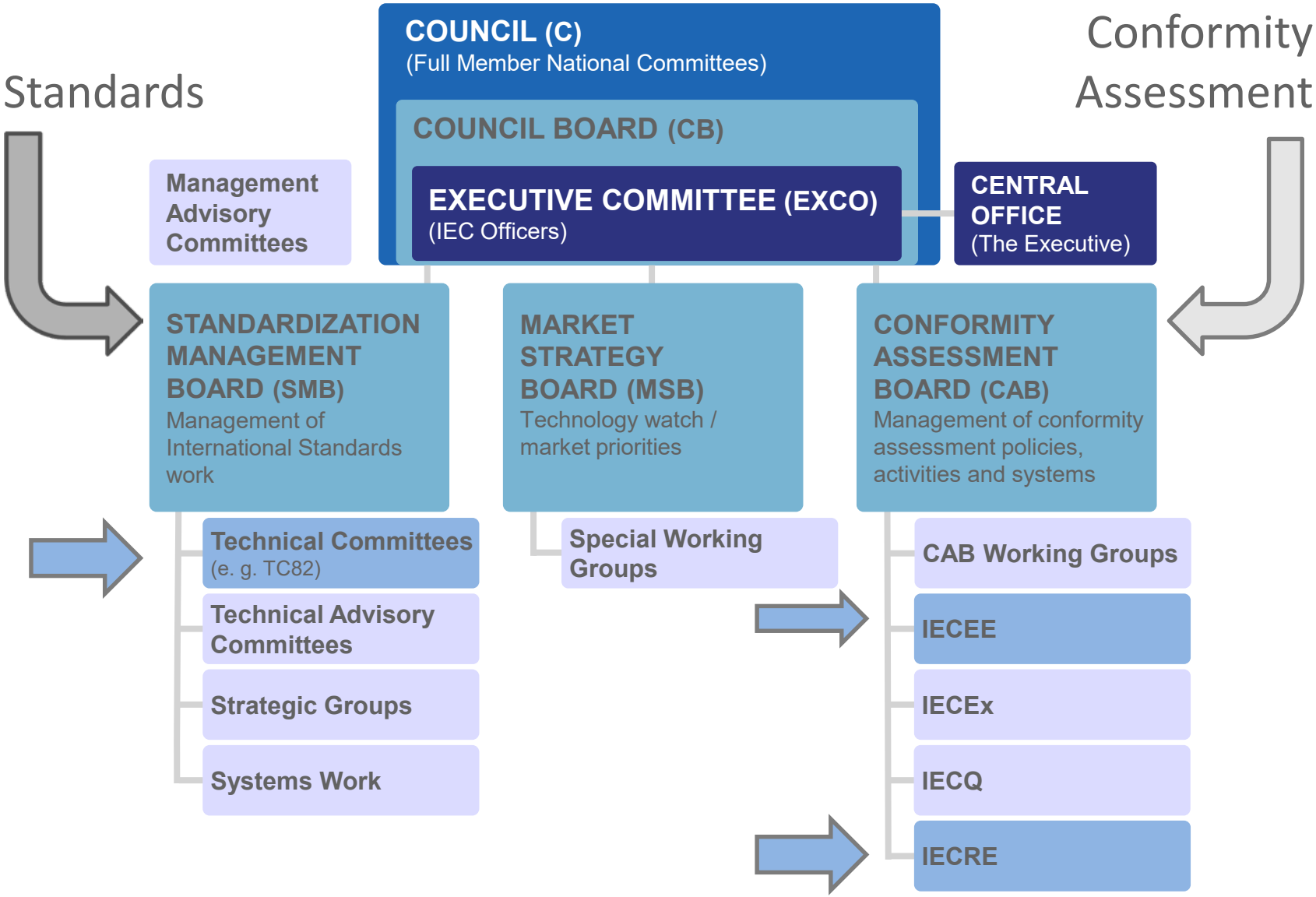


<u>IEC Central Office</u> - Geneva
<u>Regional Offices</u> - Brazil, Singapore, Kenya, US and Australia

Roles & Responsibilities

- Standards Management Board (**SMB**)
  - Technical Committees => Write the standards
  - Manage nomination of experts and voting by National Committees
- Conformity Assessment Board (**CAB**)
  - Assessment Schemes => Evaluate implementation of standards in specific situations
  - Manage accreditation of Certifying Bodies

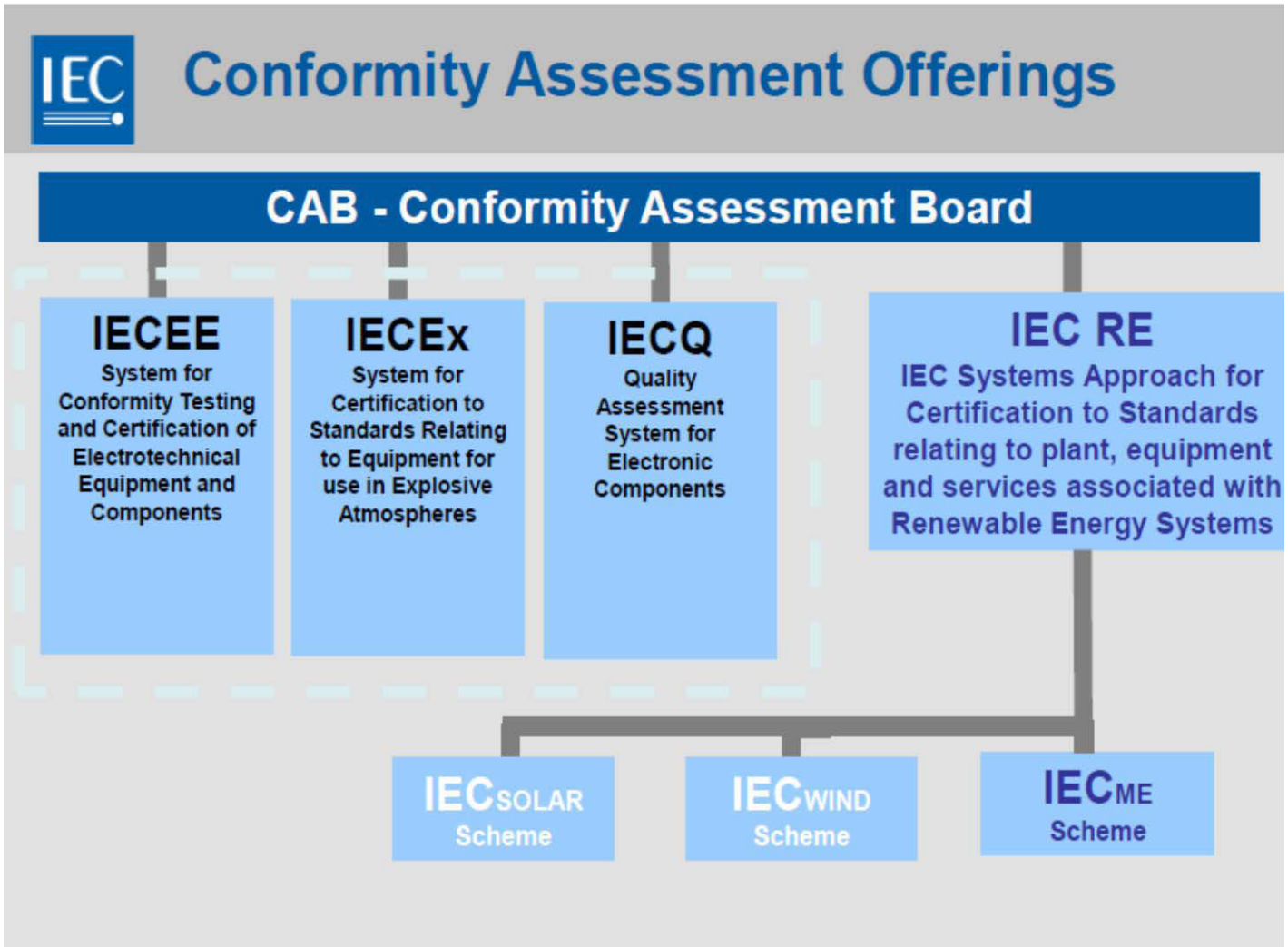
IEC Management Structure



IEC CA Systems

- **IECEE**
  - System for conformity testing and certification of electrotechnical equipment (specific categories including PV modules)
- **IECEx**
  - Conformity assessment for equipment operating in explosive atmospheres
- **IECQ**
  - Quality assessment system for electronic components and associated materials
- **IECRE**
  - System for conformity testing and certification of renewable energy applications

IEC Conformity Assessment



How does the IECRE system work ?

- IECRE itself does not certify, but administers the system and provide its framework through a systematic approach to qualify system participants who issue certificates
- Qualified registered participants are competent to assess RE equipment and projects
  - Certification Bodies, Inspection Bodies, Test Laboratories
  - Competence validation through regular, revolving peer assessment
  - Insuring appropriate interpretation of standards
- Transparency of process and influence for all stakeholders
  - All stakeholders have a voice (RECBs, REIBs, RETLs, OEMs, End Users)
  - All national member bodies have a vote
  - All participating member bodies recognize & accept IECRE certificates

Aspects of Certification

- Conformity assessment can be performed and certificate issued for an individual PV power plant on a specific site

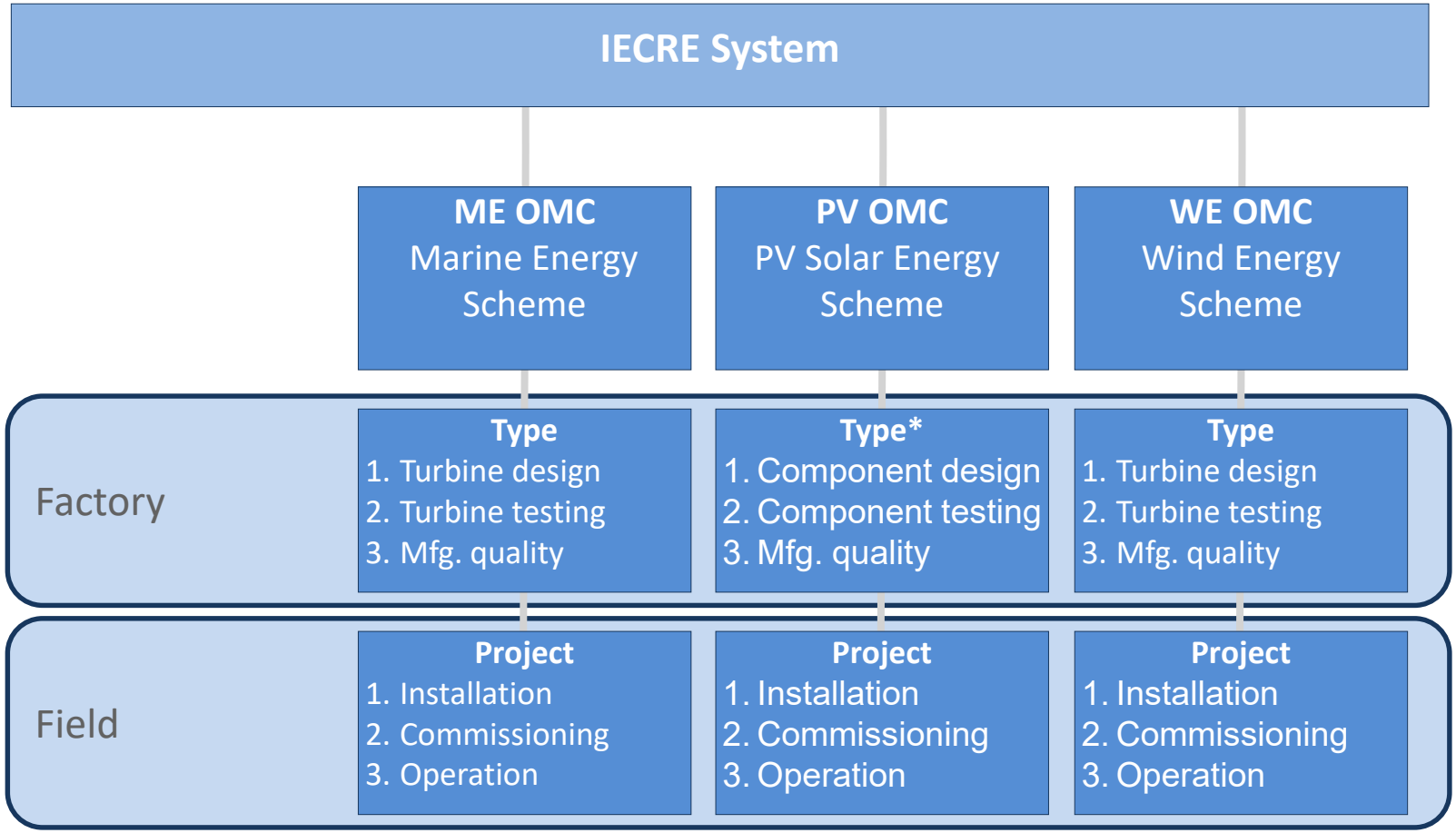
- Design Phase

- General
- Site conditions evaluation
- Design evaluation
- Equipment evaluation
- Structural and electrical evaluation

- Implementation Phase

- Installation surveillance
- Output characteristics measurement
- Commissioning surveillance
- Operation and maintenance surveillance

IECRE common elements



* Partially under IECEE (Modules, Inverters)

Standards Development

- Comprehensive review of existing international and national standards conducted by TC82 experts in 2014
- Determination of which standards would most likely be required to conduct conformity assessments
- Consideration of all IEC standards and others where appropriate (ASTM, UL, VDE, etc.)
- Used to prioritize the work of TC82 and supporting efforts by PVQAT
- Results presented at IEEE PVSC in Denver June 2014

TC 82 Summary

- Established 1981
- 43 P-members
- 11 O-members
- 500+ experts
- 6 WGs / 6 JWGs / 1 PT
- 130 publications
- 82 active projects
  - Largest work program of all IEC TCs

TC 82 Working Groups

WG 1: Glossary
WG 2: Modules, non-concentrating
WG 3: Systems
WG 6: BOS components
WG 7: Concentrator modules
WG 8: Cells

JWG 1: Off-grid systems
JWG 4: Grid code compliance (SC 8A)
JWG 5: System issues regarding integration of wind and PV generation into bulk electrical grid (SC 8A)
JWG 10: DER connection with the grid (TC 8)
JWG 32: Electrical safety of PV system installations (TC 64)
JWG 82: Secondary cells and batteries for Renewable Energy Storage (TC 21)

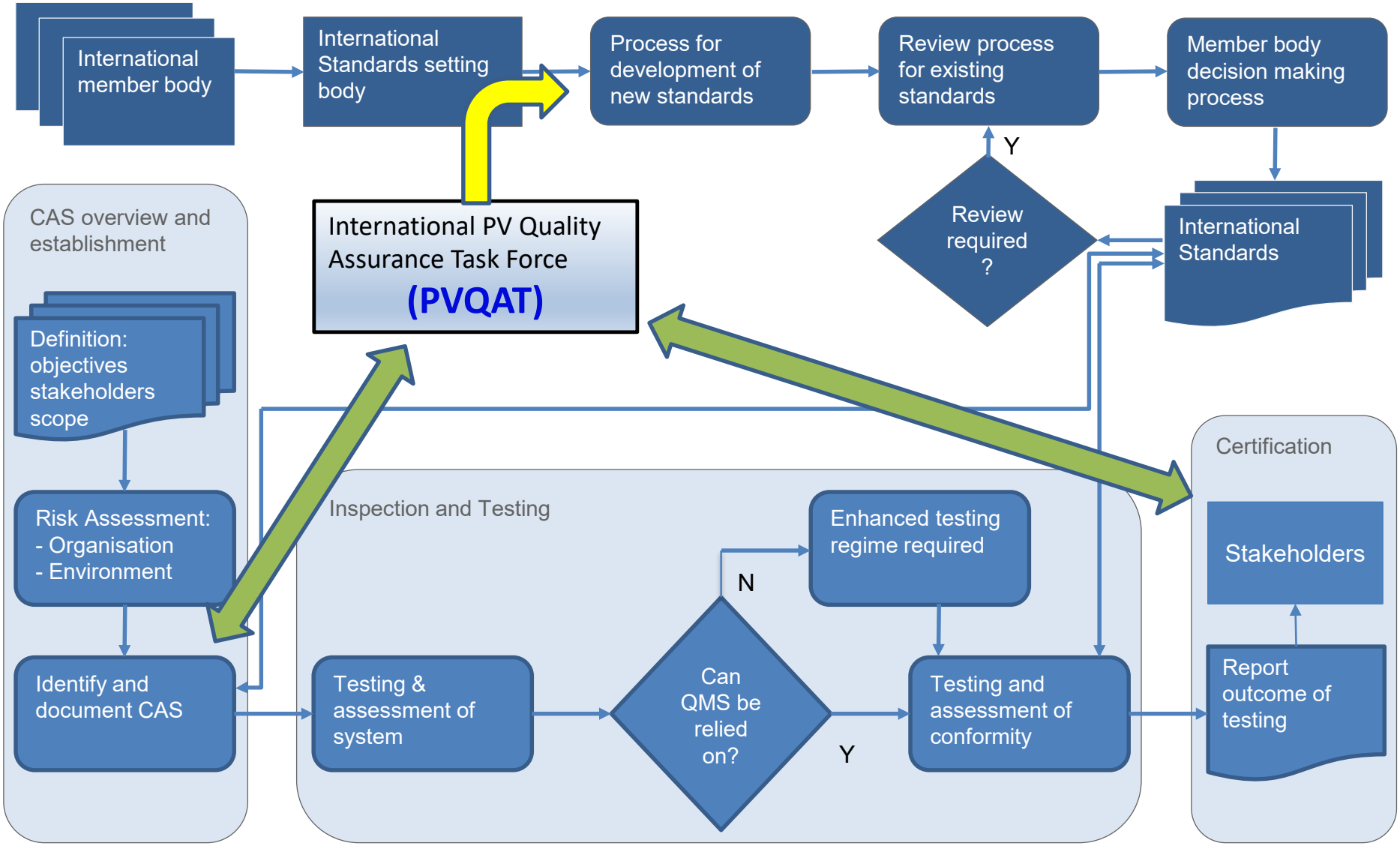
PT 63092: Building integrated PV

TC 82 Liaisons

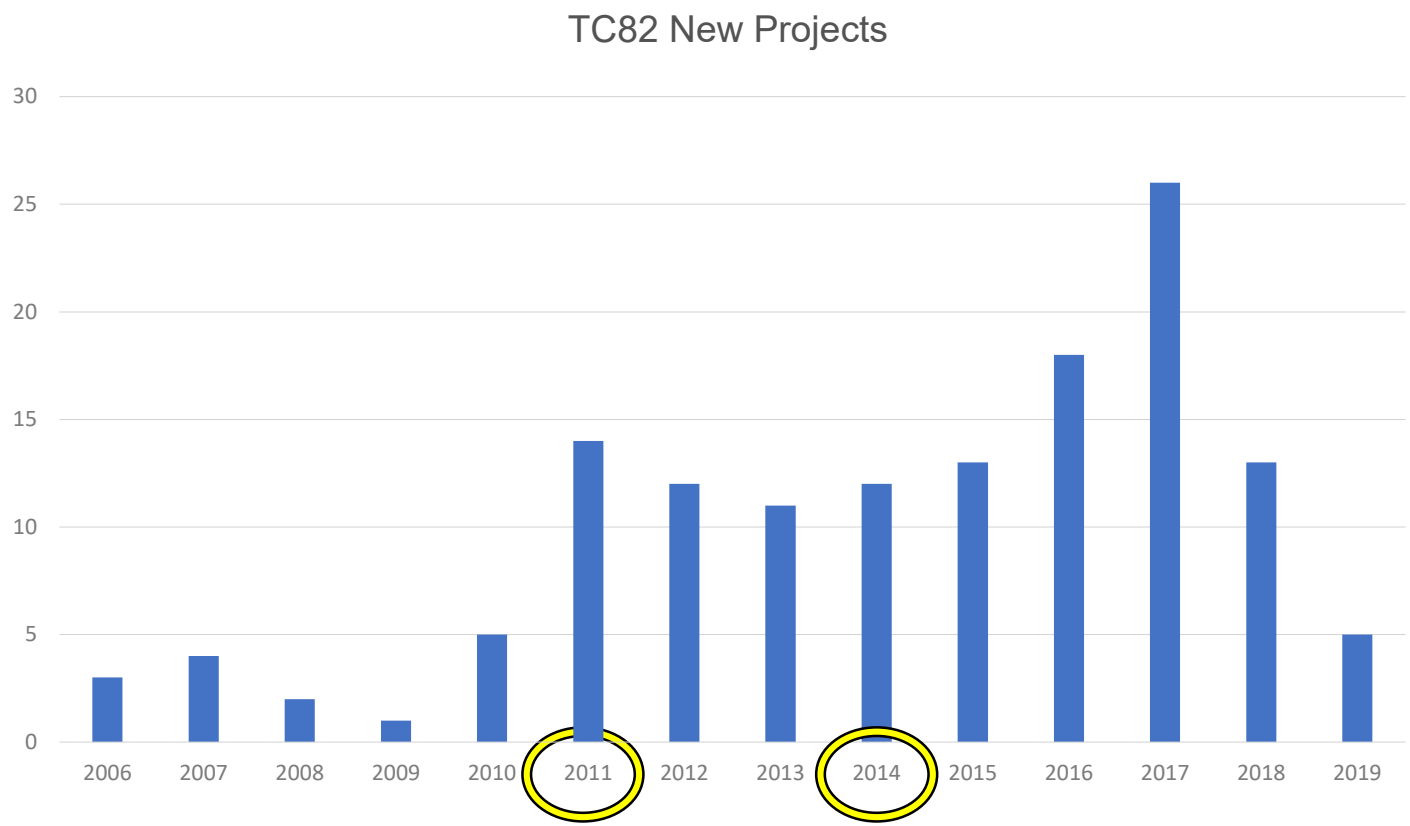
- 27 other committees in IEC and 2 in ISO
- International Energy Agency (IEA)
- EU Commission (JRC Ispra)
- Global Off-Grid Lighting Association (GOGLA)

- International PV Quality Assurance Task Force (PVQAT)
  - Formed 2011; currently 13 task groups
  - Mainly focused on scientific methods to characterize and predict possible failure modes
  - Work feeding into TC82 for NPs

Generic standards development and conformity assessment processes

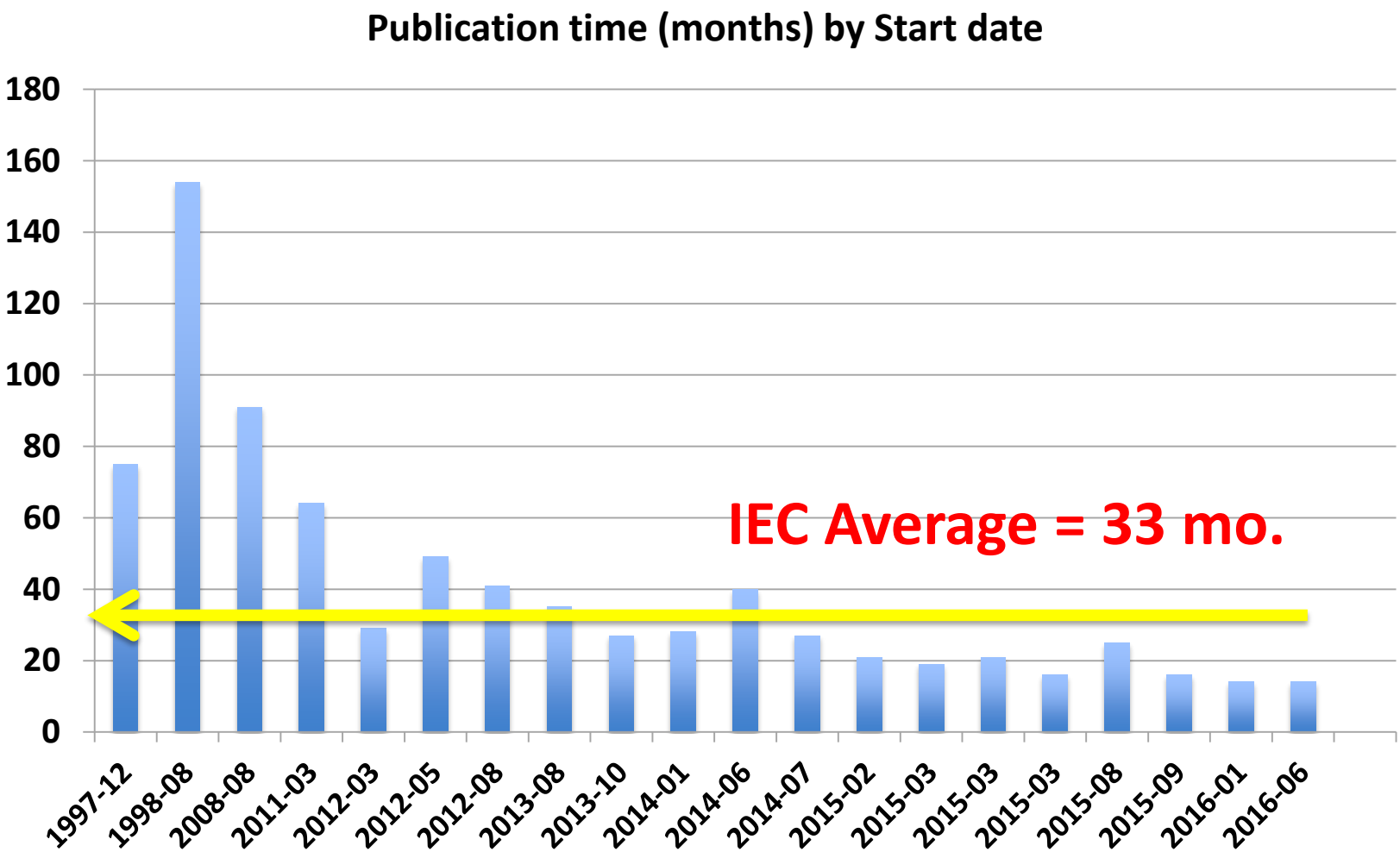


“PVQAT Effect” on TC82



Demonstrating the importance and visibility of IEC standards in PV and their targeted development for IECRE

TC82 Productivity



Review of Existing Standards (2014)

- Hardware
- Quality Management System
- System Design
- Installation
- Commissioning
- Operation
- Maintenance

Gaps Identified

- International Standards Needed:
  - Installation
  - Operation
  - Maintenance
- Standards Published or in Process:
  - IEC 63049, IEC 62446-1
  - IEC 61724, IEC 63265
  - IEC 62446-2

“Certifiable” Standards

- Design
  - 62548 Array Design
  - 62738 Power Plant Design
- Construction
  - 63049 PV System Installation
  - 62446-1 Commissioning
- Operation
  - 62446-2 System Maintenance
  - 61724-1 Performance Monitoring
  - 61724-2 Capacity Evaluation
  - 61724-3 Energy Evaluation
- Quality Management
  - 62941 PV Module Manufacturing
  - 63157 Inverter Manufacturing

Benefits of Certification

- Independent assurance of conformance with appropriate international standards
- Evaluation by accredited inspection bodies in open and transparent process
- Objective evidence of best practices for investors and financial institutions
- Common need in Renewable Energy (RE) systems across multiple industry sectors
  - PV Solar, Wind, Marine, others?

PV Standards in IECRE

PV OMC
PV Solar Energy Scheme

Type*
1. Component design
2. Component testing
3. Mfg. quality

Project
1. Installation
2. Commissioning
3. Operation

* Partially under IECEE
PV components:
- Modules
- Inverters
- Etc.

Module - 61215 / 61730
Inverter - 62109 / 62891
Tracker - 62817
BOS - 62093 + others

Module Manufacturing Quality – 62941
Inverter Manufacturing Quality – 63157

System Design - 62548 / 62738
Installation Quality – 63049
Commissioning – 62446-1
Maintenance – 62446-2
Performance – 61724 series

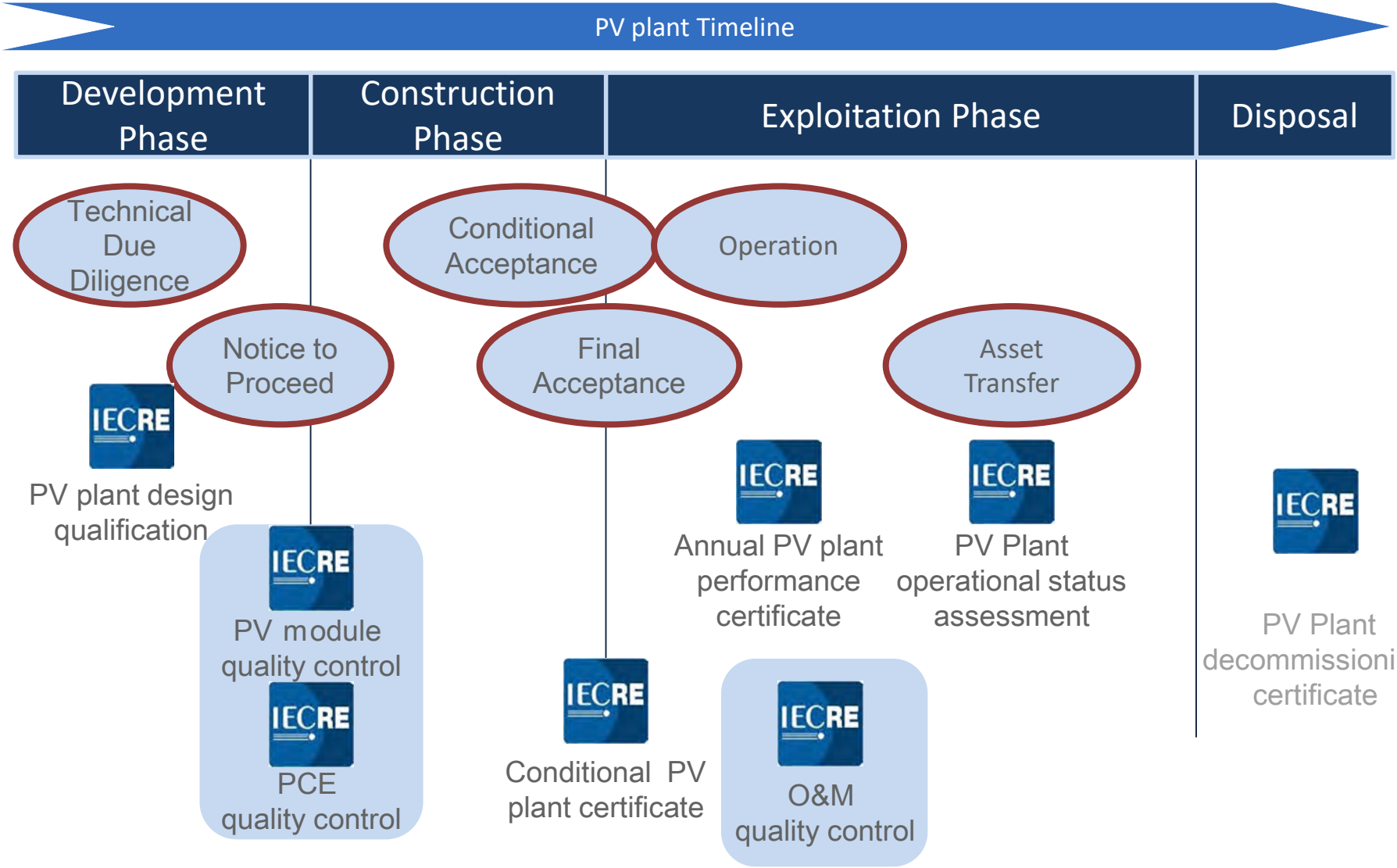
Standardized database

- Solar Bankability Data to Advance Transactions and Access (SB-DATA)
- "Orange Button" – Funded by US Dept. of Energy
  - Smart Grid Interoperability Panel (SGIP) http://www.sgip.org/orange-button/
  - SunSpec Alliance http://sunspec.org/sunspec-osdx/
  - kWh Analytics http://www.kwhanalytics.com/kwh-selected-for-department-of-energys-orange-button-initiative/
  - NREL http://www.orangebuttondata.org/
- Data set for solar asset performance metric http://www.xbrl-cet.com/international-electrotechnical-commission.html

The operational documents (ODs) define certification requirements

Certificate name	Relevant OD's	Readiness for certification	Comments
1. PV power plant milestone certificate			
1.1. PV Plant Design Qualification certificate	OD 403	+	
1.2. PV Plant Design Qualification certificate: Part 1 - PV Site Qualification	OD 401-1	+	
1.3. PV Plant Design Qualification Certificate: Part 2 - PV Power Block Design Qualification	OD 403-1	+	
1.4. Conditional PV plant certificate	OD 401, OD 401-1	+	
1.5. Annual PV plant performance certificate	OD 402	+	
1.6. PV plant operational status assessment	OD 404	+	
(1.7. Plant Decommissioning certificate)	(OD 409)	o	
2. Quality Management certificate			
2.1. Quality management certificate for PV module manufacturer	OD 405-1 OD 405-2	+	
2.2. Quality Management Certificate for PCE manufacturer	OD under development		IEC TS 63157 published Dec-2019
2.3. Quality Management Certificate for PV plant installer and O&M service provider	OD 410-1 OD 410-3	+	IEC TS 63049 needs to be revised
Others			
3. IEC RE PV Data Generation	OD 407	+	
4. PV Power Plant Rating			

The concept is to offer certification throughout the lifetime of a PV power plant



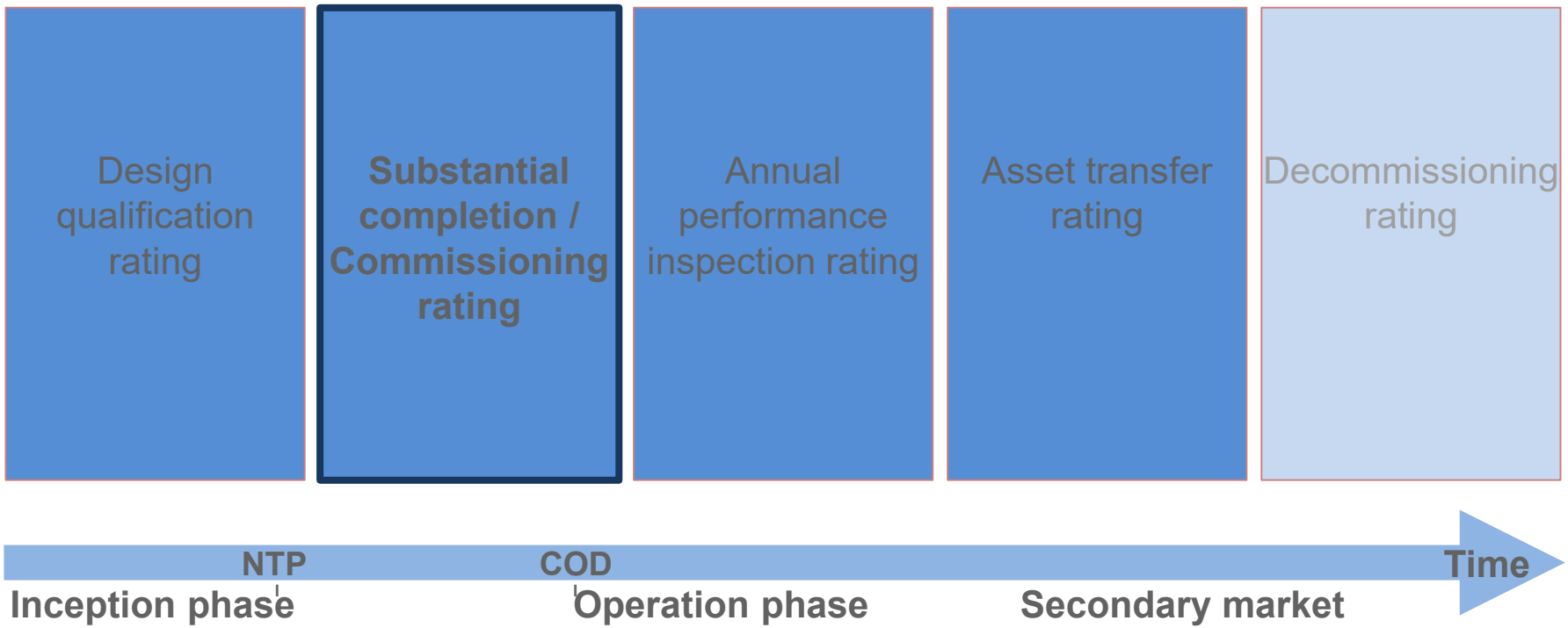
The system is just beginning to gain traction in the market

System certificate name	Major points of emphasis	Primary normative references	Remarks
QC system certificate for PV module manufactures	• Validation of design lifetime • Control of measurement tool • Monitoring and measurement of a manufacturing process • Post-delivery activities	ISO 9001:2015 IEC TS 62941 IEC 61215, IEC 61730 IEC 62108 IEC 61730-1, -2 IEC 60891, IEC 60904 IEC 61853-1, …	First IECRE certificate issued to First Solar May 2018
QC system certificate for PV PCE (inverter) manufactures	• Design and development validation • Control plan • Monitoring of product and processes during manufacturing and providing for service	ISO 9001:2015 IEC TS 63157 IEC 62891, IEC 62109 IEC 62920 …	IEC TS 63157 published Mar 2019
QC system certificate for PV plant installer and O&M service providers	• Records Requirements • Training programs • Installation Process • Ongoing installation monitoring • Requirements for PV Plant Operations & Maintenance	ISO 9001:2015 IEC TS 63049 IEC 62446-1, -2 IEC 60904, IEC 62109 IEC TS 62738 IEC TS 61724-2, -3 …	IEC 62446-2 is circulated as final draft for publication

EU Directives

- **Ecodesign** – cut out least sustainable products
- **EU Energy Label** – incentivize choice of higher sustainability products
- **EU Ecolabel** – encourage development of new, more sustainable products
- **Green Public Procurement (GPP)** – procure goods, services and works with a reduced environmental impact throughout their life cycle

PV power plant rating system



IECRE CA available

IECRE CA not yet available

Stakeholder meeting

- Tonight (Wed) Feb.26 18:00pm-19:00pm
- Venue: Jefferson Boardroom

- Goals of the meeting
  - To find what would be the market needs
  - To share values of IECRE-PV certification program
  - To encourage buy/use of IECRE-PV certificates

Summary

- The International Electrotechnical Commission (IEC) established a new conformity assessment system for renewable energy (IECRE) to address the industry's need to assure investors of the value of their PV power plants.
- There has been significant activity in the past five years devoted to defining the requirements for several types of PV system certificates, and publication of the international standards upon which these certifications are based.
- Now the IECRE system faces the challenge of defining the value proposition for certification and convincing stakeholders that it should be a standard requirement in the marketplace.

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Thank You

Questions?

Contact secretary@aresca.us

REVISED STATIC LOAD REQUIREMENTS FOR PV MODULES

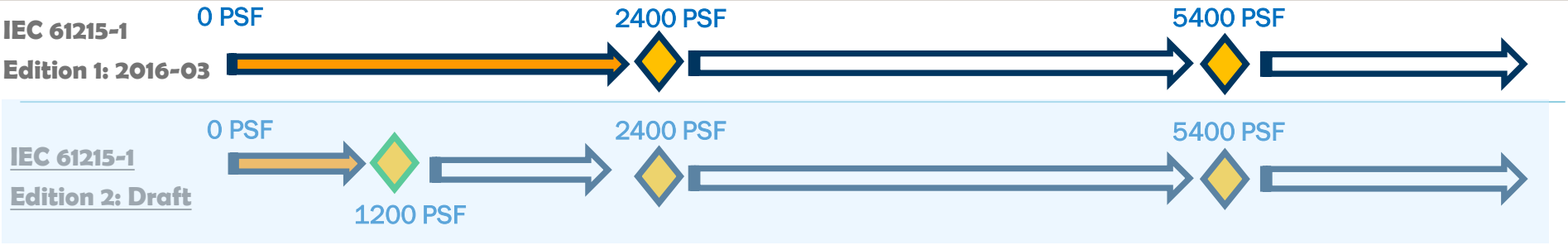
SUMANTH LOKANATH
FEB 26 2020
NREL PVRW
LAKEWOOD COLORADO

First Solar

LEADING THE WORLD'S
SUSTAINABLE ENERGY FUTURE

PROPOSAL

Revised Static Load Requirements for PV Modules



- Reduced Mechanical Load
  - Introduces an optional 1200Pa Test load (800pa design)
  - Not allowed on Rooftops
  - Allowed only for ground mounted PV power generation plants
    - With restricted access
    - Supervision by trained personnel
    - Designed by a licensed professional engineer
    - Equipment chosen specific to local site conditions

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BACKGROUND

HISTORICAL MECHANICAL LOADING REQUIREMENT - IEC

Standard: *IEC 61215 and IEC 61646 Ed2:2008-05*

10.16 Mechanical load test

NOTE 1: 2 400 Pa correspond to a wind pressure of 130 km·h^{-1} (approximately ±800 Pa) with a safety factor of 3 for gusty winds. If the module is to be qualified to withstand heavy accumulations of snow and ice, the load applied to the front of the module during this test is increased from 2400 to 5400 Pa.

Equation: $p = \frac{1}{2}\rho v^2$

p - Wind pressure, Pa [N/m^2]

ρ - Air density, approximately 1.22521 [kg/m^3] on sea level at 15ºC

v - Wind speed [m/s], 130 km/h = 130*1000/3600 = 36.112 m/s, round-up

Calculation: $p = \frac{1}{2} * 1.22521 * 36.112^2$

$p = 798.9\ [Pa]$ or approximately 800 [Pa]

With a safety factor of 3 (FoS)

p = 800 * 3 = 2 400 [Pa]

Note: Safety factor of 3 may be considered as "conservative". However, the safety factor shall meet the requirement set by local authorities.

The duration of the load applied is a total of 6 hours (3 x 1hr duration each side with load cycled).

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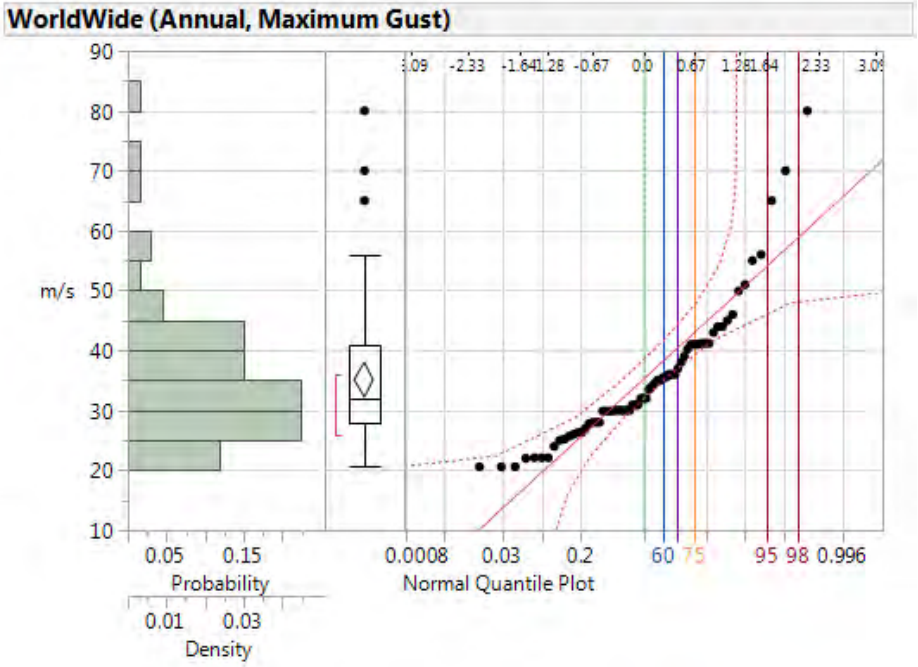
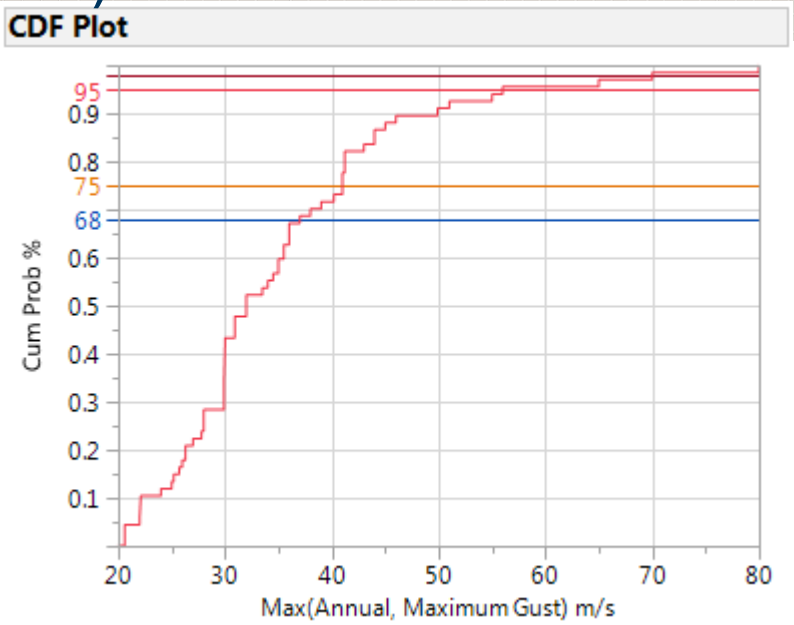
UNITED NATIONS DATA (HTTP://DATA.UN.ORG)

130kmph is a good target for design of PV





Summary Statistics	
Mean	35.170149
Std Dev	11.495032
Std Err Mean	1.4043417
Upper 95% Mean	37.974008
Lower 95% Mean	32.366291
N	67

Quantiles		
100.0%	maximum	80
99.5%		80
97.5%		73
90.0%		50.12
75.0%	quartile	41
50.0%	median	32
25.0%	quartile	28
10.0%		22.1
2.5%		20.6
0.5%		20.6
0.0%	minimum	20.6

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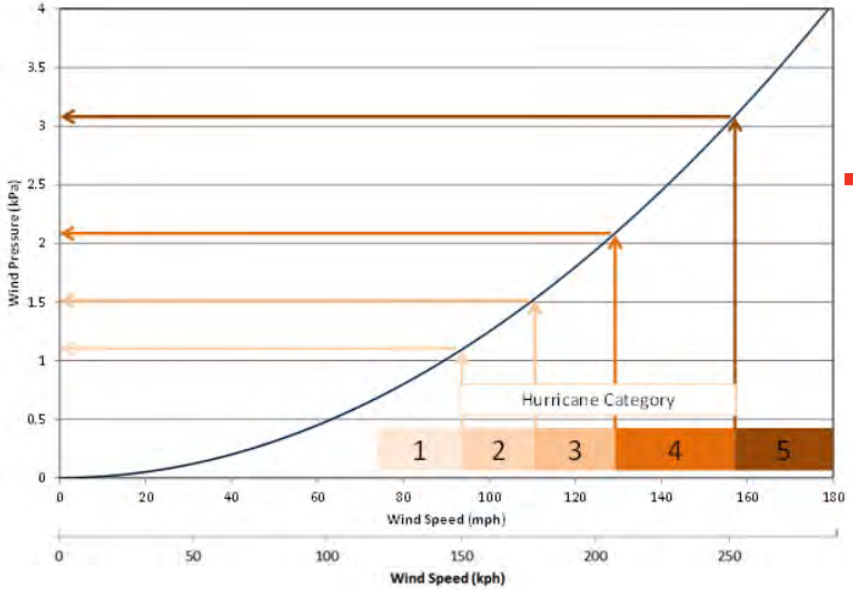
WIND PRESSURES & WIND SPEEDS

Disconnect between Roofs & PV system expectations



Load/Wind Pressure (Pa)	Wind Speed (mph/kph)	Hurricane Level	Tornado Level
1000	90/145	1	1
1440	105/170	2	1
2400	140/225	4	3

Percentile	Max Windspeed m/s	Max Windspeed kmph
98	80	288
95	55	198
75	42	151
68	35	126

CATEGORIES	Max wind (km/h)	Typical effect
5	>280	Extremely dangerous with widespread destruction.
4	280	Significant roofing and structural damage. Many caravans destroyed and blown away. Dangerous airborne debris. Widespread power failures.
3	225	Some roof and structural damage. Some caravans destroyed. Power failure likely.
2	170	Minor house damage. Significant damage to signs, trees and caravans. Heavy damage to some crops. Risk of power failure. Small boats may break moorings.
1	125	Minimal house damage. Damage to some crops, trees and caravans. Boats may drag moorings.

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EVOLVED SYSTEM DESIGN APPROACH – CONFIGURATION FOR FIXED TILT

Microsoft Word Document

ASCE 7-10 (25°)

Wind Speed (mph)	Ground Snow Load (psf) 0	5	10	15	20	25	30	35	40
110	A/A/A	A/A/B	A/B/B	A/B/B	B/C/C	C/C/C	C/C/C	C/C/C	
115	A/A/B	A/B/B	A/B/B	A/B/C	B/C/C	C/C/C	C/C/C	C/C/C	
120	A/B/B	A/B/B	A/B/C	A/C/C	B/C/C	C/C/C	C/C/C		
125	A/B/B	A/B/B	A/C/C	A/C/C	B/C/C	C/C/C	C/C/C		
130	A/B/B	A/B/C	A/C/C	A/C/C	B/C/C	C/C/C	C/C/C		
135	A/B/B	A/B/C	A/C/C	B/C/C	B/C/C	C/C/C			
140	A/B/B	A/C/C	A/C/C	B/C/C	B/C/C	C/C/C			
145	A/B/B	A/C/C	A/C/C	B/C/C	C/C/C	C/C/C			
150	A/B/C	A/C/C	A/C/C	B/C/C	C/C/C				
155	A/B/C	A/C/C	A/C/C	B/C/C					
160	A/C/C	A/C/C	B/C/C	B/C/C					
165	B/C/C	B/C/C	B/C/C						
170	B/C/C	B/C/C	B/C/C						
175	B/C/C	B/C/C							
180	B/C/C	B/C/C							

LEGEND

A/B/C	Interior Tables = Configuration A
	Edge Tables = Configuration B
	Corner Tables = Configuration C
A	2 Posts / Table, 1 Tilt Bracket / Post
B	2 Posts / Table, 2 Tilt Brackets / Post
C	3 Posts / Table, 2 Tilt Brackets / Post

CHILE (20° Tilt)

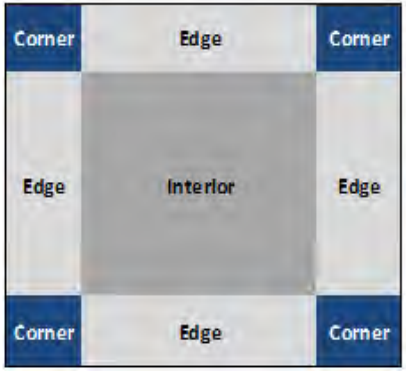
Wind Speed (m/s)	Ground Snow Load (kPa) 0	0.5	1.0	1.5	2.0
30	A/A/A	A/B/B	B/B/C	C/C/C	-
35	A/A/A	A/B/B	B/C/C	C/C/C	-
45	A/B/B	B/C/C	B/C/C	C/C/C	-
50	A/B/C	B/C/C	C/C/C	-	-

CHILE (25° Tilt)

Wind Speed (m/s)	Ground Snow Load (kPa) 0	0.5	1.0	1.5	2.0
30	A/A/A	A/A/A	B/C/C	C/C/C	C/C/C
35	A/A/A	A/B/B	B/C/C	C/C/C	-
45	A/B/B	A/C/C	B/C/C	-	-
50	A/B/B	A/C/C	C/C/C	-	-

Australia

Wind Region	Tilt Angle 20°	25°
A	A / A /A	A / A /A
B	A / B / B	A / B / B
C	B / C / C	A / B / C
D	B / C / C	B / C / C



Refer to application guide and local codes for further details

EVOLVED SYSTEM DESIGN APPROACH – CONFIGURATION FOR TRACKERS

For regions governed by ASCE7-05 and ASCE7-10, a solar power plant will fall into Risk Category I or II. It is more common for the authority having jurisdiction (AHJ) to require the structure to be considered Risk Category II but there are some exceptions to this rule. For estimation, it should be assumed Risk Category II until confirmed otherwise.

Load Combination Tables

Configuration (Interior / Exterior)														
Wind Speed (mph)	ASCE 7-05		7-10	Ground Snow Load (psf)										
	Cat-I	Cat-II		0	5	10	15	20	25	30	35	40	45	50
	85	80	100	A / B	A / B	A / B	A / B	C / C	C / C	F / F	F / F	G / G	G / G	H / H
	-	-	105	A / B	A / B	A / B	A / B	C / C	C / C	F / F	F / F	G / G	G / G	H / H
	90	85	110	A / B	A / B	A / B	A / B	C / C	C / C	F / F	F / F	G / G	G / G	H / H
	95	90	115	A / D	A / D	A / D	A / D	C / D	C / D	F / F	F / F	G / G	G / G	H / H
	100	95	120	B / D	B / D	B / D	B / D							
	-	-	125*	B / D	B / D	B / D	B / D							
	110	105	130	B / E	B / E	B / E	B / E							
	-	-	135**	C / E	C / E	C / E	C / E							
			140											

Configurations

'A' = Baseline configuration

'B' through 'E' = Torque Tube wall thickness increase

'F' through 'H' = Torque Tube wall thickness increase + additional MIBs and Posts

Array Layout

* Indicates max column spacing of 22'

** Indicates max column spacing of 18'

Note: As requirements increase, costs also increase

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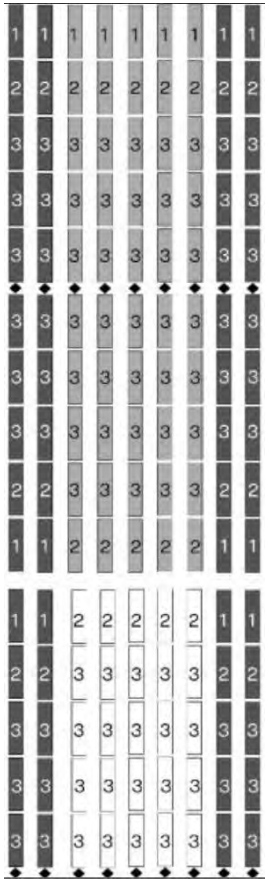
MODULE LOAD DISTRIBUTION ON SOLAR PROJECT : EXAMPLE-1

Exposure Classification	Site Qty.	% of Site	Exposure Zone	% of Zone	Governing Pressure (Pa)	% of Site
Exterior Rows	236	3%	Zone 1	20%	1187.7	0.5%
			Zone 2	20%	843.9	0.5%
			Zone 3	60%	831.4	1.5%
Edge Rows	1976	21%	Zone 1	20%	1156.5	4.2%
			Zone 2	20%	656.4	4.2%
			Zone 3	60%	800.2	12.7%
Interior Rows	7106	76%	Zone 2	20%	656.4	15.3%
			Zone 3	80%	800.2	61.0%
	9318					

Zone	Max (Gov pressure) [Pa]	Cum (% of Site)	
1	1188	4.7 %	4.7%
2	844	20%	95.3 %
3	831	75.3	

<5% of site requires higher loading (Exterior rows)



Notes:

Wind pressures are calculated for the worst case **60 degree tilt** and approach angle. For each location and zone, the highest wind pressure is selected as the governing module pressure.

Pressure values shown are the maximum **service level** loads based on the 3-sec gust wind speed per ASCE 7-10.

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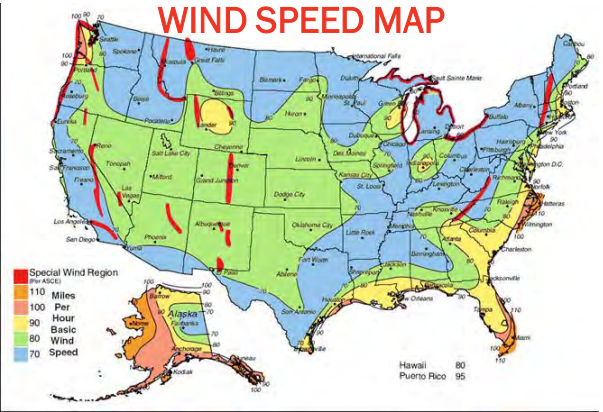
LOCAL WIND MAPS & STATIC PRESSURES

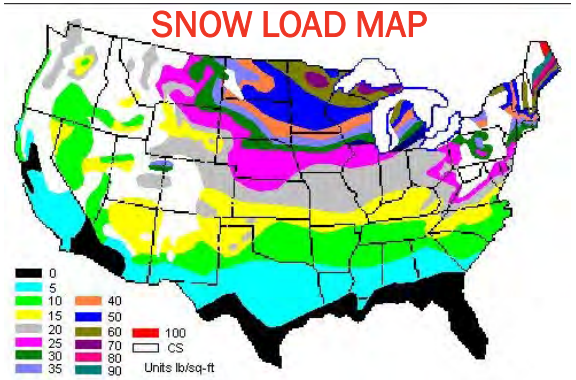
				Building Code					Site Required Load in PSF			Factor of UL 45 PSF Load			Factor of IEC 50 PSF Load		
Site	Country	State	Building Code	Dead Load	Snow Load	Wind Load	Fixed/ Tracker	Vendor	Exterior Rating	Interior Rating	Corner Rating	Exterior Rating	Interior Rating	Corner Rating	Exterior Rating	Interior Rating	Corner Rating
1	USA	CA	ASCE 7-05	5 psf	5 psf	85 mph	Fixed	A	-32.0	-23.4	-32.0	-0.71	-0.52	-0.71	-0.64	-0.47	-0.64
2	USA	CA	ASCE 7-10	5 psf	5 psf	100 mph	Tracker	B	13.9	10.8	13.9	0.31	0.24	0.31	0.28	0.22	0.28
3	USA	CA	ASCE 7-10	5 psf	5 psf	100 mph	Fixed	A	-32.0	-23.4	-32.0	-0.71	-0.52	-0.71	-0.64	-0.47	-0.64
4	USA	FL	ASCE 7-10	5 psf	0 psf	129 mph	Tracker	C	26.9	22.8	26.9	0.60	0.51	0.60	0.54	0.46	0.54
5	USA	FL	ASCE 7-10	5 psf	0 psf	132 mph	Tracker	C	27.7	23.3	27.7	0.61	0.52	0.61	0.55	0.47	0.55
6	USA	FL	ASCE 7-10	5 psf	0 psf	129 mph	Tracker	C	26.9	22.8	26.9	0.60	0.51	0.60	0.54	0.46	0.54
7	USA	FL	ASCE 7-10	5 psf	0 psf	132 mph	Tracker	C	27.7	23.3	27.7	0.61	0.52	0.61	0.55	0.47	0.55
8	USA	FL	ASCE 7-10	5 psf	0 psf	128 mph	Tracker	C	26.5	22.4	26.5	0.59	0.50	0.59	0.53	0.45	0.53
9	USA	NV	ASCE 7-10	5 psf	0 psf	105 mph	Tracker	A	-35.2	-25.8	-35.2	-0.78	-0.57	-0.78	-0.70	-0.52	-0.70
10	USA	NV	ASCE 7-10	5 psf	0 psf	105 mph	Tracker	A	-35.2	-25.8	-35.2	-0.78	-0.57	-0.78	-0.70	-0.52	-0.70
11	USA	AZ	ASCE 7-10	5 psf	0 psf	105 mph	Tracker	B	15.3	11.9	15.3	0.34	0.26	0.34	0.31	0.24	0.31
12	USA	AZ	ASCE 7-10	5 psf	0 psf	105 mph	Tracker	B	15.3	11.9	15.3	0.34	0.26	0.34	0.31	0.24	0.31

WIND SPEED MAP



- ✓ High Wind & High Snow regions do not overlap generally.
- ✓ Site specific loads nowhere close to PV module Test requirements
- ✓ Interior vs. Exterior loads can vary. Interior lower than exterior.

SNOW LOAD MAP



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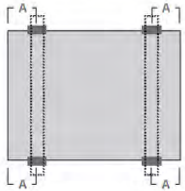
SYSTEM DESIGN APPROACH – MODULE CONFIGURATION FOR LOADING

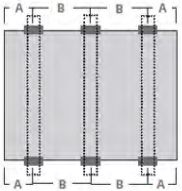
Clamping Location Illustration

Illustration A



Clamping on module long side, four clamp points; Mounting rails must run perpendicularly to the module long side.

Illustration B



Clamping on module long side, six clamp points; Mounting rails must run perpendicularly to the module long side.

Mounting Method	Supplier	Clamp Image	Clamp Type & length	Clamp Quantity & Location	Load (Pa)	Certification Body
2-A-1	NISSEI METALS CO.,LTD.		SA-TOK-UA (End clamp) / SA-KOK-UA (Middle clamp), clamp length=120 mm	four clamps, A=380±20 mm, see illustration A	Downforce load≤2400 Pa Uplift load ≤2400 Pa	VDE / CSA
2-A-2				six clamps, A=250±20 mm, B=579±20 mm, see illustration B	Downforce load≤5400 Pa Uplift load ≤2400 Pa	VDE
2-B-1	K2 Systems GmbH / Everest Solar Systems, LLC		K2 frameless clamp, 4-7.2 mm, clamp length= 100 mm	A=380±20 mm, four clamps	Downforce load≤2400 Pa Uplift load ≤2400 Pa	VDE / CSA
2-B-2			K2 frameless clamp, 4-7.2 mm, clamp length=200 mm	A=380±20 mm, four clamps	Downforce load≤5400 Pa Uplift load ≤2400 Pa	VDE / CSA
2-B-3			K2 frameless clamp, 4-7.2 mm, clamp length= 80 mm	six clamps, A=250±20 mm, B=579±20 mm, see illustration B	Downforce load≤2400 Pa Uplift load ≤2400 Pa	VDE / CSA
2-B-4			K2 frameless clamp, 4-7.2 mm, clamp length= 100 mm	six clamps, A=250±20 mm, B=579±20 mm, see illustration B	Downforce load≤5400 Pa Uplift load ≤2400 Pa	VDE / CSA

MODULE TYPE	MOUNTING OPTION	POSITION OF CLAMPS[1] [IN (MM)]	TEST-LOAD PUSH/PULL[3] [PA]
Q.PLUS L-G4.1 Q.PLUS L-G4.2 Q.PEAK L-G4.1 Q.PEAK L-G4.2 Q.PEAK L-G5.1 Q.PEAK L-G5.2 Q.PLUS L-G4.2/TAA	CL1 (4 point clamping on long side)	9.8-19.7 (250-500)	5400/2400
	FB1 (4 screws mounting on long side)	13.5 (343)	
	CL3 (4 point clamping on long side)	9.8-19.7 (250-500)	3600/2400
	IP1 (Slide-in / long side)	-	3600/2400

➔ The below mounting options are only possible under certain conditions.

MODULE TYPE	MOUNTING OPTION	POSITION OF CLAMPS[1] [IN (MM)]	TEST-LOAD PUSH/PULL[3] [PA]
Q.PLUS L-G4.1 Q.PLUS L-G4.2 Q.PEAK L-G4.1 Q.PEAK L-G4.2 Q.PEAK L-G5.1 Q.PEAK L-G5.2 Q.PLUS L-G4.2/TAA	CL2a (with rails)	0-11.8 (0-300)	2400/1600
	CL2b (without rails)	0-11.8 (0-300)	1800/1600
	IP2 (Slide-in / short side)	-	1800/1600

[3] Test procedure according to IEC 61215-2:2016 and UL 1703. Mounting options do not fulfill the requirements of the standards.

People already install modules In configurations where test load < 2400 Pa, frequently enough to put it in the documentation

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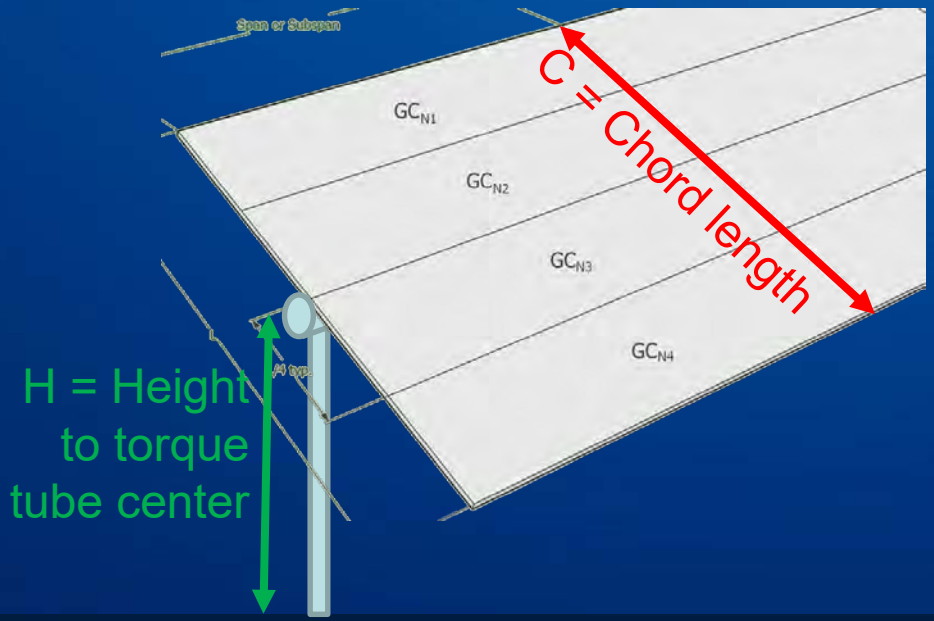
CERMAK
PETERKA
PETERSEN

Ground Mount PV Panel Wind Loads

Dr. David Banks
Principal
CPP Inc.

Tracker configuration

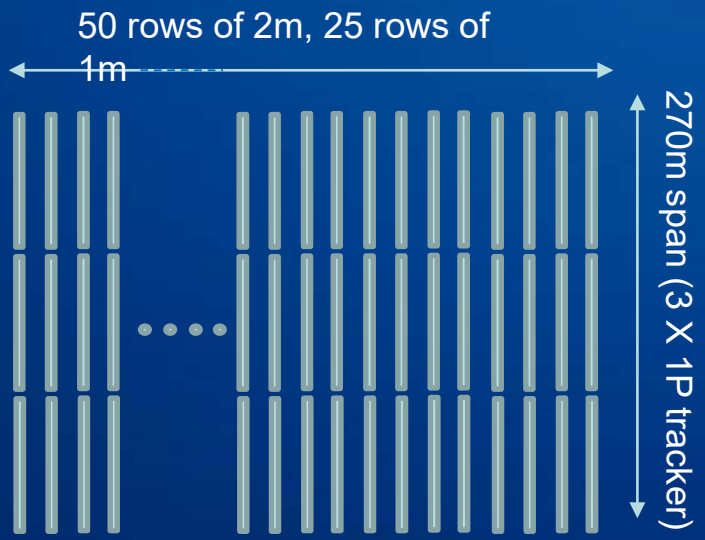
- Ground Coverage (area) Ratio = PV/total = 0.4
- Ground Clearance: Height / Chord = 0.8
- Stow Tilt = 35°



Parameter	First Solar systems		
	1-P Tracker	2-P Tracker	2-P Fixed-tilt
Chord length:	2 m	4 m	4 m
Tilt:	35°	35°	25°
Mid-chord height:	1.7 m	2.7 m	2.1 m
Ground coverage ratio (GCR):	0.40	0.35	0.38

Layout at site: assumed “block” size.

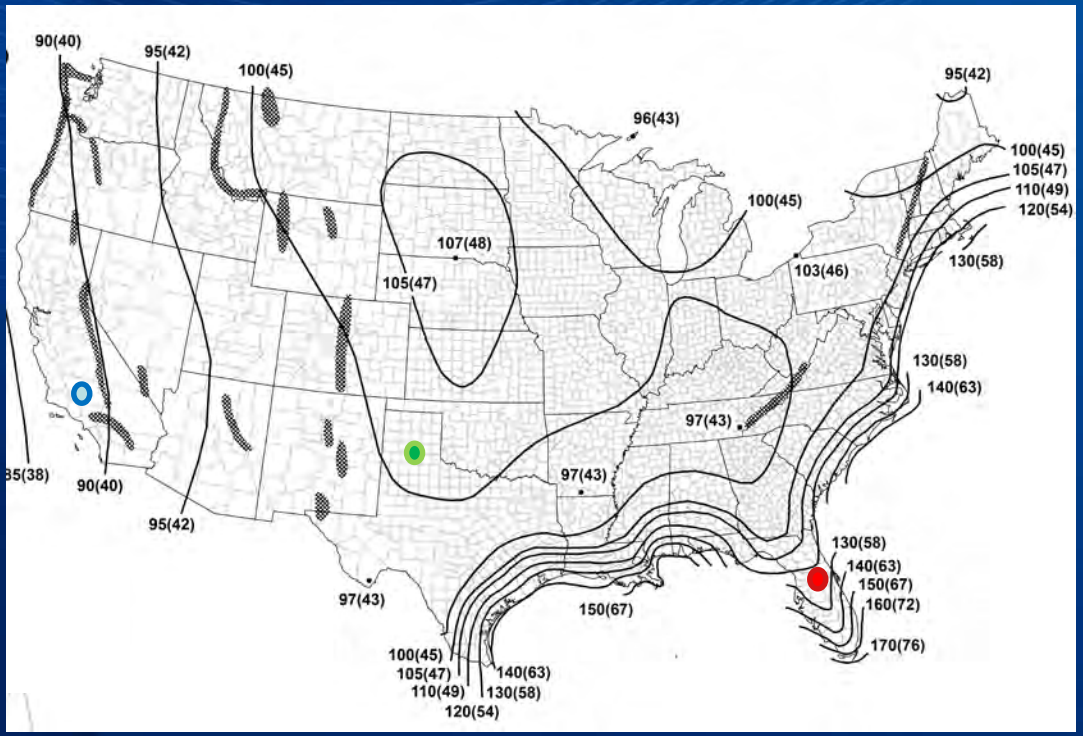
13,600 PV modules.



Block is surrounded by roads or open space (unsheltered from winds).

U_{300} for Bakersfield, Lubbock, & Orlando

from ASCE 7-16 wind map



$P = q*A*GCp$

$q = ½ \rho U_{300}^2 \cdot Kd \cdot Kz \cdot Kzt \cdot LF$

<u>We have assumed</u>

- open country (Kz = 1),
- flat ground (Kzt = 1),
- Air density is a little lower in Lubbock,
- Kd = 0.85 (this is not always conservative),
- Load Factor (LF) = 0.6 for “Allowable Stress Design”.

Results: Histograms

Fixed Tilt System

Static loads +
Static equivalent pressures from dynamic effects
(inertial loading due to modal excitation) for heaving/plunging modes
High damping was assumed to limit the effects of torsional modes.

Compared to Design loads in IEC Static Load Test

Such direct comparison may be quite conservative for the glass failures, but appears to be suitable for failures of modules frames or clamps.

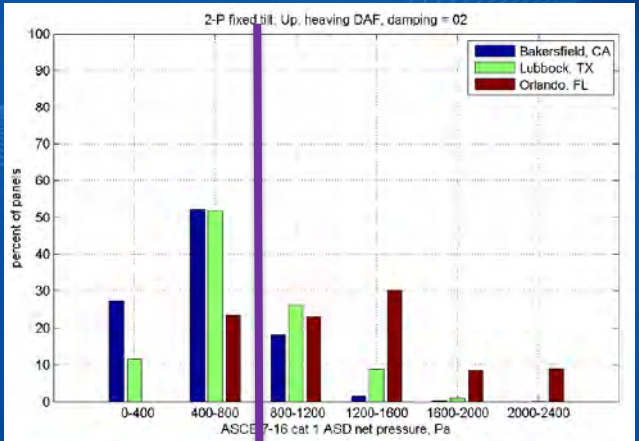


Figure 6c: Expected static+dynamic module net pressures, uplift, fixed tilt.

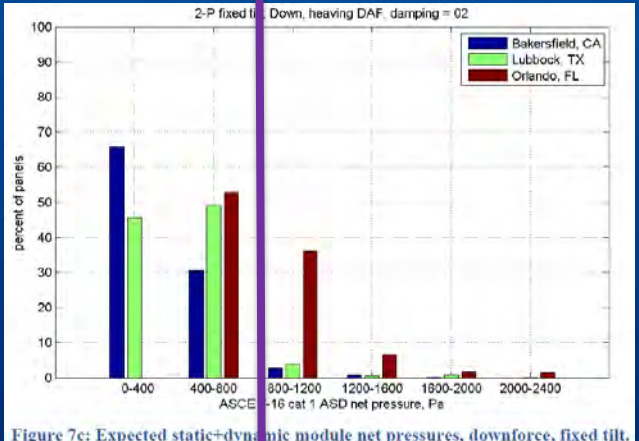


Figure 7c: Expected static+dynamic module net pressures, downforce, fixed tilt.

1P System

2P System

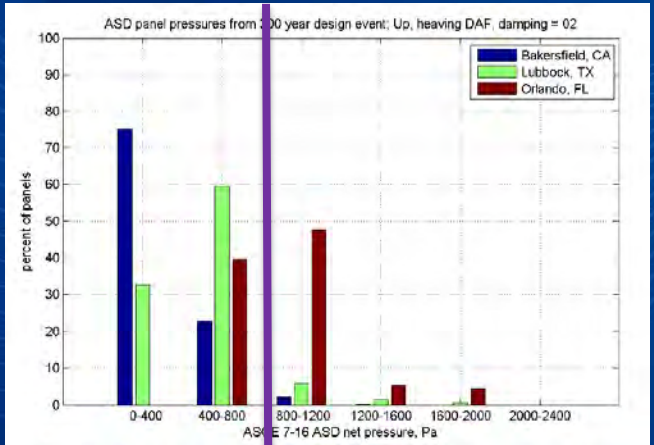


Figure 6a: Expected static+dynamic module net pressures, uplift, 1-P tracker

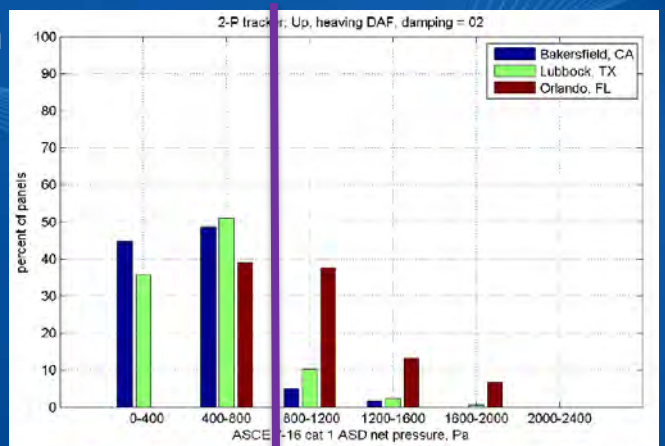


Figure 6b: Expected static+dynamic module net pressures, uplift, 2-P tracker

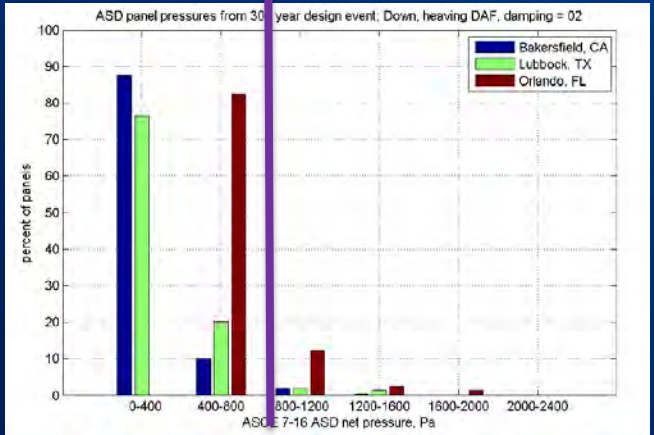


Figure 7a: Expected static+dynamic module net pressures, down force, 1-P tracker

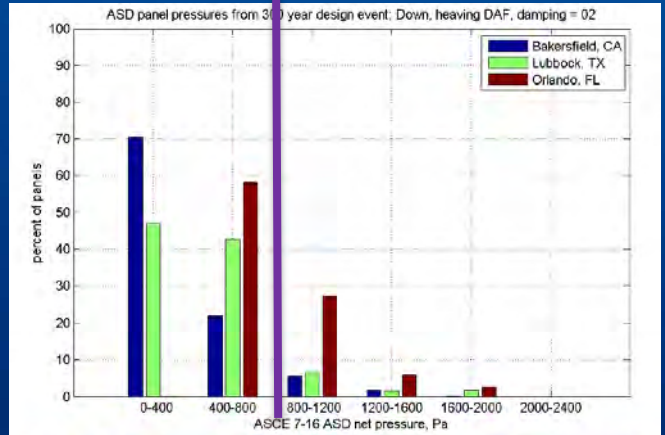


Figure 7b: Expected static+dynamic module net pressures, downforce, 2-P tracker

Static Load + Dynamic Amplification Factors (DAF)

DAF assumes a first heaving mode of 3.5Hz and that bays are independent.

*panels on the lower half of the 2-P systems experience lower loads than those on the top.

CONCLUSION

- Area-averaged pressure for interior panels is often below 800 Pa
- The analysis indicates that the majority of interior modules in the non-hurricane wind climates are expected to have ASD loads below 800 Pa.
- With glass breakage as the predominant failure mode, 6 hour test likely very conservative for glass, though perhaps not for other panel components (frame, adhesive).
- Further LCOE reductions are possible using this approach of selective placement of modules in arrays.

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First Solar®

LEADING THE WORLD'S
SUSTAINABLE ENERGY FUTURE

Damage Accumulation in Glass

Duration of the test matters when comparing to the design wind loads

Brown's integral [Eq. (1)], which is expressed as

$$DA_c = \int_0^{t_f} [p(t)]^s dt$$

where p = applied load; and s = coefficient.

A 1-minute test is generally more appropriate for comparison to design pressures calculated from wind tunnel tests.

First Solar Proprietary & Confidential - General

IECRE PV SYSTEM CERTIFICATION ON QUALITY SYSTEM OF MANUFACTURERS AND SERVICE PROVIDERS

Feb.26, 2020

Masaaki Yamamichi
IECRE PV-OMC WG409 convener
RTS Corp

George Kelly
ICE TC82 Secretary
Sunset Technology

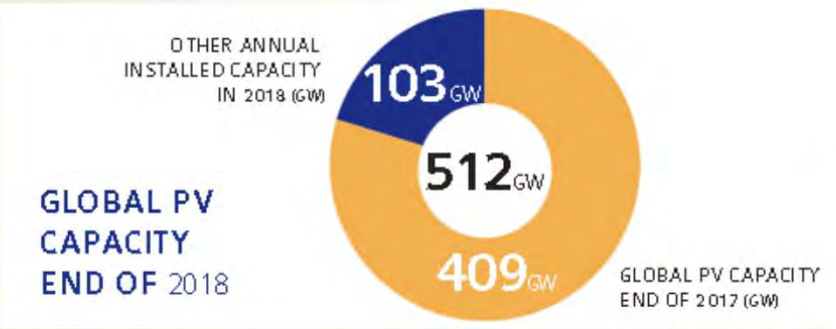
Contents

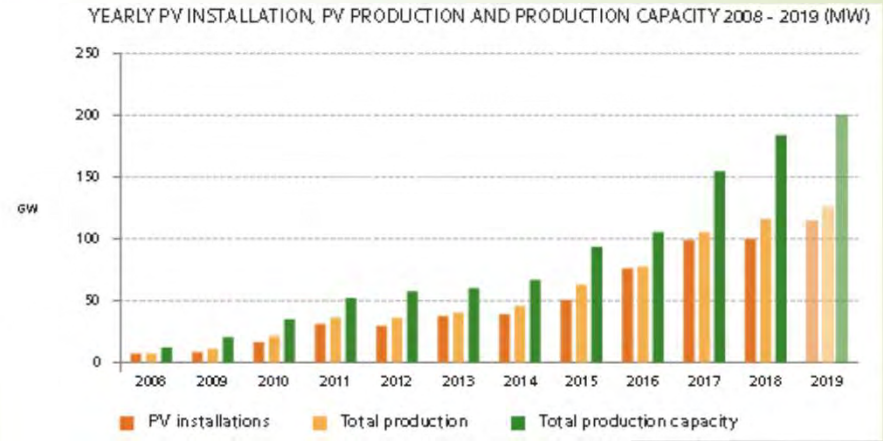
- Introduction
- Overview of IECRE-PV assessment and certification program
- IECRE PV System Certification program on Quality System of Manufactures and Service Providers
- IEC standards on PV Quality Control
  - IEC 62941:2019:ED1.0
  - IEC TS 63049:2017
  - IEC TS 63157:2019
- Challenges
- Summary

Introduction

World PV plant deployment now reached 512GW PV incl. 103GW in 2018
Most of them are working well, but some are not, due to

- Disposition
- Age over warranty period
- Quality issues caused during various stages of their life cycle.
- Other reasons….

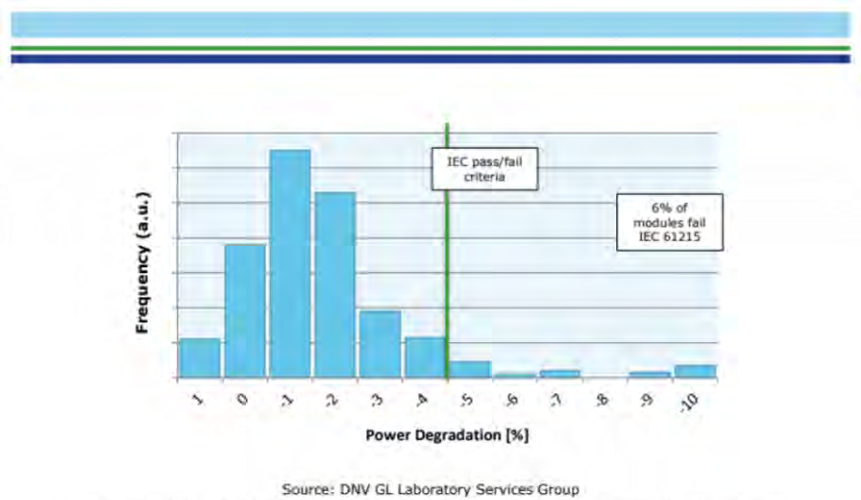




Source: IEA-PVSC report 2019

Some examples of field failures likely related to quality-control

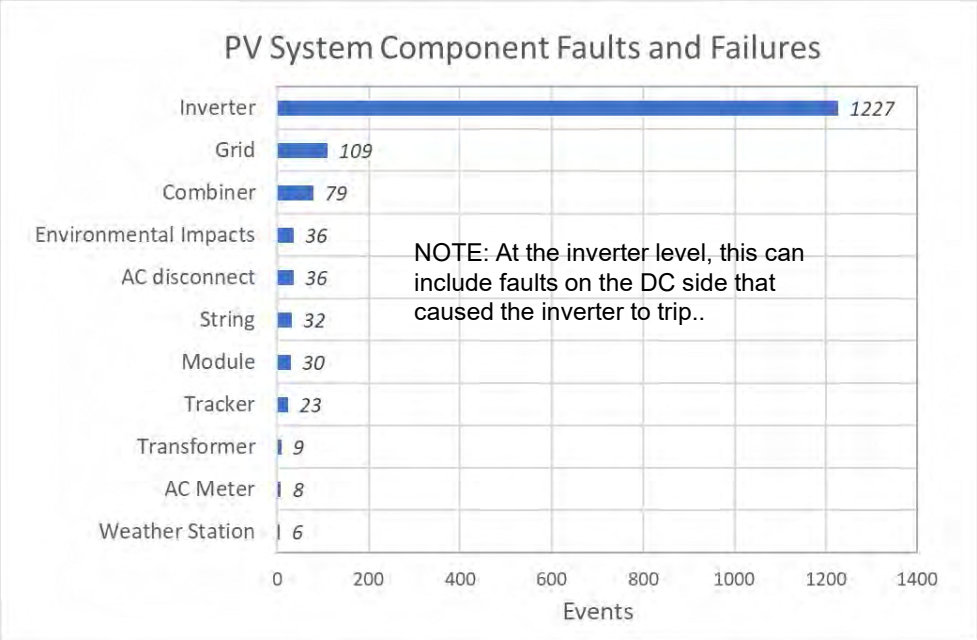
- Based on DNV GL's experience and data, at least 6% of commercial PV modules do not pass the IEC 61215 thermal cycling test
- SNL reported field data of 244 PV systems in USA. Totaling 840MW$_{dc}$



Source: DNV GL Laboratory Services Group

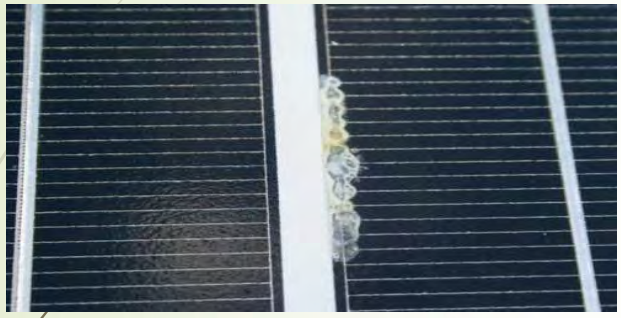
Figure 3-2 DNV GL's historical thermal cycling degradation results (200 cycles)

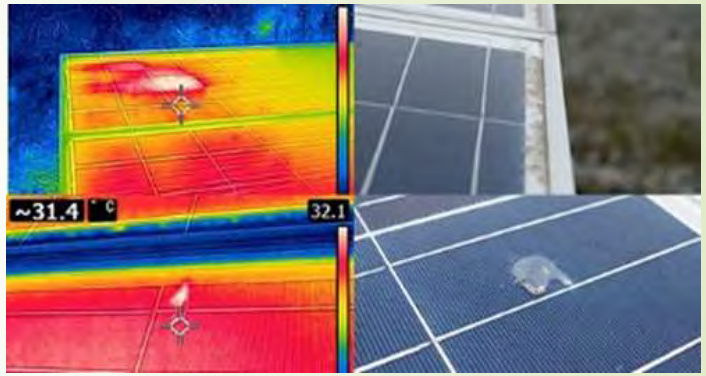
(PV Module Reliability Scorecard Report 2017 DNV-GL)

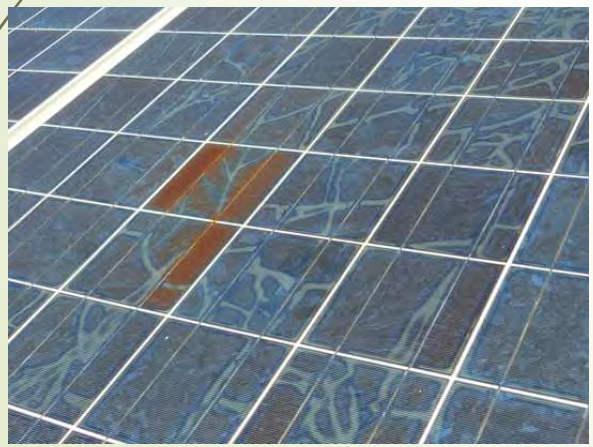


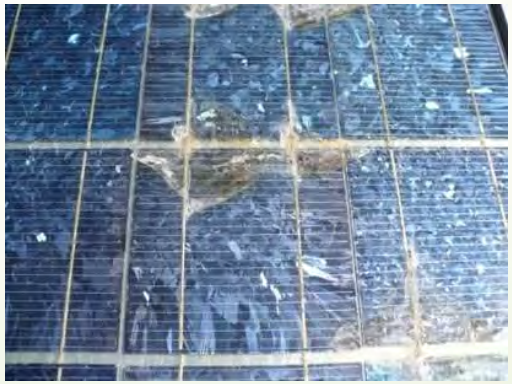
PV System Component Fault and Failure Compilation and Analysis-SAND2018-1743

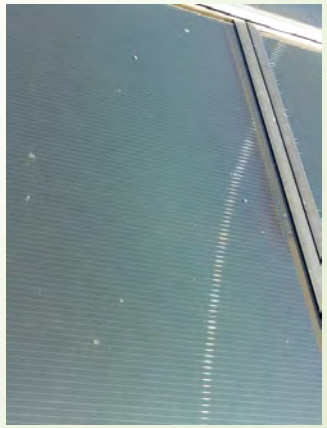
Some examples of field failures likely related to quality-control

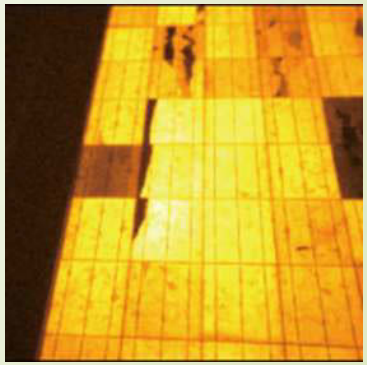




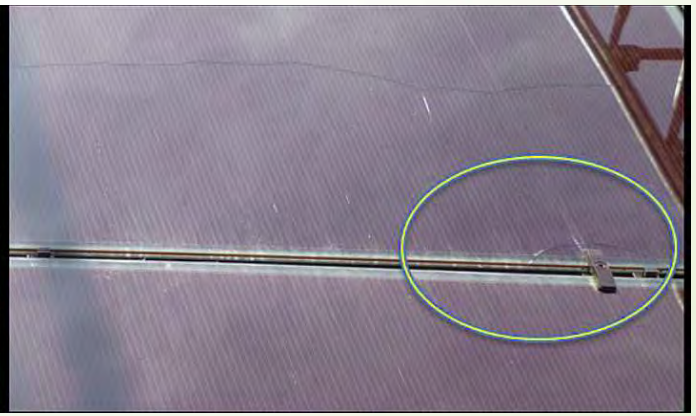








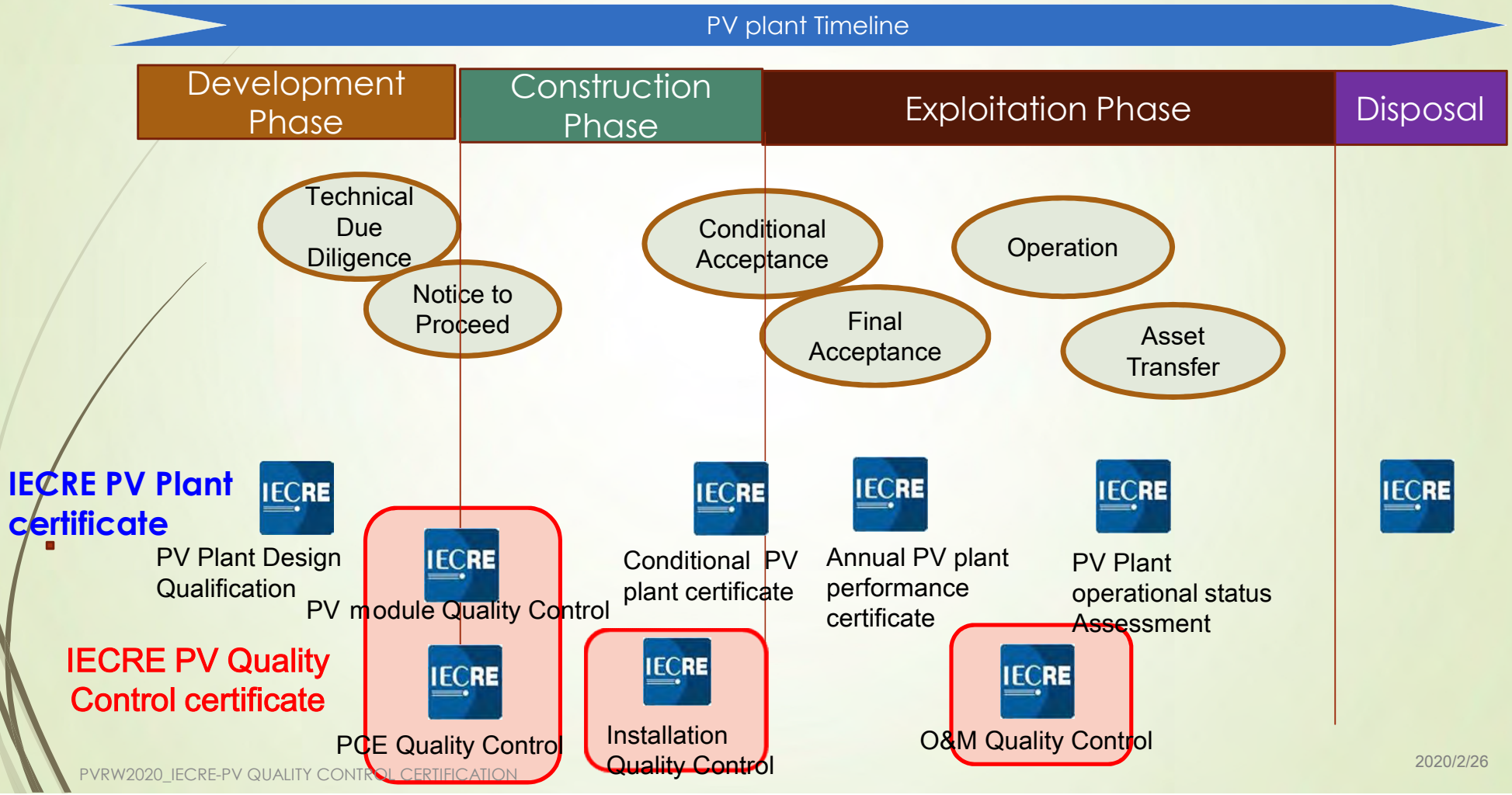
Some examples of field failures likely related to quality-control



IECRE-PV certification system

certificate name	current status
PV power plant milestone certificate	
1 PV Plant Design Qualification certificate	certificate issued to ZPMC
2 PV Plant Design Qualification Certificate: Part 1 - PV Site Qualification	
3 PV Plant Design Qualification Certificate: Part 2 - PV Power Block Design Qualification	
4 Conditional PV plant certificate	certificate issued to ZPMC
5 Annual PV plant performance certificate	
6 PV plant operational status assessment	
(7 Plant Decommissioning certificate)	under dvelopment
Quality Management certificate	
1Quality management certificate for PV module manufacturer	certificate issued to Firstsolar
2 Quality Management Certificate for PCE manufacturer	
3 Quality Management Certificate for PV plant installer and O&M service provider	

PV plant timeline view and IECRE-PV certificate types



3 IECRE-PV certificates issued

Certificate No.

IECRE.PV.QC.18.0001-R0

IECRE - IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications

QUALITY MANAGEMENT CERTIFICATE

PV Module Factory

The certificate is issued to: Fest Solar, Inc. 2810 Cedar Park Boulevard, Perrysburg, OH 43551, USA

for the factory: Fest Solar, Inc. 2810 Cedar Park Boulevard, Perrysburg, OH 43551 USA

Standard: IEC TS 62941:2016

Manufacturing conformity statement Dated: N/A

Final evaluation report Dated: UL QAR4 [illegible] May 11, 2018

The conformity evaluation was carried out in accordance with the rules and procedures of the IECRE System www.iecre.org

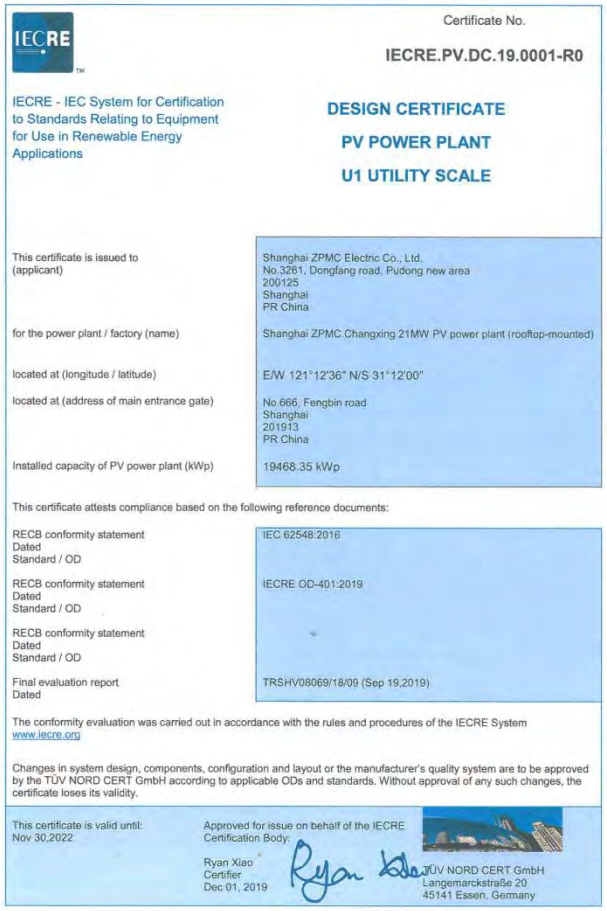
Changes in the system design or the manufacturer's quality system are to be approved by UL (US). Without approval, the certificate loses its validity.

The certificate is valid until: May 11, 2021

Approved for issue on behalf of the IECRE Certification Body: UL(US)

Scott Jarvinski, Manager, May 14, 2021

UL (US), 333 Pfingsten Road, Northbrook, IL 60062, USA



Certificate No.

IECRE.PV.DC.19.0001-R0

IECRE - IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications

DESIGN CERTIFICATE

PV POWER PLANT

U1 UTILITY SCALE

This certificate is issued to (applicant)	Shanghai ZPMC Electric Co., Ltd. No.3261, Dongfang road, Pudong new area 200125 Shanghai PR China
for the power plant / factory (name)	Shanghai ZPMC Changxing 21MW PV power plant (rooftop-mounted)
located at (longitude / latitude)	E/W 121°12'36" N/S 31°12'00"
located at (address of main entrance gate)	No.666, Fengbin road Shanghai 201913 PR China
Installed capacity of PV power plant (kWp)	19468.35 kWp

This certificate attests compliance based on the following reference documents:

RECB conformity statement Dated Standard / OD	IEC 62548:2016
RECB conformity statement Dated Standard / OD	IECRE OD-401:2019
RECB conformity statement Dated Standard / OD	-
Final evaluation report Dated	TRSHV08069/18/09 (Sep 19,2019)

The conformity evaluation was carried out in accordance with the rules and procedures of the IECRE System www.iecre.org

Changes in system design, components, configuration and layout or the manufacturer's quality system are to be approved by the TÜV NORD CERT GmbH according to applicable ODs and standards. Without approval of any such changes, the certificate loses its validity.

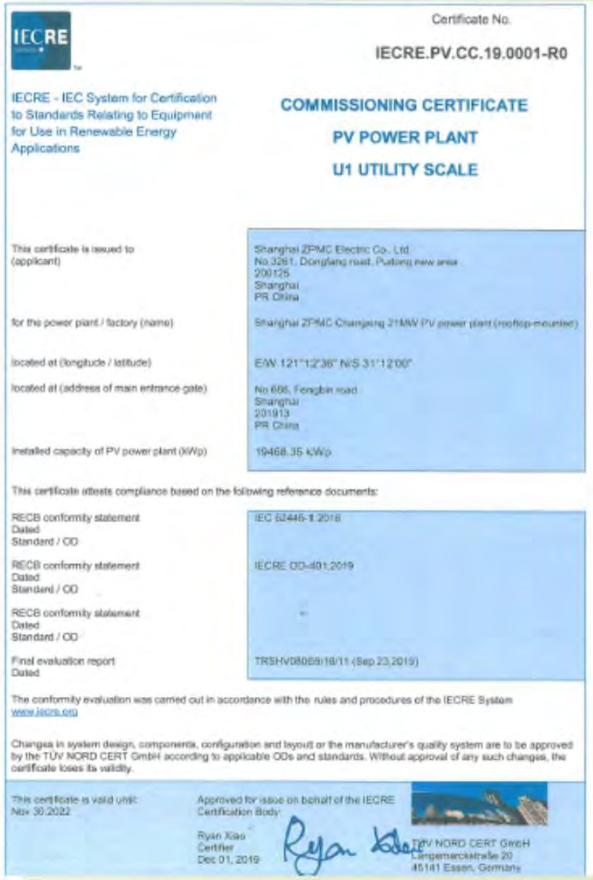
This certificate is valid until: Nov 30,2022

Approved for issue on behalf of the IECRE Certification Body:

Ryan Xiao, Certifier, Dec 01, 2019

TÜV NORD CERT GmbH, Langemarckstraße 20, 45141 Essen, Germany

Issued 2019-10-18 1/1 OD-408-T01 Ed.1.0



Certificate No.

IECRE.PV.CC.19.0001-R0

IECRE - IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications

COMMISSIONING CERTIFICATE

PV POWER PLANT

U1 UTILITY SCALE

This certificate is issued to (applicant)	Shanghai ZPMC Electric Co., Ltd. No.3261, Dongfang road, Pudong new area 200125 Shanghai PR China
for the power plant / factory (name)	Shanghai ZPMC Changxing 21MW PV power plant (rooftop-mounted)
located at (longitude / latitude)	E/W 121°12'36" N/S 31°12'00"
located at (address of main entrance gate)	No.666, Fengbin road Shanghai 201913 PR China
Installed capacity of PV power plant (kWp)	19468.35 kWp

This certificate attests compliance based on the following reference documents:

RECB conformity statement Dated Standard / OD	IEC 62446-1:2016
RECB conformity statement Dated Standard / OD	IECRE OD-401:2019
RECB conformity statement Dated Standard / OD	-
Final evaluation report Dated	TRSHV08069/18/11 (Sep 23,2019)

The conformity evaluation was carried out in accordance with the rules and procedures of the IECRE System www.iecre.org

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IECRE PV Quality Control certificate

Certificate namel	Major points of audits	Primary normative references	Remarks
QC system certificate for PV module manufactures	• Validation of design lifetime • Control of measurement tool • Monitoring and measurement of a manufacturing process • Post-delivery activities	ISO-9001:2015 IEC (TS) 62941 IEC 61215,IEC 61730 IEC 62108 IEC 61730-1,-2 IEC 60891,IEC 60904 IEC 61853-1	IEC 62941 ED1.0 published Dec-2019 certificate issued to Firstsolar May,2018
QC system certificate for PV PCE(inverter) manufactures	• Design and development validation • Monitoring of product, manufacturing processes and after-sales services	ISO-9001:2015 IEC TS 63157 IEC 62891,IEC 62109 IEC 62920	IEC TS 63157 ED1.0 published Nov-2019
QC system certificate for PV plant installer and O&M servicer	• Workers Training programs • Records Requirements • Installation Process and ongoing monitoring • PV Plant O&M operations • Continual improvement	ISO-9001:2015 IEC TS 63049 IEC 62446-1,-2 IEC 60904,IEC 62109 IEC/TS 62738 IEC/TS 61724-2,3	IEC TS 63049 ED1.0 published Sep-2017 Equivalent private certificates issued to Chinese O&M by TUV-Nord

Three IEC PV Quality Control standards

#	Title	Target
IEC 62941	Quality system for PV module manufacturing	PV modules
IEC TS 63049	Guidelines for effective quality assurance in PV systems installation, operation and maintenance	PV system installation O&M
IEC TS 63157	Guidelines for effective quality assurance of power conversion	Power PCE

Common features of the IEC QC standards

- Assumed that the quality management system of the organization has already fulfilled the requirements of ISO 9001 or equivalent quality management system.
- Provides more specific management requirements than ISO 9001
- Identifies critical technical elements and lays out best practices currently used in PV industry
- Forms the basis for factory audit criteria
- Structured in align with ISO 9001:2015

IEC 62941: Quality system for PV module manufacturing (revised from IEC TS 62941)

- Alignment of design lifetime with product warranty,
- Verification of incoming materials to maintain a consistent bill of materials,
- Traceability (so as to notify customers of defective product),
- Ongoing testing program to confirm consistency of design implementation during manufacturing,
- Control of solar simulator calibration for use in determining nameplate power rating,
- After delivery services for better implementation of warranty
- Continual improvement based on field experience

IEC TS 63049: Guidelines for effective quality assurance in PV systems installation, operation and maintenance

- Training of workers—Technical contents to be addressed
- Record requirements
- Ongoing oversight of installation,
- PV system operation and maintenance
- Maintenance planning and tracking

IEC TS 63157: Guidelines for effective quality assurance of power conversion

- Design lifetime aligned with the stated warranty
- Design and development validation
- Key design characteristics
- Control of externally provided processes, products and services
- Control of production and service provision— Control Plan
- Monitoring of product and processes during manufacturing and providing for service
- Ongoing reliability monitoring

Assessment of PV Quality Control system

- Assessment and certification processes are documented and disclosed to public as PV-OMC ODs (PV Operation Committee Operation Documents)
- Certificate is issued by IECRE certified Certification Body(RECB)
- PV Factory Auditor is qualified, registered, and trained by RECB

IECRE certified Certification Bodies

RE Certification Bodies (RECBs)

List

RE Certification Bodies (RECBs) Table search: Excel PDF Print

Country/Location	RE Certification Body Name	ME-OMC Marine	PV-OMC Solar	WE-OMC Wind
China	China Classification Society Certification Company (CCSC)			✓
China	China General Certification Center (CGC)		✓	✓
China	China Quality Certification Centre		✓	✓
France	Bureau Veritas Certification France			✓
Germany	DNV GL Renewables Certification Germanischer Lloyd Industrial Services GmbH			✓
Germany	TÜV NORD CERT GmbH		✓	✓
Germany	TÜV Rheinland Industrie Service GmbH			✓
Germany	TÜV Rheinland LGA Products GmbH		✓	
Germany	TÜV SÜD Industrie Service GmbH			✓
Germany	UL			✓
Japan	Tokyo Laboratory Japan Electrical Safety & Environment Technology Laboratories (JET)		✓	
Spain	Certification Entity for Renewable Energies, S.L.		✓	
USA	UL (US)		✓	

Requirements for IECRE PV Factory Auditor qualification

Auditor Grade	Auditor	Auditor trainee
Educational Background	a University degree / College diploma or certified / licensed master craftsman, technician or engineer in the relevant technical working field.	
General Work Experience	4 Years, or equivalent work experience	3 Years, or equivalent work experience
Solar PV specific work experience*	2 years, or equivalent of Solar PV specific work experience*	1 year, or equivalent of Solar PV specific work experience*
Auditor Training	Attended a lead assessor/auditor training on ISO 9001 approved by a accreditation body from IAF or, Attended auditor training or a training on IEC 62941 or IEC TS 63049 or IEC TS 63157 requirements interpretation	
Auditing Experience	3 Full Management Systems audit, all elements of audit cycle, 10 days of which 5 on site	None

Initial training of PV Factory Auditors

Factory Auditor/trainee are trained in the following content:

- ISO/IEC 17024 and 17021 (relevant clauses) e.g.:
  - Technical Requirements
  - Quality System
  - Personnel
- Inspection Methods and Procedures e.g.:
  - Product review according to product certification documents
  - Handling Inspection Samples
  - Records
  - Inspection Reports and Inspection Certificates.
- Requirements for surveillance sample testing and test results evaluation as needed during the performance of PV Factory Auditor in the applicable product categories.
- Familiarity with the IEC 61215 series, the IEC 61730 series, and all other standards listed in normative references of IEC 62941.

Features of IECRE PV Quality Control certification system

- Conformity assessment to relevant IEC standards by IECRE accredited Factory Auditor, carefully selected from experts with good experience and competence in the designated area
- The assessments include both “factory” and “field” aspects of Quality Management system of manufacturers of PV modules and PCEs, and service providers of installation and O&M of PV plants.
  - Module Quality – IEC 62941
  - System Installation and O&M Quality – IEC TS 63049
  - PCE Quality - IEC TS 63157
- Peer assessment by IECRE team examines the competence and independence of the Certification bodies and Factory Auditors
- Obligatory mutual recognition and peer assessment to achieve mutual confidence.

  The principle of obligatory recognition of the other members' certificates and audit results implies that no repeat audits are necessary. It enables faster and more economic entry into distant markets for manufactures and servicers and provides a global assurance that, no matter where an audit was carried out or a certificate was issued, it has the same value

Values of IECRE-PV Quality Control certificates

- IEC certificates of widely acceptance in global PV community as most reliable ones
- Faster and less expensive assessment by internationally acknowledged professionals
- Audit report and associated documents with accurate data and thoughtful comments
- Regular maintenance

IECRE Certificates provide

- customers with more confidence in quality of products and services
- Investors, financial and insurance organization with better bankability, resulting in lower financial and insurance risk and cost
- a powerful tool for differentiation from competitors in the market, quick decision making, and successful business implementation
- Audit report with good suggestions for review and improvement of quality control system of the customer

Challenges

- Market Awareness of IECRE-PV
- Alignment of program with customer needs
  - Cost
  - Flexibility
- Recruitment of Certification/Inspection bodies
  - Proficiency requirements

Summary

- Quality control of transactions along PV plant timeline from its planning through disposition is critical to ensure sustainable safety, performance, and reliability of the PV plant.
- IEC has published three standards on PV quality control to secure quality of products and services used in PV plant.
- IECRE is now offering reliable assessment and certification services on PV quality control system to provide better PV plant bankability .

Join us

IECRE-PV sub-session at NREL PVRW2020

Date/time: Feb.26(Wed.) 18:00-19:15

Venue: Jefferson conference room, Sheraton Denver West Hotel

Covering,

better understanding of IECRE-PV certification system

encouraging the use of IECRE-PV quality system certificates

Identifying potential market needs and what certifications could be added to meet them

Thank you for your kind attention

Hail Impacts Overview

NREL module Reliability Workshop
Feb 25, 2020

Heliolytics

Heliolytics Overview

37GW+

Largest global provider

3,500+

Individual sites inspected

$62M/yr +

Recoverable energy loss detected

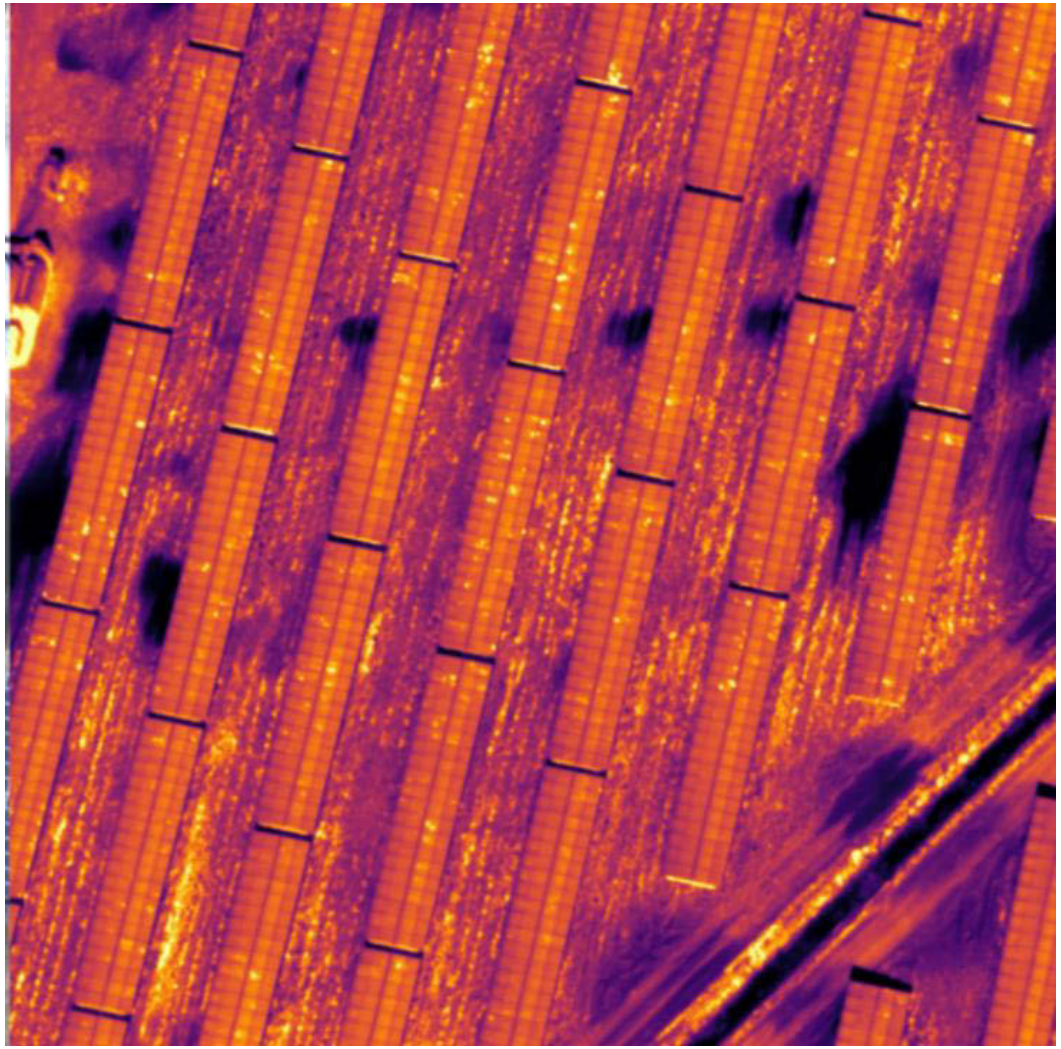
Why do we care? – Technical

Multiple sites are deployed in regions with a high hail risk

Hail can cause significant acute module damage

It can also cause long term potential energy degradation impacts which are difficult to define

We have seen that regions with 10% visible damage can have up to 100% cell damage, leading to large potential site exposure

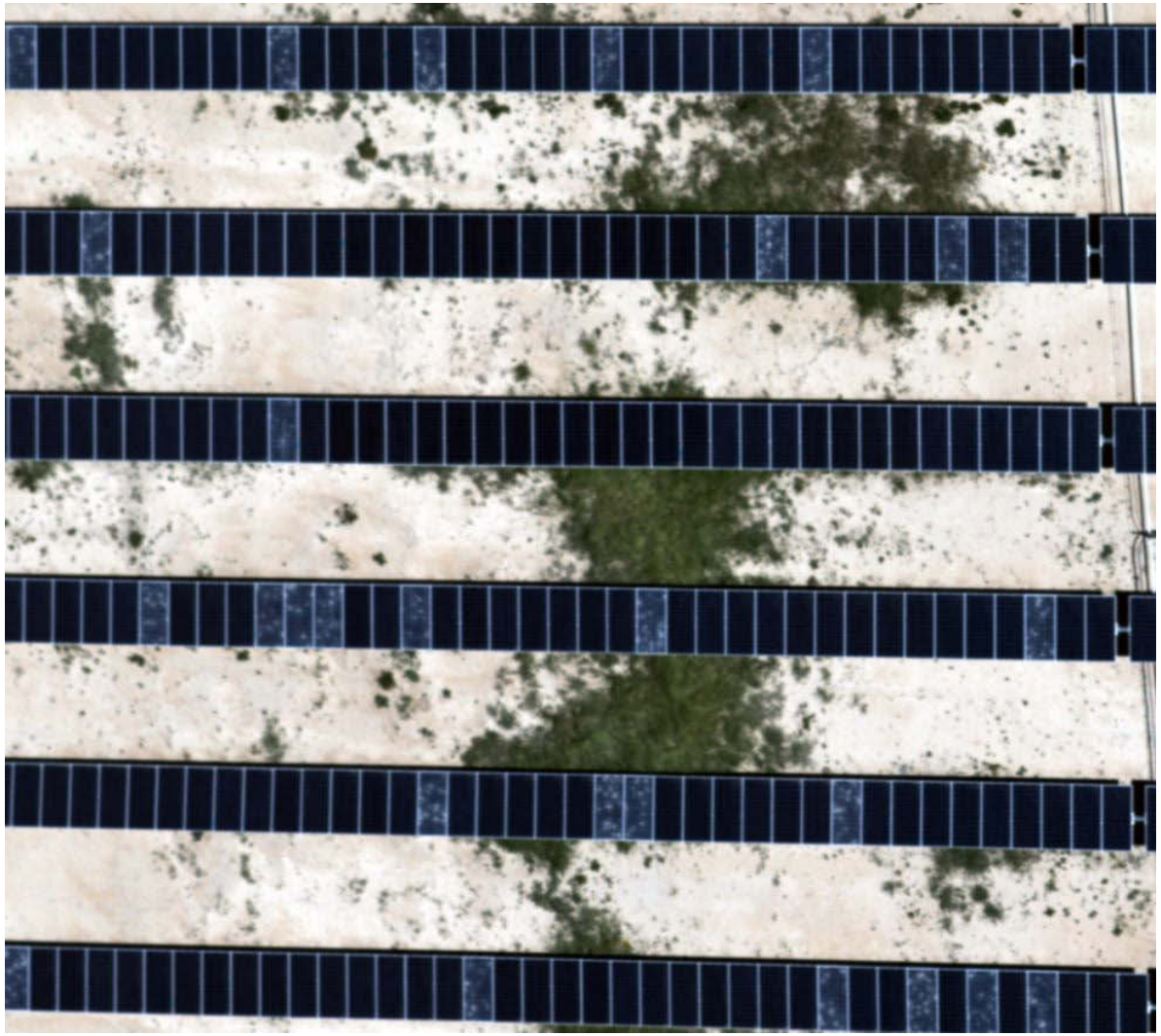


Why do we care? - Commercial

The insurance market is turning to a “Hard” market, driven by higher than expected loss ratios

Hail damage increases uncertainty in project performance projections

This risk is likely not being priced appropriately into projects

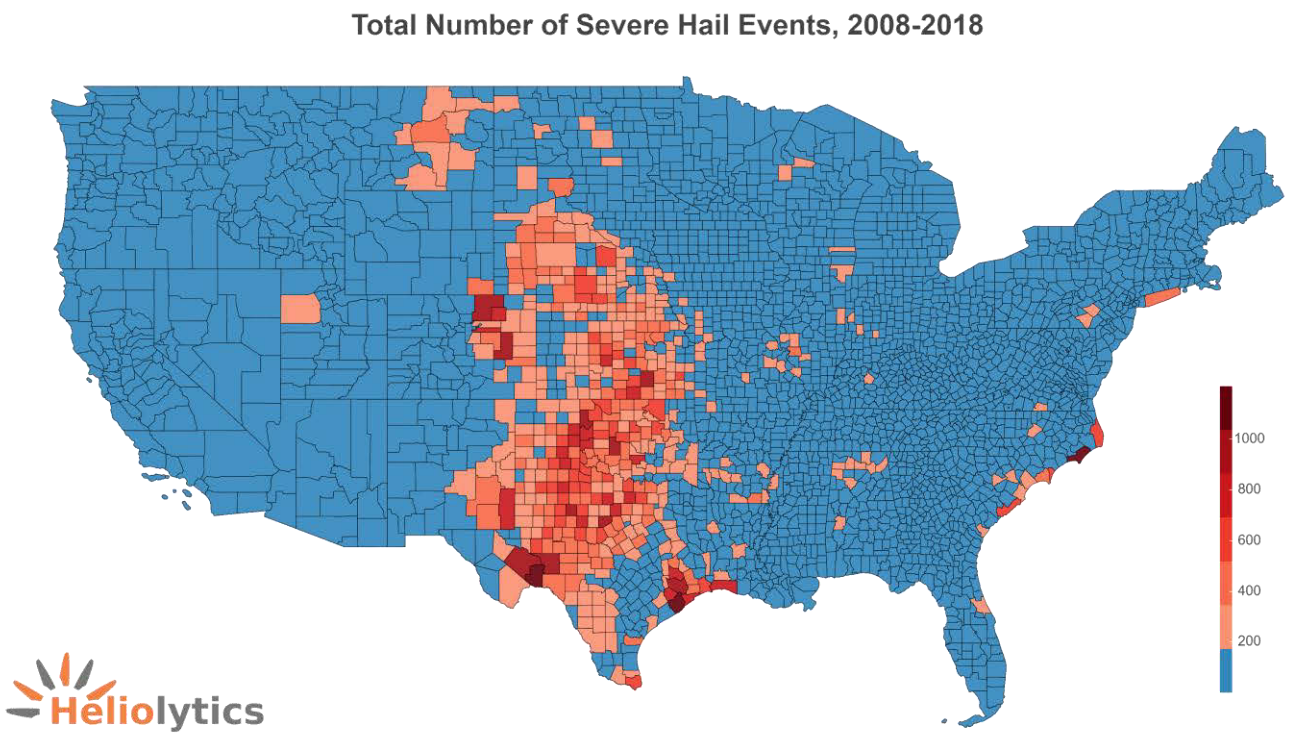


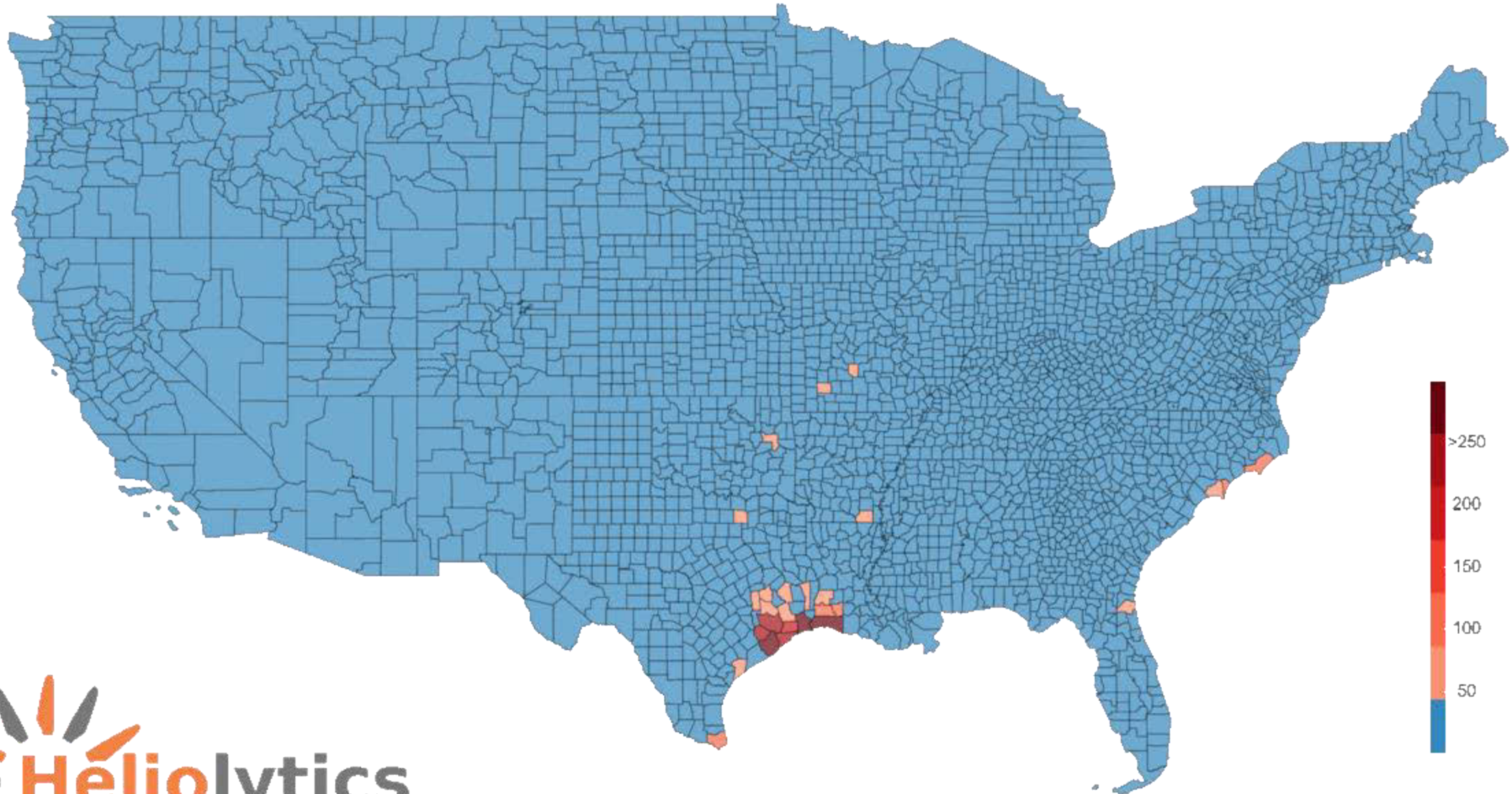
Why do we care? - Industry

~ 24% of new build PV is in Hail prone regions

~ 8% of current operating sites in Hail Prone regions

This may cause long-term reliability and performance issues for projects exposed to the risk





Heliolytics

The importance of baselining

Hail and weather related damage is not definitively identifiable from other pre-existing damage

In all insurance claims we have been a part of, the first question is how can we identify if the damage is not pre-existing

Baseline with IR or EL provides a case for comparison to enable more efficient claims

Fluro luminescence may be a tool that can be used to “age” faults IF the module has appropriate EVA

Current gaps in understanding

How to cracks propagate over time?

Do hail cracks have a larger than measured degradation trends?

What is the best methodology for detecting hail damage?

Can systems be designed to be more resistant to Hail damage?

Thank you

inspections@heliolytics.com
+1 855 888 9820
www.heliolytics.com

PVEL
MAKE DATA MATTER.

HOW PVEL IS ADDRESSING CELL CRACKING: IN THE LAB AND IN THE FIELD

Tristan Erion-Lorico
Head of PV Module Business
PVEL
tristan.erion-lorico@pvel.com

PVEL is the Independent Lab for the Downstream Solar Market

Global

300+ downstream partners worldwide with 30+GW of annual buying power

Comprehensive

Testing for every aspect of a PV project from procurement to O&M

Experienced

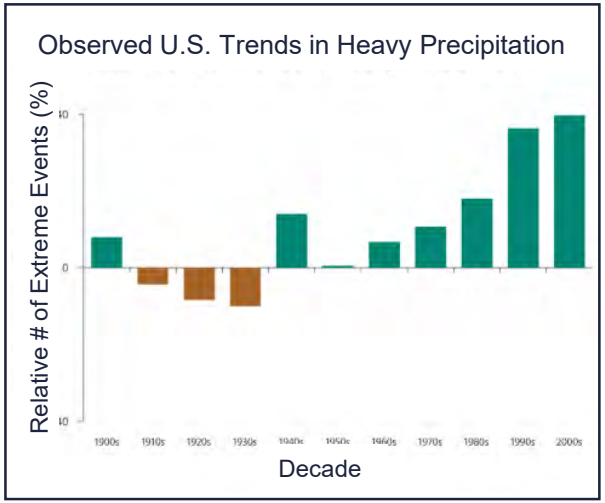
Pioneered bankability testing for PV products nearly a decade ago

Market-driven

Continuously refining test programs to meet partner needs

The solar industry needs an action plan for extreme weather

More Severe Weather



Source: National Climate Assessment 2014

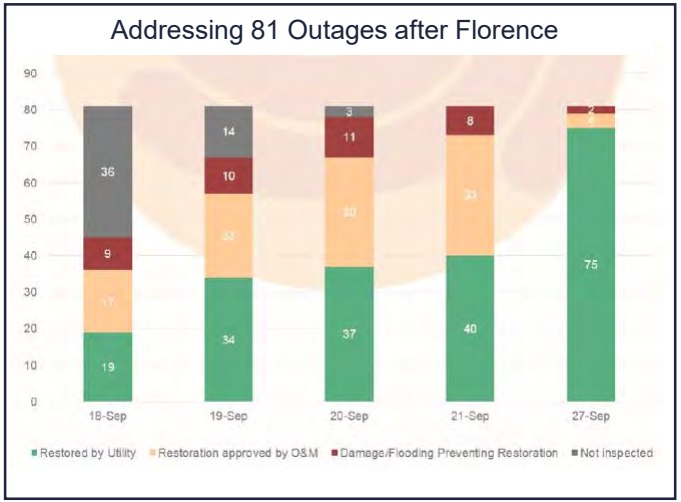
Insurance Landscape

GCube reports their weather-related claims in the renewables sector **doubled in 2018.**

GCube
Renewable Energy Insurance

Source: GCube, “Global Extreme Weather Losses Mount”

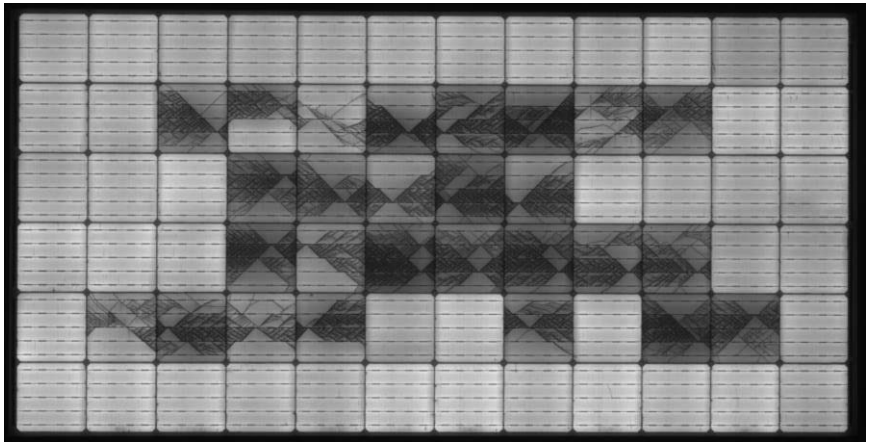
Returning to Operations



Source: Strata Solar, “Force Majeure & Energy Modeling: 1 Hurricane, 81 PV Plants Down”

Understanding cell cracking in PV modules

- Cells are *quite* thin (<0.2 mm)
- Glass thickness is 3.2 mm
- Causes of cell cracks:
  - Manufacturing defects
  - Transportation and shipping
  - improper installation
  - Force majeure/extreme weather events



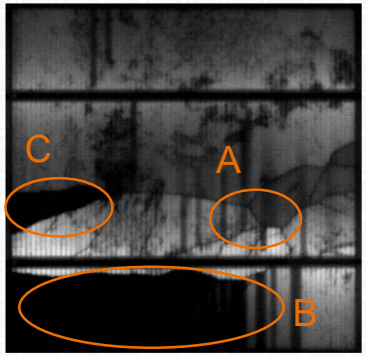
The Main Challenge:
Power loss is realized **over time** – not right away

Evaluating power loss and financial loss due to cell cracks

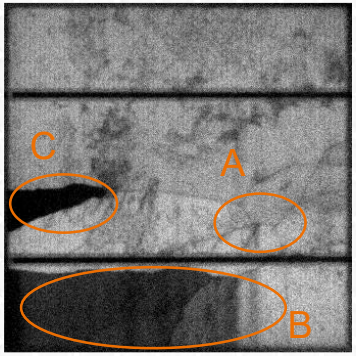
The bottom line: impact varies

- The potential for power loss varies by the type of crack
- Financial losses depend on model assumptions

EL Image at Isc



EL Image at 1/10 Isc



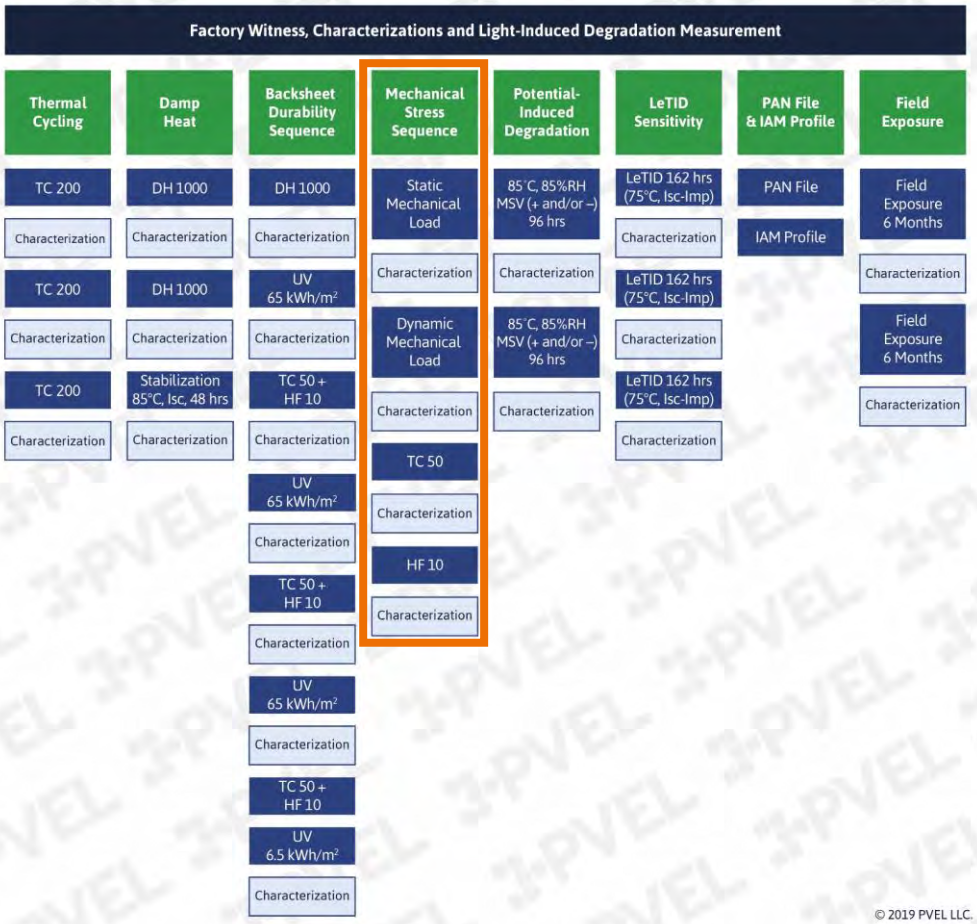
A: No resistance across crack
B: Degraded, still connected, but increased resistance
C: Isolated, inactive cell area

Source: Köntges et al., “Crack statistic of crystalline silicon photovoltaic modules,” Institute for Solar Energy Research Hamelin, (2010)

Certification testing for cell cracks

- IEC 61215
  - Static mechanical load testing at 2400 Pa with options for up to 5400 Pa
  - Includes minimum hail testing: 1” hail balls at 50 mph
- Challenges
  - No thermal cycling after stress
  - No dynamic mechanical loading
  - A pass means:
    - <5% power loss
    - No physical damage
    - **EL imaging not required**

PVEL's Module Product Qualification Program (PQP) Test Sequences



PVEL's mechanical stress sequence for cell cracking

Step 1:
Creates cell cracks in susceptible modules

Step 2:
Articulate cracks, opening them in susceptible modules

Step 3:
Reduces power output in susceptible modules

Module types at PVEL queued for MSS testing: monofacial, bifacial, n-type, p-type, 5bb, 6bb, 9bb, 12bb, IBC, MWT, thin film, full cell, half-cut, shingled, 156.75 mm, 158.75 mm, 161 mm , 166 mm, glass//backsheet, glass//glass

Improving Cell Cracking Resistance

Lower Crack Risk

- Glass/glass – no tensile stress
- More interconnect wires – smaller disconnected areas
- Conductive adhesive (some shingled) – fewer microcracks
- Parallel wiring – cells less likely to enter reverse bias
- Better packaging
- More EL quality control testing – factory, pre and post install
- Thin film – inherently impervious to cell cracks

Higher Crack Risk

- Laser cut cells (half-cut, shingled) – microcracks
- Larger modules – more deflection and tensile stress
- Thinner wafers – easier crack propagation

[Gabor, 2017 NREL PVRW]

(thanks to Brightspot Automation for this list!)

New Incident Response testing combines advanced field and aerial inspection to safeguard against financial losses

Field testing:

PVEL

MAKE DATA MATTER.

PVEL's aerial inspection partner:

Heliolytics

Incident Response: A better way to manage force majeure events

Fires | Tornadoes | Hurricanes | Lightning | High Wind | Hail

Incident Response helps you:

1. Quantity the full extent of damage to a site
2. Prioritize repairs to quickly return sites to operation
3. Receive full insurance compensation

Hypothetical: A 100 MW site is hit by major wind and hail storm

- 270,000 370W modules on site are visually inspected
- 5% show visible damage and must be replaced – 13,500 modules
- Assumptions:
  - $0.35 USD/watt for PV modules
  - $50/module for labor

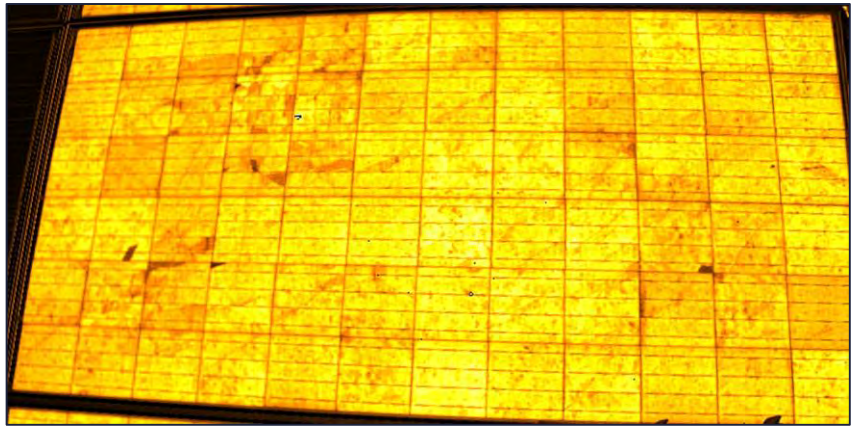
Value of insurance claim for visually inspected PV modules:
$2.42M

100 MW site damaged by major wind and hail storm
(Image Source: Heliolytics)

Insurance payout based on Incident Response

- EL imaging reveals that 15% of the modules on site have significant cell cracks
- An additional 40,500 modules must be replaced

Total payout for all damaged PV modules:
$9.69M – nearly 4x



EL image of cell cracked PV module in the field

PVEL

MAKE DATA MATTER.

QUESTIONS, AND THANKS!

Tristan Erion-Lorico
Head of PV Module Business
PVEL
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anyone else to add to the meeting?

Structural and physical properties of the dust particles in Qatar and their influence on the PV panel performance

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Qatar Environment & Energy Research Institute
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Brahim Aïssa*, Rima J. Isaifan, Vinod E. Madhavan, Maulid M. Kivambe, Najat H. Al-Jufairi, Amir A. Abdallah, Luis M. Pomares and Benjamin W. Figgis

NREL Transforming ENERGY

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Abstract

The economic prosperity has always been intimately correlated to the energy use and growth. In this context, solar photovoltaic (PV) has already demonstrated its incredible expansion, where the global production has been increasing hundreds times since its first industrial implementation. However, for an optimal management and analysis of expected PV performance, the location sites become increasingly important. As a matter of fact, the deployment of solar energy in large-scale scheme in the Middle East (ME) region is facing both the high operating temperature and dust accumulation on PV modules. While both effects result in a reduction of the kWh generated by the solar panels, focus is put here on the investigation of the soiling effect, since geographically, the ME region is frequently affected by sand storms and characterized by a high dust concentration.

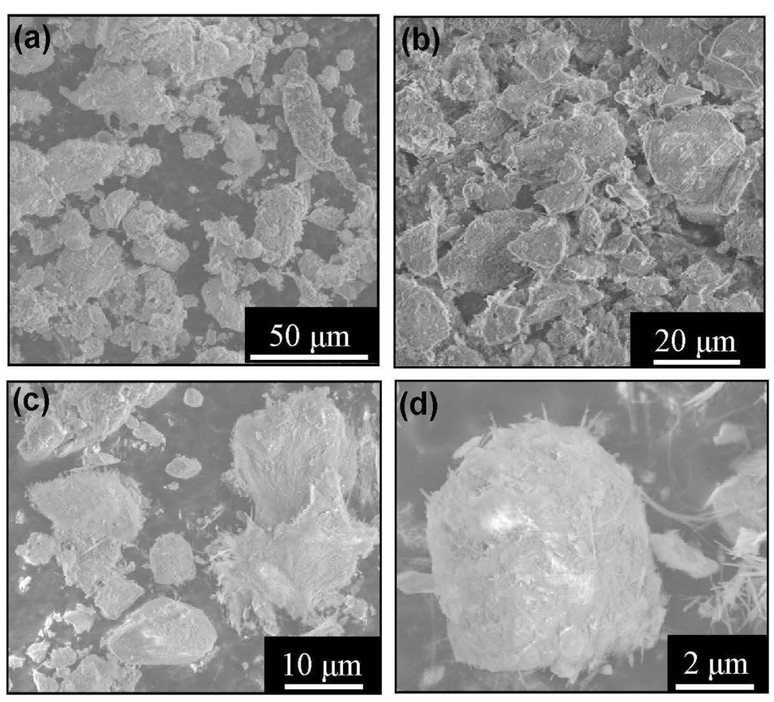
Fig. 1: The Outdoor Test Facility located at the Science and Technology Park, in Doha (State of Qatar) with different PV technologies installed to study the performance and reliability of PV in Qatar climatic conditions; (a) PV modules after scheduled cleaning and (b) PV modules after dust storm inducing soiling.

We report here on the structural and optical properties of the dust particles collected directly from solar modules installed at the Outdoor Testing Facility (OTF) in Doha (State of Qatar. Fig. 1). The influence of the dust accumulation on the photovoltaic performance is also discussed by highlighting its effect on the current-voltage (IV) curve characteristics.

Methodology

Different PV technologies were installed at the OTF with a total of 150 kW power production capacity (Fig. 1). The data acquisition system provides IV characteristics of PV modules under real operating conditions. Borosilicate plate glass samples with dimensions of 25 mm × 10 mm × 2 mm (width × length × thickness) were used as work pieces. Actual dust accumulation was performed in real environment (collected directly from PV panels). Morphological characterization of the dust was performed using SEM and AFM. Structural studies were performed using XRD. The optical transmittance was measured using a UV-Vis spectrometer. The optical analysis of the dust particles deposited on glass substrates was performed using Olympus (IX73) optical microscope.

SEM and AFM characterizations



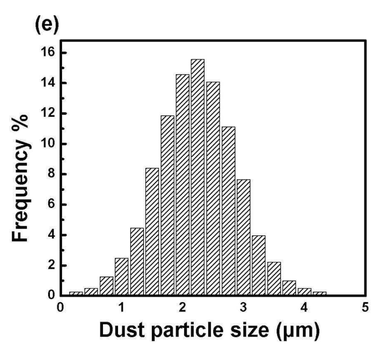


Fig. 2: (a–d) Representative SEM micrographs with various magnifications of the desert-dust particles collected directly from the PV panels. (e) Particle size distribution histogram.

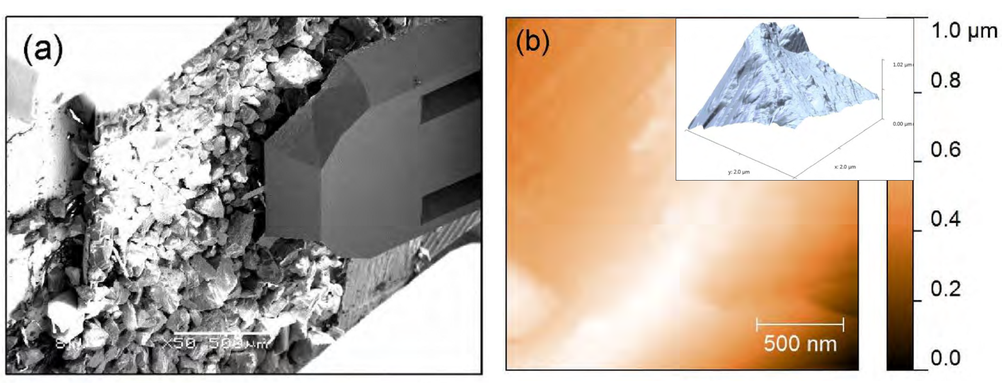


Fig. 3: (a) SEM image of the AFM cantilever approaching the dust particles, (b) Atomic force micrograph of dust particle taken in the contact mode, and its corresponding three-dimensional representation shown in the inset.

- ✓ Various particle sizes, with different morphologies are seen. The Gaussian distribution of the particles sizes was found to be centered at around 2 µm (see the histogram), however, larger particles in the order of few tens µm diameter are also observed.
- ✓ Although, some particles have irregular shapes, the majority of dust particles are rather spherical-like.
- ✓ The AFM contact mode image taken on a single dust particle, shows a 3 dimensional average size of 2 µm.

EDS and XRD characterizations

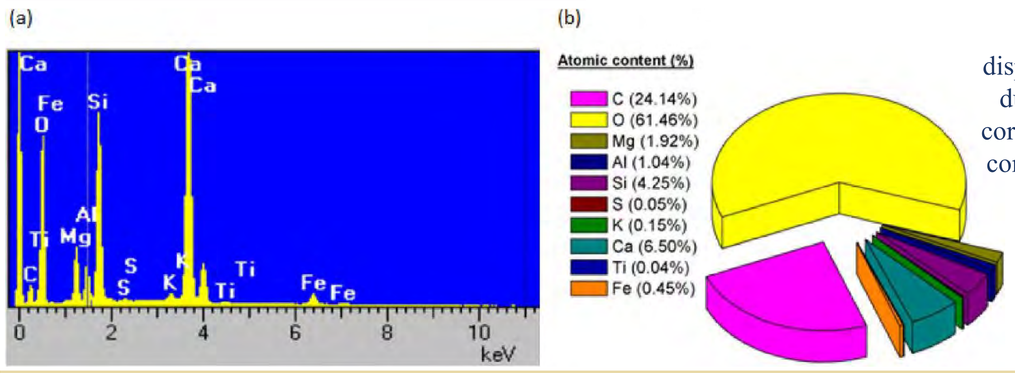


Fig. 4: (a) Energy dispersive spectra of the dust particles, (b) the corresponding chemical composition of the dust particles.

- ✓ The results show that dust particles have different concentrations of non-uniformly distributed elements and compounds. It's to underline that the quantitative atomic content of oxygen and carbon have to be taken with high care since EDS is not a suitable technique to probe these 2 elements.
- ✓ The presence of traces of potassium can be associated with sea salt as Qatar is located in the Arabian Gulf.

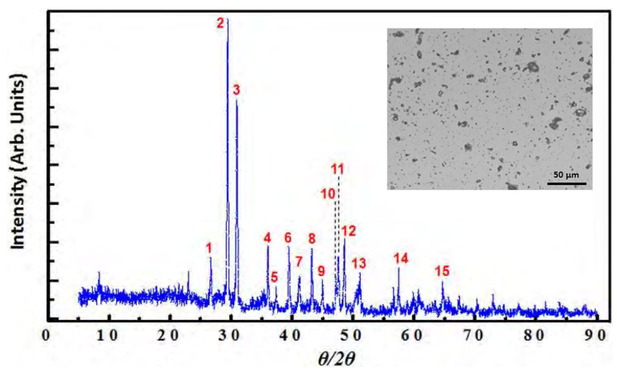


Fig. 5: Typical X-ray diffraction pattern of dust particles in Qatar.

Phase name	Chemical formula	Atomic content (%)
Calcite	$CaCO_3$	58
Quartz	SiO_2	7
Sillimanite	$Al_2(SiO_4)O$	17
Wuestite	FeO	0.6
Olivine	$Mg_2(SiO_4)$	9
Akermanite	$Ca_2Mg(SiO_7)$	8

Table 2: Most possible compositions of dust particles as suggested by XRD analysis interface software.

Peak #	2-theta (°)	Phase chemical formula
1	26.649	SiO_2, $Al_2(SiO_4)O$, $Mg_2(SiO_4)$
2	29.3922	$Ca(CO_3)$
3	30.93	$Al_2(SiO_4)O$, $Ca_2Mg(Si_2O_7)$
4	35.9954	$Ca(CO_3)$, $Ca_2Mg(Si_2O_7)$
5	37.3504	$Al_2(SiO_4)O$, $Mg_2(SiO_4)$, $Ca_2Mg(Si_2O_7)$
6	39.4116	$Ca(CO_3)$, SiO_2, $Al_2(SiO_4)O$
7	41.0783	$Al_2(SiO_4)O$, FeO, $Mg_2(SiO_4)$, $Ca_2Mg(Si_2O_7)$
8	43.1698	$Ca(CO_3)$, $Al_2(SiO_4)O$
9	44.9443	$Mg_2(SiO_4)$
10	47.1611	$Ca(CO_3)$,
11	47.5344	$Ca(CO_3)$, $Ca_2Mg(Si_2O_7)$
12	48.4681	$Ca(CO_3)$, $Ca_2Mg(Si_2O_7)$
13	51.0323	SiO_2, $Al_2(SiO_4)O$, $Mg_2(SiO_4)$, $Ca_2Mg(Si_2O_7)$
14	57.4174	$Ca(CO_3)$, $Al_2(SiO_4)O$, $Mg_2(SiO_4)$
15	64.658	$Ca(CO_3)$, $Al_2(SiO_4)O$, $Ca_2Mg(Si_2O_7)$

Table 1: Summary of the main chemical compounds of the dusty sample as identified by X-ray diffraction

Qualitative analysis of the XRD data shows that dust particle are mainly composed of calcite ($CaCO_3$), quartz (SiO_2), sillimanite ($Al_2(SiO_4)O$), wuestite (FeO), olivine ($Mg_2(SiO_4)$) and akermanite ($Ca2Mg(SiO_7)$).
Table 2 shows a summary of the quantitative analysis which reveals that 58% of the dust particles are composed of calcite.

Optical and PV characterizations

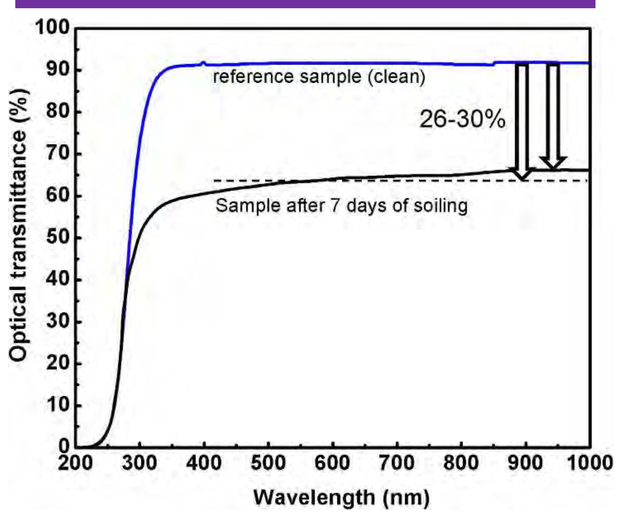


Fig. 6: UV-Vis transmission spectrum of clean/dusty samples

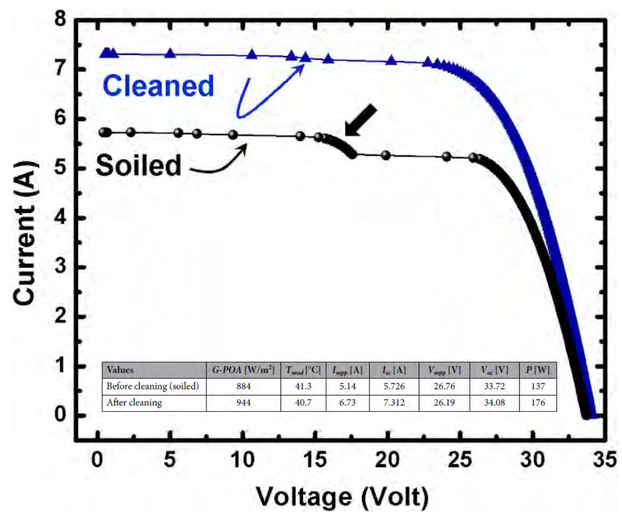


Fig. 7: IV curve measured for an individual solar module before and after cleaning. Inset is a Table summarizing the electrical parameters extracted from the IV curve.

- ✓ The dusty sample was collected from the OTF after 7 days of soiling at zero angle inclination. The spectrum shows up to 30% reduction in the optical transmittance, decreasing from 90 to 60%.
- ✓ After module cleaning, the short current circuit *Isc* increases, while the open circuit voltage *Voc* remains quite similar. It is known that the photocurrent, and therefore the *Isc*, is mainly proportional to the solar irradiance.
- ✓ Therefore, dust accumulated on the solar module will prevent the solar irradiance from reaching the solar cells and causing light to reflect from the solar module (a drop in the *Isc* was observed).
- ✓ A deviation of the IV curve (indicated by black thick arrow in Fig. 7) was observed on the soiled module and could be explained by non-uniform shading on the front-glass surface of the module caused by soiling effect.

Summary

The structural and physical characteristics of Qatar dust particles collected from PV panels installed at the OTF located at Doha city were investigated and their influences on the PV performance were evaluated. The main findings show:

- ➢ The dust particles have mainly an average size of about 2 µm, in addition to the presence of larger non-uniform particles of few tens of micron size.
- ➢ EDS and X-ray diffraction analysis have shown that the particles are mostly composed of calcite mineral structure with about 58% atomic content.
- ➢ The effect of soiling on the optical transmittance properties of the glass substrate have shown a reduction of about 30% compared with the clean reference sample.
- ➢ Finally, the influence of dust particles accumulation on the solar panels was found to cause a clear drop in the PV power output.

References

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2. Mani, M. & Pillai, R. *Renew. Sustain. Energy Rev*. 14, 3124–3131 (2010).
3. Martinez-Plaza, D., Abdallah, A., Figgis, B. W. & Mirza, T. *Energy Procedia*. 77, 386–396 (2015).

Acknowledgement

This work has been carried out at Qatar Environment and Energy Research Institute, QEERI, HBKU, Qatar Foundation.

Estimating Subhourly Inverter Clipping loss with NSRDB Data

Kevin Anderson & Kirsten Perry

National Renewable Energy Laboratory, Golden, CO

Introduction and Background

Inverter clipping caused by short-duration irradiance variability is emerging as a significant driver of PV system underperformance relative to standard hourly system energy models. The rarity of high-frequency irradiance datasets prevents direct modeling of this effect in most locations. Additionally, not all popular PV modeling tools support high-frequency simulations. The effect's magnitude can vary across climate and system design. For systems with high DC/AC ratios in climates with high irradiance variability, the effect creates bias in long-term production estimates as well as operational performance analysis.

The present work proposes two methods of predicting the energy difference between low- and high-frequency production models with the goal of enabling estimation of subhourly clipping loss for any PV system anywhere in the United States.

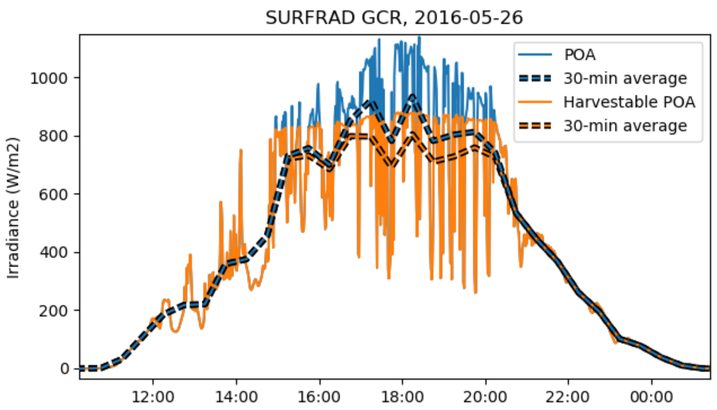

Fig 1. 1-minute GHI data showing the difference in harvestable irradiance when calculated at 30-min vs 1-min scale.

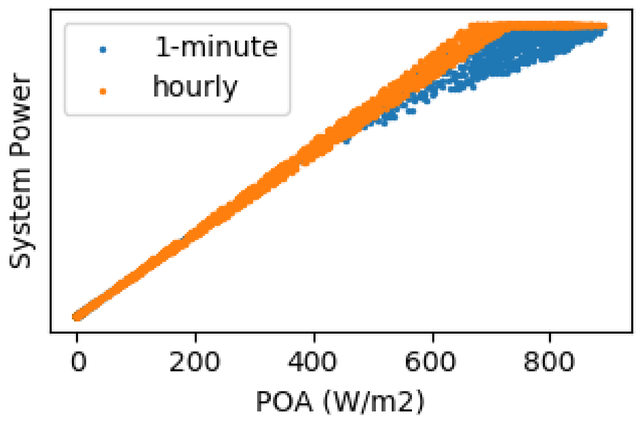

Fig 2. Expected Production vs Insolation plot comparing hourly expected production simulated with hourly and 1-minute irradiance.

Method 1: Irradiance Downscaling

Many methods of generating synthetic high-frequency irradiance signals from lower resolution measurements have been proposed to support simulations of the effect of local solar variability and increasing PV integration on grid stability.

1. Downscale 30-min NSRDB irradiance to 1-min synthetic irradiance using a method tuned with SURFRAD ground station irradiance.
2. Using a standard energy model (e.g. PVWatts), model system energy production at high-frequency and low-frequency scale and find the difference in estimated production.

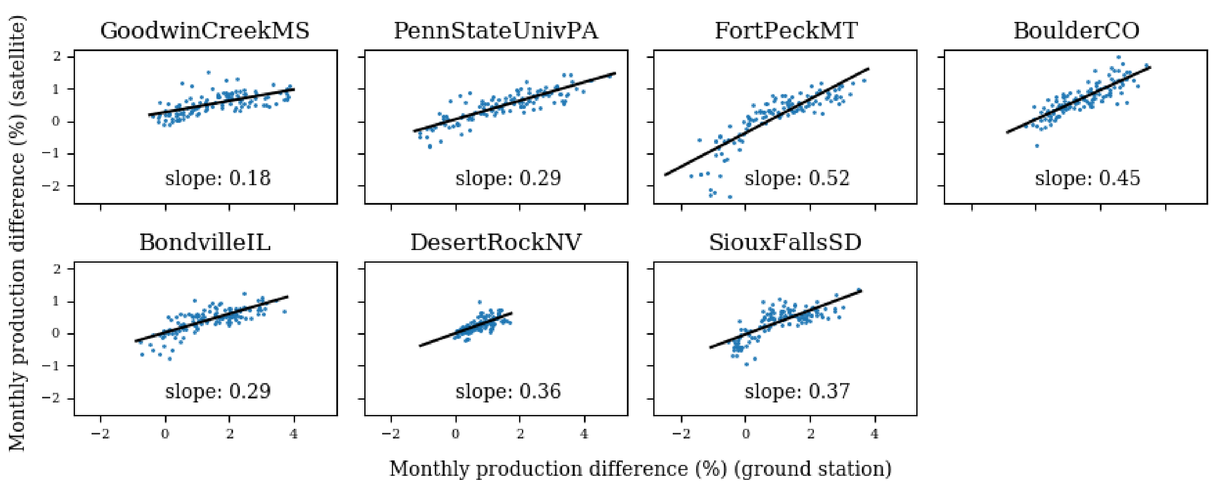

Fig 3. Comparing monthly subhourly clipping loss predicted by the irradiance downscaling method with the "ground truth" values. In all cases, the irradiance downscaling method underpredicts loss.

Method 2: Machine Learning

Relationships between multiple independent variables (clearsky GHI, clearsky POA, etc.) and a dependent variable (correction factor to apply to 30-minute power measurements, to account for sub-hourly inverter clipping loss) can be complex and non-linear. Consequently, this type of problem lends itself well to machine learning, using black box modeling. For this specific case, a regressor ensemble model consisting of a random forest and an XGBoost model was used.

1. Train the model on 30-min NSRDB irradiance and subhourly clipping losses simulated from the associated 1-min ground station data.
2. Use the model to predict subhourly clipping losses at other locations from NSRDB irradiance data.

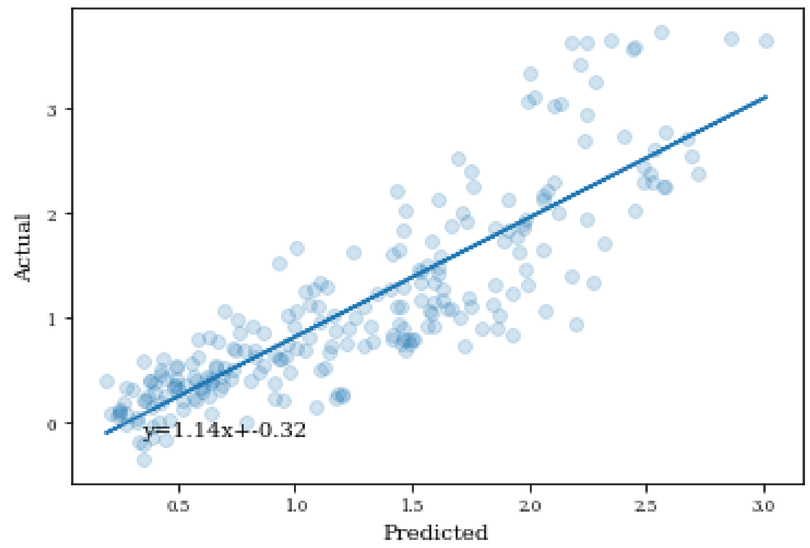

Fig 4. Comparing monthly subhourly clipping loss predicted by the machine learning method with the "ground truth" values.

RMSE=0.5% (absolute), MBE= 0.2% (absolute)

Feature Variable	Random Forest Model	XGBoost Model	Ensemble Model
Normalized Clearsky POA	21%	37%	29%
Normalized Clearsky GHI	19%	26%	22%
Normalized GHI	16%	14%	15%
Cloud Type	10%	18%	14%
Normalized POA	18%	3%	11%
Cell Temp	16%	2%	9%

Fig 5. Listed feature importances for the Random Forest, XGBoost, and combined ensemble model, respectively.

The above table shows the feature importances, in terms of percentages, for each of the ML models. Feature importance metrics help to discern the predictive power of individual features when predicting model outcome. For all three models, normalized clearsky POA and normalized clearsky GHI had the greatest effect on model outcome.

Conclusions

- Machine learning methods can predict high-frequency clipping loss from low-frequency measurements with relatively low error at monthly scale, though the results are system-specific. As one might expect, irradiance is the strongest predictor, but the model is able to make use of other NSRDB fields (cloud type and temperature) as well.
- The results of a more general method of synthesizing intermediate high-frequency irradiance and using a standard PV energy model are strongly correlated with ground truth values but show high bias. Accuracy could likely be improved with a different synthesis method.
- The low prediction scatter shown by both methods supports the overall approach of predicting the effects of high-frequency irradiance variability using low-resolution satellite irradiance data.

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2020 PV Reliability Workshop
Lakewood, CO
February 25-27, 2020
NREL/PO-___-_____

Benchmarking Performance and Loss Rates of PV Plants

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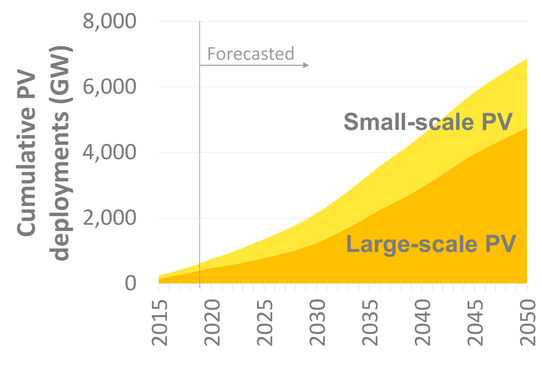
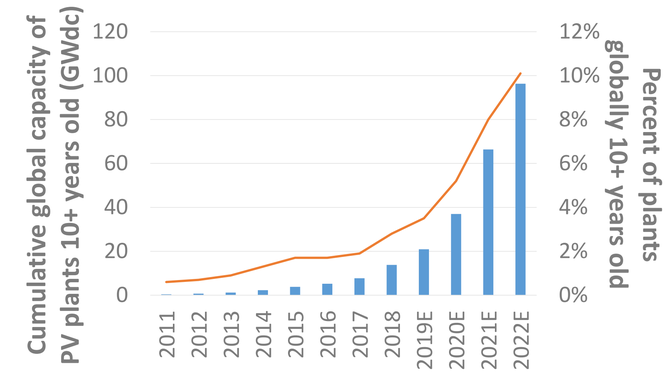
ELECTRIC POWER RESEARCH INSTITUTE

Background and Motivation

- *Approximately 90% of all global PV capacity has been deployed in the past seven years*, over half of which was installed in the past three years. *The majority of existing and future plants are anticipated to be large-scale and ground-mounted*.[1]
- *PV plants are expected to operate for 20+ years*, meaning there is a knowledge gap between actual experience and expected performance of the plant.[2]
- The majority of performance analyses have focused on research-grade or small-scale systems, *more information is needed about large-scale plant performance*.





Introduction

- EPRI has collected and analyzed the performance of PV arrays – of all sizes – for the past decade. The data used in this study includes minute-level meteorological (e.g., irradiance, ambient temp., wind speed) and performance (e.g., power at inverter and grid-tie) data collected from on-site sensors and instrumentation.
- This poster includes analysis from over a dozen large-scale plants (collective nameplate of 256 MW) and four small-scale research systems with multiple technologies under evaluation (collective nameplate of 160 kW). The average operational life of systems evaluated is 4 years.

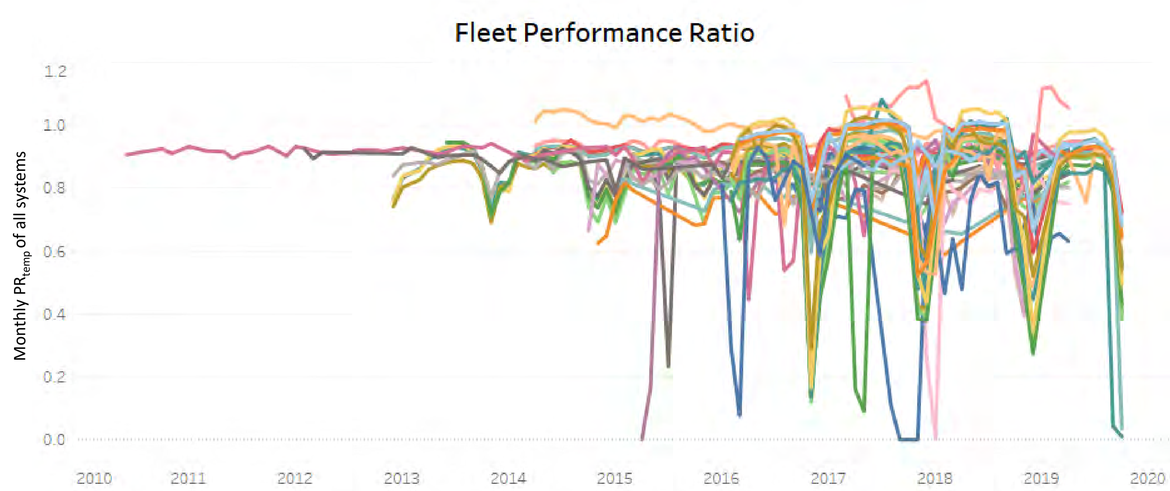
Approach and Key Findings

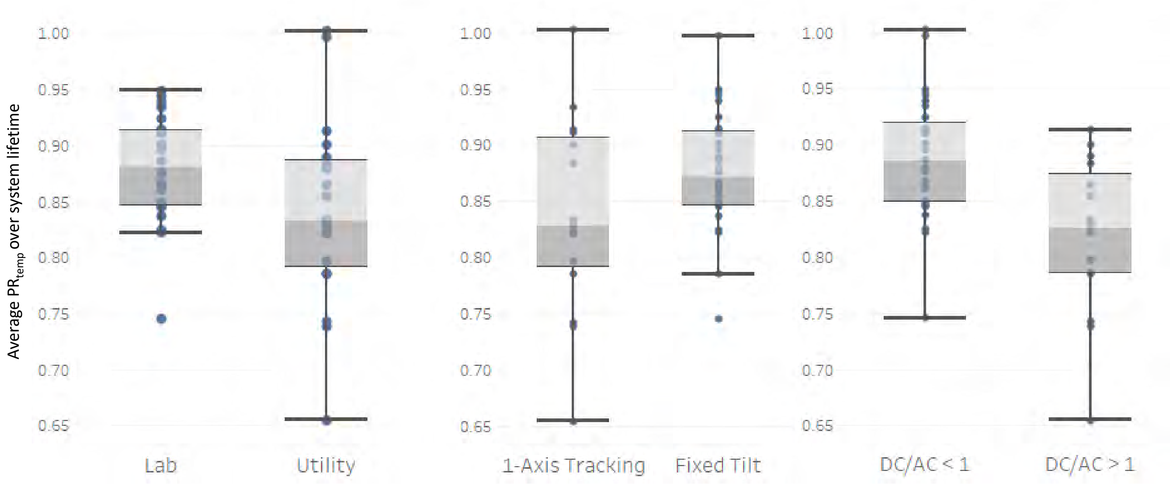
- Temperature-corrected performance ratio is calculated per IEC 61724.

$$PR_{temp} = \frac{\sum_i P_{ac}\,[kWh_{ac}]}{\sum_i \left(P_{array} \cdot \left(\frac{G_{POA,i}}{G_{ref}}\right) \cdot \left(1 + C_t \cdot (T_{m,i} - T_{ref})\right)\right)\,[kWh_{dc}]}$$

Actual energy

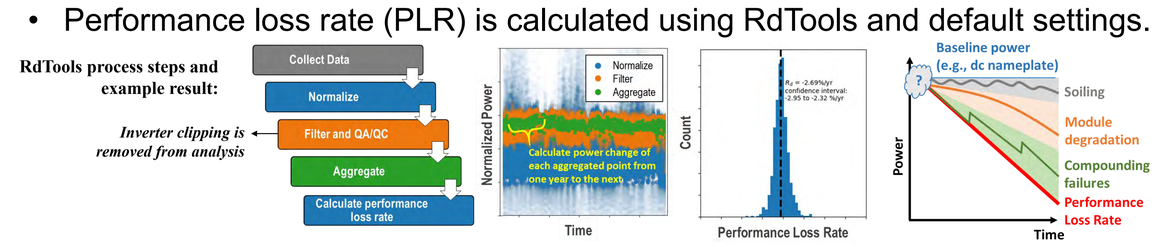
Expected energy

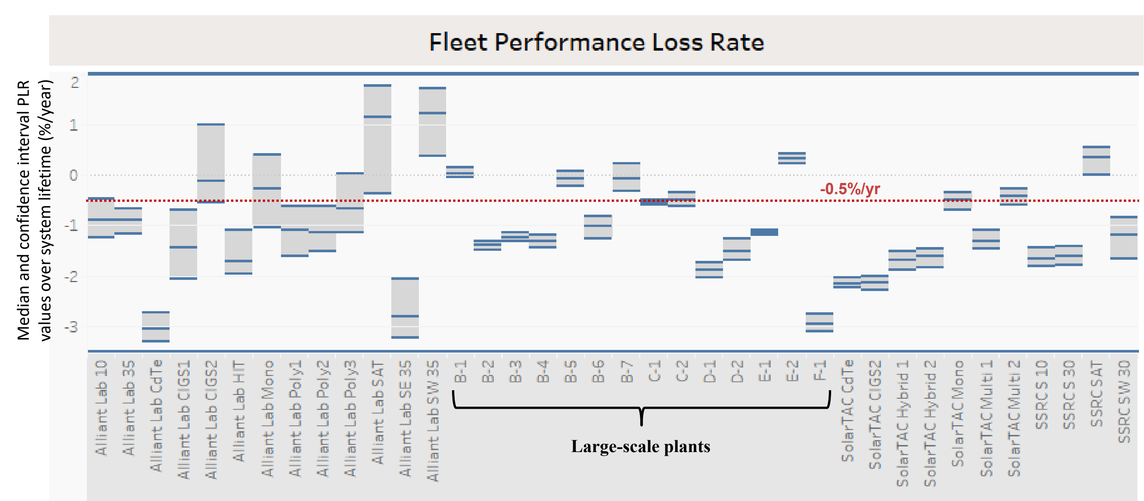


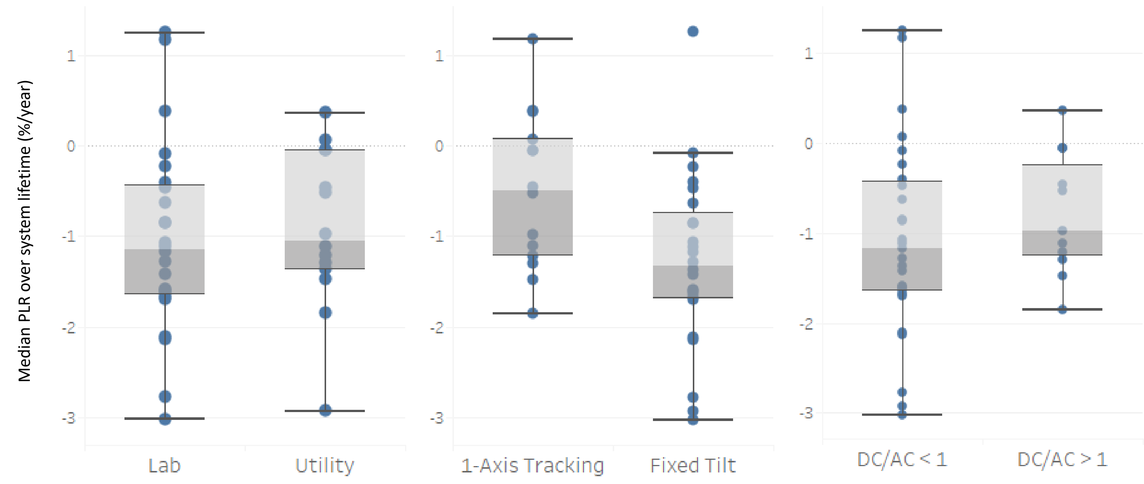


- PR_{temp} is highly sensitive to intrinsic and extrinsic power reduction, which causes spurious peaks
  - Intrinsic factors include hardware issues, such as broken trackers
  - Extrinsic factors include snow and soiling
- dc:ac ratios greater than unity reduce PR_{temp} due to clipping
  - Contributes to lower values for large-scale systems versus research systems

- Performance loss rate (PLR) is calculated using RdTools and default settings.







- PLR includes <u>all</u> factors that reduce nameplate capacity over time
  - Module degradation rate ≠ Plant performance loss rate. Module degradation is one component of performance loss rate.
- PLR values can be positive
  - Large performance excursions followed by power restoration over time can cause positive values. Masks underlying non-recoverable degradation.
- Overall PLR can be estimated by creating histogram from all sites: -0.9%/yr

Conclusion and Future Work

- Performance and degradation results from small-scale systems can inform large-scale plants, but are not be one-to-one
  - The modularity of PV is beneficial to leverage past learnings, but most industry knowledge is based on small systems that do not have same components, topology, goals / incentives, maintenance strategies, and so on as large-scale plants
- Performance analysis and benchmarking, especially for large-scale PV plants, is a burgeoning and important research topic
  - More work is needed to automate data intake and analysis, enable likewise comparisons, and report results
- One forum to discuss operations, maintenance, and performance best practices is the Solar Owners League, a users group for owners, operators, maintainers, and organizations purchasing power from large-scale PV plants

SOL
SOLAR OWNERS LEAGUE
https://www.epri.com/#/pages/product/000000003002017889/

References

[1] *New Energy Outlook 2018*. BloombergNEF. 2018.

[2] *2018 Global PV Operations and Maintenance: Competitive landscape, prices, costs, and market trends.* Wood Mackenzie Power & Renewables. 2019.

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ELECTRIC POWER RESEARCH INSTITUTE

VDE AMERICAS

A Framework for Estimating PV Energy Production and Probabilities of Exceedance

Peter Bostock Ph.D. and Bodo Littmann
VDE Americas, 2033 Gateway Place Suite 500, San Jose CA 95110.

INTRODUCTION

This summary of best practices in estimating PV energy production and P-case modeling is to improve and standardize approaches across the industry. Variations in methodology have been observed along with what appears to be a trend of underperformance among projects. Moreover Investors are starting to perform parallel predictions. Thus it is necessary to arrive at a common understanding both for project funding and for evaluation of actual versus expected performance over the project life. VDE has conducted a study of approaches used through extensive and constructive discussions with investors, IEs, research organizations and other experts. We outline a framework in this poster and encourage IEs to adopt equivalent methods and discuss deviations.

HIGH LEVEL CONSIDERATIONS

Investors are looking for the following:

- Confirmed terms and terminology e.g. Orange Button
- Input assumptions for each model step and associated uncertainties (at 1-sigma), consideration of model error, justification of chosen weather file, confirmation of PAN/OND, discussion of degradation DC/AC etc.
- Uncertainty assumptions in long term solar resource mean, IAV, performance model and degradation leading to Combined Uncertainty (see table below).
- Discussion and review of methodology including post processing.
- Provision of P50 "8760" GHI and GPOA – key for performance analysis.

Source of Uncertainity	Typical Range	Comments
Long-Term Annual Solar Resource Mean (GHI)	3.0% - 5.0%	This estimation from the satellite data provider is presented as typical and may vary from location to location.
Performance Model (Including Transposition)	4.0% - 7.0%	Uncertainty associated with estimation of model input parameters and accuracy of model in predicting energy generation through modeling steps
Interannual Variability	2.8% - 5.0%	
Combined Uncertainty of Year 0 Yield	5.7% - 9.9%	Addition in quadrature: Square root of the sum of squares
Annual Performance Degradation	0.25% - 0.50%	
Combined Uncertainty of Year 10 Yield	6.30% - 11.10%	Assuming a cumulative effect of 10 times the annual performance degradation uncertainty

Fig. 1: Sources of Combined Uncertainty for example project. ***(http://physics.nist.gov/cuu/uncertainty/combination.html/)***

RECOMMENDATIONS FOR BEST PRACTICE

It is difficult to assess validity or degree of conservatism or optimism without a detailed review of assumptions, breakdown of sources of uncertainty and methodology. Best practices include the provision and discussion of the following:

- Long term solar resource – Use high quality ground or satellite, with or without adaptation from ground-based measurements (include justification of reduction in uncertainty). Consider inclusion of long-term trends such as global brightening. Tune TMY to the long-term historical mean or use "Reference Period Mean". Provide 8760 GHI and GPOA.
- Interannual Variability – Provide year to year and month to month, note whether NSRDB or 30 years of satellite data used. Consider inclusion of high uncertainty years.
- Irradiance transposition loss factor (gain) e.g. state whether starts from the weather file GHI or include DNI and DHI. If not, then rely on model decomposition. Provide considerations for tracking strategy.
- Shading loss factor. Provide details such as division into near shading such as inter-row and horizon shading distant hills. Near shading can be thru model 3-D shading scenes but need to confirm as built or regrowth of trees etc. Discussion and review of methodology including post processing.
- Snow and soiling – Report snow losses separately from soiling losses as uncertainty snow losses can be higher than that of solar resource. Provide details of soiling model employed (e.g. Kimber) with basis for assumed uncertainty.
- Module model – Physics based in PVsyst considering equivalent circuit parameters and optical parameters along with mismatch of strings. Confirm PAN files are third party validated and representative of modules used? Provide module flash data vs. name plate/data sheet.
- Deviations from STC
    - Irradiance and Temperature – tie PAN file to 3rd party test lab results, provide heat balance model (GPOA, air temp and wind) and propagation of uncertainty.
    - Spectral effects – Discuss (function of module technology and wavelength f(bandgap)) etc., Indicate PVsyst or post process.
- DC system losses – tie to system design but note uncertainty where deltas in lengths and CSAs. Consider I^2R not fixed loss, both hourly and sub-hourly variation. Discuss "Rule of Thumb" vs network resistances. Provide check R_{equiv} from planning documents.
- Inverter model – Ensure capture of behavior under operating conditions including temp derate and elevation. Confirm OND file comports with product installed. Indicate whether PVsyst or post process? Provide considerations for clipping including sub-hourly?
- AC & balance of system – AC cables similar issues to DC losses. Transformer losses can be more complex but well understood. Rule of thumb vs network resistances. Also consider clipping at ISU and clipping at POI.
- Auxiliary and parasitic losses – specify sources, (relatively small losses due to SCADA, trackers etc.)
- Performance Degradation – discuss DC degradation of modules (include coatings?) and effect on AC degradation of DC/AC ratio etc. thru to POI. Discuss protection afforded by module warrantee.
- Availability – Provide empirical justification of assumption used. Note: usually treated as constant e.g. 99% all P-cases but in real life truly random. How to improve?
- Curtailment – forward looking and complex. How to improve?
- Sub-annual uncertainties – Discuss including tie to PPA e.g. minimum delivery requirements.
- Justify use symmetric or asymmetric uncertainties and of "Root Sum of Squares" versus Monte Carlo in deriving Combined Uncertainty.
- Provide energy model tool output file e.g. PVsyst report.

Sources of Uncertainty	Uncertainity Range 1-Sigma Individual	Combined
Irradaition		
Satellite GHI	3% - 5%	4% -5%
Direct/diffuse ratio, GPOA transposition	2% -4%	
Shading		
Horizontal	0% -0.5%	1% -4%
Inter-Row	1% -4%	
External	0% -3%	n.a.
Soiling		
Soiling	1% -4%	n.a.
Deviation from STC		
Reflection	<1%	<2%
Spectral Losses	=1%	
Irradiance Intensity	1% -2%	
Temperature	1% -2%	
Actual PV capacity and DC loss		
Module Power and mismatch	2% - 5%	<5%
Cabling	0.50%	
Inverter Loss		
Module Related	<1% -5%	<2%
Power limitation	<0.5%	
AC losses		
Cabling	0.50%	<1%
Transformers	0.50%	
Combined Total Initial Uncertainity	**Typically 5% - 11%**	

Fig. 2: Typical sources of Uncertainty and associated ranges *(Reich et al. 2015 IEEE 42nd Photo Voltaic Specialist Conference)*

CONCLUSION

Investment partners require best practices and a common understanding of uncertainties to manage risk. Improved management of risk reduces capital cost and encourages investment. While an individual project may perform above or below P50, across a portfolio, best practices should trend to a P50 mean performance with some projects above and some below P50. A common framework and a detailed elaboration of assumptions and attendant uncertainties at project funding, coupled with careful analysis of actual production over time and refinement of assumptions and attendant uncertainties, will help facilitate our industry objectives.

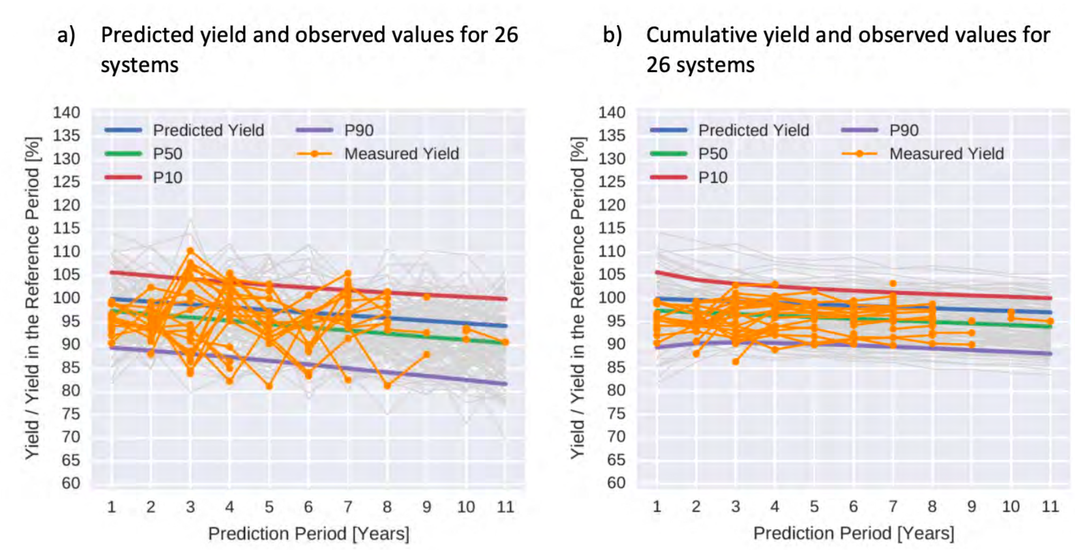

Fig. 3: Predicted vs Actual Yield 26 plants in Germany and Spain *Uncertainties in PV System Yield Predictions and Assessments IEA-PVPS T-13-12:2018*

A Case Study in Year-on-Year Trending of PV Performance Ratio

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edp renewables
powered by nature

Introduction and Summary

Monitoring and sampling solar degradation is an important input into site analysis and future site financial modeling, particularly with ever-more pressure in lowering project costs. Many papers have explored strategies for estimating PV degradation losses [1][2][3] and a standard strategy has been summarized in the Rdtools python package [4].

This poster serves as a case study for the Year-on-Year (YoY) method of degradation estimation for one site. Different data filtering methods are trialed and degradation estimations from the YoY method reported.

A filtering method for this site is recommended based on results from YoY calculations and knowledge of tracker availability. Plane of Array (POA) sensor health and alternative data sources are also explored.

Site Background, Data Sources, and Calculations

The site explored is a utility-scale mono-Si PV site in a desert environment (BWk climate zone) commissioned in 2014. It uses central inverters and single-axis tracking. Pertinent sensors include 2 revenue-grade site power meters, 31 back-of-module (BOM) temperature sensors, and 4 plane-of-array (POA) irradiance sensors. The data acquisition system records in 15-second increments and is stored in a database, but 10-minute averages (or calculations) are used for analysis.

A temperature-corrected performance ratio is calculated using methods similar to those used by Jordan et al. [1]. For the corrected power, γ (temp. coeff.) comes from a lab measurement rather than nameplate and Tcell is assumed to be equal to the measured BOM temperature. Measured POA is used, but a clear sky model POA calculated using pvlib [5] and satellite reported irradiance are also used for comparison.

Corrected power is compared with a nameplate power that comes from the number of modules installed on site and the nameplate rating of the panels' DC power at STC conditions. This is the Performance Ratio. See equations 1 and 2.

$$P_{Corrected} = \frac{P_{measured}}{\frac{POA}{1000\frac{W}{m^2}} * (1 + \gamma * [BOM - 25°C])}$$

Equation 1:
Corrected Power corrected for irradiance, temperature and temperature coefficient (γ).

$$PR = \frac{P_{corrected}}{P_{nameplateDC}}$$

Equation 2:
Performance ratio from Corrected Power and nameplate DC Power.

The PR is irradiance-weighted to an average for each day that has data points. Each day is compared to the same calendar day one year in advance and the difference in PR is noted. The mean of the PR differences is the estimated yearly degradation and the standard deviation of these PR differences is used as a metric to compare filtering methods.

Filtering Trial 1

Initial filter steps from Rdtools and Jordan et al. (2018) were expanded or altered in a "Trial 1" and compared to the standard Rdtools filters. Table 1 summarizes the filtering methods used in this step.

RDtools and Jordan et al.	Trial 1
POA: 200 – 1200 W/m2	POA 500 – 1200 w/m2
Clear sky index: 85%-115%	POA σ < 25w/m2*
Tcell -10-110 °C	BOM z < 3
Pdc 1st percentile – 98th percentile	Pdc < 99th percentile; Pdc > 10% dc capacity
	Tracker tilt | < 5°

Table 1:
Initial trial of filtering methods used to compare to standard Rdtools filters.
* σ of POA 15s values over the 10min point.

- Most importantly, due to a tracker availability issue data was filtered to times when trackers were within 5 degrees of flat (and not filtered for availability due to nature of the issue).
- Irradiance minimums were raised to 500 W/m2 after confirming clear days in winter were consistently above that value.
  - Two POA sensors were removed due to outlying data.
- The database-calculated standard deviation (σ) of the POA value was filtered to below 25 w/m2 based on a visual estimation of outliers and used in hopes of better filtering to clear sky times.
  - This is the σ calculated on the raw 15s data over the 10m period.
  - The effectiveness of this filter is explored in the next section.
- BOM temperatures were used for Tcell after removing outliers with z > 3 and averaging.
  - Rdtools Tcell filter was also used but no further data points were outside of the specified range.
- P was filtered to below 99th percentile and above 10% of DC capacity due to a fairly low DC/AC ratio and some points with low production not otherwise filtered out.

POA σ as Clear Sky Filter

Using the YoY method described in the calculations section, following main strategies in [4] and [1] with additional changes outlined in the section above, degradation estimations for "Trial 1" were calculated. The POA standard deviation and the clear sky index (CSI) were first compared for effectiveness in filtering to clear sky data, both being used with Trial 1 filters.

The CSI filtered 20 data points not removed by the POA σ (~0.4%) however the POA σ methodremoved 851 data points (19%) that the CSI method did not. Many of the points filtered by the POA σ method appear within the trend, ~15% of points obviously being below the trend (black in figure 1). The CSI method, while missing lower outliers, caught higher outliers.

While many 'good' points are filtered by the POA σ method, the removal of outliers may be valuable for final calculations and both filters can be used together.

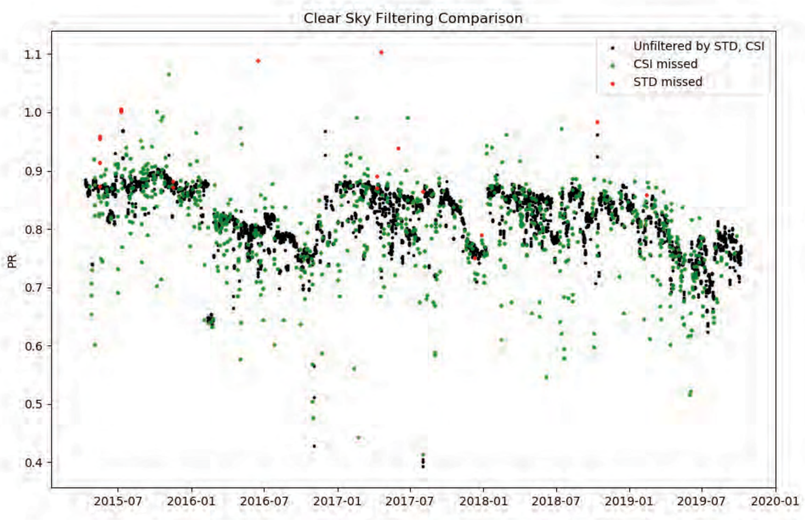


Figure 1:
Comparison of points filtered by POA σ but not CSI (green) and vice versa (red) over all Trial points (black). POA σ catches many low outliers but also filters multiple times that amount within the trend.

Trial 1 Results

Data was filtered following each column of Table 1 for observation. For fairer comparison, the tracker angle filter was not used in one calculation to account for any difference that selecting a smaller subset could cause. The YoY method was again implemented, and the standard deviation of PR differences used for comparison.

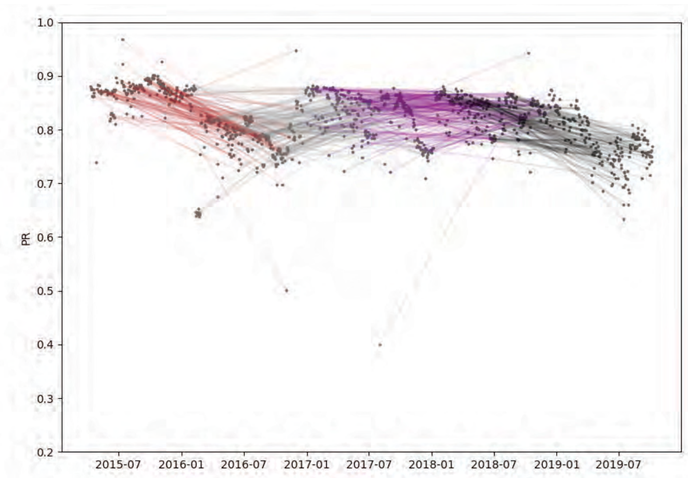


Figure 2:
PR and YoY line connections for final filtering choices. T
he average difference was -1.60% per year. A noticeable downward trend in 2016 (availability issue?) and at the end of 2019 (inverter nuisance trips?) are affecting data.

When all data points were irradiance-weighted, Trial 1 and the Rdtools methods had similar standard deviations on yearly differences. The σ drops with tracker filtering, which may be due to a smaller subset of data. Given these results, there does not appear to be a strong statistical argument for using the Trial 1 filtering methods over the Rdtools standard filters.

	POA	Clear Sky POA	Satellite POA
Rdtools	-1.59% σ = 9.55%	-1.63% σ = 9.88%	-1.71% σ = 22.82%
Trial 1 All angles, irrad-weighted	-1.21% σ = 9.57%	-1.36% σ = 10.77%	-0.51% σ = 15.40%
Trial 1 Filtered for 5°	-1.59% σ = 7.72%	-1.63% σ = 8.08%	n/a

POA vs. CS POA

Prior to using any filtering, it is important to understand the noise and health of all sensors used for calculation. The raw POA values and clear sky model for Trial 1, filtered and daily-averaged, were plotted to check POA health. Jumps of recalibration, as well as a general spread of disagreement between the 4 POA sensors can be seen, with one POA (red) stepping down and then up out of agreement with the others. Another (green) begins to drift down in 2019. The other two POA sensors stay clustered together and similar in comparison to the clear sky model. These are the two that were averaged for POA values.

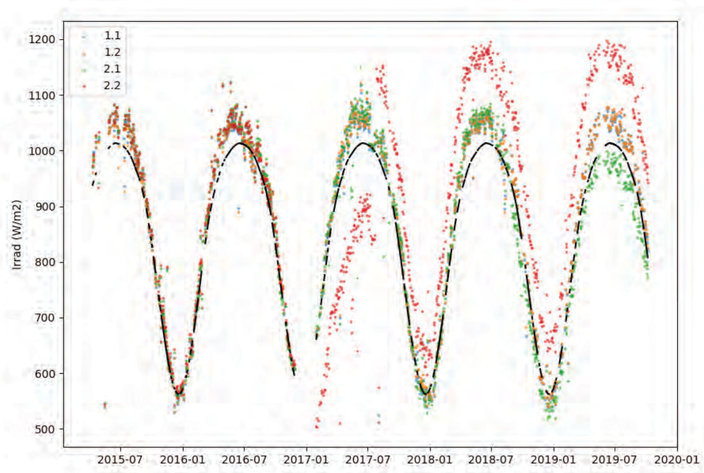
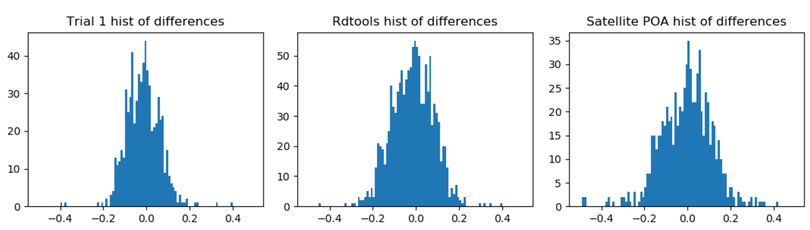


Figure 3:
Solar noon POA measurements for the 4 sensors on site show calibration and drift issues.

To quantify sensor drift, a seasonal decomposition on a normalized difference between POA and clear sky POA was attempted. A seasonal trend was obvious, but no strong, long-term trend was extracted. This is an area for future investigation.

An additional resource available is satellite irradiance data. Three vendors were available for comparison, and the reported values were combined with the same pvlib model from previous sections to estimate anticipated POA values. A simple scatter plot of satellite versus measured POA was made for the data and an R^2 value calculated. The source with the least amount of noise was chosen which had an R^2 value of 0.81. When used instead of POA in the Trial 1 data the standard deviation of PR differences was 15.4%, much higher than the other options.

Figure 4 below shows the histograms of yearly differences for Trial 1 filters, Rdtools default filters, and using satellite POA data with Trial 1 filters (with no angle filtering). Satellite values create much more noise but may be used if measured POA is unavailable. More research should be done on comparisons of satellite and clear-sky models when measured POA is unavailable.



Trial 1:
Mean -1.59%
Median: -1.48%
Std 7.72%*
*(less data points due to angle filter)

Rdtools filter:
Mean -1.59%
Median: -1.33%
Std 9.55%

Satellite Irrad. Data:
Mean -0.51%
Median +0.24%
Std 15.40%

Figure 4:
Histograms of YoY PR differences for Rdtools filter techniques, Trial 1 filter techniques, and Trial 1 filters (without tracker angle filter) with satellite POA data.

Final Filtering Choices

The filtering methods suggested in [1] and [4] are a good selection of ranges for degradation estimation and statistically there was not an improvement on Trial 1 over Rdtools standards. However, given knowledge of the site availability, comparison of clear sky filters, and analysis of the ranges of reported data, the following filters were selected for the final analysis:

- POA 500 – 1200 W/m2.
- POA σ < 25w/m2 as well as CSI 85%-115%.
- BOM z < 3 outliers removed, and averaged; also filtered to -10 – 110°C.
- Pdc minimum 10% DC capacity and maximum 99th percentile.
- Tracker tilt less than 5 degrees from flat.

Measured POA after filtering outlier sensors was used rather than clear sky or satellite sources. The average degradation rate from this method was calculated to be -1.60%/year with a standard deviation of 7.67%. Adapting the bootstrap method from [4] shows a confidence interval range of -1.24% to -2.01% per year.

Filtering for smaller angles seems to have increased the degradation estimations from all day, irradiance-weighted averages. Also note that these results are also not corrected for inverter availability.

In future work soiling and field measurements can be included in confirming estimations of degradation rates. With more data at full availability the validity of filtering to flat angles can be tested. The use of clear sky and satellite data alone can also be used to compare to actual degradation estimations. BOM temperatures can also be corrected to better estimate actual cell temperatures.

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Benefitfocus: Andrew Harris

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Key Takeaways/Summary

- A case study of YoY degradation estimation is performed for a utility-scale PV site commissioned in 2014.
- Some filtering suggestions are explored:
  - POA and BOM sensors are available for this site.
  - Due to a tracking issue over multiple periods, data is filtered to when trackers are expected to be within 5° of flat.
  - POA health and alternative options are explored with Clear Sky and Satellite models.
  - BOM temperature sensors are averaged, with outliers dropped, for Tcell.
  - Time series POA σ data may be another option for clear sky filtering when available.
- The estimated degradation from the YoY method is -1.6% per year.
  - Bootstrapping estimates this rate between -1.2% and -2.0% .
  - Future years of data should increase the confidence of results.
  - Going forward, more full availability will allow checks on effects of the 5° filter.
  - Results may be affected by availability, which is not corrected here.
- Continued data collection at full availability and field measurements should improve degradation estimation in the future.

New monitoring method to self-characterize individual modules in large photovoltaic systems

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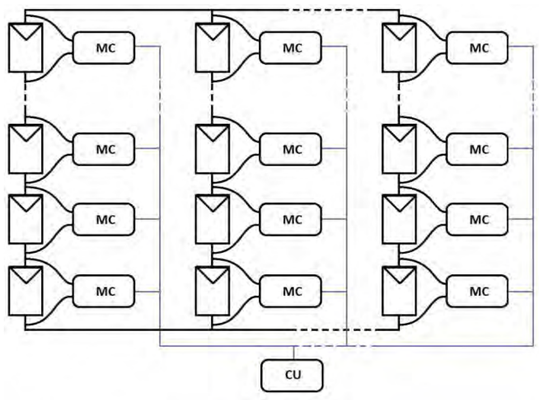
I. Introduction

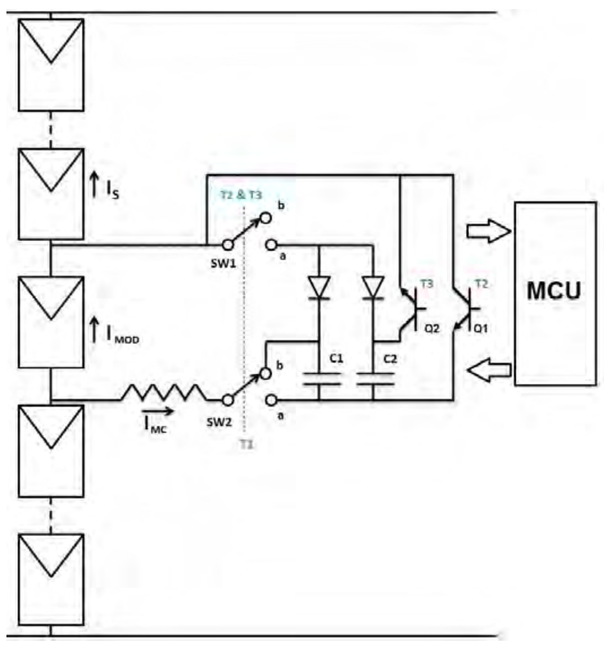
Photovoltaic (PV) power losses are around 15-20% of performance ratio in PV systems. A significant part of losses are due to PV modules failures. Several monitoring techniques have been proposed to detect faults in PV systems but only module level monitoring methods are able to detect faults on individual modules [1, 2]. I-V curve tracers are able to obtain the I-V characteristic of the PV module and to localize the power loss origin. However, they require to disconnect the PV module from the rest of the system, they need long measuring times and they use power electronics components.

This work proposes a methodology that is able to take partial measurements of individual PV modules and recompose its characteristics with only small capacitors in the range of tens of microfarads and without power electronics components. All the monitoring process is performed without disconnecting the PV module from the rest of the system.

II. Description of the System

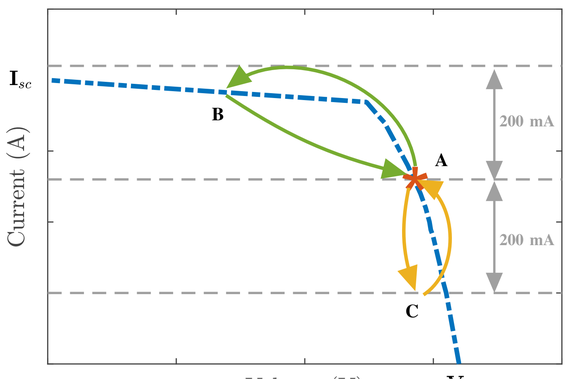
Explained in [3]. One control unit (CU) for the entire system and a monitoring circuit (MC) for each PV module. The Mc is based in two small capacitors and six switches for each module.

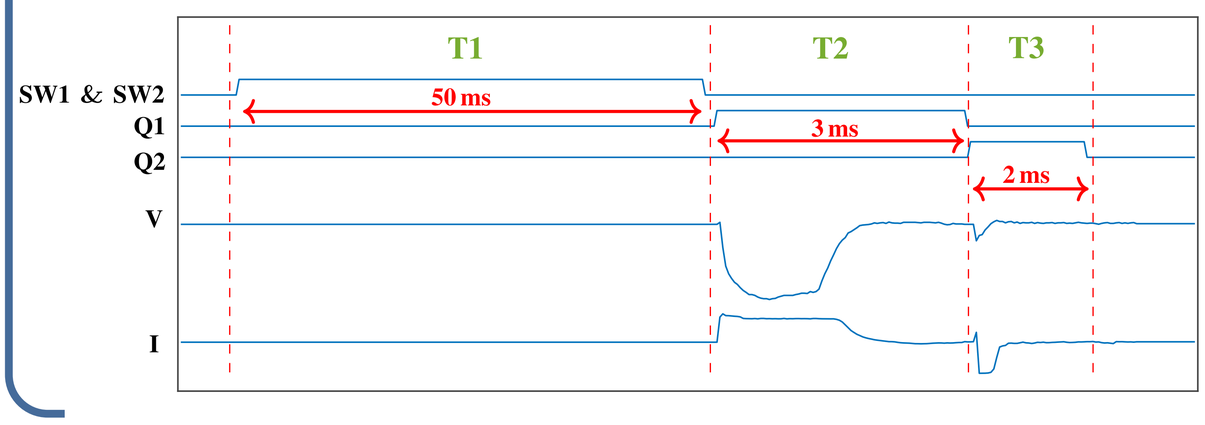




Four operating modes of the MC:

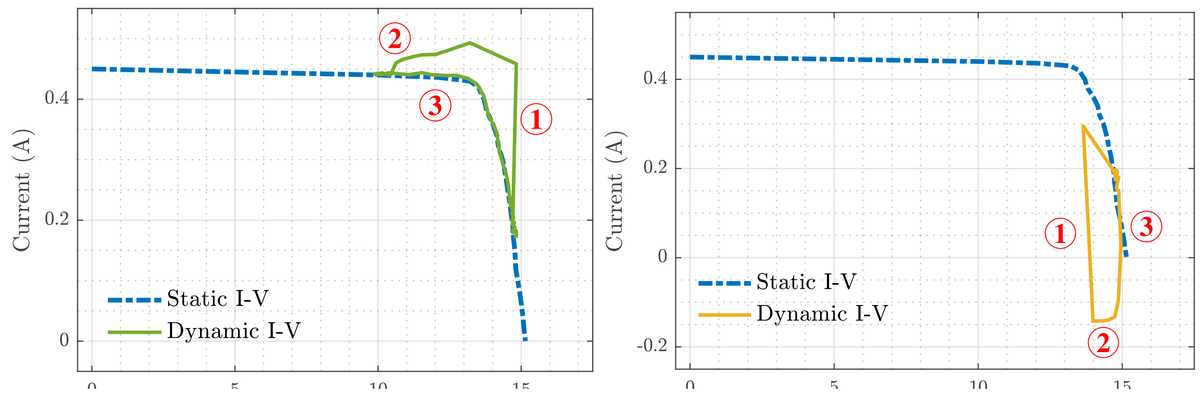
- Standby: No current extraction
- T1: C1 and C2 are charged draining litle current from module.
- T2: The operating point is displaced to short-circuit 0.3 A.
- T3: The operating point is

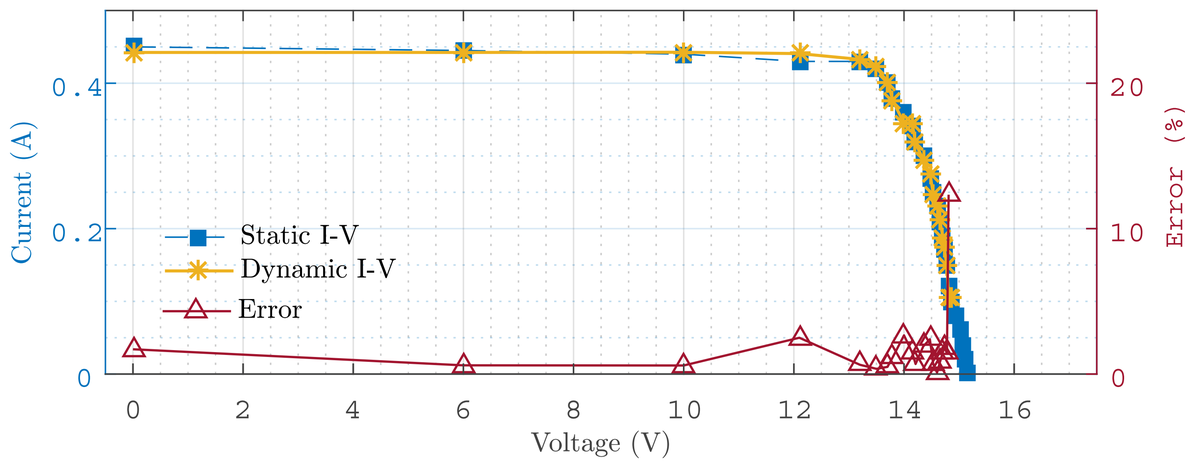




III. Dynamic I-V characteristic

- Evaluated in a 25 W bifacial PV module.
- Displacement to short-circuit (left) and open-circuit (right)
- Three sections are identified. 1: shift of the operating point, 2: discharge of the capacitors and 3: return to equilibrium.
- Movement outside the I-V curve due to parasitic capacities.
- Return points close to I-V characteristic with low error.

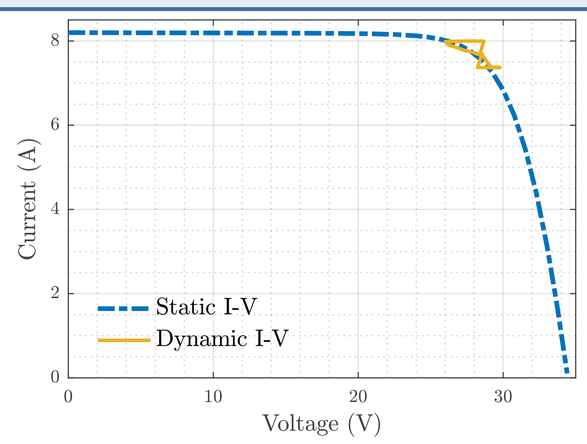




Accuracy between 1 and 3 % close to maximum power region.

IV. Commercial PV modules

- 12 JINKO JKMS285M-60 PV modules
- SMA-Sunny Boy 3000TL-21 inverter
- Dynamic effect appears due to parasitic capacities
- Further processing required to estimate I-V characteristic



V. Conclusions

The system is able to evaluate individual PV modules without disrupting the string normal operation. The monitoring process is performed in a few milliseconds using low power components and small value capacitors. From the measurement data it is possible to estimate the I-V characteristic of the PV module with an accuracy between 1 and 3 %. In commercial PV modules, with higher efficiency, further processing is required to estimate the I-V characteristic.

Acknowledgements

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Evaluation of Useful Life and System Degradation for Project Financing

Technical Advisory Services, ICF Resources

Vardaan (Dan) Chawla, Todd Tolliver, Mark Reusser, Heidi Larson

Summary

Historically, the assumed useful life for solar facilities has been 25 years. However, in the ever-changing landscape of renewable asset development, financing, and tax reform, the determination of useful life plays an important role in assessing the overall value and costs of long-term ownership. Evaluation of the useful life of a facility requires multifactor analysis, including the qualifications and experience of the contractors and suppliers; the design and construction of the facility and associated equipment; availability of replacement components; proposed operations and maintenance plans; and system performance degradation. Solar facility performance degradation is primarily attributed to performance degradation of the solar modules. Recently, several module suppliers have started offering lower warranted performance degradation rates as well as power warranties that extend out to 30 years. The lower warranted degradation rates are typically 0.5-0.55% per year as compared to 0.7-0.75% per year which has been the historically warranted degradation rate for the past 5-7 years. However, long-term data in the public domain to support these lower degradation rates is limited. In addition, historical data may be based on module technologies that are not necessarily representative of the current products on the market. Evaluation of the degradation rate requires a supplier specific analysis that includes the supplier's historical and current product design; manufacturing processes and quality controls; extended accelerated testing programs; simulation and modeling; and historical field data from deployed modules.

Check the Box

Do the following support the intended useful life?

- ❑ **Site control/access**
- ❑ **Geotechnical findings and recommendations**
- ❑ **Interconnection agreement**
- ❑ **Engineering design basis and specifications**
- ❑ **Construction quality requirements including quality monitoring and assurance**
- ❑ **Equipment design life, spare parts planning and procurement**
- ❑ **Technical financial model assumptions**
  - O&M budget
  - Major maintenance reserves
  - Availability assumption for initial, middle and late years of life
  - Degradation assumptions, specially in later years of life.

Do the following support the expected degradation rate?

- ❑ **Module design, technology and bill of materials selection**
- ❑ **Supplier specific modeling and simulation**
- ❑ **Product specific accelerated testing**
- ❑ **Supplier manufacturing experience and quality controls**
- ❑ **Historical observed degradation for similar products**
- ❑ **DC:AC ratio**

Introduction to ICF

ICF is one of the world's leading independent management and analytical consulting firms with more than 5,000 employees across the globe. With approximately 1,600 employees working on energy and environmental issues, ICF draws upon extensive industry knowledge, distinguished professionals, and innovative forecasting tools to develop solutions to complex issues in energy. ICF established a Technical Advisory Services practice in summer 2016, with a focus on providing marquee Independent Engineering, Owner's Advisory, and Expert Testimony services and the agility to tailor support to client and project needs. The core team has supported over $90B in generation and infrastructure transactions, with well over 100 years of collective technical consulting experience. ICF's Technical Advisory Services team is staffed with engineers, scientists, and technical experts that have served financial institutions, power producers, and project developers for decades through detailed technical diligence of a wide array of power projects. Together, the team has supported projects around the world including the Americas, Africa, and Asia.

Useful Life – Can 40 Be The New 25 for Solar Projects?

Recently there has been a push for 40-year useful life assumptions in solar financing deals. As technical advisors, we review the following areas to evaluate the potential useful life for a power project.

Site Factors

Site consideration primarily includes evaluation of the period during which an owner has site control, site access, and interconnection arrangements, as well as consideration of geotechnical characteristics for a project. Specific to project reliability, it is important to understand geotechnical and hydrological site factors, such as geological, soil, or seismic conditions that may impact or limit design and useful life of the project. Similarly, for project sites prone to flooding or consisting of drainage ways, the aim should be to confirm (through review studies and conclusions) that the site civil grading and, ultimately, the overall project design aligns with the long-term operating goals for the project.

System Design, Equipment and Construction

The methodology and quality of construction, as well as the design life of the major equipment (modules, inverters, trackers) to be used, play a critical role in the longevity of a facility.

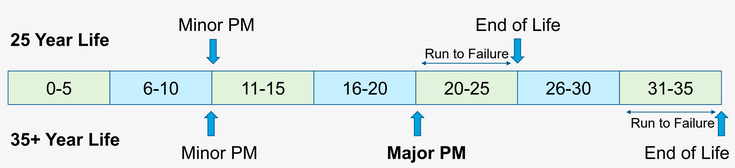
To help meet the intended useful life of a project, the design basis for the overall system or balance of a plant should reflect an appropriate design life in engineering and construction contracts. Additionally, the design life of the major equipment (modules, inverters, racking) should also reflect the intended useful life of the project, with appropriate spare parts considered. Equipment supplier stated design basis is typically equivalent to or longer than the period of the warranties provided for their products. Module warranties often suggest greater than 80% initial nameplate power is to be available after 25 or 30 years. Central inverter suppliers, on the other hand, guarantee workmanship over a period of 5 years, relying on a preventative maintenance and internal component replacement programs to maintain the inverters beyond this period. String inverter suppliers, guarantee workmanship over a period of 10 years, and expect the inverters to be replaced as they wear out.

The quality of the engineering and construction team and specifically their qualifications and experience designing and constructing high quality facilities is another important factor. Understanding and establishing appropriate construction quality standards, including requirements for quality monitoring and assurance in the field, is also valuable. For example, in solar facilities, improper module handling during delivery and installation can lead to micro-cracks within the cells. Similarly, the techniques and quality applied to back-fill and soil compaction, racking installation, wire and cable management/installation (above- and below-ground), and civil work (e.g. detention/retention system design) are other areas that can impact the expected lifetime of a solar facility.

Considerations for Long-Term Operation

Finally, O&M plans, operating budgets, and major maintenance reserve accounts are among the most significant factors useful life evaluations should incorporate. There must be adequate provisions to keep the project in operating condition during the initial and middle years of operation. At a minimum, stakeholders should develop appropriate assumptions for (i) planned/preventative maintenance, (ii) unplanned/corrective maintenance, (iii) maintenance reserves, (iv) availability, and (v) degradation for solar and storage projects.

Central Inverter Maintenance Example: 25 year vs. 35+ years



As a facility ages, it is expected that the rate of equipment failure may increase, and the availability of replacement components may become limited. It may be appropriate to consider one or more of the following in the financial model for a project intended to surpass historic norms: (i) increased O&M budget for corrective maintenance in the mid to late years of operation, (ii) reduced availability in late years of operation, and (iii) increased degradation in later years of operation.

Diligent planning during the development for construction and long-term operation of renewable assets can support determination of useful life longer than the historic norms, adding to the overall value of a project.

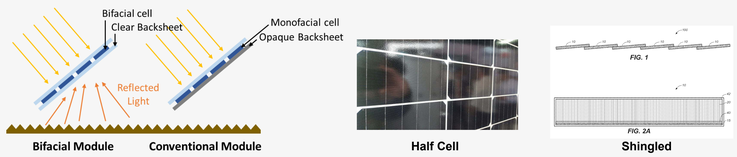
Degradation

PV systems have been shown to degrade in system performance over time. Such degradation is mainly attributed to performance degradation of the PV modules and other DC components. Recently, several module suppliers have started offering lower warranted performance degradation rates as well as power warranties that extend out to 30 years. The lower warranted degradation rates are typically 0.5-0.55% per year as compared to 0.70-0.75% per year which has been the historically warranted degradation rate for the past 5-7 years. We evaluate degradation on a module supplier and project specific basis, considering the following areas.

Module Design & Technology

While the solar industry is dominated primarily by crystalline silicon modules, thin film modules using Cadmium Telluride and Copper Indium Gallium Selenide technology are also available on the market. Modules of different core technology typically have different degradation mechanisms that must be evaluated in detail. Additionally, the module design and bill of materials selection can have a significant impact on degradation. For example, lower quality EVA that "yellows" in the field has been shown to lead to higher degradation rates in modules. Newer module designs that do not have extensive field history must also be evaluated for their potential impacts on degradation.

How do these new module technologies affect degradation rate?



Modeling and Simulation

Some suppliers evaluate and model specific degradation mechanisms that affect their modules. We review the analysis conducted by the supplier as well as the results of their life modeling, accelerated life testing, as well as correlation with real-world performance.

Accelerated Testing

Several module suppliers test their modules beyond industry accelerated testing standards. While the correlation between accelerated testing and degradation rate can be challenging, in some cases it can provide guidance in lieu of other data.

Manufacturing and Quality

A supplier's manufacturing experience and quality controls can impact the median degradation rate as well as the range of degradation rates observed in modules deployed at the same project. We typically evaluate the supplier's experience in manufacturing and their quality practices such as incoming materials inspection, in-process checkpoints, and outgoing quality controls. Additionally, third party factory audits and production monitoring to ensure bill of materials integrity are also considered in our evaluation.

Historical Degradation Rates

Multi-year measurements of modules deployed in the field, or measurements conducted at the system level, are extremely valuable when evaluating degradation rate. We typically review (i) the measurement methodology, (ii) the analysis conducted, (iii) the number of modules tested, (iv) locations the modules were deployed in, and the design of the modules.

Ideally, we prefer to evaluate data that is specific to the module supplier and the module product being considered for deployment. Given the experience of most module suppliers, and the degree of innovation in the industry, it is often not possible to get data for the new products being deployed. In these situation, we evaluate the similarities between the new products and previous products for which historical data may be available.

If no data is available for the supplier's products, we resort to degradation rates reported in publicly available studies for similar products.

DC to AC Ratio

The degradation of the DC system does not directly translate to equivalent rates of degradation in the project production. For projects with DC:AC ratios above 1.0, particularly early in the operating life, we evaluate the impact of inverter clipping and develop a non-linear AC degradation rate for the project's production.

Improving the predictive value of Performance Ratio Capacity Tests via parameter adjustment

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e-mail: dcormode@bay4.com

Introduction

The Capacity Test is a common stage gate in the development of investor owned PV power plants. The critical feature of a useful Capacity Test methodology is that it must evaluate the congruence between an as-built facility and an energy model for the system in a relatively short period of time, often less than a week.

As an Independent Engineer, Bay4 Energy Services is often asked to opine on modifications to various Capacity Test methodologies, with these changes most commonly for the purpose of completing the test more quickly. In principle such expediency comes at the cost of reduced accuracy.

This poster presents sample findings from a study which Bay4 conducted to better understand the implications of relaxing a contractual requirement for a minimum number of high irradiance data points in a "Performance Ratio" style test.

Performance Ratio Capacity Test

A common Capacity Test is a "Temperature Compensated Performance Ratio" with the following general form:

$$PR = \frac{\sum_i E_{measured\ i}}{\sum_i \left[KW_{DC} \frac{POA_i}{1000} \left[1 - tk(T_{exp} - T_{mod\ i}) \right] \right]}$$

Where T_{exp} is an expected operating temperature and KW_{DC} is the expected size of the system. This is calculated over some number of sequential time periods i. In many test methodologies this value is compared to a PR derived from an Energy Model, such as PVsyst.

By setting T_{exp} to 25 C and assuming a PR = 1, the formula may be adjusted to return a system size. While the returned system size is not expected to be accurate, this formulation can be useful for understanding how the test performs under various conditions and at various times of year.

$$KW_{DC} = \frac{\sum_i E_{measured\ i}}{\sum_i \left[PR \frac{POA_i}{1000} \left[1 - tk(25 - T_{mod\ i}) \right] \right]}$$

Example PV Plant Description

A PV plant located in Ohio was selected for analysis. This plant has demonstrated excellent inverter reliability and data availability. The local climate includes features typically challenging for Capacity Tests; there are relatively few clear sky days and occasional snow cover.

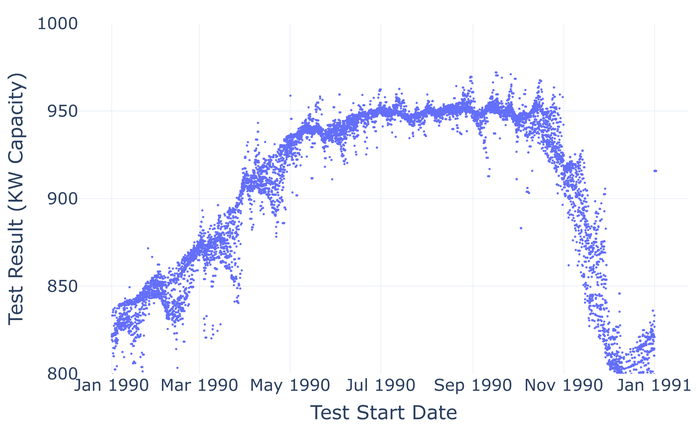
The onsite suite of meteorological sensors includes 2 GHI pyranometers, 2 POA pyranometers and 2 reference cells as well as air temperature, back of module and windspeed sensors.

Many PR style tests were run and a system size extracted from the example PV system. The tests were run with randomized start days and randomized lengths of test, ranging from 1 to 200 hours. Test data was filtered to exclude times when any of the inverters were clipping or were offline.

This study benefits from multiple years of data from the irradiance sensors. More than two years of sensor data is available in less than 5-minute timesteps. This allows us to identify and correct for a common problem in Capacity Test execution; confirmation that the orientation of the POA sensor(s) are well understood. We found through analysis of multiple clear sky (cloudless) days that three of the four POA sensors were more than 4 degrees out of alignment from the orientation recorded by the firm which constructed the site.

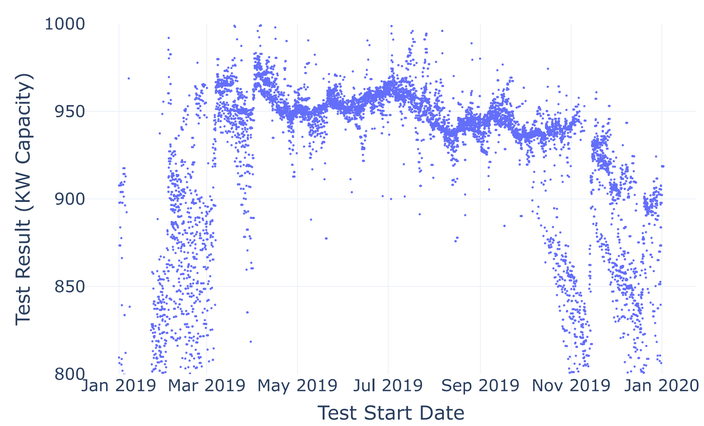
Test results anticipated by Energy Model

Often, Energy Model simulation data is used to anticipate the result of an PR style. The actual performance of the constructed system is evaluated by comparing the PR test result to the anticipated value. The figure below represents random PR tests run against Energy Model simulation data.



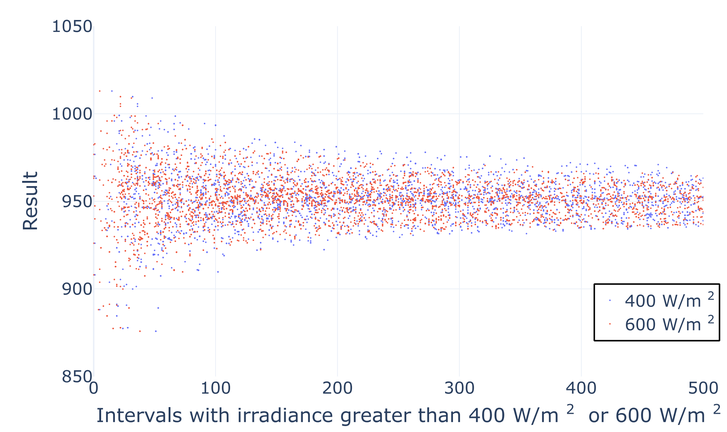
PR style test used to extract system size

The absolute value of the PR test result is less important in this case than is the variability of the test result. We find that a very strong seasonal component exists, which cannot be fully understood as a result of imperfect angle matching between the array and the sensor.



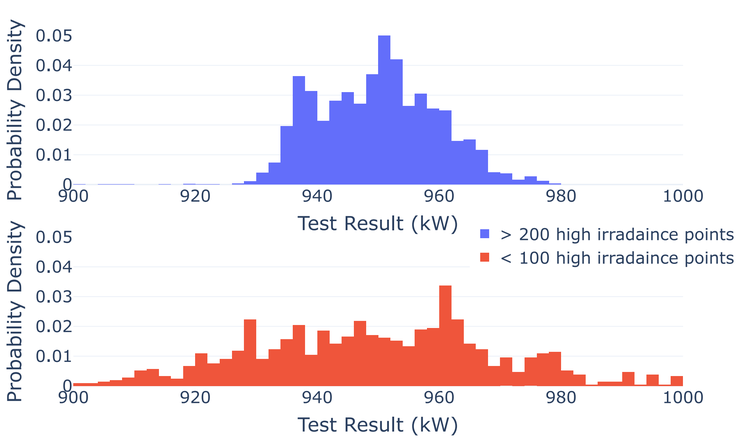
Test Quality as a function of high irradiance

The confidence interval of a test result decreases with larger amounts of intervals of high irradiance in the test period. The graph below shows results for tests starting between April and September versus the number of 15-minute intervals with measured irradiance above 400 W/m^2 and 600 W/m^2. A significant difference in the range of outcomes for setting the high irradiance threshold to 400 W/m^2 versus 600 W/m^2 is not seen.



Discussion

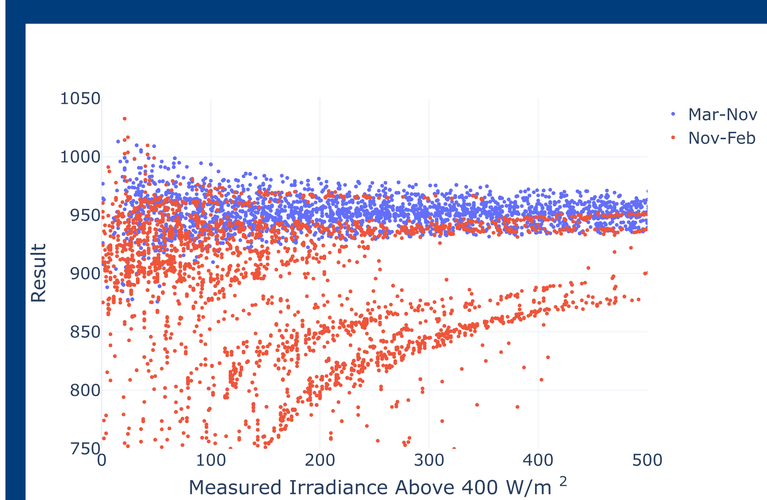
The uncertainty in the result of the test is higher for shorter duration tests that have smaller numbers of high irradiance points.



Test results, excluding those below 900 kW, grouped by number of high irradiance points (above 400 W/m^2). Tests starting between March – October.

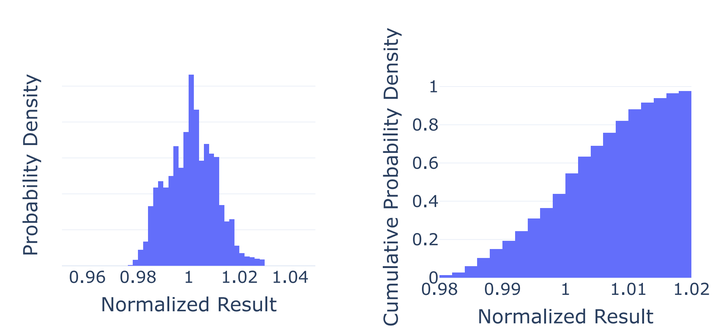
Seasonality

Seasonality had a large impact on the efficacy of the test to predict system performance. Regardless of the number of high irradiance points included in the test, tests starting in November –February were more likely to under report system capacity.



Testing Uncertainty

Assuming a minimum irradiance threshold has been met (number of intervals above 400W/m^2 is more than 200), the test is performed in the optimal season (starting between April – September), and a result within 5% of the 'true' result is achieved, there is still an uncertainty in the result of the test of approximately +/- 2%. A "passing' capacity test could still be overreporting or underreporting actual system performance by as much as 2%.



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A Comparison of Ground-based PV Module Soiling Measurement Systems at a Semi-arid Site in Northern Utah

Michael Dooraghi, Kenneth Morley, Julie Chard and Justin Robinson
GroundWork Renewables, Inc.

ABSTRACT

Soiling of photovoltaic (PV) modules occurs as a result of dry and wet deposition of atmospheric aerosols onto the glass surface of PV modules which reduces power output and has a negative impact on project economics. Accurately quantifying this soiling effect using ground-based measurements, satellite data, and models has been challenging for the solar industry. This poster provides a comparison of five ground-based measurement systems located at the GroundWork Test Facility in Logan, Utah.

Three of the systems represent the legacy method of clean and soiled module comparisons: the Eclipse and the PVSoil (GroundWork) and the RDE300 series (Atonometrics), while the other two represent a new approach monitoring the loss of light by optical means: the Mars Soiling Sensor (Atonometrics) and the DustIQ Soiling Monitoring System (Kipp & Zonen).

The five systems at this facility have been in concurrent operation for several months and are maintained daily. The Utah location provides a wide variety of weather and particulate conditions including snow.

This inter-comparison summarizes the theory of operation, initialization procedures, operation and maintenance requirements, and output variables for the five systems. In addition, a summary of the soiling losses reported by the five systems is provided.

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Figure 1. Soiling measurement systems located at the GroundWork research facility in Logan, Utah: the Mars Soiling Sensor (Atonometrics), the RDE300 series (Atonometrics), the DustIQ Soiling Monitoring System (Kipp & Zonen), the Eclipse (GroundWork) and the PVSoil (GroundWork).

SOILING SYSTEM INFORMATION

Eclipse and PVSoil: These products leverage IEC 61724-1 "method 2," the short circuit current (Isc) method, to measure soiling losses [1]. The measured Isc of a "clean" regularly washed control module is compared to the Isc of an unmaintained "soiled" module. The main difference between the two models is that Eclipse measures two full-size production modules whereas the PVSoil utilizes two 20-Watt mini modules [2, 3].

RDE300: This product leverages IEC 61724-1 "method 1," the max power (Pmax) method, and "method 2" to measure soiling losses. The Pmax method has been shown to more accurately represent array power losses when non-uniform soiling occurs [4]. The output of a "soiled" PV module is compared to that of a "clean" PV module or reference cell. The RDE300 at the Logan, Utah site utilizes two full-size PV modules.

Mars: This soiling sensor detects the accumulation of particulates onto a collection window utilizing an embedded digital camera. Sunlight illuminates the window, and the camera captures an image of the shadows cast by the soiling particles once per day at sunset [5].

DustIQ: This instrument utilizes Optical Soiling Measurement (OSM) technology to measure transmission losses caused by soiling. Two separate LEDs are used to pulse blue light onto the two detector windows. When particulate matter is present on the detector window the LED light is scattered and the paired photodiode sensor detects the scattered light. Post-processing of the real-time data is required to generate daily values. The DustIQ requires a local dust calibration to be performed. An optional back of module temperature sensor is available [6].

System	Maintenance Requirements*	Utah Test Site Module Type	Normalization or Calibration Requirements	Data Outputs	Data Resolution
PVSoil	Wash "clean" module	Ameresco 20M	In-field normalization	Back of module temperature, Isc, effective irradiance (G), soiling ratios (Isc and G)	One-minute and Daily
Eclipse	Wash "clean" module	Q Cells Q.PRO L-G3 300	In-field normalization	Back of module temperature, Isc, effective irradiance (G), soiling ratios (Isc and G)	One-minute and Daily
RDE300	Wash "clean" module	Q Cells Q.PRO L-G3 300	In-field calibration	Back of module temperature, Isc, Pmax, effective irradiance (G), soiling ratios (Isc, Pmax, and weighted average of both)	One-minute and Daily
Mars	Yearly clock check	None	No calibration requirements	Soiling ratio Transmission loss	Daily
DustIQ	Yearly system checks	None	Initial dust calibration requires >800 W/m² and >5% soiling.**	Two soiling ratios and two transmission losses from two separate detectors	One-minute

*The PVSoil, Eclipse and RDE300 modules are cleaned 5 times each week (excluding weekends) the Mars and DustIQ are not cleaned.
** These conditions have not yet been met at the Logan, Utah test site.

Table 1. O&M requirements, initialization procedures and data outputs for the five systems.

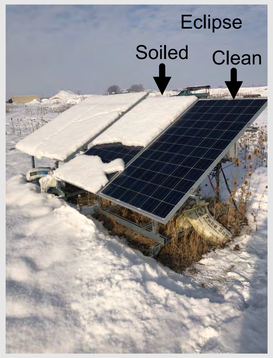

Figure 5. Irregular sloughing of snow from the soiled Eclipse module after the "clean" module was cleared of snow. See Figure 4 for test details.

Figure 6. DustIQ, Mars and RDE300 before the RDE300 "clean" module was cleared of snow. See Figure 4 for test details.

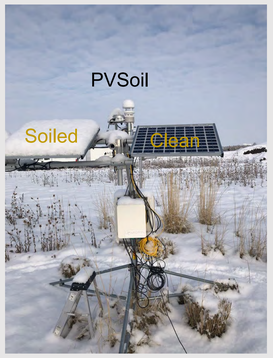

Figure 7. The PVSoil system after the "clean" module was cleared of snow. See Figure 4 for test details.

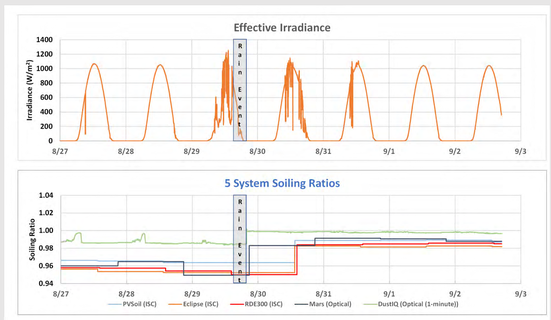

Figure 3. The top plot shows the RDE300 effective irradiance for a few days before and after a significant rain event. The bottom plot shows the soiling ratio behavior of all five units before and after the same rain event.

Figure 8. Typical summer soiling of the Mars.

Figure 9. Typical summer soiling of the RDE300.

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SOILING SYSTEM DATA COMPARISON

Figure 2. Regression comparison of soiling ratios from two dry periods with clear soiling signatures. Plot A shows daily soiling ratios from the five soiling systems from May 14, 2019 to January 24, 2020. The period highlighted in peach in Plot A is expanded in Plots B and C (July 4 to July 24). The period highlighted in blue in Plot A is expanded in Plots D and E (August 12 to August 29). Plots B and D show effective irradiance (G) while Plots C and E show regression lines with slope and R-squared for all seven outputs.

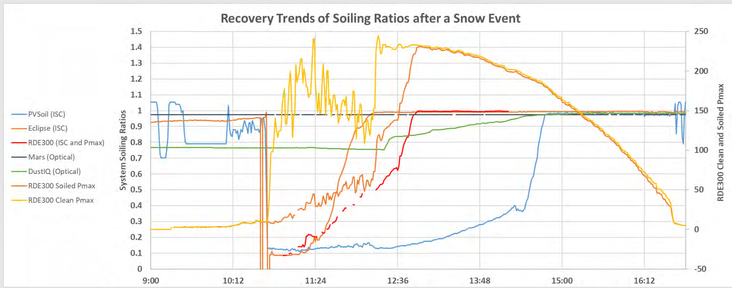

Figure 4. On December 30, 2019, a snow event completely covered all soiling systems. At 10:42 AM the "clean" PV modules on the PVSoil, Eclipse and RDE300 were cleaned while the "soiled" modules for those three systems as well as the Mars and DustIQ sensors were left untouched. The cloud cover cleared at 12:20 PM. The RDE300's "soiled" panel Isc and soiling ratio both recover after snow sloughed off around 12:50 PM. The Eclipse's soiling ratio recovers at 12:20 PM, while the PVSoil and the DustIQ recover at 14:45 PM. This sunny afternoon was followed by days of freezing weather and the Mars did not recover its daily value until a few days later.

CONCLUSIONS

During normal operating conditions, all PV module-based systems show strong soiling rate correlation as seen in the Plot C and E dry period linear regression slopes. The MARS accumulation rates also agree well during these periods, but the consistent diurnal sawtooth pattern significantly reduces the R^2 value as compared to the DustIQ, Eclipse, PVSoil, and RDE300 regressions. The DustIQ requires an in-field dust calibration that has not yet been performed because the irradiance and soiling threshold criteria have not been satisfied. Lack of calibration most likely explains the DustIQ's deviation from all other devices.

Harsh winter conditions observed at this location present unique challenges to all soiling measurement systems tested. Unfavorable solar elevations, persistent low irradiance conditions, and non-uniform snow and ice accumulation significantly reduced both the observed correlation and data availability of all devices. Transient periods do occur, particularly at higher temporal scales, which require further investigation as they could be problematic for real-time operational performance monitoring.

Daily soiling rates correlated with air quality in Oakland CA

Jessica Forbess, Teff Reed
Sunshine Analytics

Introduction

Analysis of a 33 month data set of clean and unwashed daily energy totals from a PV array on a rooftop in light industrial neighborhood in Oakland, California. Air quality from a nearby EPA PM2.5 station correlated relatively well, over a range of daily soiling losses from 0.12% to -0.36%, and a range of average daily PM2.5 of 3.9 to 32.5 ug/m³.

Objectives

- Capture soiling data for light industrial urban neighborhood
- Calculate daily soiling loss rate
- Test correlation of soiling and air quality data
- Test correlations with other meteo data

Methods

- Microinverter based rooftop PV array
- 10° tilt, SW az, landscape 280 poly-Si
- Identified two pairs of unshaded modules
- Cleaned one of each pair weekly (daily starting March 2019)
- Calculated Soiling Ratio based on daily energy
- Collected daily PM 2.5 average from EPC site <1km away

Conclusions and Future Work

- PM2.5 air quality captured has a reasonably strong correlation, with an updated fit of y= -5e-5+0.0011
- Recovery after rain in 2019 was significantly less than 100%. May be influenced by higher incidence angle in winter. Lowest recovery levels were very low rain/dew levels.

References

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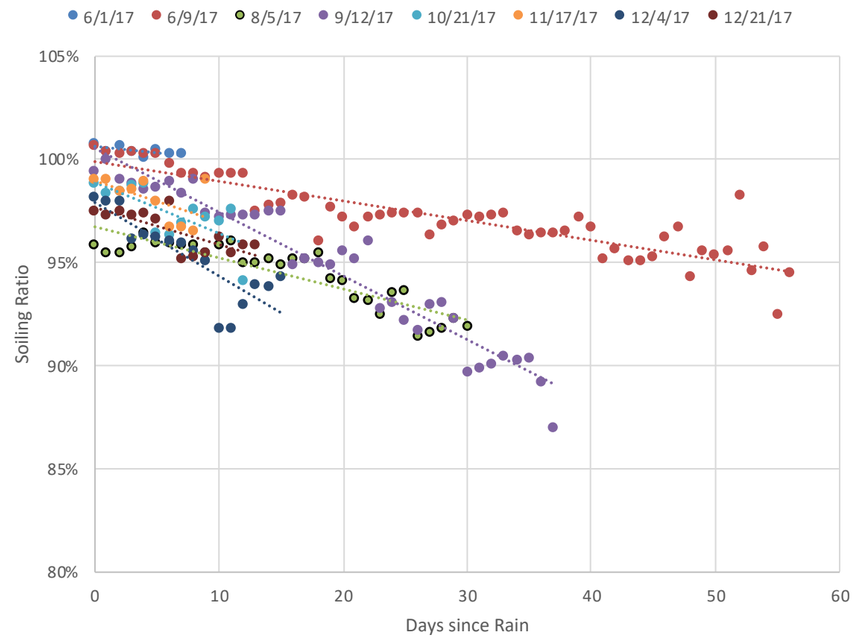
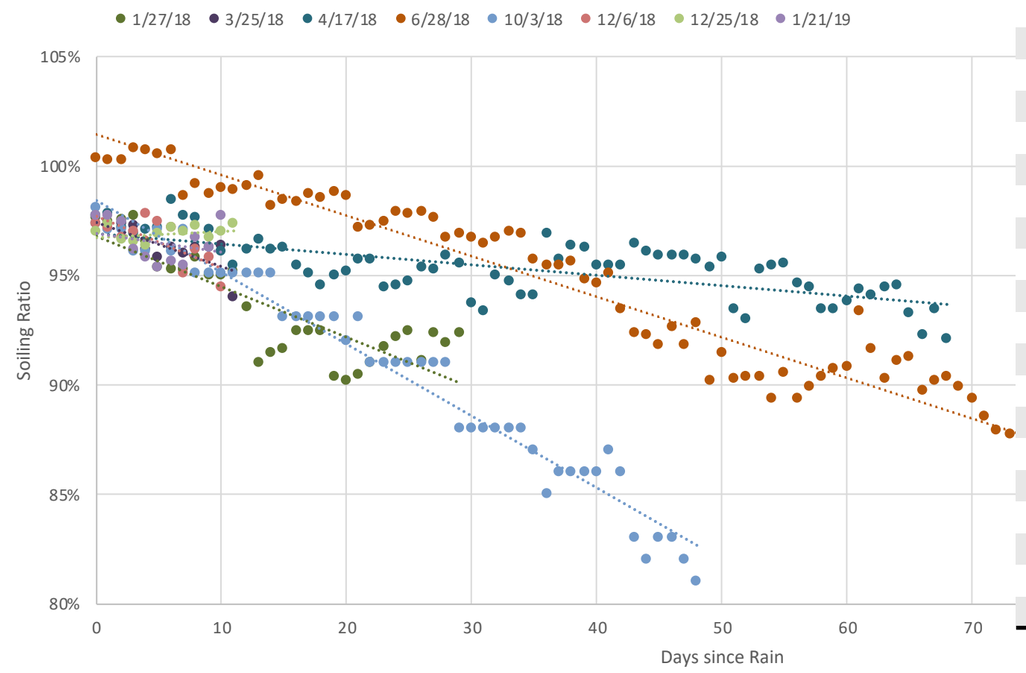
Results

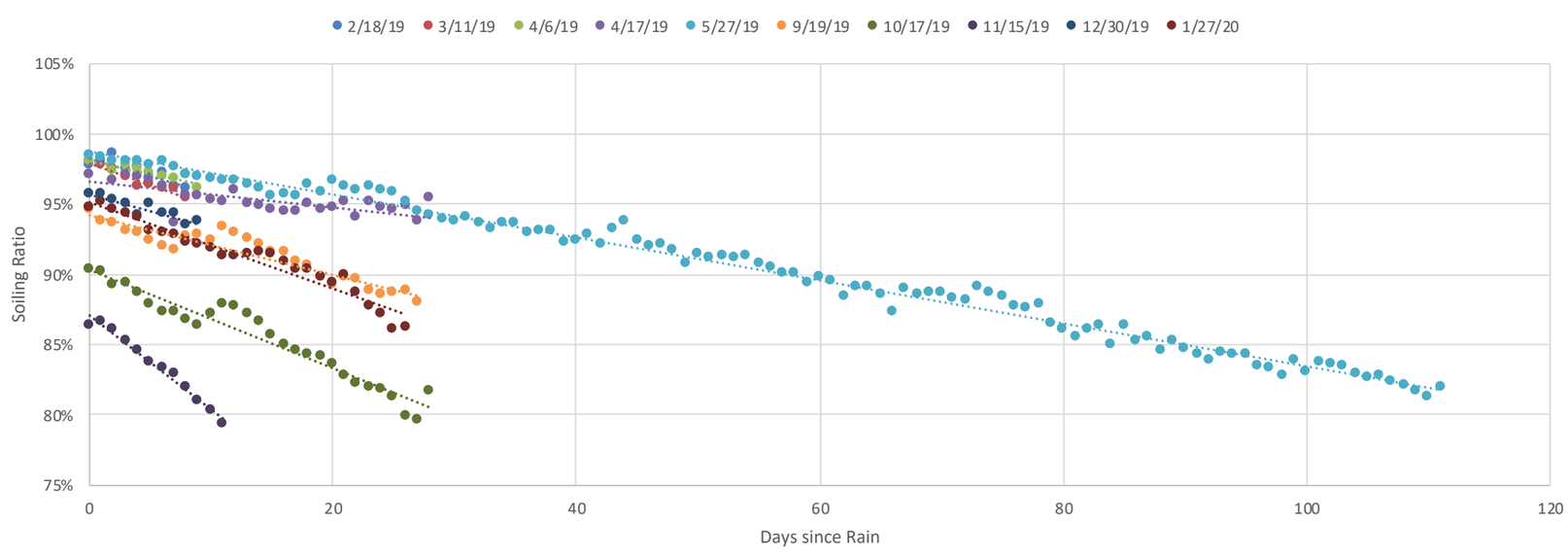
2017

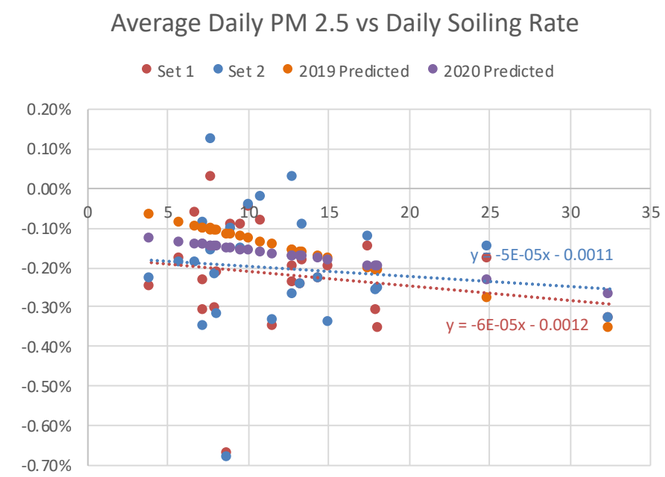


2018



2019





	Set 1	Set 2	Avg Daily PM2.5 (ug/m3)	2019 Predicted	2020 Predicted
6/1/17	-0.06%	-0.19%	6.79	-0.10%	-0.14%
6/9/17	-0.10%	-0.15%	9.63	-0.13%	-0.16%
8/5/17	-0.15%	-0.13%	17.48	-0.20%	-0.20%
9/12/17	-0.31%	-0.26%	17.95	-0.21%	-0.20%
10/21/17	-0.25%	-0.24%	13.34	-0.16%	-0.18%
11/17/17	-0.20%	-0.34%	14.98	-0.18%	-0.18%
12/4/17	-0.36%	-0.26%	18.06	-0.21%	-0.20%
12/21/17	-0.18%	-0.15%	24.88	-0.28%	-0.23%
1/27/18	-0.23%	-0.23%	14.43	-0.17%	-0.18%
3/25/18	-0.20%	-0.27%	12.74	-0.16%	-0.17%
4/17/18	-0.05%	-0.05%	10.10	-0.13%	-0.16%
6/28/18	-0.19%	-0.10%	13.40	-0.16%	-0.18%
10/3/18	-0.33%	-0.33%	32.48	-0.35%	-0.27%
12/6/18	-0.24%	0.03%	12.78	-0.16%	-0.17%
12/25/18	0.03%	0.12%	7.67	-0.11%	-0.15%
1/21/19	-0.08%	-0.02%	10.85	-0.14%	-0.16%
2/18/19	-0.25%	-0.23%	3.94	-0.07%	-0.13%
3/11/19	-0.31%	-0.35%	7.28	-0.10%	-0.15%
4/6/19	-0.18%	-0.19%	5.71	-0.09%	-0.14%
4/17/19	-0.09%	-0.11%	8.97	-0.12%	-0.15%
5/27/19	-0.15%	-0.16%	7.73	-0.11%	-0.15%
9/19/19	-0.21%	-0.32%	8.13	-0.11%	-0.15%
10/17/19	-0.35%	-0.34%	11.50	-0.15%	-0.17%
11/15/19	-0.67%	-0.68%	8.70	-0.12%	-0.15%
12/30/19	-0.24%	-0.09%	7.28	-0.10%	-0.15%
1/27/20	-0.31%	-0.22%	7.94	-0.11%	-0.15%

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PV Storm Hardening Costs

James Elsworth, Otto Van Geet
National Renewable Energy Laboratory

Abstract

- *Photovoltaic (PV) systems can provide added resilience to the power sector (through distributed generation, backup power, and more)*
- *In some cases, PV systems can provide power after a severe weather event when other grid infrastructure may be down*
- *PV systems have survived hurricanes and other severe weather events with no or minimal damage*
- *Some hurricanes and high-wind events have caused damage to PV systems, rendering them powerless when their power is most needed*
- *By designing, installing, and maintaining PV systems to be stronger in the face of storms, we can increase their value and the resilience of the power system*
- *Previous work (Robinson 2018) has identified best design and maintenance practices for PV systems in severe weather regions*
- *This poster summarizes estimates for initial cost premiums to implement these best practice measures*

Photo from Gerald Robinson, LBNL

PV Storm Hardening Measures And Estimated Costs

For select measures only. The forthcoming report analyzes additional measures.

1. System Audit Torque Check — 0.10 ¢/W

Loose bolts have led to modules blowing off racking. Performing bolt torque checks regularly can help secure the modules and is an easy, low-cost measure.

2. Improved Fasteners — 0.12 – 1.4 ¢/W

Fasteners, especially module-racking bolts, are a common point of failure in wind-damaged PV systems. The fastener solutions below can help mitigate loss from the various modes of bolted joint failure.

2a. Wedge-lock Washers Lock into place when tightened and can resist bolted joint self-loosening from wind vibrations

Image from NordLock

2b. Nylon Insert Nuts can also help mitigate self-loosening. They are inexpensive and commonly available. Potential concerns over UV degradation.

2c. Rivet-Lock Bolts are one-time assembly locking fasteners

2d. Belleville Washers act as springs and help hold load through preload relaxation of a bolted joint

2e. Thread Lock is applied to the threads of a bolt and creates a seal when tightened

Images from Wikimedia Commons

3. Modules — 20.1 ¢/W

Select modules with uplift rating that match site conditions. For hurricane-prone regions, modules with >3600 Pa dynamic load test uplift rating.

4. Through Bolting — 0.24 ¢/W

Photo showing bent end clamp recovered from a PV site after a hurricane.

Photo from Andy Walker, NREL

Through bolting attaches individual modules to the racking directly. It is more secure than top down clamps and attachment clips and prevents the possibility of cascading domino failure of adjacent modules.

5. Three Framed Rail System — 15.6 ¢/W

Three rails are more secure than two and limit module flexing when wind loaded. It also allows more module attachment points. The cost is higher and includes additional hardware.

Image from Commercial Solar Guy 2019

6. Racking Material Design

Photo from Andy Walker, NREL

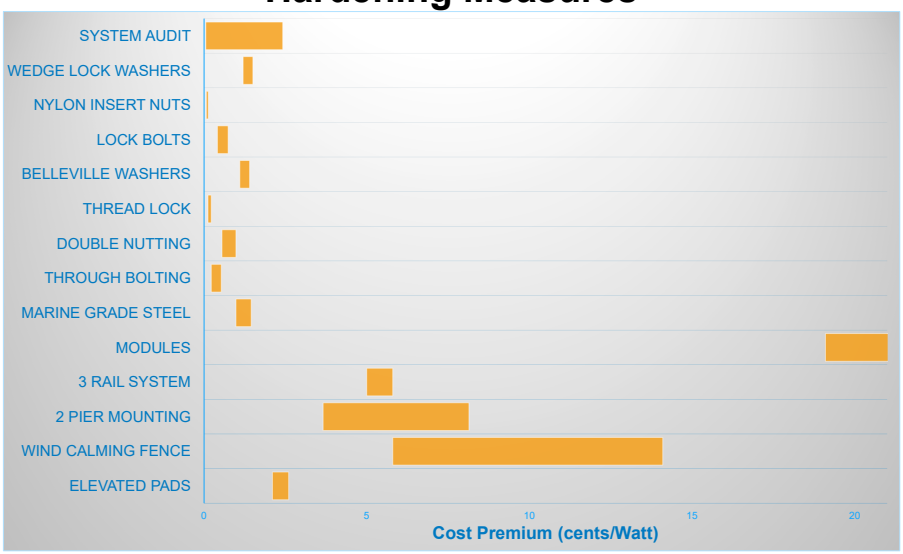
Light gauge, cold-rolled steel "C" channels can bend when subject to loads in certain directions. Tubular steel racking components provide more resistance to damage from storms.

7. Wind Calming Fence — 14.1 ¢/W

A wind-calming fence can reduce wind loads on the crucial perimeter modules of an array. It could also reduce dust, block debris, embers from wildfires, and reduce perimeter design and installation costs.

Image by DCT-Dust Solutions, Inc.

Estimated Cost Premiums of Select PV Storm Hardening Measures



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Robinson, G. et al. 2018. "Solar Photovoltaic Systems in Hurricanes and Other Severe Weather." US Department of Energy Office of Energy Efficiency & Renewable Energy. Federal Energy Management Program. https://www.energy.gov/sites/prod/files/2018/08/f55/pv_severe_weather.pdf

Burgess, Christoper and Joseph Goodman. 2018. "Solar Under Storm. Select Best Practices for Resilient Ground –Mount PV Systems with Hurricane Exposure." Rocky Mountain Institute. https://rmi.org/wp-content/uploads/2018/06/Islands_SolarUnderStorm_Report_digitalJune122018.pdf

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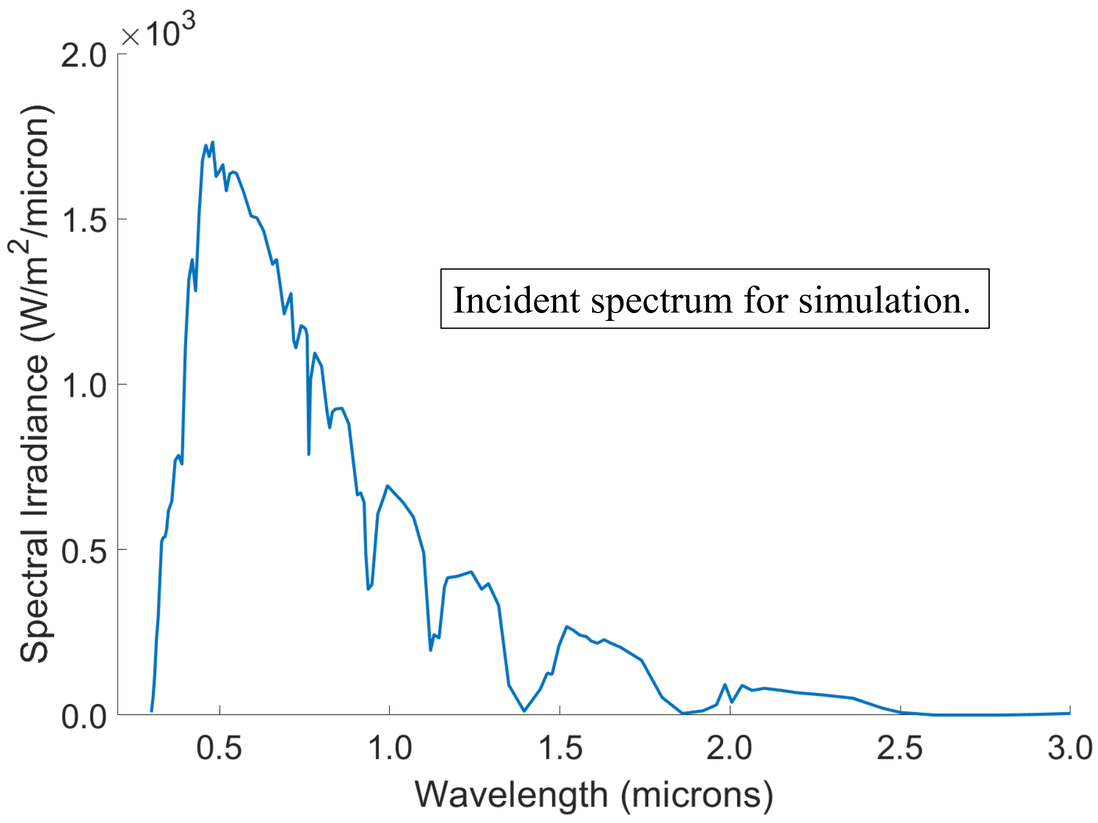
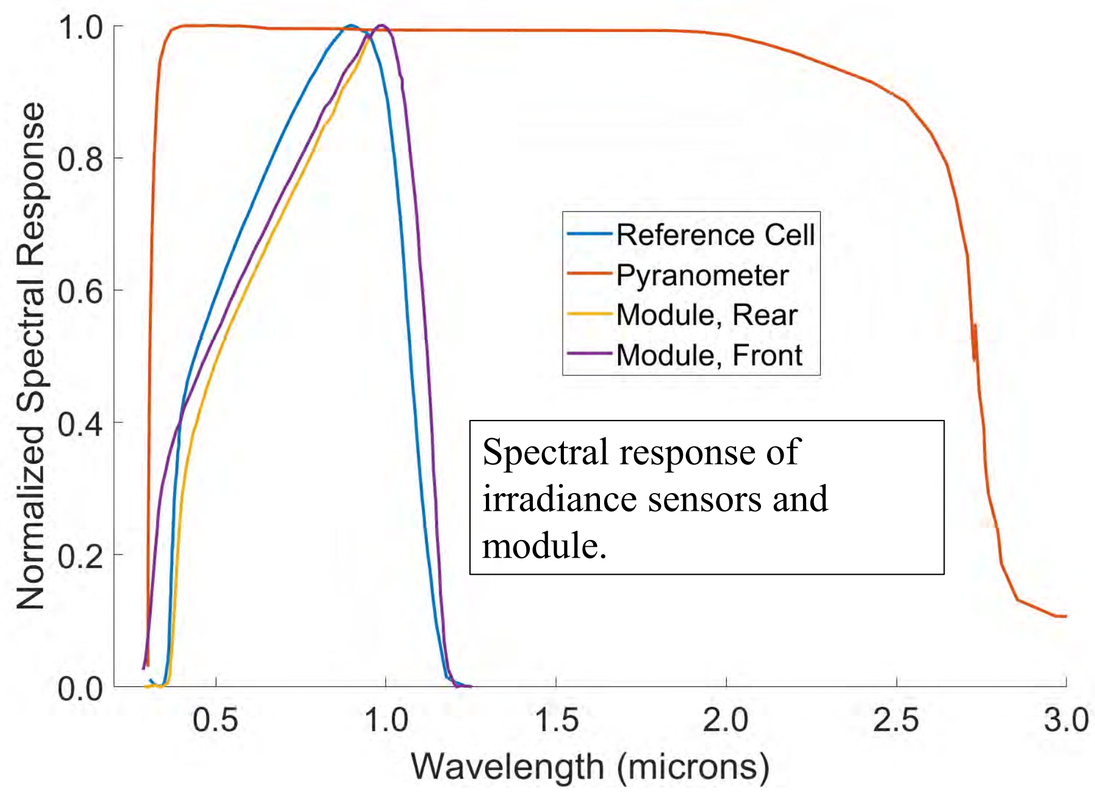
PV Reliability Workshop
Lakewood, CO
February 25-27, 2019
NREL/PO-7A40-76045

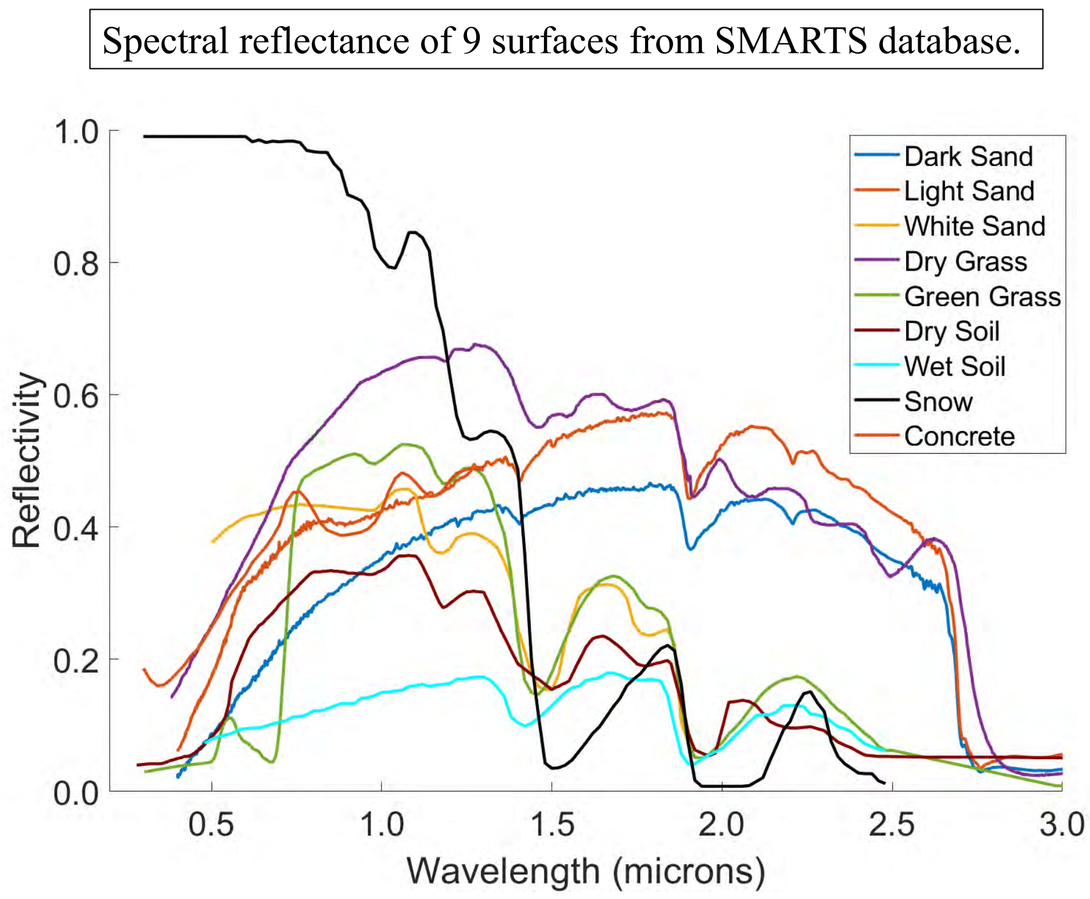
Spectral Mismatch of Albedo Measurements for Bifacial PV Performance Estimation with Thermopile Pyranometers and PV Reference Cells

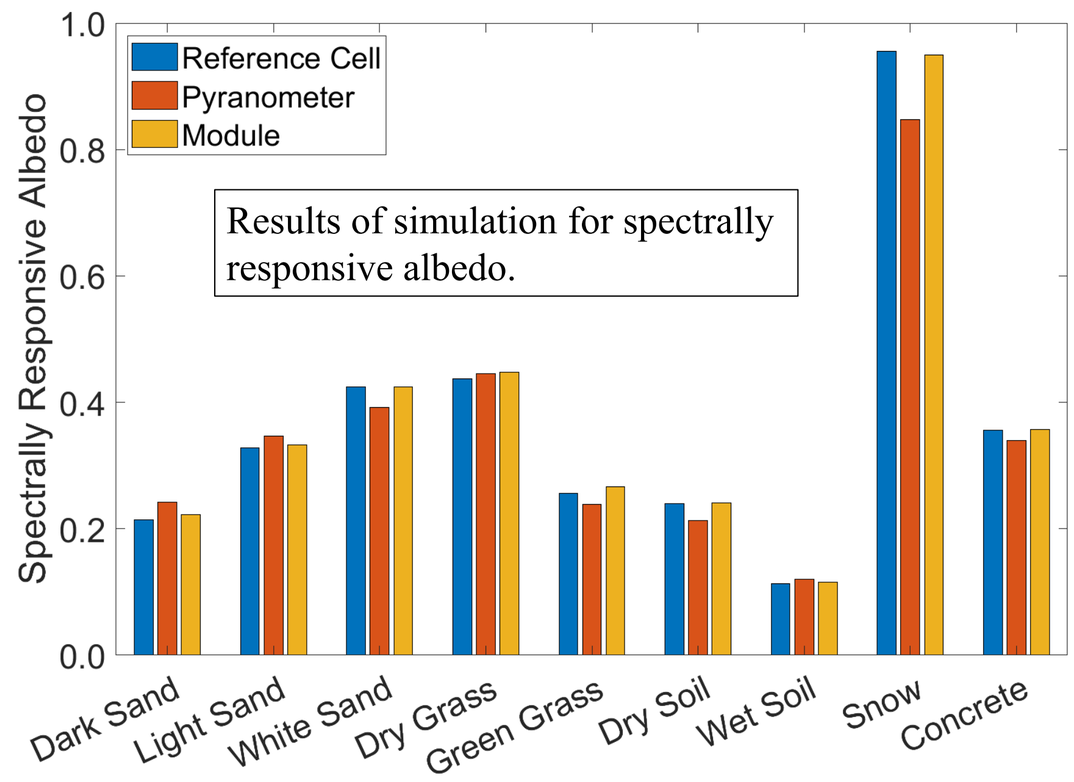
Michael Gostein[1], Bill Marion[2], Bill Stueve[1] – [1]Atonometrics, [2]NREL

- Albedo data are essential for accurate prediction of bifacial PV module performance.
- However, spectral response mismatch between PV modules and irradiance sensors used in albedometers can limit the accuracy of performance predictions.
- In order to provide quantitative assessment of this effect, we investigate via simulation the differences in spectrally responsive albedo measured with thermopile pyranometers and crystalline silicon PV reference cells in comparison to a representative crystalline-silicon bifacial PV module for nine different representative ground surface materials.
- Calculations are performed using simulated solar spectra together with catalogued spectral reflectivity data distributed with the SMARTS simulation software.
- For the specific materials considered, the results show that albedo measurement using thermopile pyranometers could over- or under-estimate the ground-reflected radiation usable by a bifacial PV module by up to 10%, versus only approximately 4% total range of variation for a PV reference cell.









Spectrally responsive albedo:

$$a_S = \frac{\int R(\lambda) SR(\lambda) G(\lambda) d\lambda}{SR(\lambda) G(\lambda) d\lambda} \quad (1)$$

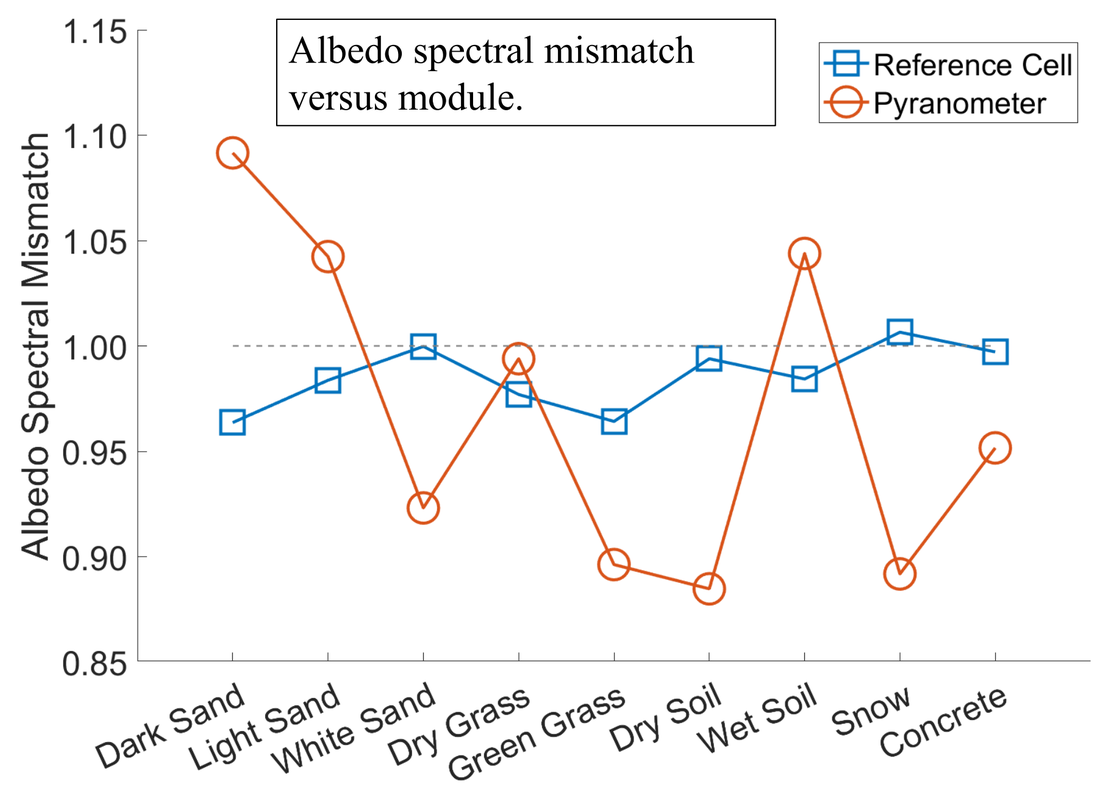
$G(\lambda)$: spectral irradiance of incident radiation from the sky
$SR(\lambda)$: spectral response of the measurement device
$R(\lambda)$: reflectivity of the ground surface

Spectral mismatch factor versus the PV module:

$$M^{Pyr} = a_S^{Pyr} / a_S^{Module} \quad (2)$$

and

$$M^{Refcell} = a_S^{Refcell} / a_S^{Module} \quad (3)$$



Simulation & Monitoring of a Solar Plant in Polar Vortex Conditions

Axel De Mendoza and Zachary Hammond, Invenergy LLC

Invenergy

Introduction

On January 30th, 2019, the city of Chicago experienced a record low temperature of -29°C. The weather pattern, known as a Polar Vortex, is characterized by low-pressure fronts that arise from one of Earth's poles [1]. Over the course of the week, over 22 people were reported dead as a result of hypothermia [2].

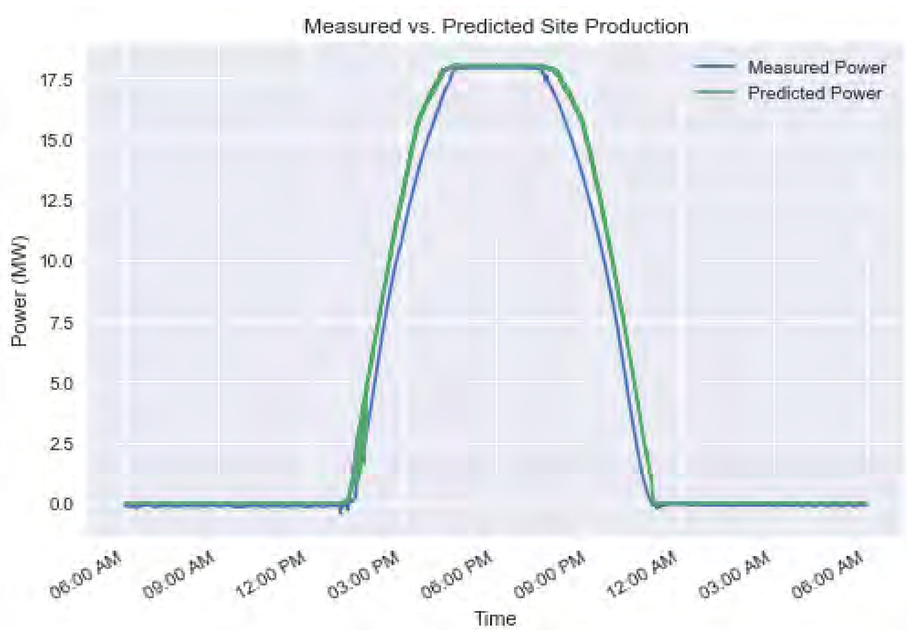
After conditions returned to normal, the Invenergy operations department was led to wonder how the Polar Vortex affected the production and availability of their solar plants. In order to answer this question, data was analyzed from Invenergy's Grand Ridge plant, based in Marseilles, Illinois.

Initial predictions were made using PVLib Python, after which measured site data and heatmap monitoring were used to assess actual site production.

Predicted vs Measured Production

To start, the site production for January 30th was predicted from the site's POA irradiance data. The PVWatts DC Model was used to calculate POA irradiance, while the Sandia Inverter Model was used to predict AC output power for a given DC power and voltage. The availability of the inverters was incorporated into the prediction as well, using the heatmaps shown in the *Availability Monitoring* section of this poster.

After a prediction was made, it was compared to the measured active power on-site. As shown in the figure below, the predicted site production was relatively close to the measured values, having a mean absolute percentage error (MAPE) of 1.01%.

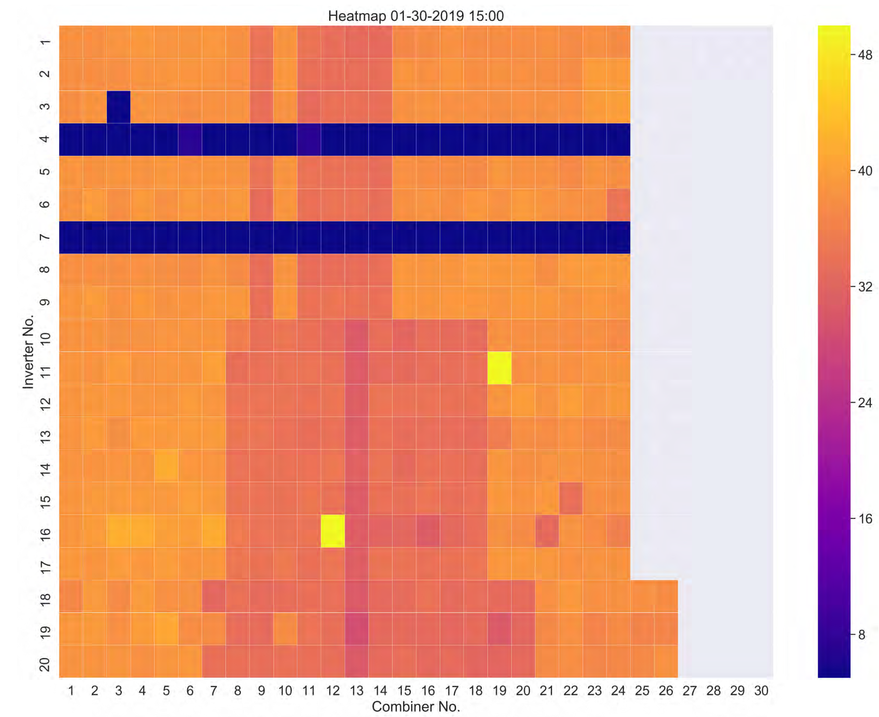


It should be noted that other January days with more moderate temperatures saw lower power and did not experience inverter clipping during midday.

Availability Monitoring

Heatmaps were used to visualize inverter and combiner-level outages. An image from each hour is created, then packaged into a GIF file to be played as an animated image.

As can be shown from the picture below, inverters #4 and #7 were down on January 30th. However, from observing past days, it was concluded that inverter #7 had been down for several days before the winter event. Therefore, only the outage of inverter #4 could possibly be attributed to the polar vortex.



Conclusion

The low ambient temperatures experienced at the Grand Ridge solar plant did not cause significant failures to inverters, combiners, or modules at the facility. However, they did help provide an increase in sitewide power, as shown by the PVLib production model and measured site data. To improve the 1.01% error seen during the production predictions, a new POA irradiance model such as the Sandia Array Performance Model (SAPM) should be used to better account for thin-film technologies. Furthermore, the DC losses should be modeled with more attention on site wiring specifications and ambient temperature.

Sources

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[2] A. Diaz, "Polar vortex 2019: Record cold grips the Midwest as Chicago River turns to ice," *CBS News*, 31-Jan-2019. [Online]. Available: https://www.cbsnews.com/news/polar-vortex-2019-record-cold-grips-the-midwest-as-chicago-river-turns-to-ice/. [Accessed: 23-Jan-2020].

UL and IEC Standard Updates on PV Connectors – Field Assembly and Incompatibility

Authors: Liang Ji; Scott Jezwinski;
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August 28, 2014
(Title Page Reprinted: December 22, 2017)

ANSI/UL 6703-2017

1

UL 6703

Standard for Connectors for Use in Photovoltaic Systems

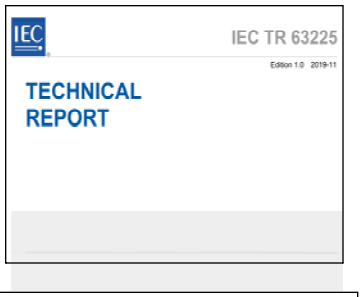
Prior to the first edition, the requirements for the products covered by this standard were included in the Outline of Investigation for Connectors for Use in Photovoltaic Systems, UL 6703 and the Outline of Investigation for Multi-Role Connectors for Use in Photovoltaic Systems, UL 6703A.

First Edition

August 28, 2014

This ANSI/UL Standard for Safety consists of the First Edition including revisions through December 22, 2017.

The most recent designation of ANSI/UL 6703 as an American National Standard


IEC TR 63225

Edition 1.0 2019-11

TECHNICAL REPORT

Related Standards:

UL 6703 Connectors for Use in Photovoltaic Systems

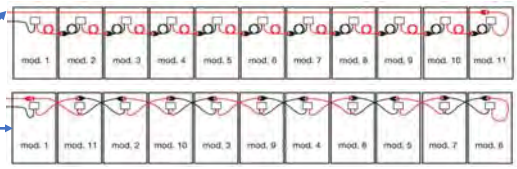
IEC TR 63225 Incompatibility of connectors for DC-application in photovoltaic systems

What is a Field Assembled Connector?

Most PV modules are shipped with a pigtail cable and connectors, and these connectors are assembled in a factory with reasonable quality control. However, due to the difficulty in predicting the required lengths of home-run cables, field assembly of connectors and PV string cable is often required at the installation site.

"Home-run" cable with Field Assembled Connectors.

One method to avoid "home-run" cables.



Problems with Field Assembled Connectors

UL 6703 Proposal for Field Assembled Connectors

- **All test samples shall be assembled in the testing lab from the connector components provided by the manufacturer.**
- **The assembly shall be performed precisely according to manufacturer's assembly instructions, including proper tools.**

Additional requirements for field assembly instructions:

- If any special tools are required, the required tool or reliable supplier's information shall be provided.
- Torques, including any tightening torque for sealing and strain relief means. It may be related to the part's temperature during assembly.
- Suitable ambient temperature range for field assembly.
- Application of adhesive or sealant, if it is required.
- Insulation stripping requirements.
- Precautions in abnormal environmental conditions, such as in rain or snow, extremely hot or cold ambient, or in an area where there is excessive dust.

Should a seal cap be required for shipment?

Discussion continues on this topic, considering the cost of the cap itself, benefits, response from inspectors, and collecting used caps after final connections.

Intermatability

ANSI/UL 6703 Section 1.5 This standard covers PV connectors whose dimensions are not defined in any national or international technical standard. Connectors are identified and tested with compatible mating part (or parts if multiple exist) and are to be of the same brand, **unless multiple product manufacturers are submitting under the same evaluation for the purpose of proving intermatability.**

Note: Related parties shall have an agreement on certification file for "In the event future modifications to the connectors are made that may impact mating compatibility, we agree to notify the other party of these modifications".

IEC TR 63225 Incompatibility: Background

In 1990s, a range of different PV connectors were on the market. Due to dimensional differences, they could not be plugged into each other. Since the early 2000s, one type began to dominate the market. Other manufacturers adapted their connectors to this popular type, and claimed **"Compatibility"** with the market-leading connector.

This "compatible" claim is misleading. Reasons are:

- Different metal alloys are used.
- Different contact designs are used.
- Mechanical tolerances are not specified.
- Polymeric material used are not specified.

These create risks of increased contact resistance and ingress of dust and water. Several countries report that problems with PV connectors are a major cause for failure such as fire hazards in PV systems.

Mated connectors from different manufacturers were often used on "home-run" cables.

IEC TR 63225 Suggested Interim Measures

- **Increase the awareness of risks** of mating PV connectors from different manufacturers.
- The term **"XX compatible" should no longer be used**, unless specifically evaluated and confirmed by all related parties.
- **Module manufacturers** should either distribute suitable spare connectors and assembly instructions (preferred), or provide such information for their modules (minimum requirement).
- **System owners** should request that only truly compatible PV connectors be used.
- **Installers** should contact and put pressure on their suppliers, distributors, product manufacturers, to standardize long-term compatibility.

IEC TR 63225 Long-term Aim

- Develop a **common interface standard** to ensure complete compatibility of materials, dimensions, tolerances and other properties needed.
- Create a **coordinated quality management system** for manufacturers.
- Modify existing test standard and certification program to allow the use of such new connectors.

If this long-term aim cannot be achieved, measures to avoid the intermating of PV connectors from different manufacturers should be intensified.

NON-LINEAR REGRESSION MODEL BETWEEN SOLAR IRRADIATION AND PV GENERATION OUTPUT IN SOUTH KOREAN

Boyoung Kim[1], Alba Vilanova Cortezon[2], Chang Ki Kim[1], Yong-Heack Kang[1], Hyun-Goo Kim[1*]
[1] Korea Institute of Energy Research, New and Renewable Energy Resource & Policy Center
[2] Higher Polytechnic School, University of Lleida, Lleida, Spain

I. Introduction

- ✓The forecasting process for PV power generation can be divided into two steps. The first is to forecast solar irradiation and the second is to transform forecasted solar irradiation into power generation. There are two methods for the transformation. One is to simulate with physical model, and another is to use regression model.
- ✓For small-size PV operators or brokers does not have in-situ observed solar irradiation or all other observed data that is needed for physical model.
- ✓The regression model between solar irradiation and PV generation is known as linear model.
- ✓In this study, we will find the best regression model between solar irradiation from satellite imagery and in-situ PV generation output in South Korea.

Purpose

01 To find a best regression model between solar irradiation and PV generation in South Korea.

II. Method

- ✓Normalize power generation data and create a data set
- ✓Obtain the best coefficients of linear and 6 sigmoidal models respectively by using the least-squares method.
- ✓Rank the fidelity of the models by using AIC(Aikake Information Criterion)

III. Data

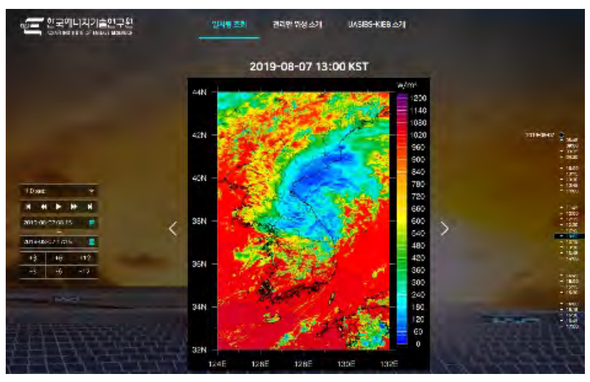
1. Power output

✓The power transaction data (AMGO: Adjusted Metered Generation Output) held by KPX was used, and its location and number are shown in the right figure

Strata	Selected	Total
Jeollanam-do	82	209
Jeollabuk-do	28	71
Gyeongsangnam-do	24	61
Gyeongsangbuk-do	34	85
Chungcheongnam-do	13	33
Chungcheongbuk-do	6	13
Gyeonggi-do	11	26
Gangwon-do	9	23
Jeju-do	14	34
Seoul	2	5
Incheon	4	8
Sejong	1	1
Daejeon	2	5
Daegu	2	5
Gwangju	4	8
Ulsan	1	1
Busan	5	11
Sum	**242**	**599**

2. Solar Irradiance

✓The satellite image-based solar radiation data produced by the UASIBS-KIER model developed by the Korea Institute of Energy Research and Technology were used.



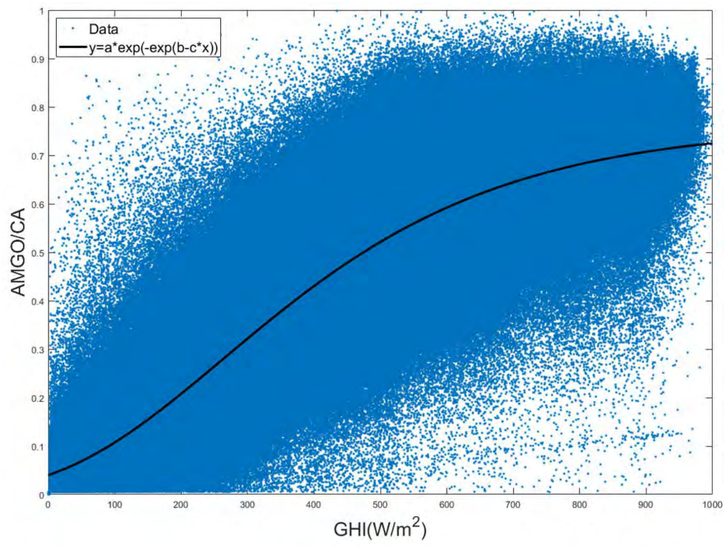
IV. Result

✓**Fidelity rank**

Ranking	No. of 1st	No. of 2nd	No. of 3rd	No. of 4th	No. of 5th	No. of 6th	No. of 7th	Average Ranking
Gompertz	164	35	41	1	1	0	0	1.51
MMF	41	89	25	34	6	17	30	3.19
Weibull	24	51	52	105	4	6	0	3.13
Richards	9	59	98	44	0	0	32	3.39
Logistic	2	4	19	39	177	1	0	4.6
Ratkowsky	0	2	3	14	43	180	0	5.64
Linear	2	2	4	5	11	38	180	6.53

✓In fidelity analysis, the linear model showed the lowest rank, and among the Sigmoid models, the Gompertz model showed the overwhelming number of relevance first rank.

✓**Unified Gompertz model for all sites**

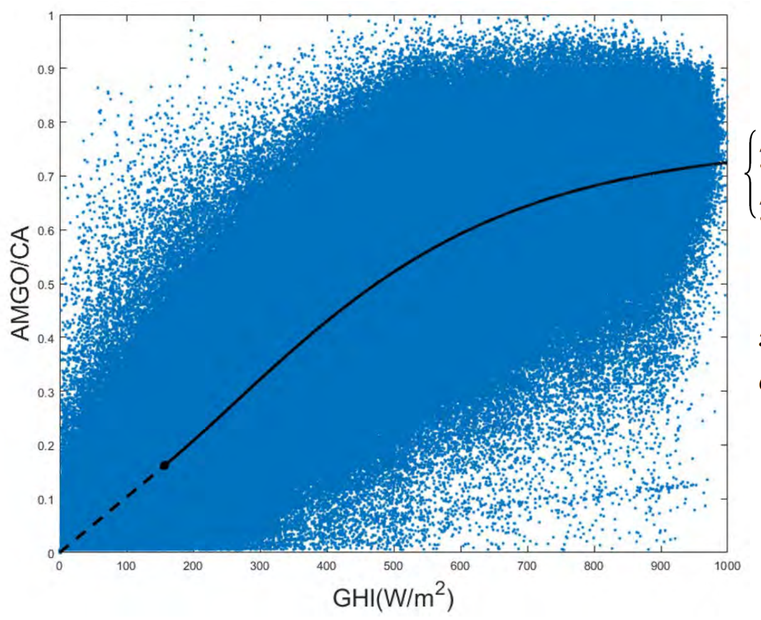


$$y = ae^{-e^{b-cx}}$$

$$a = 0.761$$
$$b = 1.083$$
$$c = 0.00411$$

✓**Generation is not 0 at GHI=0**

✓**Combined model (Linear-Gompertz model)**



$$\begin{cases} y = d \cdot x & (x \le x_{meet}) \\ y = a \cdot e^{-e^{b-c \cdot x}} & (x > x_{meet}) \end{cases}$$

$$x_{meet} = 157.158$$
$$d = 0.00103$$

✓x_{meet} and d was determined to connect two lines smoothly

✓f(x) and f'(x) are same respectively.

V. Conclusion

- ✓Best regression model was Gompertz model
- ✓Linear-Gompertz model was made for physical fidelity

Model	Linear	Gompertz	Combined
R^2	0.809	0.831	0.831
RMSE	0.105	0.099	0.099
MBE	0.0789	0.0735	0.0730

Modeling of Ultraviolet Irradiance from Total Irradiance: A Simplified Approach

Aron Habte and Manajit Sengupta

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Abstract

- Terrestrial ultraviolet (UV) irradiance is a small portion of the solar spectrum. However, the high energy contained within those wavelengths can cause degradation of materials, such as photovoltaic (PV) modules.
- Measured terrestrial UV data is limited and is prone to high measurement uncertainty resulting from calibration error and directional response.
- Measured or modeled total irradiance data of relatively low uncertainty is relatively abundant for many locations.
- In this poster, we demonstrate and validate a method [1] to estimate terrestrial UV using a model that provides ratio of terrestrial UV to total irradiance spectra.
- This study examines the total UV irradiance on a horizontal surface derived from a model of the UV/GHI ratio developed using simulations obtained using Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) [1], [2] with observed atmospheric parameters.
- The model demonstrates good agreement with measurements.

Method

Fig. 1. Selected locations included in the study

- At the earth surface, the irradiance is strongly affected by the airmass factor, which depends on solar geometry.
- Using the SMARTS model, airmass-dependent irradiance simulations were generated for the locations under study (Fig 1).

$$UV_m = TS_m * R_{uv}$$

$$R_{uv} = \frac{UV_s}{TS_s}$$

where UV_S and TS_S are the total UV irradiance and total shortwave irradiance estimated with SMARTS, respectively (W/m^2).

The result of UV:TS ratios were then multiplied with available TS to obtain modeled UV for these locations.

$$UV_m = TS_m\left(\sum_0^4 m_i\, AM^i\right)$$

where TS_m (W/m^2) is the measured or modeled total solar irradiance, AM_i are airmasses, and m_i are numerical coefficients obtained by least-squares fitting (Fig. 2). A fourth-order polynomial function was fitted to Fig. 2 for 280 – 400 nm and 285–385 nm. Similar relationships for other spectral wavebands were also developed (295–400 nm, and 295–385 nm).

However, for locations with limited meteorological information an average of the 15 location lines (black thick line in Fig. 2) can be used to develop the R_{uv}.

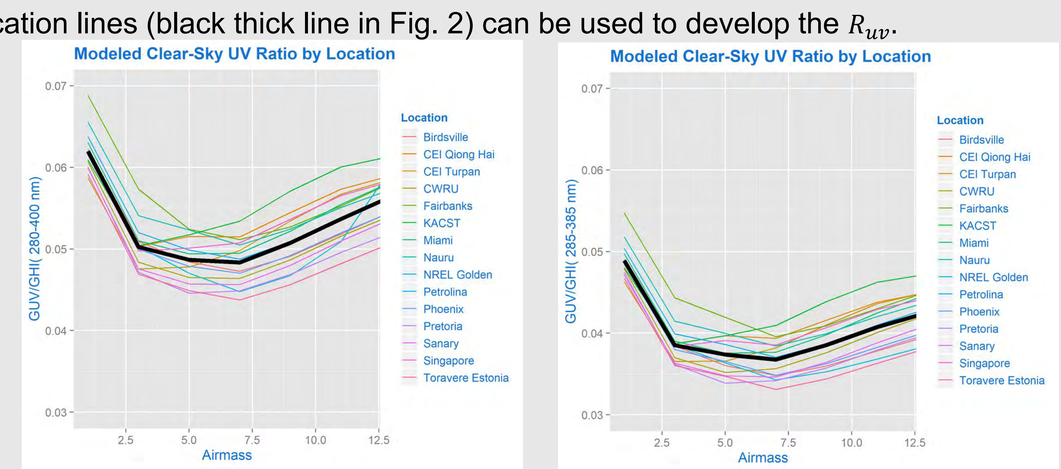


Fig. 2. (Right) R_{uv} (GUV/GHI) as a function of airmass for mean annual fixed atmospheric conditions (prevailing conditions) of 15 locations for the range 280–400 nm and (Left) for 285–385 nm . The black thick line is the average of all 15 lines.

Results

- The model demonstrated good agreement with the measured UV (Fig.3 and 4)
- Cloudiness did not affect the agreement between model and observations (Fig 3 and 4).

Validation using Individual Polynomial Function

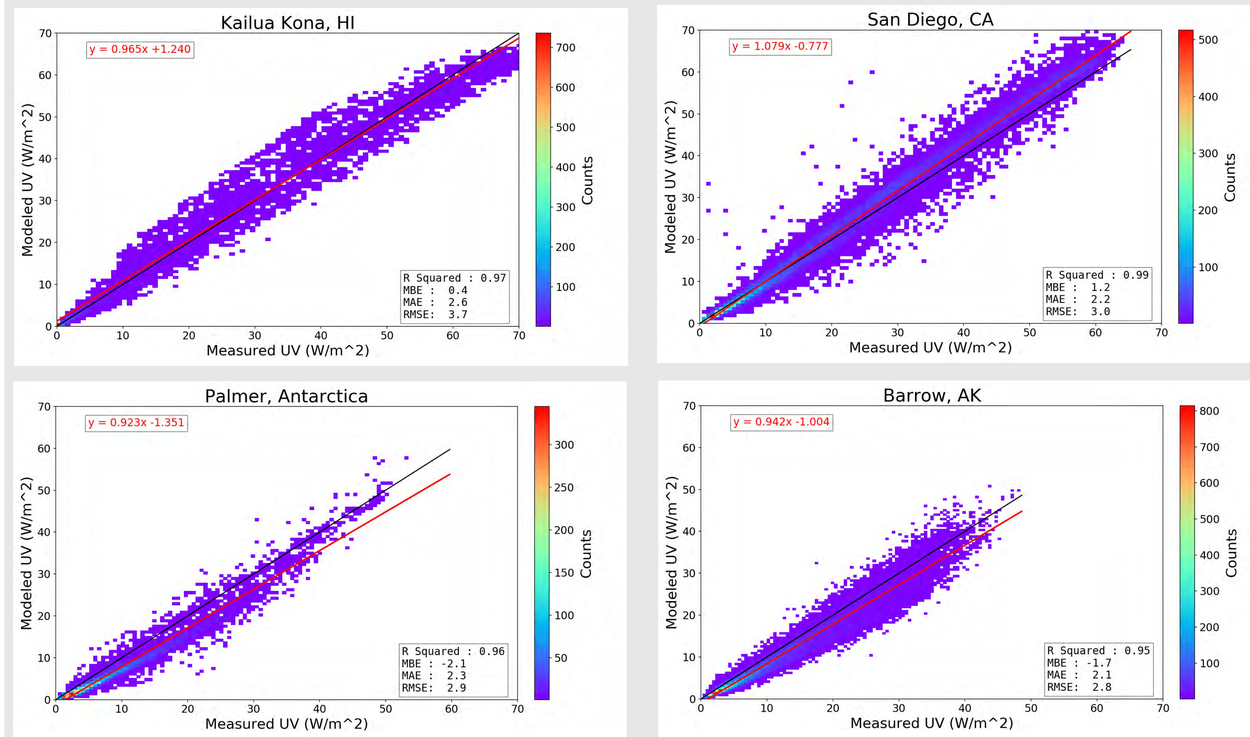
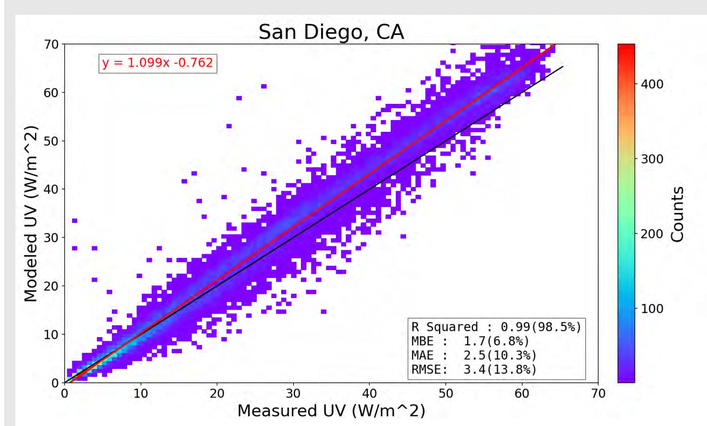


Fig. 3. Modeled vs. measured global UV irradiance under all sky conditions and zero tilt for multiple locations. Black line is 1:1 line and red line is a regression fit (obtained from [1]).

Validation using Average Polynomial Function



- Fig. 4 demonstrates insignificant difference (see statistics from Fig. 4 and top right panel of Fig. 3 for comparison) between using individual polynomial coefficients and an average of the 15 polynomial functions from Fig. 2 (right panel).

Fig. 4. The same as Fig. 3 but using average polynomial coefficients (Fig. 2)

Conclusions and Future Work

- NREL in collaboration with industry partners, published a journal article [1], and the model can be applied to estimate the total UV irradiance from measured or modeled total solar irradiance under all-sky conditions.
- The validation of both individual and average functions shows good agreement with measurement and provides confidence about the accuracy of the model.
- The model bias on average is only ±2W/m^2 when validated for multiple locations.
- Based on this approach, a new ASTM standard on the estimation of UV irradiance received by samples as a function of location has been drafted and balloted.

References

1. Aron Habte, Manajit Sengupta, Christian A. Gueymard, Ranganath Narasappa, Olivier Rosseler, David M. Burns. "Estimating Ultraviolet Radiation from Global Horizontal Irradiance." IEEE Journal of Photovoltaics, Vol. 9 (2019): pp. 139-146. https://doi.org/10.1109/JPHOTOV.2018.2871780.
2. C.A. Gueymard, *Simple Model of the Atmospheric Radiative Transfer of Sunshine, Version 2 (SMARTS2): Algorithm Description and Performance Assessment* (FSEC-PF-270-95) (Cocoa, FL: Florida Solar Energy Center, 1995).
3. C.A. Gueymard, "Parameterized Transmittance Model for Direct Beam and Circumsolar Spectral Irradiance," *Solar Energy* 71 (2001): 325–346.
4. M. Poliskie, *Solar Module Packaging: Polymeric Requirements and Selection* (Boca Raton, FL: CRC Press, 2011).
5. C.C. White. *Service Life Prediction of Polymers and Plastics Exposed to Outdoor Weathering* (Saint Louis, MO: William Andrew, 2017). http://lib.myilibrary.com?id=1039678.

This work was 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. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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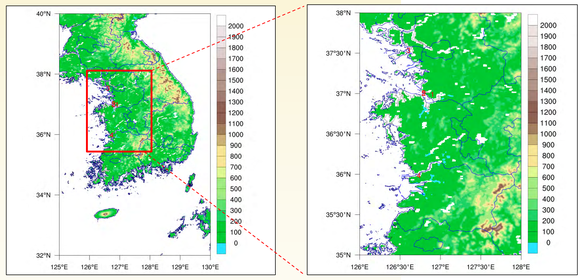
Examination of Performance Ratio for Solar Power Plants Based on Satellite-Derived Solar Irradiance in the Korean Peninsula

Chang Ki Kim (ckkim@kier.re.kr), Hyungoo Kim, Yong-Heack Kang, Bo-Young Kim and Chang-Yeol Yun
New and Renewable Energy Resource Map Laboratory, Korea Institute of Energy Research, Daejeon, Korea

Introduction

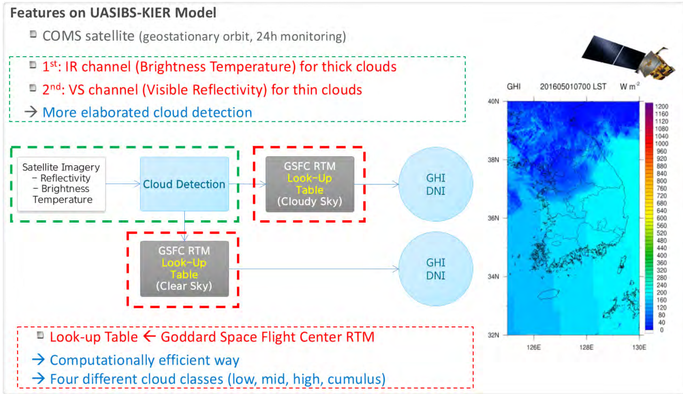
- Solar Irradiance as Renewable Energy
- Photovoltaic System Degradation
- Performance Ratio
- Prediction of PV power from Solar Irradiance
- In-situ observation vs. Remote Sensing
- Prediction based on Remote Sensing?
- Examination of Performance Ratio
- Relationship between in-situ observation and satellite derived solar irradiance
- Prediction of PV power generation by using satellite derived solar irradiance

Station Details

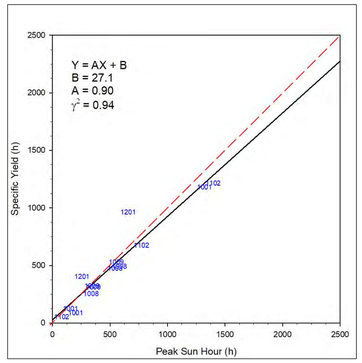


ID	1	2	3	4	5
Station Number	1001	1008	1102	1201	1009
Capacity	200 kW	218 kW	90 kW	250 kW	236 kW
Data Period	2017.11 ~ 2018.12	2017.05 ~ 2019.06	2017.12 ~ 2019.06	2018.02 ~ 2019.7	2017.05 ~ 2019.06
Hourly Power	80.2 kWh	95.0 kWh	32 kWh	70 kWh	95.0 kWh
Hourly GHI	406 Wh	409 Wh	388 Wh	172 Wh	409 Wh
Hourly POAI	443 Wh	439 Wh	402 Wh	182 Wh	439 Wh
Annual P.R.	0.76	0.81	0.81	1.58	0.91

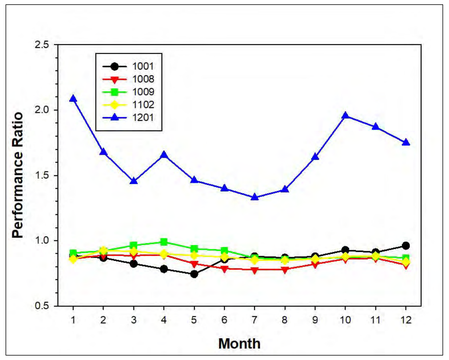
UASIBS-KIER model (Satellite-Derived Solar Irradiance)



Results from Performance Ratio



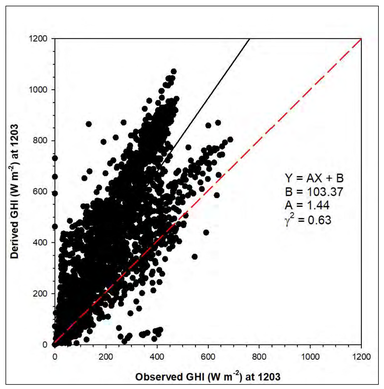
Annual Statistics



Monthly Statistics

Overestimated Performance Ratio in 1201 station

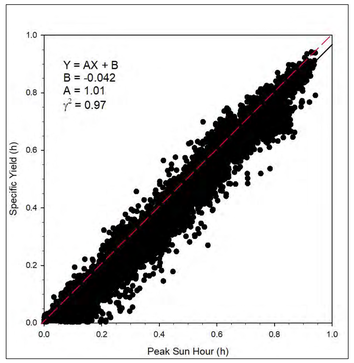
- ✓ Annual system yield exceeds annual peak sun hour
- ✓ Monthly performance ratio is higher than 1
- ✓ 1201 station have a problem.

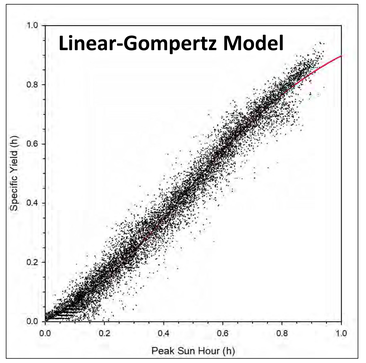


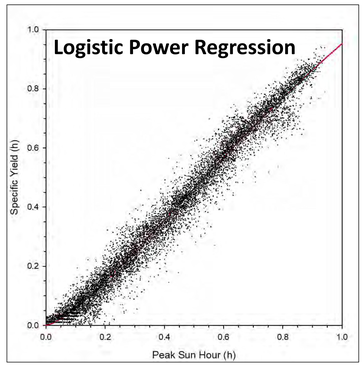
Comparison with Satellite derived GHI

- ✓ In-situ observation is very low
- ✓ There would be a problem in pyranometer at 1203 station.
- ✓ We exclude 1203 station from the further analysis.

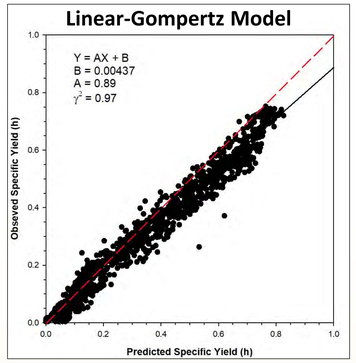
Results from Specific Yield and Peak Sun Hour (In-situ Observation)

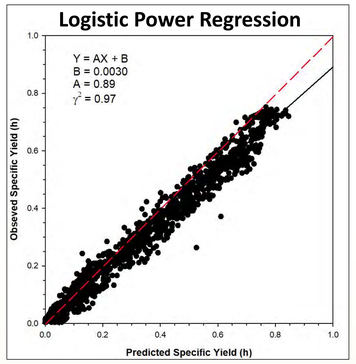






Training Dataset (2018 ~ 2019)





Test Dataset (2017)

Linear-Gompertz Model

$$y = a \times \exp\left(-\exp\left(\frac{x_0 - x}{b}\right)\right) \quad (x \geq 0.142879)$$

$$= d \times x \quad (x < 0.142879)$$

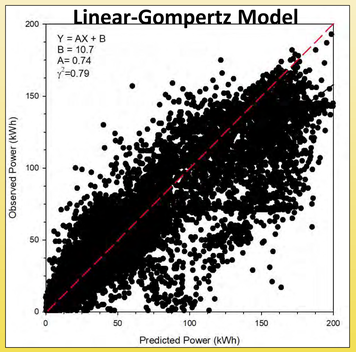
$$a = 1.0989,\ b = 0.3452,\ d = 0.142879,\ x_0 = 0.4474$$

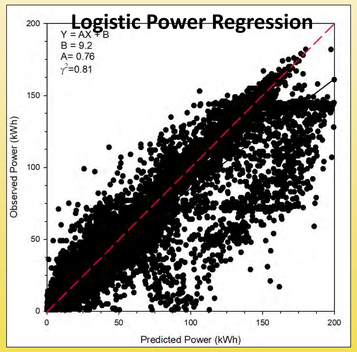
Logistic Power Regression

$$y = \frac{a}{1 + \left(\frac{x}{x_0}\right)^b}$$

$$a = 2.7852,\ b = -1.3834,\ x_0 = 1.6039$$

Prediction by Satellite derived POA





Nominal RMSE

- ✓ Linear-Gompertz
- ✓ 13.6%
- ✓ Logistic Power
- ✓ 12.8%

References

Kim, C. K., H.-G. Kim, Y.-H. Kang, and C.-Y. Yun, 2017: Toward Improved Solar Irradiance Forecasts: Comparison of the Global Horizontal Irradiances Derived from the COMS Satellite Imagery Over the Korean Peninsula. *Pure Appl. Geophys.*, 174, 2773-2792.

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Albedo Data for Bifacial PV Systems Update

Bill Marion
National Renewable Energy Laboratory, Golden, CO

Introduction

For better performance estimates of bifacial PV systems and to reduce the risk for the PV and financial communities, the U.S. Department of Energy (DOE) funded the National Renewable Energy Laboratory (NREL) to develop albedo data sets for use in modeling and decision making. The data sets of ground albedo and associated meteorological data were developed by using existing SURFRAD and AmeriFlux measurement network data and data contributed by Canadian Solar, Inc. and SunPower Corp. The data sets include time-series data as well as summary information consisting of tabular monthly and yearly data and plots of monthly and hourly albedo values. A list of the measurement stations and their overall albedos are listed in Table 1.

Background

For mono-facial PV systems, the ground-reflected radiation typically comprises only 1% to 2% of the total radiation received by the PV module. Consequently, a rudimentary understanding of the ground albedo is adequate for predicting their performance. However, for bifacial PV modules where their benefit is determined by the additional radiation reflected by the ground to their backside, a better understanding of albedo values and characteristics is needed by both the PV and financial communities to better estimate performance and to reduce risk.

The albedo of a surface is the fraction of the incident irradiance that it reflects. Albedo data are derived from measurements by two horizontal pyranometers, one facing the sky and the other inverted and facing the ground. The resulting albedo is the irradiance reflected by the ground and measured by the ground-facing pyranometer divided by the global horizontal irradiance (GHI) measured by the sky-facing pyranometer.

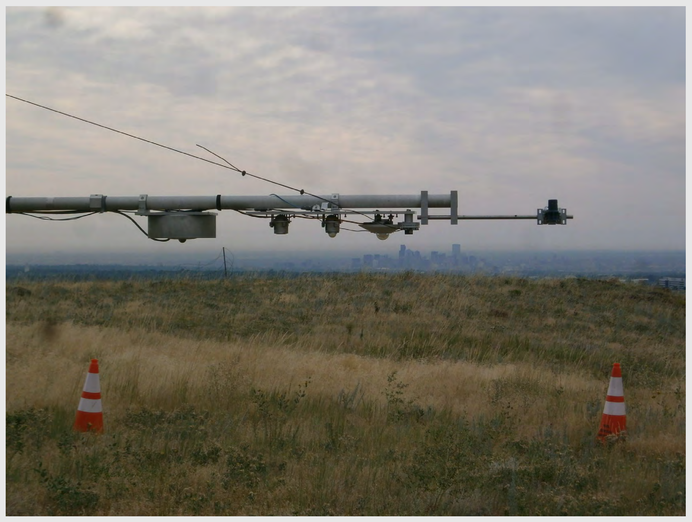


Fig 1. Albedo measurements at NREL's Solar Radiation Research Laboratory.

Data Availability

The albedo data sets may be download from NREL's DuraMAT website at https://datahub.duramat.org/project/about/albedo-study. The data sets include time-series data as well as summary information of tabular monthly and yearly data and plots of monthly and hourly albedo values. Complete information about the measurement stations and their data is presented in a user's guide. This work will add more albedo data sets as they become available from contributions by the PV community.

Figures 2 and 3 are example plots of monthly and hourly albedos presented in the user's guide.

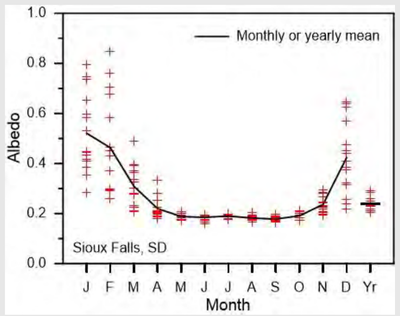


Fig. 2. Monthly and yearly albedo means for Sioux Falls, SD. The variability of albedo during the winter months is because the snowfall is variable from year to year.

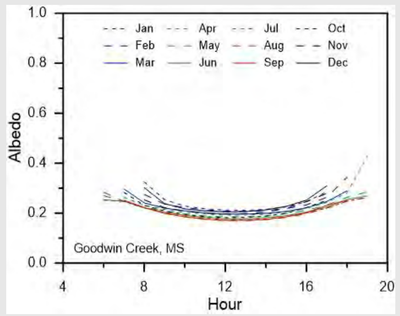


Fig. 3. Mean hourly albedos for Goodwin Creek, MS. The albedos are greater for early morning and late afternoon because of angular effects, and because the grass surface is more reflective to the longer wavelengths of the solar radiation present at those times.

Acknowledgment

We appreciate the contributions of the following organizations and individuals in providing their albedo and meteorological data: the SURFRAD network managed by the National Oceanic and Atmospheric Administration (NOAA); Jean-Nicolas Jaubert and Baohua He (Canadian Solar, Inc.); Ben Bourne, Fabrizio Farina, and Adam Hoffman (SunPower Corporation); and the AmeriFlux Network managed by the Lawrence Berkeley National Laboratory and with stations managed by Andy Suyker (University of Nebraska-Lincoln), Dennis Baldocchi (University of California), Nathaniel Brunsell (Kansas University), Chris Oishi (USDA Forest Service), David Bowling (University of Utah), Dave Billesbach (University of Nebraska), David Cook (Argonne National Laboratory), Gerald Flerchinger (USDA Agricultural Research Service), John Baker (USDA Agricultural Research Service), Lawrence B. Flanagan (University of Lethbridge), Joe McFadden (University of California), Mike Goulden (University of California-Irvine), Marcy Litvak (University of New Mexico), Russell Scott (United States Department of Agriculture), Sabina Dore (Northern Arizona University), Tilden Meyers (NOAA/ARL), and Sonia Wharton (Lawrence Livermore National Laboratory).

Table 1. Measurement Stations and Overall Albedos

StationID	Location	Data Source	Data Years	Ground Surface	Overall Albedo
BondvilleIL	Bondville, IL, USA	SURFRAD	24	Native grasses	0.247
BoulderCO	Boulder, CO, USA	SURFRAD	23	Sandy with exposed rocks, sparse grass, desert shrubs, cactus	0.199
DesertRockNV	Desert Rock, NV, USA	SURFRAD	20	Fine rock and scattered creosote bush	0.211
FortPeckMT	Fort Peck, MT, USA	SURFRAD	23	Native grasses	0.247
GoodwinCreekMS	Goodwin Creek, MS, USA	SURFRAD	24	Pasture grass and sparse deciduous trees	0.200
PennStateUnivPA	Penn State Univ, PA, USA	SURFRAD	20	¾ grass and ¼ crops	0.252
SiouxFallsSD	Sioux Falls, SD, USA	SURFRAD	15	Native grasses	0.238
ChangshuJiangsu	Changshu, Jiangsu, China	Canadian Solar, Inc	1.3	Concrete White-painted concrete	0.236 0.533
DavisCA	Davis, CA, USA	SunPower Corp.	0.8	Gravel, light to medium gray White tarp	0.145 0.568
LethbridgeAlberta	Lethbridge, Alberta, Canada	AmeriFlux	1	Mixed grass prairie	0.250
MedfordOK	Medford, OK, USA	AmeriFlux	3	Hay pasture	0.211
WoodwardOK_1	Woodward, OK, USA	AmeriFlux	4	Switchgrass	0.186
WoodwardOK_2	Woodward, OK, USA	AmeriFlux	4	Switchgrass	0.204
AudubonRanchAZ	Audubon Research Ranch, AZ, USA	AmeriFlux	10	Native grasses	0.217
BouldinCA	Bouldin Island, CA, USA	AmeriFlux	3	Alfalfa	0.221
BrookingsSD	Brookings, SD, USA	AmeriFlux	7	Pasture grass	0.262
CanaanValleyWV	Canaan Valley, WV, USA	AmeriFlux	6	Grassland	0.294
CorralPocketUT	Corral Pocket, UT, USA	AmeriFlux	7	Semi-arid grassland with 38-80% bare ground from livestock grazing	0.238
CottonwoodSD	Cottonwood, SD, USA	AmeriFlux	4	Grassland	0.181
DiabloCA	Diablo, CA, USA	AmeriFlux	3	Grassland	0.206
DukeFieldNC	Duke Field, NC, USA	AmeriFlux	5	Tall fescue grass mowed annually	0.203
FlagstaffAZ	Flagstaff, AZ, USA	AmeriFlux	6	Post forest fire grasslands	0.219
FermilabIL	Fermilab – Batavia, IL, USA	AmeriFlux	14	Prairie grass	0.221
FieldStationKS	Kansas Field Station, KS, USA	AmeriFlux	8	Grassland	0.193
KonzaPrairieKS	Konza Prairie, KS, USA	AmeriFlux	6	Grassland	0.190
TurfgrassFieldMN	Turfgrass Field, MN, USA	AmeriFlux	4	Turfgrass lawn	0.322
ReynoldsCreekID_1	Reynolds Creek, ID, USA	AmeriFlux	3	Low sagebrush	0.179
ReynoldsCreekID_2	Reynolds Creek, ID, USA	AmeriFlux	3	Mountain big sagebrush	0.231
RosemountMN	Rosemount, MN, USA	AmeriFlux	5	Grassland	0.247
SonoranDesertCA	Sonoran Desert, CA, USA	AmeriFlux	7	Desert	0.245
SouthGrasslandCA	Southern Californian Grassland, CA, USA	AmeriFlux	9	Grassland	0.165
McKenzieFlatsNM	McKenzie Flats, NM, USA	AmeriFlux	12	Desert Grassland	0.219
ShidlerOK	Shidler, OK, USA	AmeriFlux	4	Tall grass prairie	0.217
SantaRitaAZ	Santa Rita, AZ, USA	AmeriFlux	11	Semidesert grassland	0.204
TwitchellCA	Twitchell Island, CA, USA	AmeriFlux	5	Alfalfa	0.223
WalnutGulchAZ	Walnut Gulch, AZ, USA	AmeriFlux	15	Grassland	0.182
SmileyburgKS	Smileyburg, KS, USA	AmeriFlux	3	Tall grass prairie	0.210

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

2020 PV Reliability Workshop
Lakewood, CO
February 25-27, 2020
NREL/PO-5K00-76135

Solar Data Tools: Automatic Solar Data Processing Pipeline

Bennet Meyers[1,2], Laura Schelhas[1]

1 Applied Energy Division, SLAC National Accelerator Lab
2 Dept. of Electrical Engineering, Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

GISMO Grid Integration, Systems & Mobility

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

Introduction

- Increasing volume of PV system performance data
- Opportunities for
  → Remote system health monitoring
  → Optimizing O&M activities
- Data comes in variety of formats
- Data can have quality issues and missing values
- Often missing/unreliable metadata and system configuration information

The inability to automatically ingest, quality check, filter, and flag data at fleet-scale is a major roadblock to unlocking the potential of PV system performance data at scale

SDT Overview

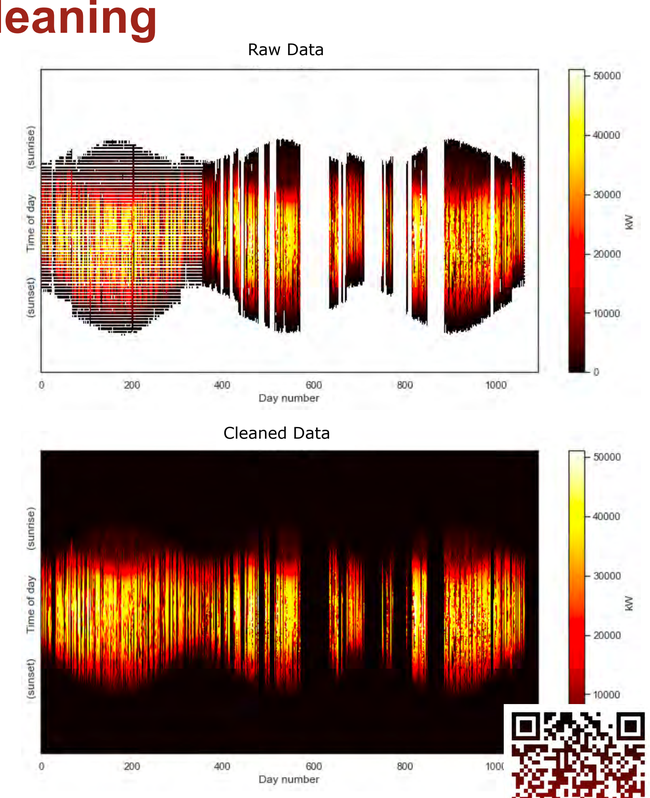
- Take generic, tabular PV time-series data as input
- Any sub-daily sampling frequency
- Possibly with missing or corrupted data
- No site info or meta data
- Automatically performs preprocessing, cleaning, and filtering tasks
- Five algorithms utilize a new, generalized approach to signal separation problems called **Optimal Signal Demixing** (OSD)

← more info on OSD

SDT Algorithms

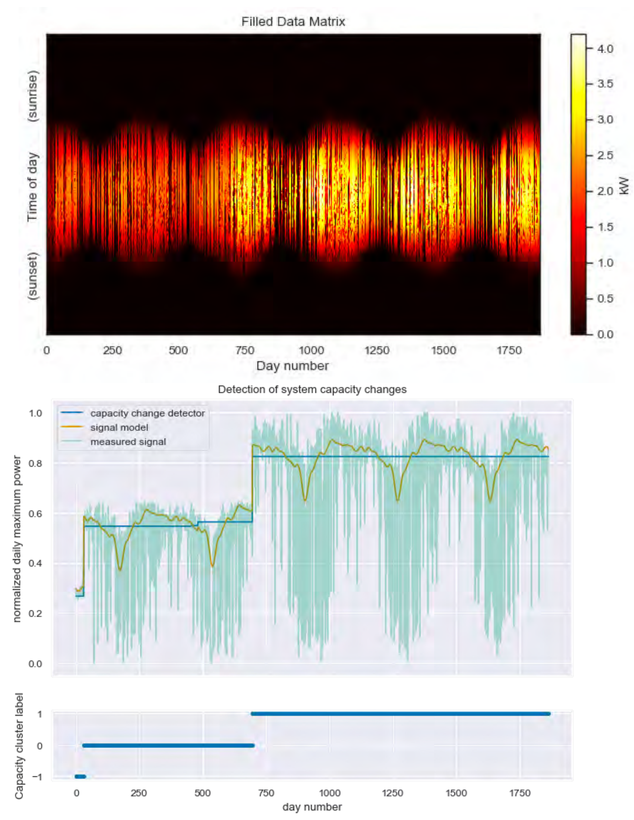
Tool	Preproc.	Cleaning	Filtering	OSD
Time stamp cleanup	✓			
Sampling rate detection	✓			
Matrix embedding	✓			
Missing data		✓		
Time shift		✓		✓
Data quality			✓	✓
Clear/cloudy			✓	✓
Inverter clipping			✓	✓
Capacity change			✓	✓

Cleaning

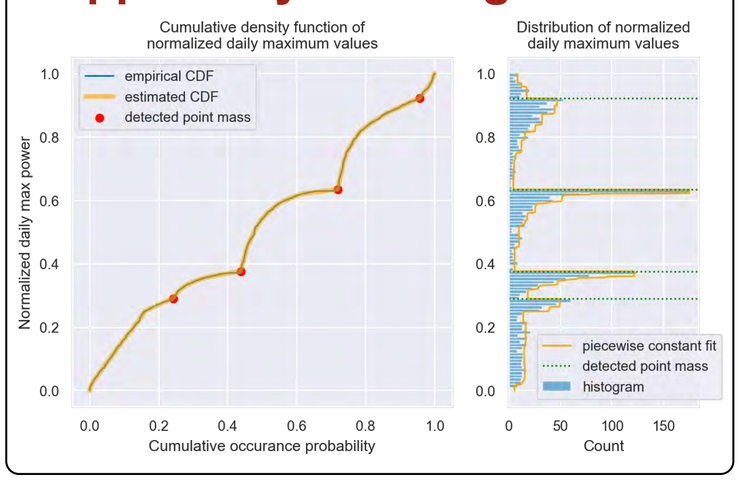


Tutorial →

Capacity Change Detection



Clipped Day Labeling



Jupyter Notebook Usage

```
dh = DataHandler(df)
dh.run_pipeline()
print('\n### Data Set Report ###')
dh.report()
```

```
total time: 3.00 seconds
form matrix: 0.10, fill matrix: 0.72, fix time shifts: 0.63,
daily scores: 0.26, daily flags: 0.03, clear detect: 0.23,
clipping check: 0.19, data scoring: 0.83

### Data Set Report ###
Length:                 1522 days
Data sampling:          5 minute
Data quality score:     96.6%
Data clearness score:   15.7%
Inverter clipping:      True
Time shifts corrected:  False
```

Future Work

- Improved documentation
- Remove Mosek dependence
- Test at scale

Conclusions

- Tools intended to support and expand data science in the PV community.
- Automated algorithms for scalable pipelines
  → Scripts, cluster computing
- Convenient class structure with built-in plotting functions for data inspection
  → Jupyter notebooks, IPython
- Solving data preparation problems with unsupervised machine learning
- `solar-data-tools` on GitHub, PyPI, and Anaconda

GitHub repo →

Acknowledgments

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The Influence on Cracked Solar Cell Degradation from Hurricane Dorian Wind Loading Events and the Influence of *RailPad* Bracing Elements

Hubert Seigneur[1], Eric J. Schneller[1], Dylan Colvin[1], Rob Janoch[2], Andrew Anselmo[2], Andrew M. Gabor[2]

[1]Florida Solar Energy Center, University of Central Florida, Cocoa, FL USA
[2]BrightSpot Automation, Westford, MA, USA

UCF

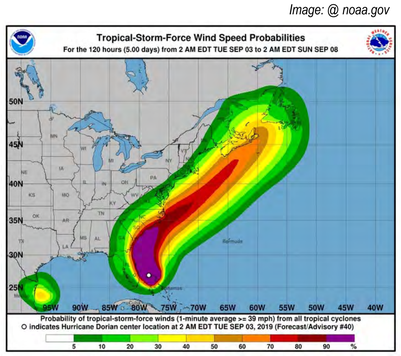
Introduction

- Cracks evolve over time and so do their influence on the overall power degradation of PV modules [1-3] as well as their safe operation [4].
- Incidents leading to crack formation, propagation or subsequent opening can occur at all stages of the PV module life including manufacturing [5-7], transportation [8], installation [9], and field operation [10-11].
- This work investigates the effect of moderate wind loading events on PV module with pre-existing cracks together with the influence of *RailPad* bracing elements from *BrightSpot Automation* [12].

Case Study: Hurricane Dorian

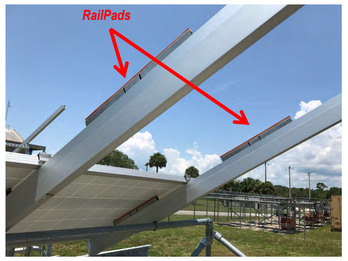
- Hurricane Dorian's nearby trajectory off the Florida coast produced 1-min average wind speeds up to 64 km/h (40 mph) at our facility.

Image: @ noaa.gov



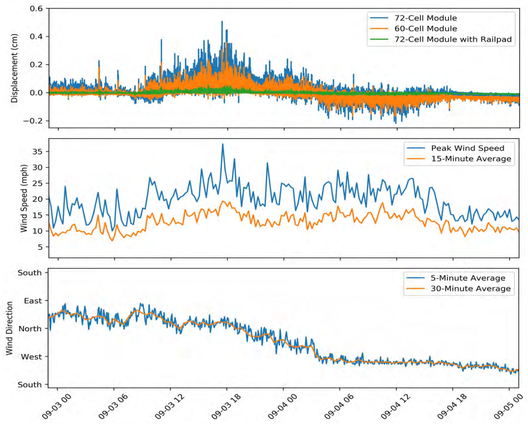
Experimental Setup

- 4 Modules installed
  - 2 multi-PERC 60-cell modules (4 busbars) called A1 and A2
    - Cracks created with a 5400 Pa static load
    - No *RailPads* used
  - 2 multi-PERC 72-cell modules (5 busbars) called B1 and B2
    - Cracks initiated with ½TC (-40°C) then propagated with a 2400 Pa Load
    - Module B1 is installed with *RailPads*
- 1 second displacement data
- 1 minute weather data
  - Wind speed, wind direction, temperature, RH, atmospheric pressure, etc.



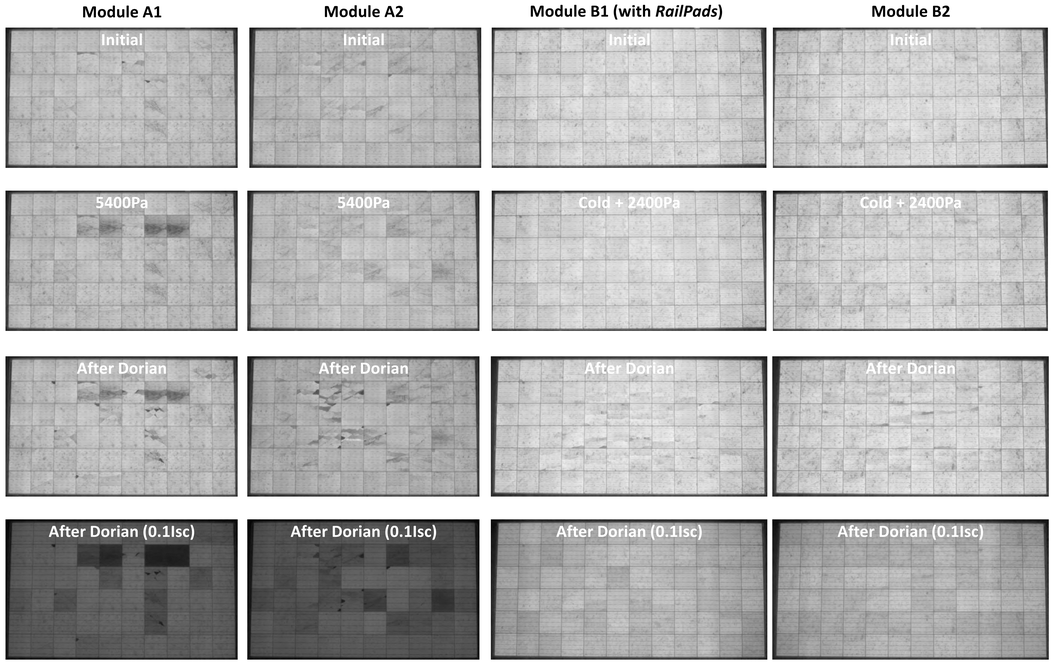
Results

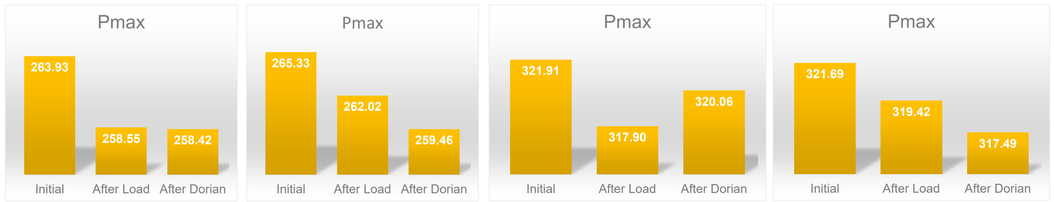
Displacement data as a function of Wind Speed and Wind Direction



Note:
Module orientation is due south

Crack Opening and Power Degradation





Module A1	Module A2	Module B1 (with *RailPads*)	Module B2
Some crack opening	Significant crack opening	Some crack opening (note: EL taken without the *RailPads*)	Some crack opening
No degradation in Pmax after Dorian	**1% loss in Pmax after Dorian**	**1% gain in Pmax after Dorian**	**1% loss in Pmax after Dorian**

Discussion

- The measured maximum deflection of modules without *RailPads* was 0.5cm, which is equivalent to about a 150 Pa uniform load for a 60-cell module. This is *smaller* in contrast with the 2400 Pa load applied in IEC 61215 standard wind load testing.
- The measured displacement data of all modules exhibited high frequency, *much higher* in contrast to 1 to 10 cycles per minute used in the IEC 61215 standard wind load testing, and a strong asymmetry in the cycles depending on the wind direction.
- When the winds came from the North (blowing behind the module), the module without *RailPads* oscillated in a regime that put the cells in more compression.
- When the winds came from the West, the module without *RailPads* oscillated on both side of the resting position resulting in both more compression and more tension.
- When the winds came from the South-West (blowing in front of the module), the module without *RailPads* experienced oscillated in a regime that put the cells in more tension.
- The module mounted with *RailPads* showed strikingly reduced deflection and a gain 1% in maximum power after the hurricane.
- 2/3 of the modules without *RailPads* lost 1% in maximum power

Conclusion

- Moderate wind loading events can produce non-visible damage to PV module (i.e. force closed cracks to open) resulting in measurable power degradation overnight
- It is critical that avoid creating cracks at any stage of the PV module lifecycle
- The use of *RailPad* bracing elements to mitigate power degradation in already cracked module or to prevent cracks from forming in new installs is promising
- To our knowledge, this is the first publication using EL imaging to observe crack opening in the field due to cyclic loading from a single storm event

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FSEC BrightSpot Automation Powered by SunShot U.S. Department of Energy

This material is based upon work supported by the U.S. Department of Energy's Solar Energy Technologies Office under the Photovoltaic Research and Development (PVRD) program Award Number DE-EE0008152

PV High Wind User Test Facility

Otto Van Geet, Jeroen van Dam, Scott Dana, James Elsworth
National Renewable Energy Laboratory

Gerald Robinson, Lawrence Berkeley National Laboratory

WE WANT YOUR INPUT!

The Challenge

Wind loading, such as that experienced during hurricanes Irma and Maria, has caused catastrophic damage to solar fields. This significantly reduces the potential value of solar as a resilient power solution. In many locations, there is a need and demand for stronger PV systems.

Photo from Above Photography

Photo from Andy Walker, NREL

Impact

There can be a tendency to race to the bottom cutting capital costs, devaluing robust design features and technologies. This project seeks to enable testing of various designs for PV systems in high wind or storm prone regions, with the goal of helping industry identify effective ways of hardening PV arrays in the face of high wind loads and protecting solar modules exposed to extreme or repetitive stresses. There is some indication that cost-effective, storm hardened design elements exist that could benefit from further evaluation and validation.

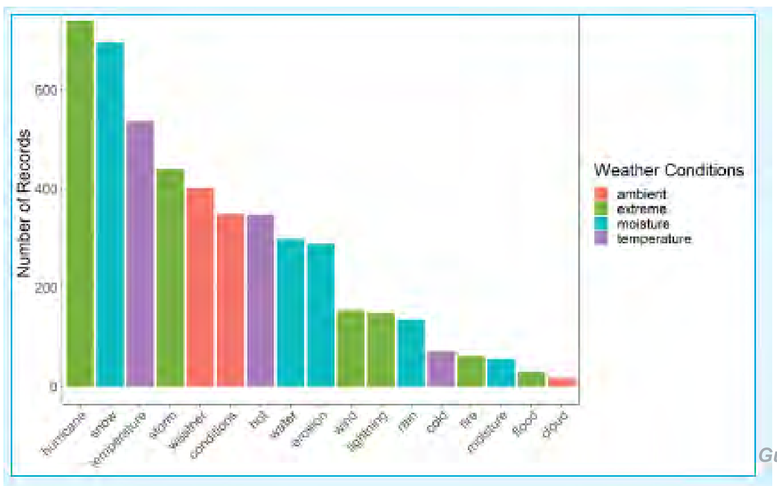

Figure from Gunda, T., 2019

The PVROM database documents common words featured in PV O&M tickets. The figure above shows that 'hurricane',' 'storm,' and 'wind' are the most common extreme weather events causing damage to the PV systems included in this analysis. The figure below shows that hurricanes were the top source of PV insurance claims, as well.

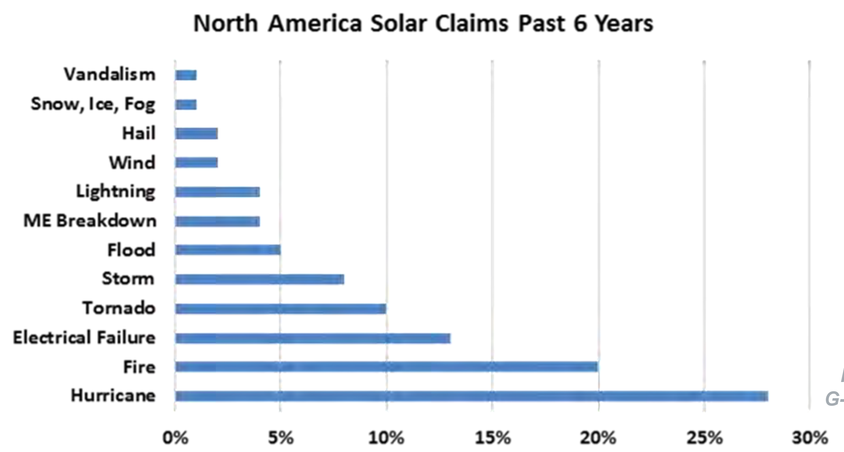

Figure from G-Cube, 2018

Photo from UTMSI

Proposed Project

The creation of a PV high wind test facility at the NREL Flatirons Campus that will enable private and public research efforts aimed at storm hardening PV systems. The facility will be instrumented to monitor effects of high wind conditions on modules and other array components. These in-field tests will coordinate with flow models, wind tunnel testing, validation of PV aeroelastic design codes, and post-testing module and system component analysis.

Initial Concept

Creation of an L-shaped testbed with a "strong floor" – a poured concrete slab with embedded threated inserts on a grid to which we could attach various system configurations for in-field testing. In-field testing will validate flow models and wind tunnel testing

Two images showing various impacts from the same storm in Puerto Rico. Humacao installation (left) suffered near total damage while Oriana array (right) needed replacement of only ~10% of modules, largely because of superior structural design

Potential Projects:

<u>Fasteners and Bolted Joints</u>: Testing of various bolted joint or clamping configurations such as through bolting, locking fasteners, clamp position, number, length

<u>Array shapes and layouts</u>: Testing of various tilt angles, heights, row spacing

<u>Tracker systems</u>: testing locking trackers, stow angles, racking designs

<u>Racking systems</u>: Various materials, shapes, and designs that can maintain structural integrity in the face of high winds and other severe weather

<u>Wind-calming fence:</u> Installing a fence around an array to reduce loads on perimeter rows.

(left) A solar PV tracker wind loading experimental setup showing instrumentation

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PV Reliability Workshop
Lakewood, CO
February 25-27, 2020
NREL/PO-7A40-76046

DuraMAT
Durable Module Materials Consortium

Discover, Develop, and De-Risk module materials, architectures, accelerated testing protocols,data analytics, and financial models to reduce the LCOE of solar energy

Combined-Accelerated Stress Testing for Advanced Reliability Assessment of Photovoltaic Modules

Michael Owen-Bellini*[1], Peter Hacke[1], Sergiu Spataru[2], Dana Sulas[1], Hannah North[1], David C. Miller[1], Michael D. Kempe[1]
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DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. Predictive Simulation
3. Advanced Characterization & Forensics
4. **Module Testing: Module Prototyping and Combined-Accelerated Stress Testing (C-AST)**
5. Field Deployment
6. Techno-Economic Analysis

Capability Goals

Combining the stress factors of the natural environment, with fewer modules and with fewer parallel tests, it will be possible to discover potential weaknesses that are not known a-priori in new module designs, reduce residual risk, accelerate time to market and bankability, reduce costly overdesign, and apply known degradation rate equations to estimate service life for the degradation mechanisms observed in C-AST.

Milestones

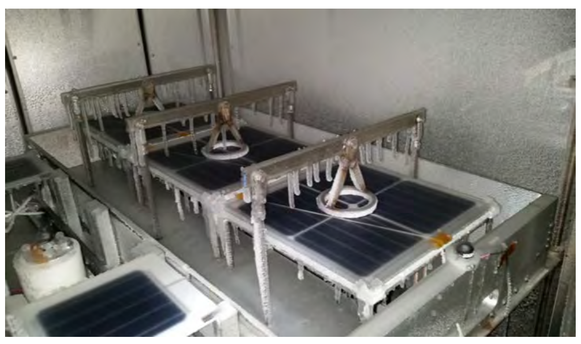
- C-AST tool brought to operational status
  - humidity, light, temperature, voltage & mechanical stress
  - automated, programmed stress cycle control, with database
- Build modules for C-AST backsheet experiment
- Indentation hardness testers differentiate backsheets
- Develop C-AST testing protocol
- Develop In-situ EL and IV capability

Outcomes and Impact

- Evaluation of backsheets as the vehicle for demonstration
- Show interactions between BOM and environmental stress
- Observation of failure mechanisms not seen in single factor tests, reducing risk.
  - exchange of samples with capability 3 and 5 for forensics and fielding

Capabilities and Test Protocol

- New and previously undiscovered degradation mechanisms continue to be identified after field exposure in new photovoltaic module designs or materials
- Oftentimes results in significant losses in investment
- This is despite passing certification tests. Testing is insufficient largely due to their single- or double-stress nature.
- A Combined-Accelerated Stress Test (C-AST) has recently been developed
- The test combines multiple stress factors of the natural environment to better replicate conditions experienced by modules in the field and detect mechanisms not *a-priori* known in new materials and designs



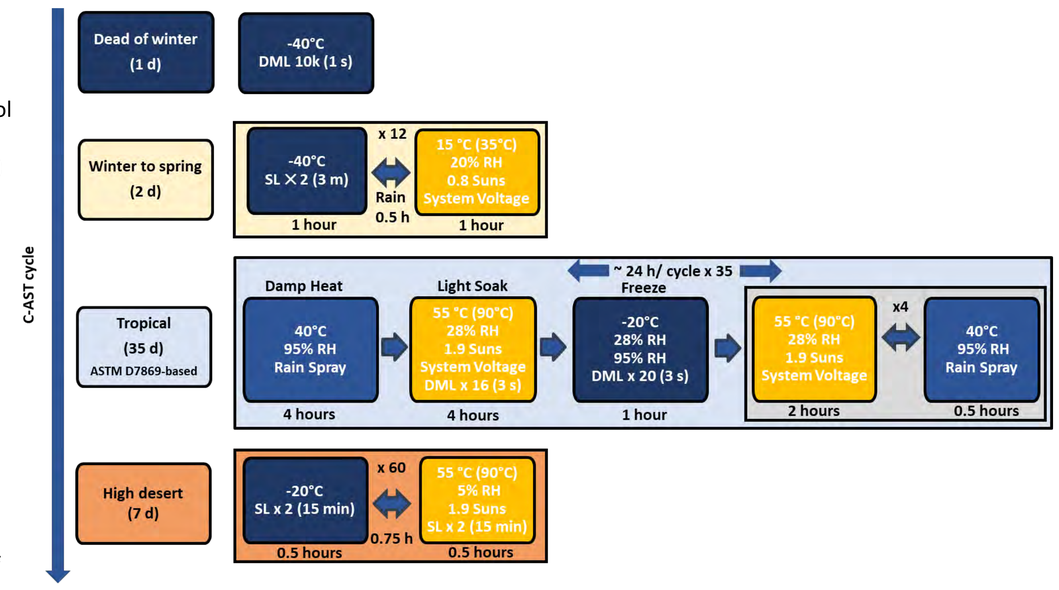
Inside the chamber during wet freeze stage

Modified Atlas XR-260 :

- -40°C to 90°C temperature control
- 5% to >95% relative humidity
- 2-sun Xe light exposure (4 lamps)
- Water spray (front and back)
- Mechanical loading
- System voltage (±1200 V)
- Reverse Bias*
- Variable load resistors
- Reflective troughs
- Keithley 2651a for EL/IV

*planned

- Module temperature monitored via T-type thermocouples on rear surface
- 6x LI-COR LI-61713 pyranometers positioned next to each sample
- LI-CORs monitored using National Instruments 9205 digital-to-analogue card with sampling rate of 2kHz



Multiple environment combined-accelerated stress testing (C-AST) cycle. Module temperature, when different from chamber air temperature, is shown in parenthesis. Ramp times are not necessarily included and shown time is sometimes rounded to the next higher integer unit.

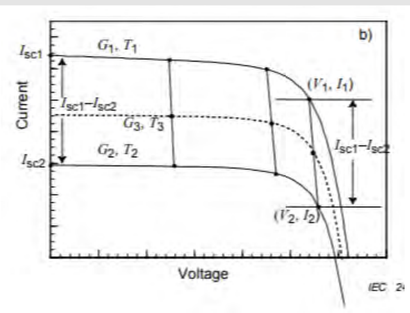
In-situ IV Curve

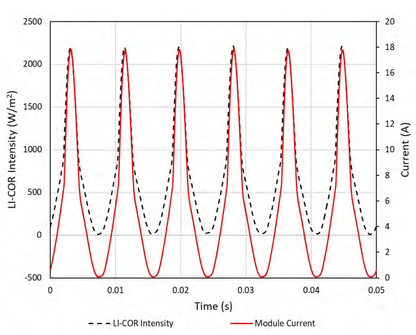
- Xe light source driven by AC supply means light fluctuates at ~100Hz
- Solution:
- Pulse voltage and take multiple current measurements (100kHz)
- Filter for highest current value where highest irradiance is known

Difficult to set lights such that peak irradiance = 1000W

Tow curves measured at different irradiance

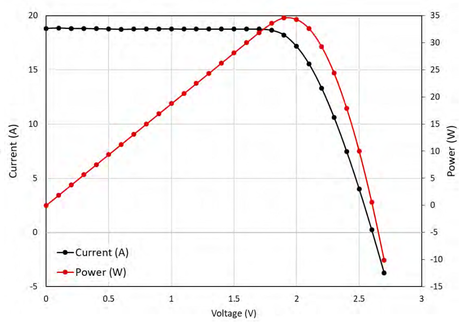
Curves at Standard Test Conditions can be interpolated/extrapolated from two IV curves using protocols outlined in IEC 60891





Current measurements for a 0.05s 0.1V pulse

Repeat & Filter



Light-IV curve constructed from multiple pulses in 0.1V increments

$$V_3 = V_1 + a(V_2 - V_1)$$
$$I_3 = I_1 + a(I_2 - I_1)$$
$$a = \frac{G_3 - G_1}{G_2 - G_1}$$

I_1, V_1 = I-V points for G1
I_2, V_2 = I-V points for G2
I_3, V_3 = Corrected points for G3
G_1, G_2 = Irradiances for curves 1 and 2
G_3 = Target/corrected irradiance
a = interpolation constant

Acceleration Factor Modeling

Failure of AAA in 3000 hours C-AST testing

Example field-aged AAA

$$t_1 = t_2 \left(\frac{L_2 I_2^x (b + mTOW_1) \left(T_f^{\left(\frac{T_2 - T_1}{10}\right)} \right)}{L_1 I_1^x (b + mTOW_2)} \right)$$

t_1 = time in test 1 (outdoors)	T_1 = specimen temperature in test 1
t_2 = time in test 2 (accelerated)	T_2 = specimen temperature in test 2
I_1 = actual irradiance in test 1	T_f = thermal acceleration per 10°C
I_2 = actual irradiance in test 2	TOW_1 = time of wetness for test 1
L_1 = light on fraction in test 1	TOW_2 = time of wetness for test 2
L_2 = ligt on fraction in test 2	X, b, m, T_f – extracted constants

R. M. Fischer and W. D. Ketola, "*Error Analyses and Associated Risk for Accelerated Weathering Results*," in 3rd International Service Life Symposium, 2004, no. February

Location	Time in outdoors		Acceleration Factor
	Hours	Years	
Miami, Florida	36110	4.12	12.04
Phoenix, Arizona	36968	4.22	12.32
St. Paul, Minnesota	92438	10.55	30.8

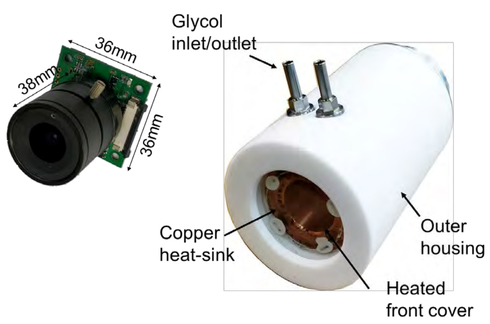
3000 hours in C-AST tropical sequence represents ~4 years in worst-case locations for AAA

Lines up with reports of field failure of AAA within 4-5 years exposure

Calculated time-to-failure using Fischer equation based on time-to-failure in C-AST and field data from 3 locations. Calculated values based on mean extracted constants

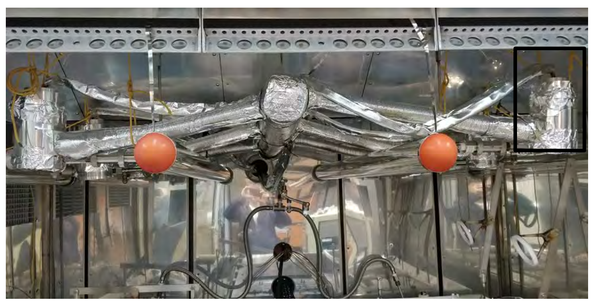
In-Situ Electroluminescence Imaging

- Sony IMX219PQ 8.08Mpixel camera with an Arducam LS-61018CS lens is used for imaging



- Camera has small form factor (36mm x 36mm x 38mm) and is very low-cost
- Camera position is limited to 0.59m above the sample plane, so a wide-angle lens (70°) is used which introduces some lens distortion
- A custom-designed camera housing has been developed to protect camera from the harsh conditions of the chamber
  - PTFE outer housing
  - Copper heat-sink inner housing with ethylene glycol feed through for liquid cooling
  - Heated front cover for defogging

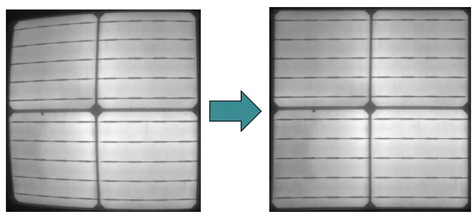
Image of cameras installed in all six locations in chamber



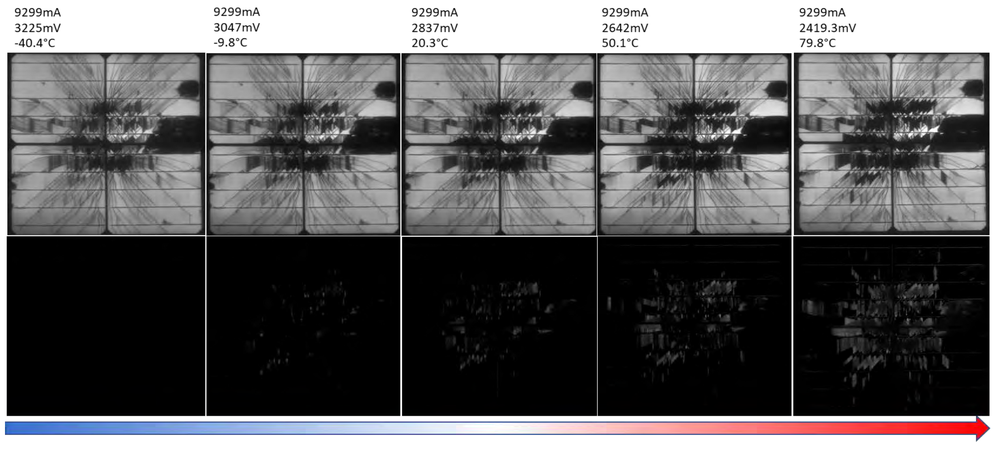
Lens Distortion Correction

Radial
$$X_{corrected} = x(1+k_1r^2+k_2r^4+k_3r^6)$$
$$Y_{corrected} = y(1+k_1r2+k_2r4+k_3r6)$$

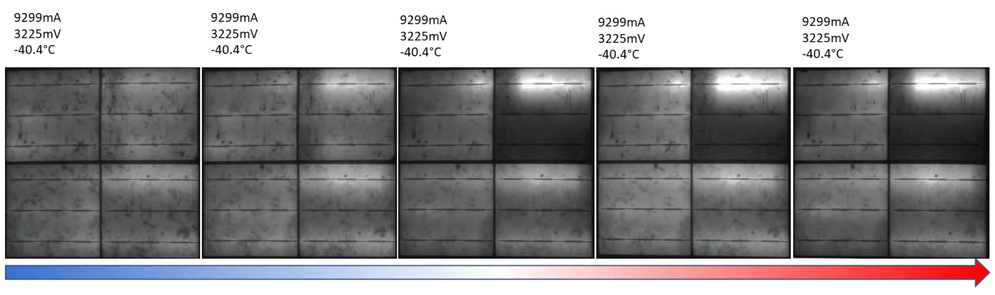
Tangential
$$X_{corrected} = x + [2p_1xy + p_2(r^2 + 2x2)]$$
$$Y_{corrected} = y + [p_1(r^2 + 2y^2) + 2p_2xy]$$



Severely cracked glass-glass module. As temperature increases, cracks can be seen to open and more of the cell area becomes disconnected



Module with degraded solder bonds. Solder bonds open and close depending on temperature



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Photovoltaic Reliability Workshop
Denver, CO
2/25/2019 – 2/28/2019
NREL/PO-5K00-73367

Determination of Outdoor Soiling Rates in Desert Environment by Comparing Daily I_{mpp} Current of Soiled and Cleaned Photovoltaic Strings

Elsa Kam-Lum , D. Cosme, M. Sakhuja, J. Chapon, M. Sander, S. Aid

Total R&D, GRP (Gas, Renewable and Power)

ABSTRACT

Soiling ratios derived from the daily median I_{mpp} currents of strings of 8 mc-Si modules, cleaned at two different frequencies, were monitored for a single axis tracker and a 22º fixed tilt in a Koppen Bwh, dry, subtropical desert site. The soiling ratio is represented by the ratio of the median daily I_{mpp} of a string cleaned every two months over a sibling string cleaned weekly. The daily median soiling ratios obtained between July 2019 to January 2020, for each mounting type are shown. Using the method presented, the site's soiling rate of 0.4 to 0.5%/day was found to be linear during July to early November's dry, ≤1 rain day/month period and accounts for between 80 to 96% of the soiling rate variation observed. Following a period of rain days, the site's soiling ratio decreased significantly to less than 0.1%/day from late December to January. These rates agree with B. Figgis, et.al [1] reports of a range of 0.1 to 1%/day soiling rate in the same climatic area. Comparable soiling rates obtained with one of two sensors of a commercial soiling meter installed on the fixed tilt rack provides further reasonableness of the results.

EXPERIMENTAL SET-UP

Four strings consisting of 8 mc-Si 220W commercial modules with 6 years prior same field exposure in Doha, Qatar, were installed in two mounting configurations : two strings on 22º fixed tilt racks and two strings on a single axis tracker stowed at 45º at night. Modules with prior same field exposure, in the more stable, lower constant failure rate of the bathtub degradation curve, were chosen to minimize the impact on the results from the typically higher early degradation rates (LID , LeTID, infant mortality, etc.). Using commercial modules provided the added advantage of site soiling rate determination on a larger area for better site representation, on specific PV technology and modules' build of materials such as glass and AR coatings that can affect the soiling deposition rate of the modules of interest. For each mounting system, one string was cleaned weekly and the other, every 2 months.

DATA and DATA TREATMENT

Data: one minute string I_{mpp} and irradiance measurements

Data Treatment:

(1) Irradiances of <500 W/m² were filtered out of the raw 1 minute data to minimize irradiance losses and effects associated with low irradiances farther from solar noon [2]. The 500 W/m² value was selected arbitrarily as a starting point and may be further optimized.

(2) The minute by minute soiling ratio was calculated as follows:

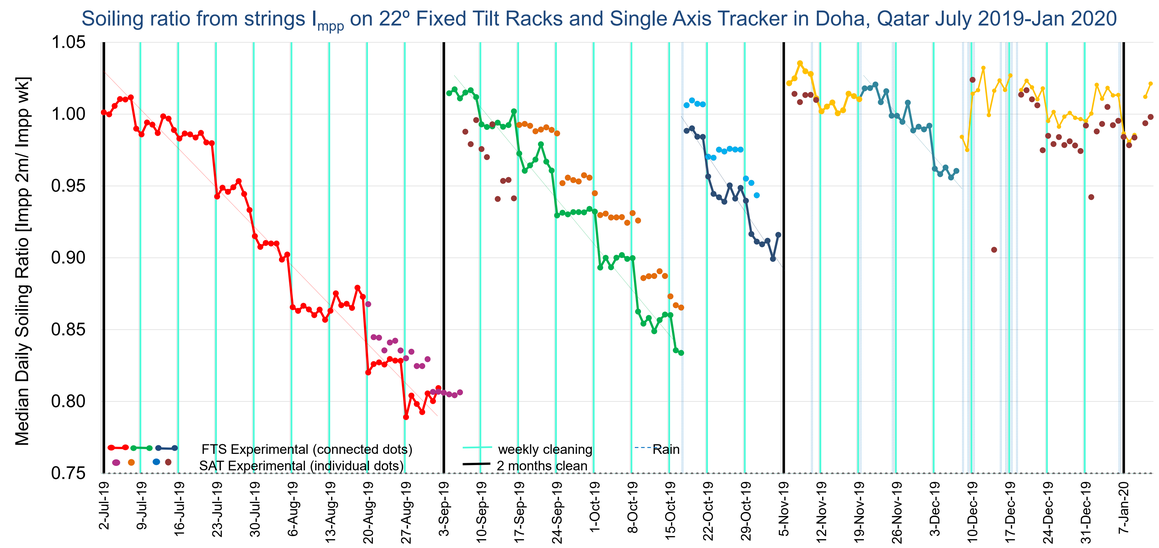
$$Soiling\ Ratio_{\ minute Impp} = \frac{Impp\ (minute) of\ string\ cleaned\ every\ 2 months}{Impp\ (minute) of\ string\ cleaned\ weekly}$$

(3) Outliers: >3 sigma were filtered out to minimize events that could skew the ratio by affecting only one of the two strings. These include but are not limited to momentary cloud shadows, missing data, etc.

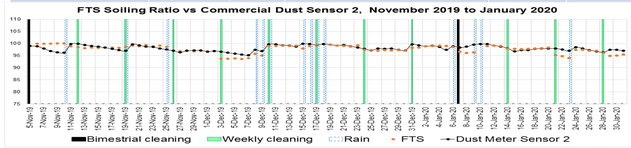
(4) The median daily soiling ratio (graphed values)

Daily Median Soiling Ratio = median of the filtered minute soiling ratios for the day

RESULTS and DISCUSSION



Period	Fixed Tilt System (FTS)			Period	Single Axis Tracker (SAT)		
2019-2020	**Soiling rate**	**Equation**	**R^2**	**2019**	**Soiling rate**	**Equation**	**R^2**
July 2-Sep2	0.38 %/day	Y=-0.0038x + 1.032	0.955	Aug 20-Sep 6	0.32 %/day	y=-0.0032x + 1.014	0.882
Sep 4-Oct 16	0.44 %/day	Y=-0.0044x + 1.315	0.960	Sep 17-Oct 16	0.44 %/day	Y=-0.0044x + 1.35	0.947
Oct 17-Nov 5	0.51 %/day	Y=-0.0051x + 1.544	0.877	Oct 17-Nov 5	0.46 %/day	Y=-0.0046x + 1.51	0.799
Nov21-Dec 7	0.41 %/day	Y=-0.0041x + 1.608	0.875	Nov21-Dec 7	System down	grid connection problems	NA



The I_{mpp} ratio method results in comparable indications of soiling with one sensor of two from a commercial dust meter installed on the fixed tilt rack.

Note: The discrepancy between the two sensors in the meter is being investigated.

- Soiling rate for this Koppen Bwh subtropical desert site, using the described Impp ratio method, was between 0.4 to 0.5%/day during July to November, dry period with 0 to 1 rain day for the month, typical of 5 months (June-October) of the year in Doha.
- I_{mpp} current of the strings with modules not cleaned for 2 months decreased to about 80% of their initial cleaned state during the drier periods with ≤ 1 rain day/month
- During the ≤1 rain day/month dry period, the soiling rate calculated by this method resulted in a linear rate that accounted for 88 to 96% of the soiling rate variation on the strings on the fixed tilt rack, and 80-95% for the strings on the single axis tracker, latter attributed to significantly higher data gaps.
- After rain days in November to mid December, the soiling rate decreased to less than 0.1%/day in late December and January.
- It is not clear whether the soiling rate reduction after several rain days are a result of the additional cleaning, or whether the rains are part of the change in seasonality and associated factors that affect soiling rates
- The rates measured are within reported rates for Doha, Qatar by B. Figgis, et.al.[1]
- Some rain days had the equivalent effect as the bimestrial cleaning of resetting the I_{mpp} ratio to 1.0
- Further research on identification of specific factors that significantly impact soiling rate are needed for better long term and more complete seasonal soiling rates characterization.

CONCLUSIONS and RECOMMENDATIONS

- A method to estimate site soiling rates using data readily obtained from existing plant equipment and site installed PV modules, holds early promise for deriving linear median specific site and module's soiling rates during dry periods with non to infrequent rain days. In locations like Doha, Qatar, where the dry period lasts typically 5 to 6 months, if the soiling rates are highest during this period, this information may be valuable for optimizing cleaning frequency and costs against energy production losses
- Verification of these findings with longer duration data and replication is needed. For more complete soiling rates characterization and prediction, consideration of many more factors, too many to list, are needed [1,2,3,4,5]. Please refer to bibliographies of cited references and extensive published soiling literature

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NREL is a national laboratory of the U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Analysis of Hail Damage in PV Modules with Respect to Mounting Angle and Direction

Peter Hacke [1], Kent Terwilliger [1], Andy Walker [1], and Vincent Guthrie [2]
[1] National Renewable Energy Laboratory
[2] Fort Carson - Utility Programs

1. Overview

Hailstorm events are sometimes catastrophic for PV solar fields.

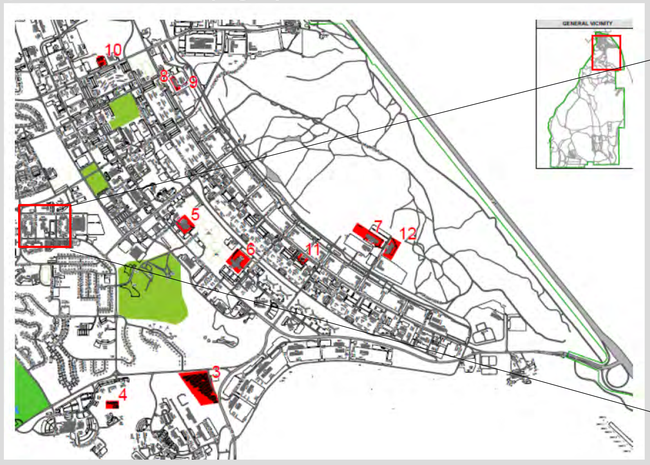
Numerous PV installations in Fort Carson, Colorado suffered in a great hailstorm on June 13, 2018.

Because it is difficult to prevent breakage of glass module superstrates from direct hail impact, appropriately choosing tilt and orientation (for wind effects on hail) may significantly reduce breakage of modules in the event of hailstorms.

We examined different systems at Fort Carson that were mounted at different angles and different orientations to see statistically which survived better. This report tests the hypothesis that modules at greater mounting angle and facing away from the wind direction would survive better. These factors may be considered when mounting modules in hail-prone areas.

2. Background

Seven sites across the military base (selecting from those highlighted in red) and a residential area in the red square and pictured below (right) were examined



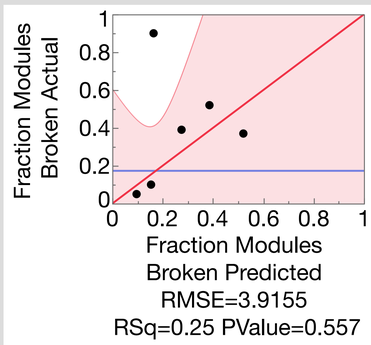
3. Results – Military Base

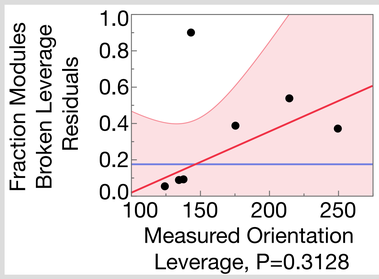
BLD	Location note	Measured Orientation	Measured Tilt	images	Size of PV System	Type of System	Total Modules	Broken Modules	Fractions Modules Broken
1283	site 9	144	11.2	23-29	35 kW	Roof Mount	96	**86**	**0.90**
1280	site 8	250	12	30-33	50 kW	Roof Mount	108	**40**	**0.37**
842	carport, site 10	141	6	34-38	235 kW	Carport	940	**91**	**0.10**
9067	site 7	210	22.5	39-46	20 kW	Ground Mount	56	**29**	**0.52**
9079	site 12	177	9.5	47-48	33 kW	Roof Mount	140	**54**	**0.39**
2039	site 6	124	35.5	57	62 kW	Ground Mount	240	**12**	**0.05**
1925	athletic center site 5	124	13.5	58	87 kW	Roof Mount	348	**17**	**0.05**

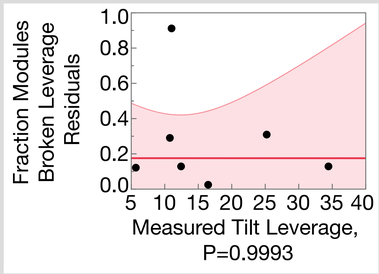
Magnetic N = 0, E = 90, S = 180, W = 270 orientation
The winds blew and the hailstorm travelled from the northwest to the southeast

Can increasing tilt and orienting modules away from storm winds reduce hail damage?

4. Linear Regression – Military base







Blue line is set at the mean of the Y leverage residuals; fit is solid red

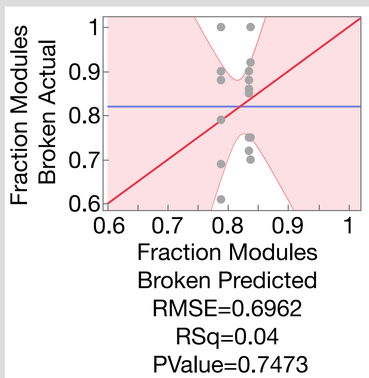
- ***Some possible dependence of breakage on orientation, but no relationship with tilt angle observed. Maybe range of tilt was too small and too close to horizontal?***
- ***Analysis not controlled for module type, which may have confounded results***

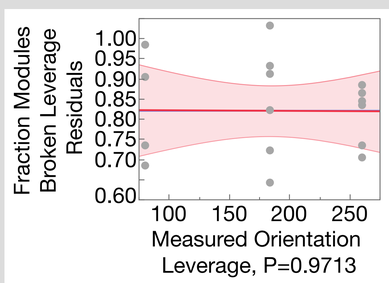
5. Results – Residential Area

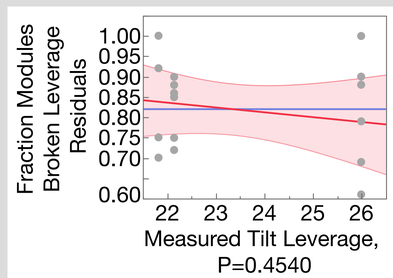
BLD	Location note	Measured Orientation	Measured Tilt	images	Size of PV System	Type of System	Total Modules	Broken Modules	Fractions Modules Broken
6087		177	26	59		Ground Mount	16	16	**1.00**
6087		84	22	80		Ground Mount	40	40	**1.00**
6088		84	22	81		Ground Mount	37	34	**0.92**
6088		177	26	81		Ground Mount	8	7	**0.88**
6087		264	22	60,61		Ground Mount	40	36	**0.90**
6083		84	22	62,63		Ground Mount	44	31	**0.70**
6082	S array only	177	26	64,65		Ground Mount	16	11	**0.69**
6082	E array only	84	22	76		Ground Mount	40	30	**0.75**
6089		264	22	66		Ground Mount	42	36	**0.86**
6088		264	22	67		Ground Mount	34	30	**0.88**
6090		264	22	68		Ground Mount	40	34	**0.85**
6094		177	26	69		Ground Mount	46	28	**0.61**
6093	W array only	264	22	71		Ground Mount	18	13	**0.72**
6091		264	22	72		Ground Mount	44	33	**0.75**
6093		177	26	73,74		Ground Mount	50	45	**0.90**
6092		177	26	75		Ground Mount	56	44	**0.79**

Magnetic N = 0, E = 90, S = 180, W = 270 orientation

6. Linear Regression – Residential Area





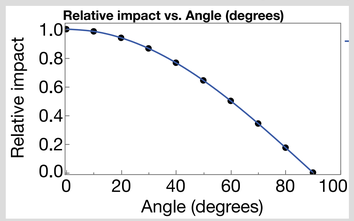


Blue line is set at the mean of the Y leverage residuals; fit is solid red

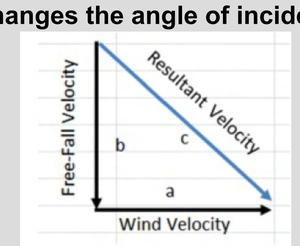
- ***Some possible dependence of tilt angle observed, but no effect of orientation seen; again, maybe range of tilt was too small and too close to horizontal? (modules are believed to be of the same type)***

7. Discussion

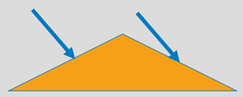
Assuming elastic collisions of hail with glass, force of impact should fall with angle of incidence as follows (cosine)



Wind increases the velocity and changes the angle of incidence[1]



We would anticipate wind to increase impact force on some surfaces, and reduce impact force on others



While giving some indication of these effects — the results were not statistically significant.

Considering the straight-forward physics, more research into mounting angle, orientation and use of trackers to reduce hail damage is warranted.

[1] https://donan.com/article/wind-effects-on-hail-velocity-and-impact-energy/ accessed 24 Feb 2020

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2020 PVRW, Lakewood, CO

Reliability Aspects of Adhesive Mounting of Conventional PV Solar Modules

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MOTIVATION & APPROACH

All current mounting approaches require roof penetration and associated flashing, which puts a time, cost and complexity floor on installation cost. In addition, rail-based mounting is heavy, has a high part-count and a complex installation process.

The project team, formerly based at Fraunhofer USA, has developed a non-penetrating adhesive mounting system for conventional framed c-Si modules for residential steep-slope asphalt shingled roofs. A substructure is adhered to the roof, and the PV modules are mounted to these substructures with traditional mounting clamps. The substructure transmits and distributes the module loads, including wind uplift, to the shingles. By distributing the force (and thus reducing stress) over the full area of the module, the integrity of the load-path between module and roof is maintained, ensuring that the system can meet uplift requirements.

CREEP

The creep was assessed by monitoring a small installation of both designs (D1 and I1) on a 6:12 sloped roof deck in Albuquerque. The systems experienced the hot season in Albuquerque, NM.

Installation of Creep study test arrays

Array Position.

Date	Ruler 01	Ruler 02	Ruler 03
9192018	10.5mm	203mm	402mm
9202018	10.5mm	203mm	402mm
9212018	10.5mm	203mm	402mm
9242018	11mm	203mm	402mm
9252018	11mm	203mm	402mm
9262018	11mm	203mm	402mm
9272018	11mm	203mm	402mm
10312018	11mm	203mm	402mm

Creep study test array

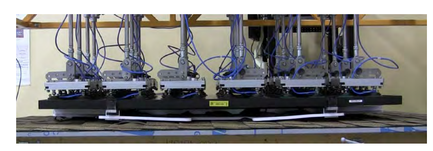
No significant movement observed in either array.

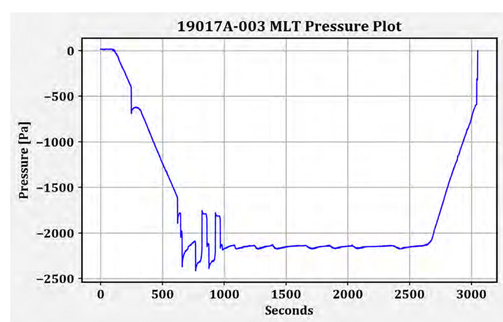
MECHANICAL UPLIFT TESTING

Four roof decks with asphalt shingles, using six nails per shingle were built and conditioned for 1 week outside in Albuquerque, NM for the sealant strip of the asphalt shingle to cure. Following the curing the substructures were applied using the foam adhesive.

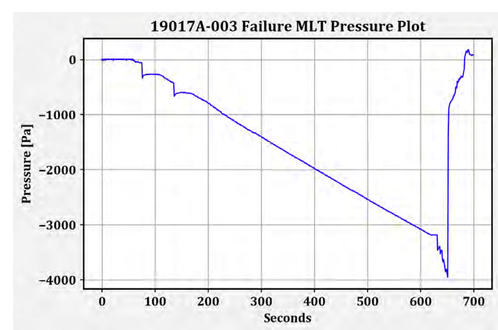
PV modules were mounted on the substructures using standard racking mounting clamps. Two decks were tested according to UL1703: The sample passes this mechanical load test if it stays in place for 30 minutes of 45 psf (2155Pa) pull force.

Roof decks after application of adhesive to the substructures





Pressure profile for UL1703 uplift test



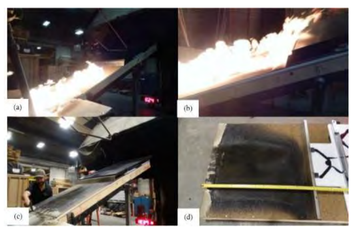
Pressure profile for test to failure

The adhesively mounted structure with mounted PV module setup was able to withstand the required 30 minutes of 45 psf (2155Pa) pull force.
→ The adhesively mounted framed module passed the UL1703 uplift requirement.

After the UL test, additional force was applied to determine the load at failure. Complete failure occurred at -3185 Pa (66.5 psf) for sample 1 and -3700 Pa (77.3 psf) for sample 2. Some shingle damage was observed during the test (adhesive failure at adhesive/shingle interface) (shingle tab uplift).

FIRE TESTING

Substructure with mounted modules during (a-b) and after (c-d) the UL1703 Class A spread of flame test, which was passed at the Western fire Center in Kelso, WA.



Substructure with mounted modules during (a-b) and after (c-d) the UL1703 Class A Burning Brand test, which was passed at the Western fire Center in Kelso, WA..

CONCLUSION

- No significant creep.
- Passed UL1703 mechanical uplift testing.
- Passed UL 1703 fire testing.

This work was supported by the Department of Energy under Award Number DEEE0008173 Adhesive Mounting of Conventional PV Modules for Residential Solar.

TOWARDS AN IEC LETID TEST STANDARD: PROCEDURES, KINETICS, AND SEPARATION OF B-O DEGRADATION FROM LETID

Q CELLS
Engineered in Germany

NREL Workshop 2020

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➔ MOTIVATION

LID effects have the most direct impact on the performance of a pv system, they translate 1:1 into energy losses. In crystalline silicon modules, light induced degradation mechanisms of different origins and time-scales are present:

- BO complex: mainly p-Cz, up to ~ 6%
- FeB/Fei: Cz and mc, up to ~2%
- LETID:Cz and mc, up to ~10%

BO-LID and FeB happen quickly (first days), included in IEC 61215 requirements
LETID happens over years, relevant for yield prediction & performance model of a pv system and is currently not included in qualification standards. A separate test spec is urgently needed. IEC round robin ongoing to establish appropriate conditions.

CHARACTERISTICS OF LETID

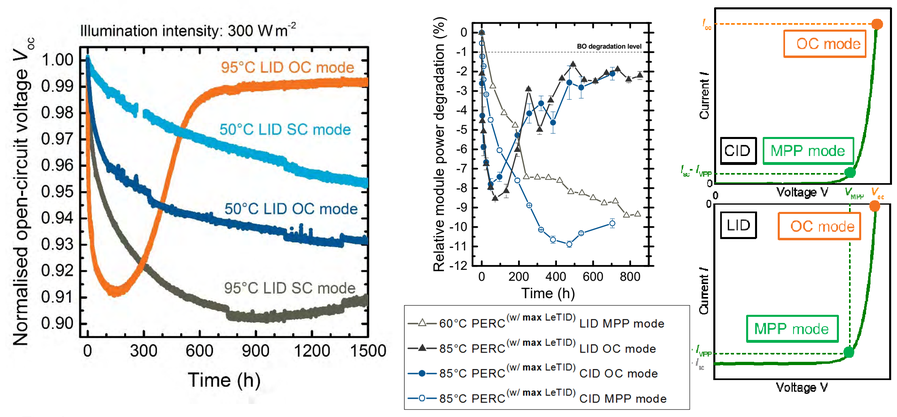


Fig. 1:
(left): light induced LETID degradation over time for different temperatures and injection levels (OC=open circuit, SC=short circuit, MPP=maximum power point)
(center): same, but induced by injecting current instead of illumination
(right): illustration of injection level conditions in dark, i.e. current induced (top) and light induced conditions (bottom).

Characteristics of LETID

A slow degradation induced by light at high T

- mainly seen in PERC-type modules
- can be present in Cz and mc-Si
- slow process - hundreds of hours in lab & up to many years in field for full cycle
- different from BO-LID (which takes hours to days)
- Occurs at T >50 °C
- degradation of Isc, Voc, Pmpp followed by slow recovery over time (years in field)
- Caused by excess carriers → can be induced either via illumination or current injection
- Speed depends on injection level and temperature

EXPECTATIONS TOWARDS STANDARD

General requirements of a standard

- detect LETID sensitivity, magnitude
  → a sample with LETID needs to show this in the test and the magnitude needs to be determined
- avoid false fails
  → it should not label other effects such as e.g. BO-LID as LETID
- be reproducible
  → two labs should get same result
  → repetition should yield same result
- work on every sample
  → needs to work on mc-Si as well as Cz-Si
  → different samples should be possible to test with same test instructions
- be practical from a lab perspective
  → easy, incomplicated handling
  → no constant manual monitoring
  → no changing or unpredictable test times or test flows
- easy to implement for a lab w/o prior knowledge
  → no custom, complex self-built equipment
  → no equipment with only one source, or patent protection
  → no complex engineering or analysis knowledge required
- be economical in order to be adopted widely
  → no expensive equipment
  → use simplest feasible approach
  → easily scalable for throughput

Use case specific requirements

- cell manufacturers
  → quick sampling tests (product/manufacturer specific, can require knowledge about process), feedback time critical
  → large statistics, exact value secondary
- module manufacturers
  → incoming inspection (fast, estimate, similiar to cell manufacturers but w/o internal knowledge about cell) vs. product qualification (durability, show product reliability, quantitative, slow test ok)
- Module customers
  → reliability of product, quantitative, pass-fail conditions
  → field relevance, separation of initial degradation from annual / slow effect for yield model
  → cost, lead time, simplicity
- test labs
  → handling (similar test times for different samples to avoid interruptions, chamber openings, daily schedule)
  → easy to implement
  → cost of equipment and scalability
  → reproducible
  → pass/fail that is relevant to the market, test conditions that create demand

➢ Cell test likely to differ from module test
➢ Standardization easier for module test as speed less critical

SCOPE OF AN IEC TS ON LETID

This test specification is designed to **assess the effect of light induced degradation at elevated temperatures (LeTID) by application of electrical current at higher temperatures**. LeTID is activated by excess carriers caused either through illumination or injection of electrical current at temperatures above 50°C. It usually develops on time scales slower than Boron Oxygen (B-O) such as months to years in fielded conditions. The degradation phase is followed by an even slower recovery phase that develops over a significantly longer time scale.

It **does not address the B-O and Iron Boron (Fe-B) related degradation phenomena**, which already occur at room temperatures under the presence of light and on much faster time scales. **B-O defects may influence the results, and this specification attempts to separate them by application of certain procedures**. However, it is noted that the separation may not be perfect. Fe-B effects are excluded by introduction of waiting times before power determination.

The proposed test procedure **may reveal sample sensitivity to LeTID degradation mechanisms, but does not provide an exact measure of field observable degradation**. The magnitude and time scale of degradation seen in the field depends on climate and the module technology.

LETID TEST CONDITIONS

TEST PROCEDURE	& PARAMETERS
Use current instead of light to stress module →minimize cost and effort Injection level comparable to maximum power point conditions.	Climatic cabinet with power sources to inject current into modules Current level $I_{test} = I_{sc} - I_{mpp}$
Use a temperature that allows test in reasonable time without missing some of the effect	75 °C
Monitor dark voltage at fixed current to identify the minimum	Test with weekly readout until dark voltage starts to recover, but at least 1 week

STANDARDIZATION STATUS

IEC module qualification standards IEC 61730, 61215 series

- LETID test was proposed but removed at CDV stage to speed up next edition
  → moved to a separate standard, currently under development
- Round robin for test conditions ongoing.

IEC TC82 WG8 wafer/cell

- Activities ongoing, but current focus on LID, LETID to be included at later stage

SEMI SEMI draft proposes cell- and module test conditions

- Standard test conditions same as IEC draft (75°C, I=Isc-Imp), other exploratory conditions for research purposes

TÜV Rheinland

- 2PfG published. Testing commercially available
- Similar (not same) conditions to other proposals
- Current I=2*(Isc-Imp) → slightly accelerated

FIELD RELEVANCE – CYPRUS TEST

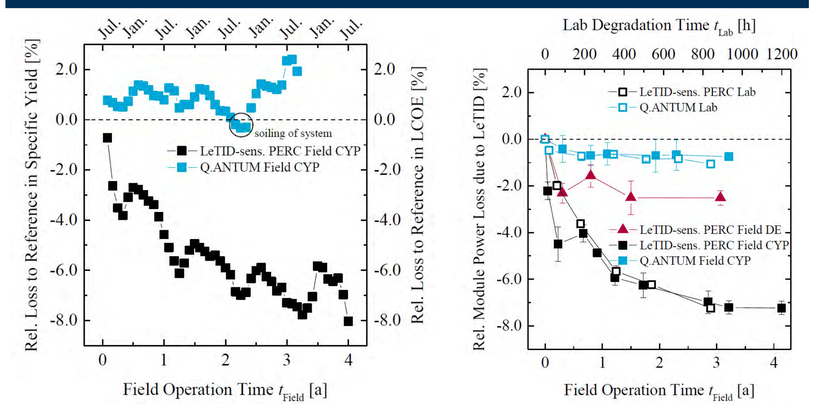


Fig. 3: (left) Relative specific yield loss over time in years for LETID sensitive mc-Si (black) and Q.ANTUM modules (blue) at Cyprus, i.e. Southern Mediterranean, test site.
(right) Comparison between relative module power loss due to LETID for sensitive (black) and Q.ANTUM (blue) as measured in lab setup (upper legend) versus outdoor results from Cyprus (black, blue) and Germany (red) test sites.

LONG TERM STABILITY > 15 YEARS

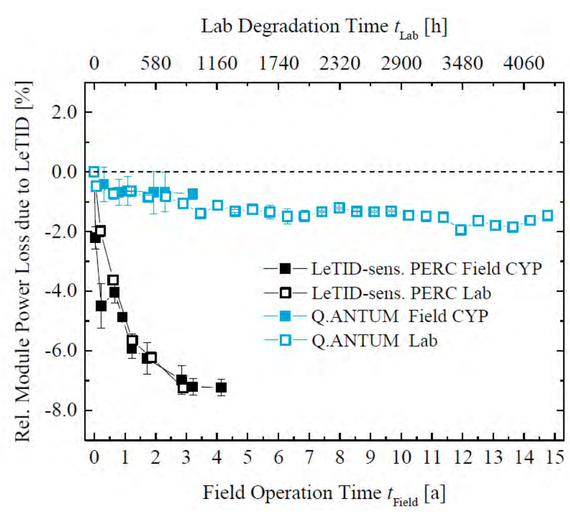


Fig. 4: Degradation over time for LETID sensitive (black) and Q.ANTUM (blue) modules. Correlation between field degradation in Cyprus (solid) and lab data (MPP mode 75°C, open symbols) allows extrapolation to service life.

- LETID is preventable and modules are long term stable

B-O LID DURING LETID TESTING

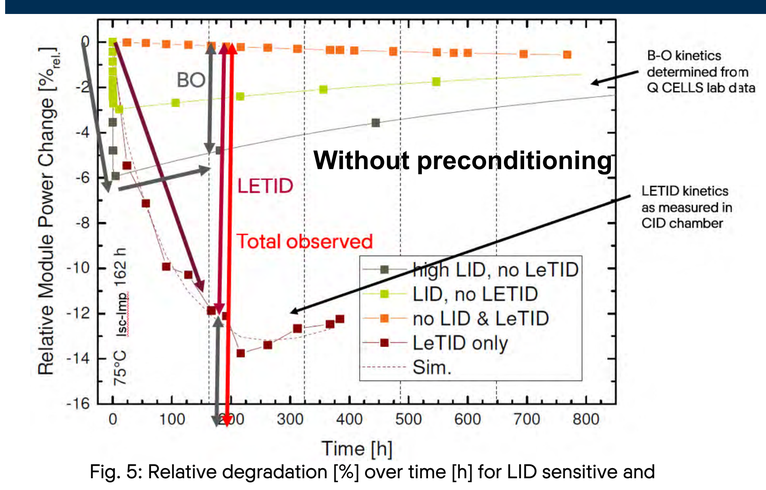


Fig. 5: Relative degradation [%] over time [h] for LID sensitive and LETID sensitive modules during LETID test sequence at 75°C

- During LETID sequence, B-O degrades fully, leading to an additional signal of up to 5%, thereby failing LETID insensitive modules falsely

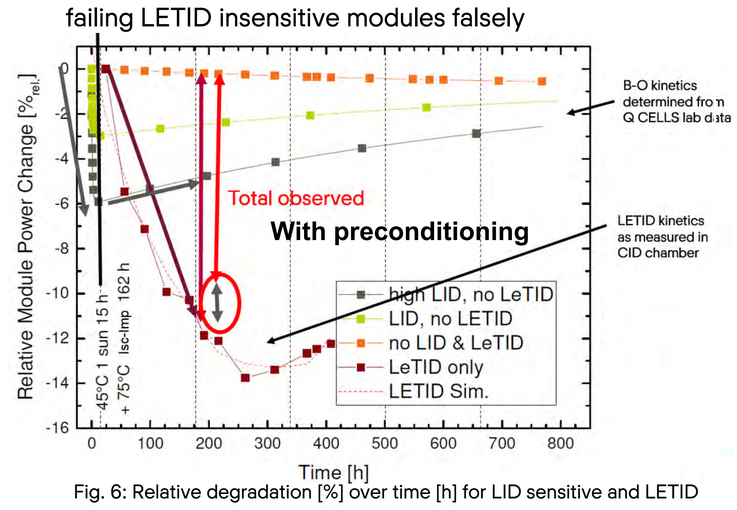
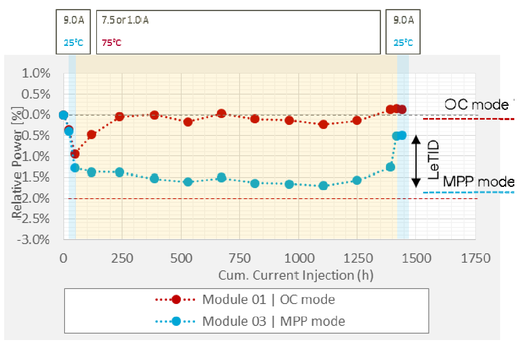


Fig. 6: Relative degradation [%] over time [h] for LID sensitive and LETID sensitive modules during LETID test sequence at 75°C

- With typical B-O LID present, the error due to regeneration is <0.5%
- Even in presence of extreme B-O degradation, the error remains small

SEPARATION OF LID & LETID (II)



(1)25°C 9.0 A 24 h
→ B-O LID
(2)75°C Isc-Imp
→ BO + LeTID (until minimum)
(3)25°C 9.0 A 24 h
→ switch back to B-O level
Difference between (2) and (3) = LeTID

- Current injection at 25°C deactivates LETID defects, only BO-LID remains.
- LETID can be determined as difference between before and after 25°C cycle

➔ CONCLUSION

- LID effects can have very significant effect on energy yield production of PERC modules
- LETID occurs in multi- as well as mono-crystalline PERC modules
- LETID testing can be done more efficiently using current induced degradation (CID)
- Test conditions 75°C CID I=Isc-Imp, preceded by preconditioning for BO-LID. (CID @25°C).
- B-O LID can significantly influence results and cause false fails in LETID testing when initial stabilization is omitted
- Separation of BO-LID and LETID is possible
- An IEC TS is currently in preparation

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➔ participation in IEC project team welcome

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Performance Comparison of Bifacial PV Modules due to Soiling in Desert Climates

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2020 PV Reliability Workshop

Background

Despite having a large solar resource, the desert climate of the Middle East region is challenging to PV, since many of the factors affecting PV system reliability and durability are in simultaneous operation. In Doha, for example, average module temperature can reach 50º C during the summer [1], the ambient monthly average humidity is over 50% [2], and soiling losses can decrease the power of 22º tilted modules by up to 20% per month [4].

In this study, we explored the potential of bifacial PV modules in the desert climate, focusing on the impact of the environmental conditions such as soiling on energy yield. During 8 weeks of field exposure, power loss due to soiling for bifacial modules was approximately half that of monofacial modules, thereby giving significant additional average bifacial gain in daily specific yield.

Experimental

Six 270W-rated crystalline silicon PV modules, four bifacial (Bifaciality 90%) and two monofacial ones were studied. The two monofacial modules and two bifacial modules were installed at standard 22º tilt, facing south, while the other two bifacial modules were installed vertically facing east. One module in each category was cleaned weekly (Clean), while the other was never cleaned (Soiled).

Results

Figure1a: Clean Modules (Day 01)

Figure 1b: Modules after3 weeks of outdoor exposure (Day 24).

Figure 1 shows the installed modules in clean condition (Fig. 1a) and after three weeks of field exposure (Fig. 1b). The 22º tilted modules are significantly soiled, while the vertical module is still clean.

Figure 2 shows power generation during a typical day, after the three weeks of field exposure. For the 22º tilted modules, average power loss due to soiling is 3.6% for bifacial modules, and 7.4% for monofacial modules. Even though no significant soiling is observed for vertically installed modules, the modules produced 12% less power relative to the 22º tilted module due to significantly lower irradiance received between 08 hrs and 15 hrs.

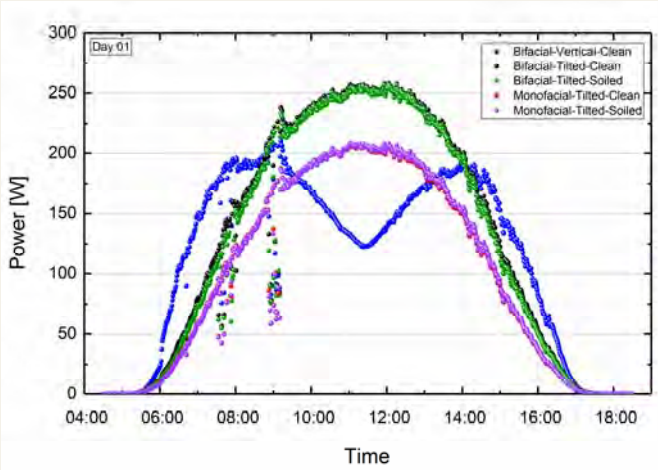

Figure 2a. Module power for clean modules on a typical day

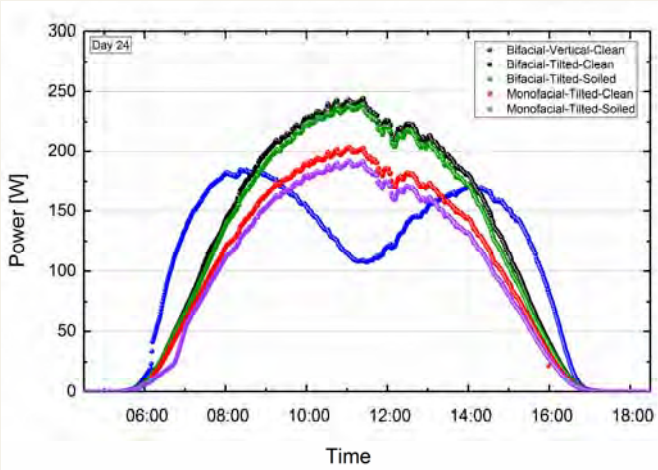

Figure 2b. Module power on a typical day, after three weeks of field exposure.

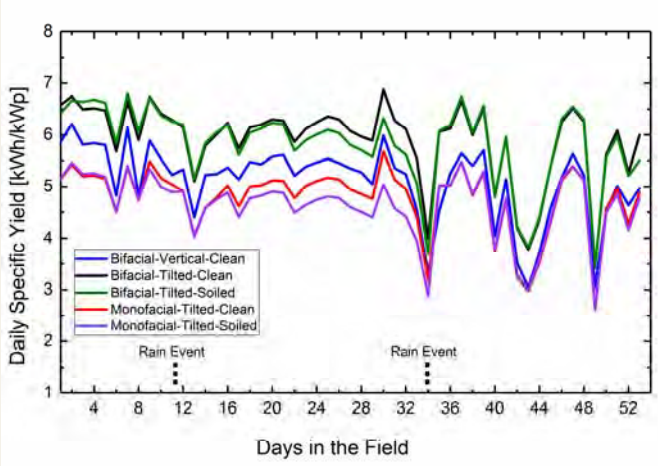

Figure 3. Daily Specific Energy Yield.

Figure 3 shows daily specific yield during 8 weeks of field exposure. The average yield loss due to soiling was 1.3% for bifacial modules, and 2.7% for monofacial modules. It has to be noted that there were no significant dust events such as dust storms characteristic of the region, and several significant rain events occurred during the experimental period.

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IEC PV Standards Activities

John Wohlgemuth
PowerMark Corporation

Summary

IEC Technical Committee (TC) 82 writes PV Standards

PowerMark serves as Technical Advisor (TA) to US TAG of TC82 under NREL Agreement AHR-9-92022-01.

TC 82 published six International Standards, seven Technical Specifications and two Technical Reports in 2019.

IEC PV Standards published in 2019

IEC 60904-3: Edition 4: Photovoltaic devices - Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data
IEC 60904-4: Edition 2: Photovoltaic devices - Part 4: Reference solar devices - Procedures for establishing calibration traceability
IEC 60904-7: Edition 4: Photovoltaic devices - Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices
IEC 62892: Extended thermal cycling of PV modules - Test procedure
IEC 62941: Terrestrial photovoltaic (PV) modules - Quality system for PV module manufacturing
IEC 63202-1: Photovoltaic cells - Part 1: Measurement of light-induced degradation of crystalline silicon photovoltaic cells

Published Technical Reports (TR) in 2019

IEC TR 63225: Incompatibility of connectors for DC application in photovoltaic systems
IEC TR 63228: Measurement protocols for photovoltaic devices based on organic, dye-sensitized or perovskite materials

IEC PV TS's published in 2019

IEC TS 60904-1-2: Photovoltaic devices - Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices
IEC TS 62257-7-4: Edition 2: Recommendations for renewable energy and hybrid systems for rural electrification - Part 7-4: Generators - Integration of solar with other forms of power generation within hybrid power systems
IEC TS 62257-9-6: Edition 2: Renewable energy and hybrid systems for rural electrification - Part 9-6: Integrated systems - Recommendations for selection of Photovoltaic Individual Electrification Systems (PV-IES)
IEC TS 62257-9-7: Renewable energy and hybrid systems for rural electrification - Part 9-7: Recommendations for selection of inverters
IEC TS 62994: Photovoltaic (PV) modules through the life cycle - Environmental health and safety (EH&S) risk assessment - General principles and nomenclature
IEC TS 63019: Photovoltaic power systems (PVPS) - Information model for availability
IEC TS 63157: Photovoltaic systems - Guidelines for effective quality assurance of power conversion equipment

Requirements for Participation in IEC

Join your National TAG
In the US, this means joining the ANSI TAG for IEC TC82 and paying the $310 annual dues
For more information, contact John Wohlgemuth at JWPVReliability@ieee.org

Towards 50 Year Module Lifetimes: Impact of Module Architecture and Packaging Materials

Sameera Nalin Venkat[1], Jiqi Liu[1], Nick S. Bosco[2], Jianfang Dai[3], William J. Gambogi[4], Brent Brownell[3], Yuan Gu[5], Jennifer Carter[1], Laura S. Bruckman[1], Jean-Nicolas Jaubert[5], Jennifer L. Braid[1], Roger H. French[1]

[1]Solar Durability and Lifetime Extension Center, Materials Science and Engineering Department, Case Western Reserve University, Cleveland, Ohio, USA
[2]National Renewable Energy Laboratory, Golden, Colorado, USA, [3]Cybrid Technologies, [4]DuPont, Electronics and Imaging, [7]Canadian Solar Inc.

Case Western Reserve University EST. 1826 — think beyond the possible

SDLE — SOLAR DURABILITY AND LIFETIME EXTENSION CENTER

Introduction

- c-Si solar cells
  - Used for 40 years[1]
  - Warranty: 20-25 years
- Real-world affects module
  - Durability
  - Lifetime
- T50 project
  - Lifetime increase: 50 years
    - Power drop: 0.2%/year
    - 2030 SunShot goal: $0.03/kWh

Materials

Encapsulants

- EVA
  - **Metallization corrosion**
- POE
  - **Possible adhesion issues[2]**
  - **No long-term studies**

Backsheet

- KPf
  - PVDF/PET/fluorocoating

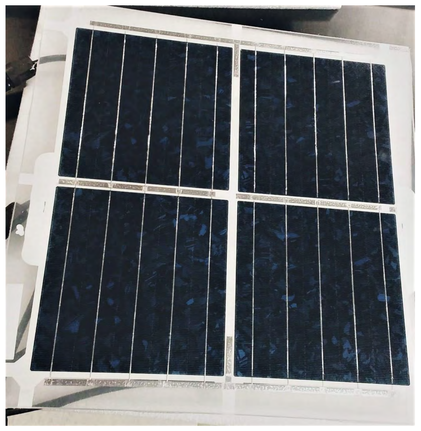

Figure 2: GB minimodule.

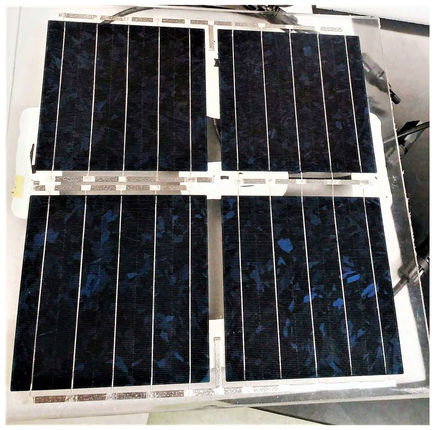

Figure 3: DG minimodule.

Module architectures

GB: Glass/backsheet

- 3.2 mm tempered glass
- Asymmetric stress state
  - Leads to cracking

DG: Double glass

- 2.5 mm heat-strengthened glass
- Constant concentration
  - Moisture, O_2
- Increased rigidity

Overview of the T50 project

- Study impact of
  - **Packaging materials**
    - Encapsulants (EVA, POE)
    - Backsheet (KPf)
  - **Module architectures**
    - Glass/backsheet (GB)
    - Double glass (DG)
- **Mono-facial** and bi-facial PERC
  - Multicrystalline Si
- Stepwise minimodule (MM) exposure
  - CSI: outdoor
  - SDLE+CSI: accelerated

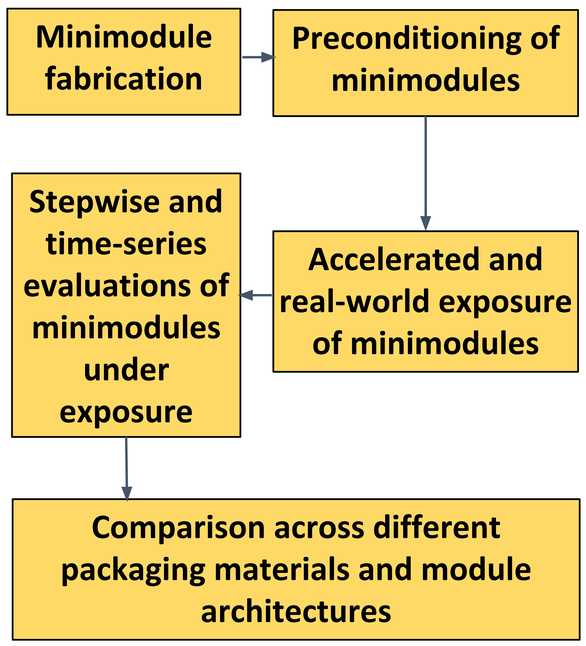

Figure 1: Study progress in the T50 project.

- Current progress
  - Baseline measurements
    - 8 CSI MMs
  - Conditions: 504 hours
    - mDH: 4 MMs
    - mDH + full spectrum (FS): 4 MMs
- Baseline evaluation
  - *I-V* and *Suns-V_{oc}* measurements
  - EL/PL imaging

Electrical measurements

***I-V* characteristics**

- Electrical changes
  - *I-V* features
    - Mechanistic predictors[3]
- Monitor losses

***Suns-V_{oc}* measurements**

- No effects of
  - Series resistance
- Used to determine
  - Minority carrier density versus effective lifetime[4]

Mechanical testing

4-point bending

- Study cell cracking
  - With encapsulant changes
- Strain for cell fracture
  - Through packaging material
- Probability of cell cracking
  - For different combinations

Figure 4: 4-point bending fixture at SDLE.

EL/PL imaging

- Spatial info[6]
  - Module performance
- Observations
  - Series resistance
  - Recombination
  - I_{sc} loss
  - Shunting

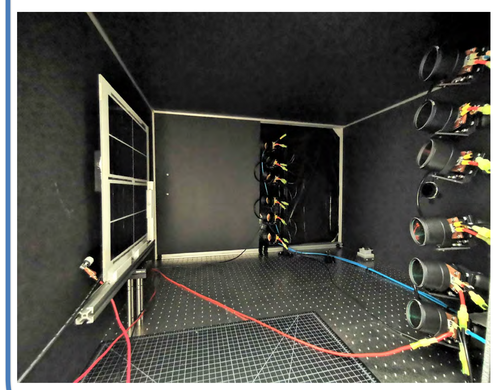

Figure 5: EL/PL system.

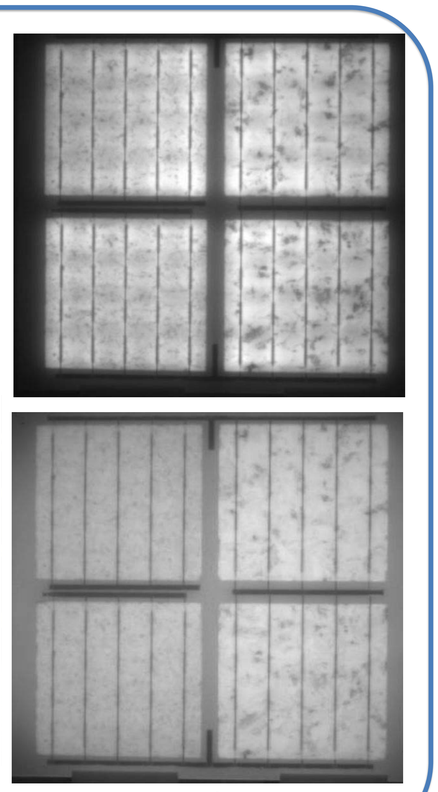

Figure 6: EL/PL images.

Results and discussion

Cell-level *I-V* features

- 4 cell measurements/MM
- Differences in GB and DG
- GB minimodules
  - Higher P_{mp}, I_{mp} and I_{sc}
- Differences in current
  - Two possibilities
    - Glass thickness
    - Backsheet scattering[7]

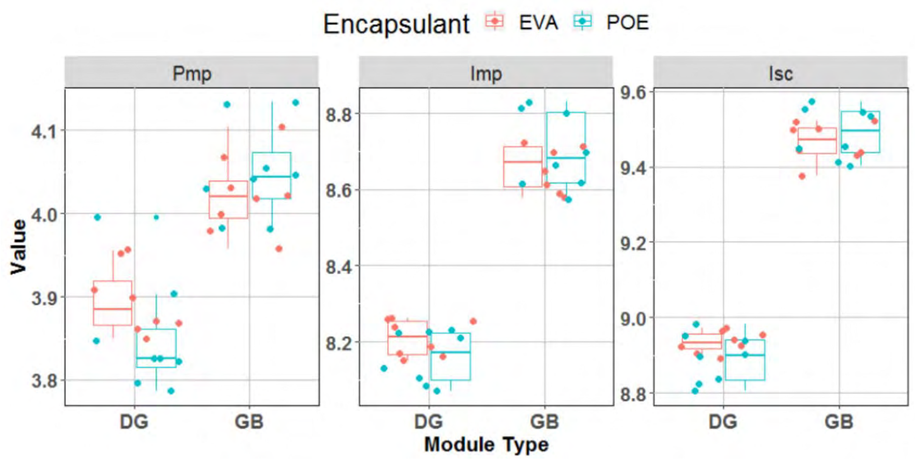

Figure 7: Cell-level *I-V* features.

***I-V* and *Suns-V_{oc}* curves**

- Efficiency of 1 MM
  - GB
  - EVA
  - *Suns-V_{oc}*: 0.215
  - *I-V*: 0.167
- At efficiency of 0.215
  - Limitation to FF value
    - Due to recombination
    - No effect of series resistance

Path forward

Accelerated & real-world exposure

- Indoor: 2520 hours (mDH, mDH+FS)
- Outdoor: 2 years

Stepwise evaluations of minimodules under exposure

- Using four techniques

Comparison of results

- netSEM: degradation pathway

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Acknowledgements

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Testing for Risk of Hot Spots and Bypass Diode Activations in Bifacial Arrays on Single-Axis Trackers

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Abstract

- Tests simulating worst-case scenarios were carried out to determine if backside structural shading poses a reliability risk for bifacial PV arrays on single-axis trackers.
- An array of bifacial modules was mounted in the one-module-in-portrait (1MIP) configuration at the south end of a single-axis tracker row and operated with a string inverter.
- The ground was covered with a white reflective material below and around the arrays, to simulate snow cover. The measured albedo for the ground cover was higher than 0.60.
- In the Stowed Case Test, the tracker was intentionally parked at 52 degrees to the east, simulating a wind-slip event. The idea was to maximize the effect of backside-irradiance mismatch on the module circuitry. The array was monitored for hot spots and BPD activations via periodic IR imaging and string voltage measurement over a fully sunny day. The string voltage data showed no indication of BPD activations, and the IR images indicated that the temperature non-uniformity stayed below 5 degrees Celsius.
- In the Tracking Case test, the high-albedo setup was reused but the tracker continuously tracked the sun. The string voltage was monitored through sunny days. Again, the string voltage data showed no indication of BPD activations. Our results indicate that the risk of hot spots or BPD activations in bifacial arrays on single-axis trackers is minimal to non-existent.
- The tests were carried out at CFV Labs in Albuquerque. (CFV Report 19076-PR-E-001)

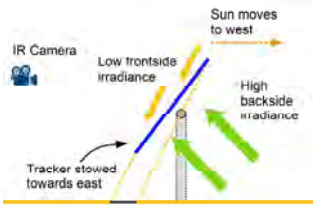
Test Setup

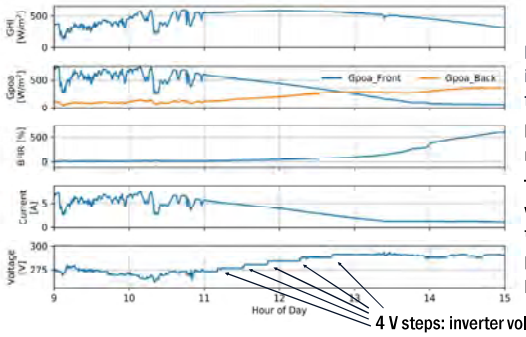
- Bifacial poly-PERC half-cell modules
- Seven modules continuously operated with a string inverter, with global MPPT on
- Dummy modules on the north
- String voltage and current measured with high-accuracy equipment (presented by CFV at 2019 PVPMC Workshop)
- Pyranometer measuring the backside irradiance installed on the torque tube, behind the closest dummy module
- Also recorded: GHI, DNI, frontside POA irradiance, ambient temperature, wind speed, and albedo (separate setup, using identical ground cover)

Backside irradiance measurement behind this module with a thermopile pyranometer

Test Details and Results: Stowed Case

- Tracker parked at 52 degrees from horizontal towards the east, to increase the effect of backside irradiance mismatch on the total irradiance as the sun moves west
- Thermal IR imaging every 10 minutes
- String voltage and current data captured every 30 seconds
- Test conducted on one sunny day





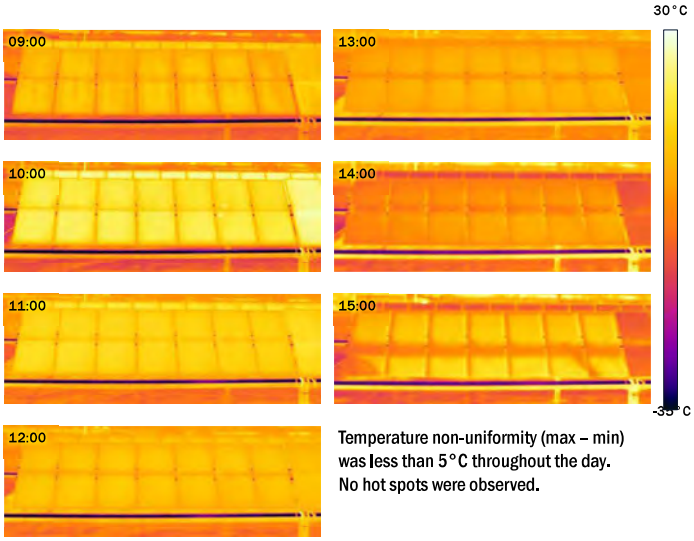
From ~1 PM, backside irradiance is larger than frontside irradiance.

BFIR (back-to-front irradiance ratio) gets as high as 500%.

The current decreases and the voltage increases. MPP moves towards Voc.

No voltage drop attributable to BPD triggering (ΔV > 10 V)

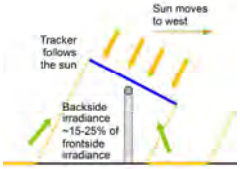
4 V steps: inverter voltage resolution for MPPT

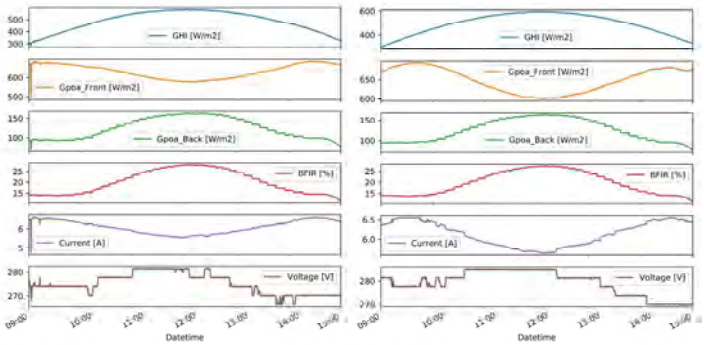


Temperature non-uniformity (max – min) was less than 5 °C throughout the day. No hot spots were observed.

Test Details and Results: Tracking Case

- Tracker continuously tracked the sun, except during backtracking.
- String voltage and current data captured every 30 seconds
- Test conducted over two sunny days





No voltage drop attributable to BPD triggering (ΔV > 10 V); The 4 V steps are from inverter MPPT.

Summary and Discussion

- In our previous bifacial studies at CFV with normal albedo (~0.3), we did not observe any hot spots. To investigate if hot spots and bypass diode activations can occur in high-albedo situations, we conducted high-albedo tests at CFV, with a bifacial array mounted on Array Technologies 1MIP (one module-in-portrait) trackers.
- The tests were designed to reflect the worst-case scenarios that can happen with the tracker in stowed and tracking positions, to our best effort.
  - White reflective ground cover with albedo > 0.60, to simulate snow
  - Array installed on the south end of a row, to maximize edge brightening
- In the tests conducted, we did not observe any hot spot or bypass diode activations.
- Edge brightening and structural shading did create cell-to-cell irradiance mismatch, but
  - when tracking normally, the irradiance mismatch was not big enough to cause the lowest-irradiance cell to go into reverse bias (hot spot or bypass diode activation), and
  - when stowed and when the BFIR exceeded 100%, the string's maximum power point moved towards the Voc, helping to avoid BPD activations.

FOLLOW THE SUN. FOLLOW THE LEADER.

EFFECTIVE EFFICIENCY OF ENERGY GENERATION BY FIELD DEPLOYED PV MODULES AS A LONG-TERM PERFORMANCE INDICATOR

Wei Shan[1,2] and Helen Zhou[2]

[1]JA Solar USA, San Jose, California [2]R&D Center, JA Solar Technology Co. Yangzhou, China

Abstract

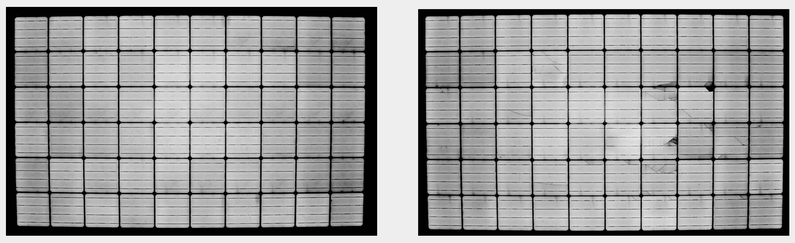
Outdoor performance of various types of PV modules assembled with multi-Si BSF and mono-Si PERC cells has been monitored as a function of time using so-called effective efficiency of energy generation (EEEG). The data collected from modules deployed in utility-scale solar farms and experimental testing fields over the past few years do show that the degree of performance degradation depends on the types of solar cells assembled in the modules. The degradation rates of those modules derived from the measured EEEG are observed to vary with not only the types of the solar cells assembled in the modules as well as module BOMs but also to be influenced by a few other factors.

Background

Performance degradation of PV modules for various applications including utility scaled solar farms, commercial and residential rooftops has long been a subject of debate. Historically, the consensus is 20% degradation over 25 years regardless the types of modules. Almost all the Si-wafer based module manufacturers warrant their products with a first-year 2-3% power decay then linearly down to 80% at the end of 25th year. However, the push in recent years for lower decay rate has resulted in various numbers that are yet to be verified and validated by long-term performance data.

In this presentation, we show that Effective Efficiency of Energy Generation (EEEG) which is defined as the energy generated over the total irradiance accepted per unity area of a module can be used as a performance indicator to derive degradation rate from long-term energy generation from the modules in the outdoor fields.

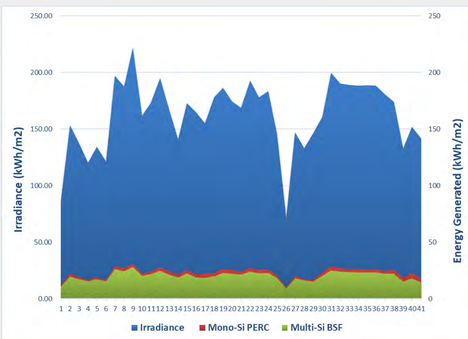
EL Images of mono-Si PERC modules after 34 months of operation



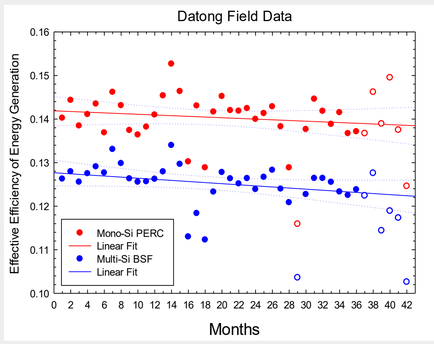
EL Images of multi-Si BSF modules after 34 months of operation

Case Study 1: Results from Datong 40-MW Field

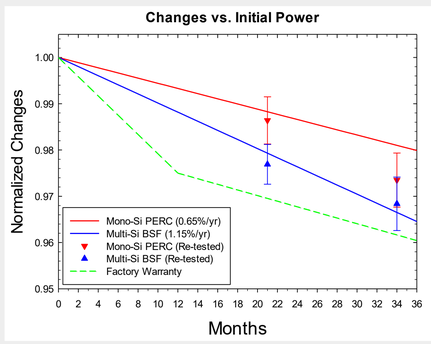
- 40 MW installed at a location near the city of Datong, Shanxi Province (a part of China's Front Runner Project)
  - 31-MW mono-Si PERC, 16-MW multi-Si BSF, 3-MW DG RIE multi-Si BSF
  - Fixed mount, 31° tilted, connected to grid since July 2016
- Data are collected from two sections of mono-Si PERC modules and multi-Si BSF modules with 542 and 517 kWp, as well as 3057.4 and 3129.7 m^2 of total module surface areas, respectively



Comparison between energy generation of two sampling sections consisted of mono-Si PERC and multi-Si BSF modules along with accumulated irradiance in terms of kWh/m^2. The EEEG can be straightforwardly calculated for each type of the modules from the data on a daily, weekly, or monthly basis



The best fit by linear regression to the monthly EEEG data collected from the sampling sections of mono-Si PERC and multi-Si BSF modules in the field from September 2016 to September 2019. The open-circled data points are not included in the fitting.



The overall performance degradation can be readily obtained from the normalized changes of EEEG as a function of time based on the slope of the best fit to the monthly data. Re-test results of the modules taken out from the sampling sections are shown in the figure for comparison.

Changes of performance parameters relative to factory tested ones after 22 and 34 months of operation in the field

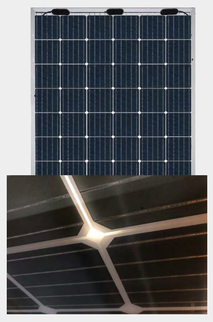
Months after Installed	ΔPmax (%)		ΔVoc (%)		ΔIsc (%)		ΔFF (%)	
	Mono-Si PERC	Multi-Si BSF	Mono-Si PERC	Multi-Si BSF	Mono-Si PERC	Multi-Si BSF	Mono-Si PERC	Multi-Si BSF
22	-1.36±0.51	-2.31±0.43	0.02±0.20	-0.22±0.09	-1.91±0.23	-1.17±0.40	0.54±0.25	-0.94±0.72
34	-2.65±0.38	-3.16±0.79	-0.29±0.19	-0.43±0.37	-1.26±0.51	-3.17±0.78	-1.21±0.45	0.44±0.39

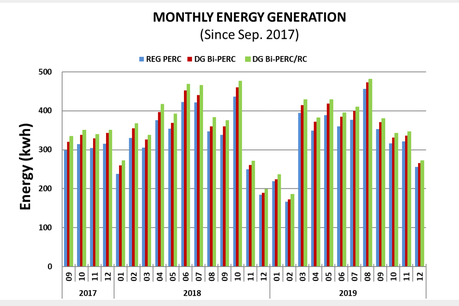
- Averaged over ten modules of each type
- The modules were randomly selected and taken down for retest

Case Study 2: Results from Yangzhou Testing Site

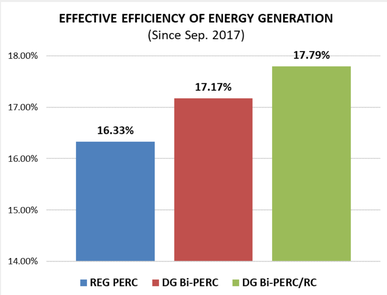
- Three types of module arrays, Reg. PERC, DG Bi-PERC, and DG Bi-PERC/RC, are mounted on the same rack next to each other
  - Each array consists of 11 modules
  - 25°-tilt, facing south on concrete paved ground (N32°23'; E119°27')
  - Energy generation data are monitored by grid-connected inverters
  - The installed modules are well maintained and cleaned once a week

Module Types	Module Configurations	Rated Power (W)	Modules Per String	Total Power (kW)	Module Size (m^2)
REG PERC	6x10	295.0	11	3.245	1.635
DG Bi-PERC	6x10	290.9	11	3.200	1.645
DG Bi-PERC/RC	6x10	300.3	11	3.303	1.645

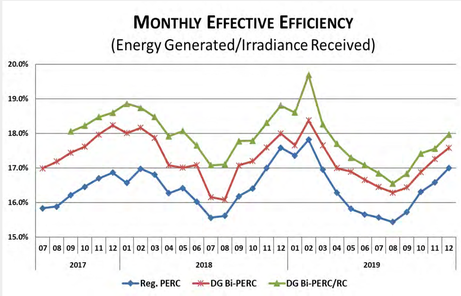




Month to month energy generation comparison between three types of PERC modules since September 2017. The ability of utilizing the light incident on the backside of bifacial modules boosts the energy yield of both types of bifacial PERC modules.



Averaged EEEG from three types of PERC modules over the past 28 months. The higher energy generation and better EEEG of both types of double-glass bifacial PERC modules are the results of higher currents.



Monthly EEEG from three types of PERC modules as a function of time. The data suggest that higher current may cause slightly faster degradation as the slope of EEEG change from DG Bi-PERC/RC modules is 0.1%/year steeper than that of DG Bi-PERC modules. Nevertheless, this requires longer time to verify.

Summary

- Effective efficiency of energy generation has been demonstrated to be a straightforward performance indicator for various types of PV modules deployed in outdoor field
- EEEG provides a way to derive the degradation rate of PV modules deployed in the fields at different locations and under different climate conditions from their collective long-term performance in terms of energy generation
  - It is of vital importance to derive degradation rate from long-term data as monthly or weekly EEEG is seasonal and performance decay is a slow process
- The field data collected over past 40 months indicate that modules assembled with multi-Si BSF cells have a higher performance degradation rate compared to those with mono-Si PERC cells using the same BOM
  - Other factors causing module performance degradation include soiling and cell cracking and broke
  - Higher current might be also one of them but requires further study

IEC 62788-7-3 Standard: PV Abrasion; Development Update

NREL is a national laboratory of the U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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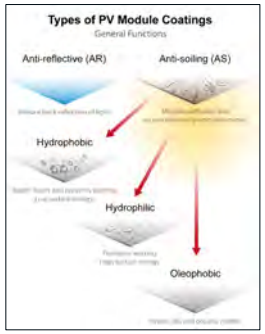
I. Introduction

Background and Motivation

Natural soiling reduces PV energy output, increasing levelized cost of electricity. Mitigation often includes dry brush cleaning.

Images of Ecoppia's robotic cleaning system



Coatings used on PV front surfaces.
Einhorn et. al., J PV, 9, 2018, 233-239.

Research Goals

- Develop artificial laboratory test procedures
  - Part of suite of artificial abrasion test methods[1] within the presently developing IEC 62788-7-3 standard.[2]
  - Quantify appropriate test parameters to emulate field results.

II. Method

Developing artificial laboratory tests

- Falling sand test. E.g., Mathiak et. al., Proc. EU PVSEC 2018.
- Forced sand impingement test. E.g., Klimm et. al., Proc. Euro. Weathering Symp. 2015.
- Linear and rotating brush tests

Inexpensive modification where made to commercially available linear abrasion test systems to perform the artificial laboratory tests with linear and rotating brushes.

Different test parameters being adjusted to mimic real world cleaning and observed abrasion on field samples.

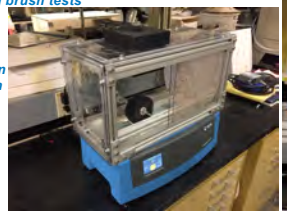


Image of the dry dust rotating brush system. Dust is dropped onto the sample with each brush sweep.

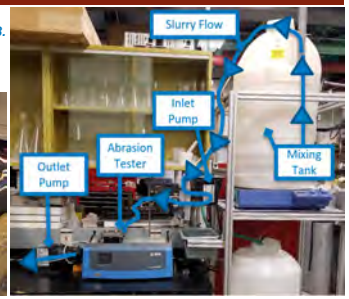


Image of the slurry system used to provide continuous contamination and water to simulate cleaning during abrasion testing

Performing Field Experiments

- Coated test coupons were deployed in high soiling regions around the world. The specimens were cleaned at prescribed intervals with different cleaning methods.
- Samples are brought back to the laboratory every year and evaluated to determine the specific damage induced from the environment and/or cleaning.

Compare field and laboratory results to identify appropriate test parameters

- Compare durability of popular coating types.
- Compare rate- and damage characteristics between wet & dry dust abrasion.
- Compare rate- and damage characteristics for other factors affecting abrasion.

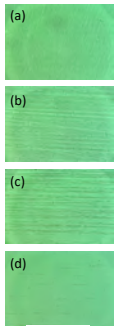
Acknowledgements

The authors would like to acknowledge and thank all those who contributed to this project including all the people at NREL who designed and assembled the equipment. This work was authored [in part] by the 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. Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office (SETO) Agreement Numbers 30311 and 10311. The views expressed in the poster do not necessarily represent the views of the DOE or the U.S. Government.

III. Results

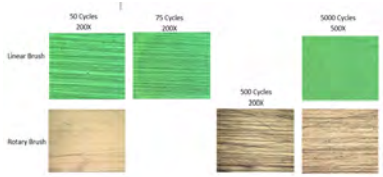
Work on artificial linear brush abrasion test nearing completion

- "Artificial Linear Brush Abrasion of Coatings for Photovoltaic Module First Surfaces," 2019 International Soiling Workshop, Marrakech, Morocco. NREL/TP-5J00-66334, 2016, 1-25.
  - Overt correlation observed between transmittance (τ_D), yellowness index (YI), contact angle (CA), and coating roughness (R_a), particularly for specimens with a coating of thickness greater than nanometers. Consistent with: damage initiation, damage accumulation, destruction of the film (converging to characteristics of glass substrate).
  - From Atomic Force Microscopy (AFM), abrasion damage primarily results from facets/edges of dust or sharp features on bristles, which provide localized damage during brush testing
  - Variety of longevities (100 to 10000) cycles observed.
    - Some specimens durability consistent with use in western locations, i.e., a few cleanings per year - up to 100 cycles total.
    - Some specimens durability consistent with use in more challenging locations (e.g., MENA), where daily cleaning (10000 cycles) may be required
  - XPS confirms details of the test parameters (A3 test dust; bristle length) improved the linear artificial brush abrasion method relative to previous studies.

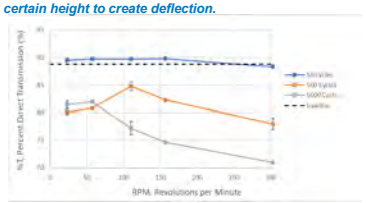


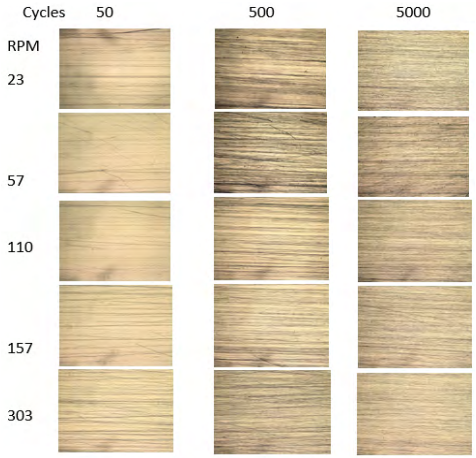
Work on artificial rotating brush abrasion test just starting

- "Artificial Rotating Brush Abrasion Test of Coatings for Photovoltaic Module," 2019 International Soiling Workshop, Marrakech, Morocco.
- Must correlate rotations per minute, brush deflection, and cycles with linear brush results.



Comparison of linear and rotary acrylic test samples at similar cycle counts. The coloration is due to polarizing lenses that were used differently between imaging the two sample sets. The linear abrasion causes damage much quicker (the 500 cycles with a rotary brush looks like the 75 cycles with a linear brush). This is probably related to the much lower contact force of the rotating brush. The force is greater because the linear brush rests on the sample with its entire weight when in use, while the rotary brush is held at a certain height to create deflection.





Pictures of acrylic samples after linear (top) and rotating (bottom) abrasion tests with dust slurry..

- Rotary brush abrasion tester built to known specifications with the flexibility to try different characteristics to test potential standards.
- Rotary brush bristle buckling is an issue; may limit the contact force
- Analysis started to determine appropriate rpm testing standards. Relationship between rotational and translational speeds is key

IV. Conclusions and Future Pursuits

- Initial results demonstrate that the system can provide appropriate control of critical parameters.
  - Rotating brush force is substantially lower than linear brush, so induced degradation is much less.

Future Plans

- Rotating brush test with glass and coated glass samples
- Results used to inform best practices for operations and maintenance plans and to analyze the durability of potential antireflective and anti-soiling surface glass coatings and potentially in the development of cleaning robots.
- Other key issues to investigate include: material integrity, surface energy, scratch density and size, contact angle, and surface roughness
- Validate rotating abrasion test relative to fielded coupon samples and veteran modules.

References

1. Review of Artificial Abrasion Test Methods for PV Module Technology, NREL Technical Report NREL/TP-5J00-66334, 2016.
2. Soiling Related Abrasion and the Development of a PV Abrasion Standard, Proc. Intl. Soiling Work., 2018.

Validating Module Temperature Model in Single-Axis Tracking Photovoltaic Systems

Christopher W. Wolfrom, Sara M. MacAlpine ● juwi Inc., Boulder, CO 80301

juwi Energy is here

ABSTRACT

Photovoltaic system modeling requires accurate prediction of cell temperature. The temperature of a solar cell is modeled using an energy balance equation that typically correlates the cell temperature to the irradiation received by the module, the ambient air temperature, the wind speed, and a thermal loss factor. The thermal loss factor is comprised of a constant component and a linear factor that is proportional to wind speed. As cell temperature is highly impactful on a solar cell's efficiency, the accuracy of these coefficients is significantly influential to generation modeling. This presentation will demonstrate the method for determining the specific thermal loss factor associated with a given as-built system using the Faiman Model and the model developed at Sandia. Specifically, this presentation utilizes data from eight single-axis tracking systems. This type of analysis is useful to validate and adjust a plant's generation model such that accurate loss calculations and accurate performance modeling can be achieved.

METHOD – *FAIMAN MODEL*

Faiman outlines a methodology based on a simple heat balance equation that relates incoming irradiance, ambient temperature, and wind speed to cell temperature using two coefficients, U_0 and U_1.[1]

$$T_c = T_a + \frac{E_{POA}}{U_0 + U_1 \times WS} \tag{1}$$

T_c: Cell Temperature (°C)
T_a: Ambient Temperature (°C)
E_{POA}: Plane of Array Irradiance (W/m²)
WS: Wind Speed (m/s)
U_0: Constant Heat Transfer Component (W/m²K)
U_1: Convective Heat Transfer Component (W/m³sK)

Since module temperature, ambient temperature, plane of array irradiance, wind speed is part of standard meteorological measurement practice in photovoltaic systems, the heat transfer components can be solved using a least squares regression. By rearranging equation (1), we can see the linear equation where the fitting coefficients are the heat transfer components.

$$\frac{E_{POA}}{T_c - T_a} = U_1 \times WS + U_0 \tag{2}$$

Cell temperature is difficult to measure in the field. Sandia has a method for estimating the cell temperature via a correlation between irradiance and module temperature seen in equation (3).[3]

$$T_c = T_m + \frac{E_{POA}}{E_0}\Delta T \tag{3}$$

T_m: Module Temperature (°C)
E_0: Reference Irradiance, 1000 W/m²
ΔT: Temperature Difference Parameter, 3°C[3]

Figure 1 results when plotting the quotient of plane of array irradiance and the difference between cell and ambient temperature against wind speed. The slope and y-intercept of the least squares regression are the U_1 and U_0, of the Faiman Model, respectively.

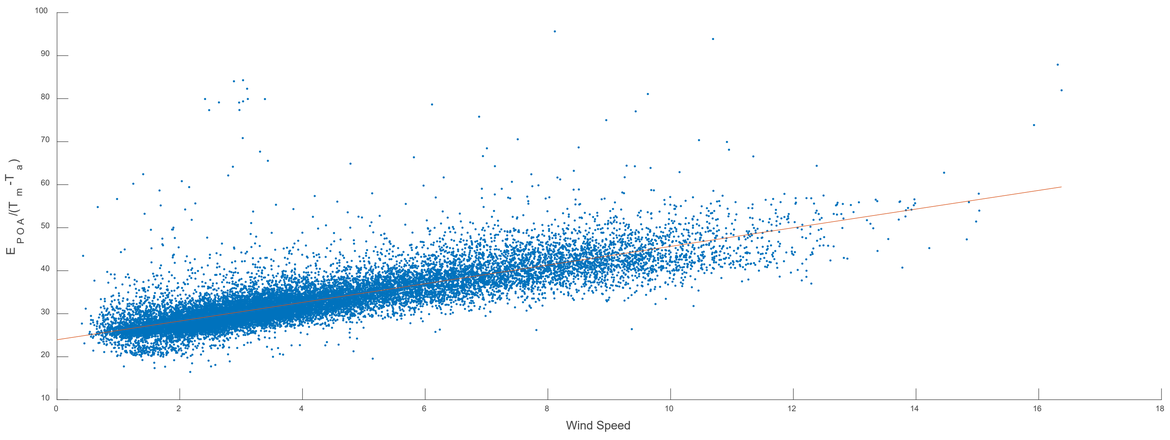


Figure 1: The figure above demonstrates the linear relationship between the thermal losses of the system and the wind speed experienced by the system. The positive slope indicates that increased wind speeds increase the convective heat transfer of the modules and thus decrease cell temperature.

APPLICATION NOTES

The data in our analysis are subject to the following criteria:

- Ambient Temperature must be less than or equal to Cell Temperature
- 2½ minute interval data
- Irradiance ≥ 400 W/m²
- Meteorological stability
  - Irradiance: 2 W/m²·min
  - Temperature: 0.8 °C/min
  - Wind Speed: 1.6 m/s·min

METHOD – *SANDIA MODEL*

King et al outlines a methodology based on another heat balance equation that relates incoming irradiance, ambient temperature, and wind speed to cell temperature using two coefficients, a and b.[3]

$$T_c = E_{POA}\left(e^{a+b\times WS}\right) + T_a \tag{4}$$

T_c: Cell Temperature (°C)
T_a: Ambient Temperature (°C)
E_{POA}: Plane of Array Irradiance (W/m²)
WS: Wind Speed (m/s)
a: Constant Heat Transfer Component
b: Convective Heat Transfer Component

With the same field measurements required as the Faiman Model and the module temperature being converted to cell temperature via equation (3), the heat transfer components can be solved using a least squares regression. By rearranging equation (4), we can see the linear equation where the fitting coefficients are the heat transfer components.

$$\ln\left(\frac{T_c - T_a}{E_{POA}}\right) = a + b \times WS \tag{5}$$

Figure 2 plots wind speed against the natural log of the quotient of the difference between cell temperature and ambient temperature and plane of array irradiance. The slope and y-intercept of the least squares regression are the b and a of the Sandia Model, respectively.

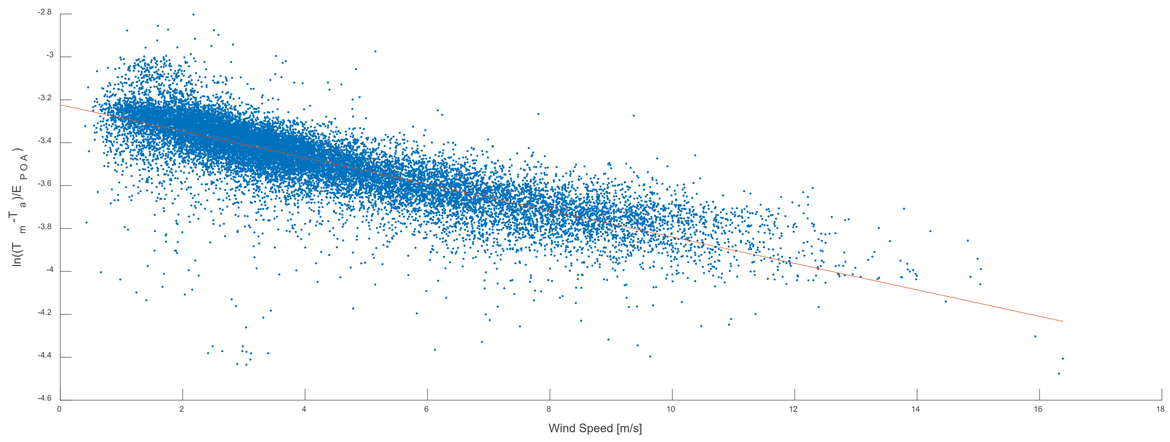


Figure 2: The figure above demonstrates the linear relationship between the thermal losses of the system and the wind speed experienced by the system.

CONCLUSION

Table 1 shows the coefficients of determination for the Faiman and Sandia Models after this analysis was performed on eight single-axis tracking photovoltaic systems.

While both fitting methodologies have similar coefficients of determination, neither is a perfect solution to modeling cell temperature. With that said, the Sandia model has a stronger fit in terms of correlating a specific plant's data with the model. This is evidenced by the higher average r^2 value. In addition, the Sandia model provides a more reliable fit across the examined plants as indicated by the lower standard deviation of the r^2 values.

Thus, we suggest adding the Sandia Model of cell temperature modeling to all standard modeling software as it is an adequate alternative to the Faiman Model.

Table 1: The accuracy of fit of the two models in eight horizontal, single-axis tracking photovoltaic systems as determined by their coefficient of determination. The higher this coefficient, the more accurate the fit to the measured plant data.

	Faiman	**Sandia**
Plant	**r^2**	**r^2**
A	0.50	0.61
B	0.58	0.60
C	0.76	0.76
D	0.70	0.71
E	0.72	0.71
F	0.79	0.81
G	0.77	0.78
H	0.58	0.60
Mean	**0.67**	**0.70**
σ	**0.11**	**0.09**

REFERENCES

[1] Faiman, D. (2008). "Assessing the outdoor operating temperature of photovoltaic modules." Progress in Photovoltaics 16(4): 307-315.
[2] Faiman, D. "PVsyst Cell Temperature Model." PV Performance Modeling Collaborative, Sandia National Laboratories, pvpmc.sandia.gov/modeling-steps/2-dc-module-iv/cell-temperature/pvsyst-cell-temperature-model/.
[3] King, D & Kratochvil, J & Boyson, W. (2004). Photovoltaic Array Performance Model.

Sandia National Laboratories

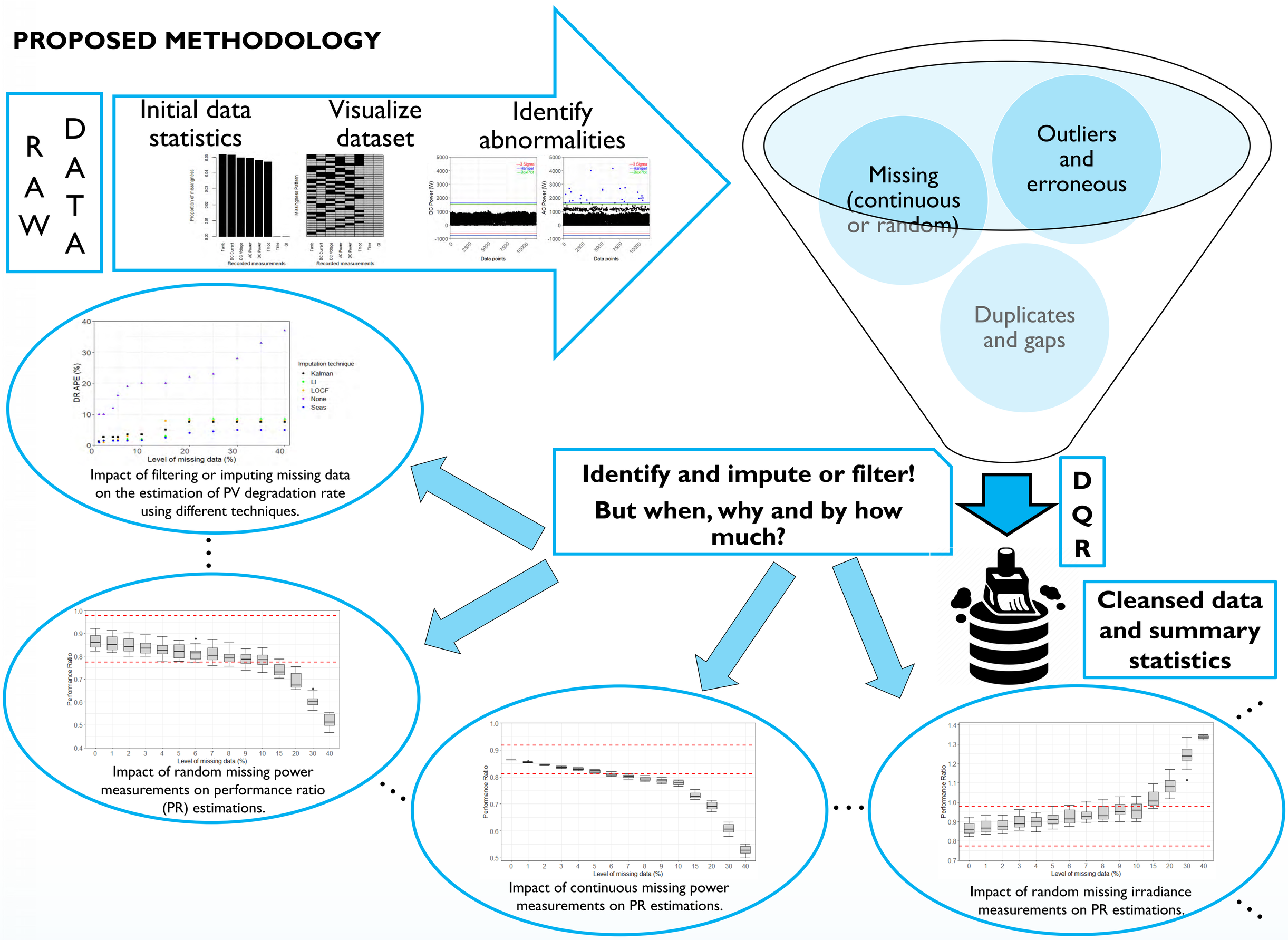
Guidelines for ensuring data quality for photovoltaic system performance assessment and monitoring

A. Livera (UCY), M. Theristis (SNL; mtheris@sandia.gov), E. Koumpli (SC), G. Makrides (UCY), J. S. Stein (SNL), G. E. Georghiou (UCY)

INTRODUCTION

- Invalid data (i.e. missing, erroneous and outlying values) caused by power outages or component failures are common problems exhibited in photovoltaic (PV) monitoring systems
- The way to handle such data can introduce bias in PV performance, reliability and degradation analyses
- A complete methodology of data quality routines (DQR) is being developed for data processing and quality checks
- Builds on IEC 61724 and other reports that provide justifiable and quantifiable criteria (mainly filtering, uncertainty, sampling) and also provides initial and summary data statistics
- Each step/decision is described in a quantitative manner based on detailed analyses and not arbitrary assumptions
- Potential of creating an open-source library for PV performance analysts and researchers

PROPOSED METHODOLOGY



GENERAL SUMMARY AND CONCLUSIONS

- DQRs are being developed to ensure data sanity and validity for PV reliability, monitoring and performance analyses
- Algorithms are used for identifying, imputing and/or filtering abnormal data (missing, erroneous, duplicate, etc.)
- It was verified that PV performance analysis is sensitive to the amount and location of abnormal data within a dataset
- Treating data using k-NN and seasonal decomposition proved to be effective
- A manuscript will be submitted soon and the complete procedure will be coded and published on GitHub

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CFV Labs

Bankability Testing for New Generations of PV Modules

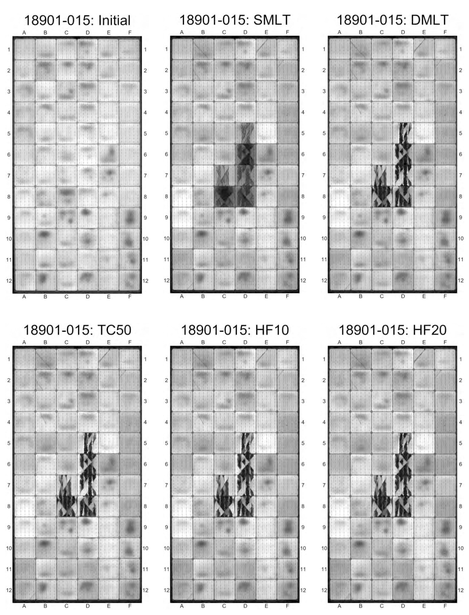
Daniel Zirzow, Jim Crimmins, Colin Sillerud, James Richards

A new generation of PV modules is coming to market with more variation than ever before. The lack of field data validating the reliability of these newer technologies beyond a few years and the acceptance that module certification testing alone is inadequate for long term reliability assessment places new demands on reliability and quality assurance testing.

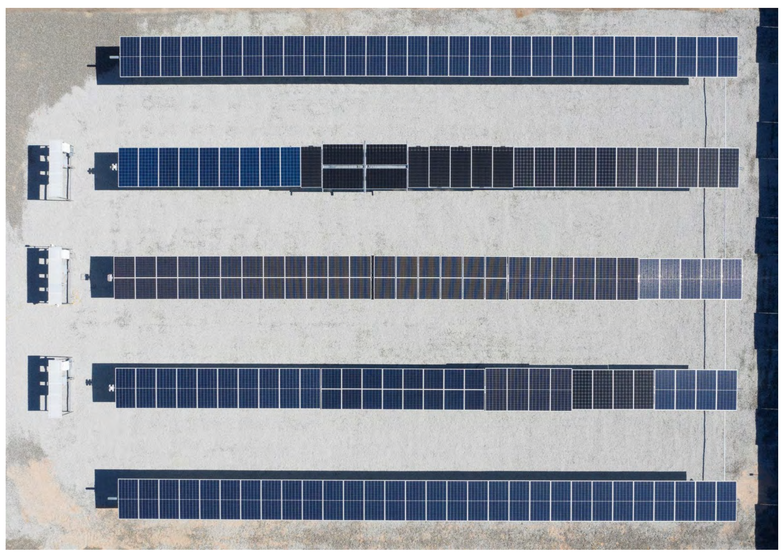
Cell Technology
- PERC
- Bifacial
- Half-cut
- HJT

Module Construction
- Multi Bus Bars
- Multi-wire Interconnects
- Shingled Cells
- Thin Frame Profiles
- Clear Backsheets

Module Deployment
- Single Axis Tracker
- Bifacial Gain Optimization



Static & dynamic mechanical loading with varied mounting configurations coupled with chamber stress testing for evaluation of cell crack susceptibility .



Validation of bifacial module/system performance under real world conditions.

EXTENDED STRESS TESTING:

IEC 63209, C450 for establishing baseline module reliability and performance, with additional tests where applicable.

Sequence 1	Sequence 2	Sequence 3	Sequence 4	Sequence 5
Thermal Cycling Sequence	Mechanical Load Sequence	UV / Backsheet Sequence	Damp Heat Sequence	PID Sequence
@Initial Characterizations	@Initial Characterizations	@Initial Characterizations	@Initial Characterizations	@Initial Characterizations
MQT 19 Stabilization	MQT 19 Stabilization	MQT 19 Stabilization	MQT 19 Stabilization	MQT 19 Stabilization
Initial Characterizations	Initial Characterizations	Initial Characterizations	Initial Characterizations	Initial Characterizations
@TC200 #1	@Static MLT	@DH200	@DH1000 #1	@PID
MQT 11 Thermal Cycling (200 cycles @ -40C/+85C)	MQT 16 Static Mechanical Load (3 cycles, +- 2400 Pa)	MQT 13 Damp Heat (200 hrs. @85C/85% RH)	MQT 13 Damp Heat (1000 hrs. @85C/85% RH)	MQT 21 PID Testing (192 hours @ 85C/85% RH, (+ and/or -))
Interim Characterizations	Interim Characterizations	@UV60/TC50/HF10 #1-#3	Interim Characterizations	@Final Characterizations
@TC200 #2	@Dynamic MLT	MST 54 UV (60 kwh/m2 @ 60 C)	@DH1000 #2	MQT 19 Stabilization
MQT 11 Thermal Cycling (200 cycles @ -40C/+85C)	Cyclic Mechanical Loading (IEC TS 62782 , 1000 Cycles / +- 1000 Pa)	MQT 11 Thermal Cycling (50 cycles @ -40C/+85C)	MQT 13 Damp Heat (1000 hrs. @85C/85% RH)	Final Characterizations
Interim Characterizations	Interim Characterizations	MQT 12 Humidity Freeze (10 cycles @ -40C / +85C/85% RH)	@Final Characterizations	
@TC200 #3	@TC50	Interim Characterizations	MQT 19 Stabilization	
MQT 11 Thermal Cycling (200 cycles @ -40C/+85C)	MQT 11 Thermal Cycling (50 cycles @ -40C/+85C)	@UV6.0	Final Characterizations	
@Final Characterizations	Interim Characterizations	MST 54 UV (6.0 kwh/m2 @ 60 C)		
MQT 19 Stabilization	@HF10	@Final Characterizations		
Final Characterizations	MQT 12 Humidity Freeze (10 cycles @ -40C / +85C/85% RH)	MQT 19 Stabilization		
	@Final Characterizations	Final Characterizations		
	MQT 19 Stabilization			
	Final Characterizations			

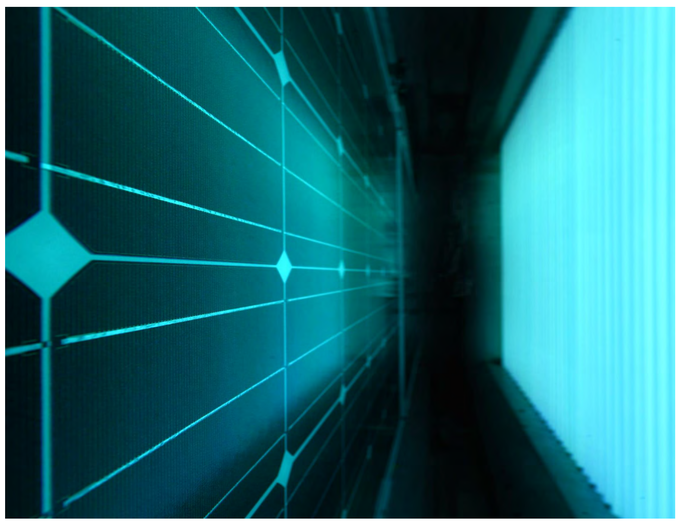
Extended reliability sequence from draft IEC 63209 (subject to change)

Outdoor characterization of modules per IEC 61853-2 (IAM, NMOT)

Batch module acceptance testing, indoor characterization of bifacial modules (IEC 60904-1-2), IEC 61853-1 performance matrix measurements and optimized PAN file generation.

Extended chamber stress testing (TC, HF, DH, UV, PID)

LID / LeTID Test Sequence	
Initial Check	Visual Inspection
	STC I-V + EL Imaging
LID Test (40 kWh/m² cumulative)	Outdoor Light Soak #1 (20 kWh/m²) + STC I-V + EL Imaging
	Outdoor Light Soak #2 (>=10 kWh/m²) + STC I-V + EL Imaging
	Outdoor Light Soak #3 (>=10 kWh/m²) + STC I-V + EL Imaging
LeTID Test	LeTID #1 (75°C, Isc-Imp, 162 hrs.) + STC I-V + EL Imaging
	LeTID #2 (75°C, Isc-Imp, 162 hrs.) + STC I-V + EL Imaging
	LeTID #3 (75°C, Isc-Imp, 162 hrs.)+ STC I-V + EL Imaging



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